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Fire Spalling of Concrete Members

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Abstract: Thermal instability "spalling" occurs when concrete is exposed to fire. This phenomenon, which happens early after a fire starts (about twenty minutes), is one of the most detrimental effects causing damage to concrete members. It can trigger an immediate degradation of concrete, exposure of steel reinforcements to high temperatures and then eventually can cause failure of the concrete members during or after a fire by decreasing the residual mechanical properties and durability of the structure. In spite of many experimental and numerical studies, the real mechanism of spalling is still not well established. Hence, more comprehensive studies on simulating the behaviour of concrete members exposed to fire to investigate the real physics involved and the affecting factors on this phenomenon are currently lacking. The current study at University of Melbourne is attempted to fill this gap. The lack of understanding of the origin of fire spalling is mainly due to the erratic nature of this phenomenon and inhomogeneity of the concrete structures. To establish a more clear view of the phenomenon further investigation is needed. This paper reports the latest findings on fire spalling behaviour of concrete members and shows the deficiencies of the current experimental work and knowledge.

Keywords: fire, spalling, concrete, influencing factors

1. Introduction

"Spalling" can be defined as a thermal instability that occurs when concrete is exposed to fire [1]. Experimental results indicate that by exposing fire to the surface of a concrete member, some micro cracks generate on the surface. By continuing the heating process the cracks develop and some pieces of concrete from the exposed surface dislodge or even fail in an explosive manner. The dislodgement of concrete pieces during a fire is called fire spalling. Referring to spalling, in addition to material loss, reduction of concrete cover, decrease in the cross-section of the concrete member, and exposure of reinforcement to fire might happen [2,3]. Since steel reinforcement has a low yield point, the exposure and sudden increase in the temperature reduces the durability and lead to yielding. As a result, the integrity and the bearing capacity of the structural elements decline and in some circumstances, even structural failure has been reported [4,5].

General studies on fire spalling go back to 1940s and specific attention was paid on this phenomenon after 1996, when the fire spalling happened in three European tunnels.

In spite of many implemented studies, researchers have not yet achieved a consensus agreement on the relative contribution of the influencing factors on the fire spalling phenomenon. Also, no certain results have led to unique established safety code and design guidance for fire spalling [6]. The gap that has been reported is due to the erratic nature of spalling phenomenon. Other functions include non-homogenous structure of concrete material, large number of factors that influence spalling and their interdependency.

Weak understanding of the origin of fire spalling in concrete members can bring about the following problems:

- It slows down the developments on technological solutions to mitigate the magnitude of spalling and embeds achieving predictive calculation of the risk of this phenomenon;
- Due to increasing usage of high strength concrete (HSC) susceptible to higher risk of fire spalling in many engineering applications, it has become a major challenge for concrete designers [7].

The main objective of this study is to present a comprehensive report on research progress which is aimed at contributing to understanding of the origin of fire spalling in concrete members.

2. Reviewing codes and guidelines with special focus on fire spalling

In this section, only two standards are reviewed as other major codes such as American Code, ACI318 do not cover spalling behaviour in concrete.

2.1. Australian guidelines: AS3600, Concrete Structures Standard (2014) [8]

Section 5 of the Commentary to the Concrete Structures Standard discusses design criteria to improve general fire performance of structures such as fire resistance period, fire resistance level, fire-separating function, insulation and integrity of reinforced and pre-stressed concrete members including beams, slabs, columns and walls. To enhance the fire resistance of concrete members tabulated data including the dimensions of the members are suggested. This code commentary was written by Prof. Priyan Mendis, who is a member of the code committee.

In this part some general observations on spalling behaviour of concrete members is mentioned as follows:

"The tendency for spalling is high when

- the element is made of HSC rather than normal strength concrete (NSC);
- the cover to the reinforcement is increased, especially more than about 40 mm
- the moisture content of the concrete is high
- the temperature rise of the fire is rapid and concrete is subjected to a high thermal gradient
- the concrete is subjected to compressive stress; or
- when concrete is subjected to a hydrocarbon fire compared to a standard fire."

In AS3600, referring to the experimental results, adding Polypropylene fibres (PP) with a dosage of 1.2 kg/m^3 and 6 mm length is recommended to reduce the magnitude of spalling.

2.2. European guidelines (2004)

2.2.1. Eurocode -1 [9]

Eurocode-1 presents standard fire curves, which are designed on the basis of real fire experiences to show a more accurate estimate of fire severity using time-temperature curves. These curves are used in testing, analysis and designing to simulate the behaviour of building elements exposed to fire in both experimental and numerical analysis. Referring to different reasons causing a fire, specific time-temperature curves are introduced. The major fire curves are plotted graphically in Figure 1 and described mathematically as follows.

- Standard fires

The fire curve is the most popular fire curve for predicting the fire resistance of building elements. Most standards around the world follow this time-temperature relationship. Mathematically, the fire curve is defined via the following equation:

$$T = T_0 + 345\log_{10}(8t+1) \qquad (1)$$

Where t is time (minutes), T_0 is ambient temperature (degrees centigrade) and T is Temperature (degrees centigrade).

- Hydrocarbon Fire

The hydrocarbon fire curve is applicable where petroleum fires might occur. This type of fire is defined as follows:

$$T = T_0 + 1080(1 - 0.325e^{-0.167t} - 0.675e^{-2.5t}) \qquad (2)$$

Where t is time in minutes, T_0 is ambient temperature (°C) and T is Temperature (°C). In hydrocarbon fire curve the temperature rise is significantly more rapid when compared to a standard fire.

- External Fire Curve

The external fire curve, which is defined via the following equation, presents the time-temperature relationship for members outside the fire compartment. External member is defined as "structural member located outside the building that may be exposed to fire through openings in the building enclosure"

$$T = T_0 + 660(1 - 0.687e^{-0.32t} - 0.313e^{-3.8t}) \qquad (3)$$

Where t is time in minutes, T_0 is ambient temperature (°C) and T is Temperature (°C).

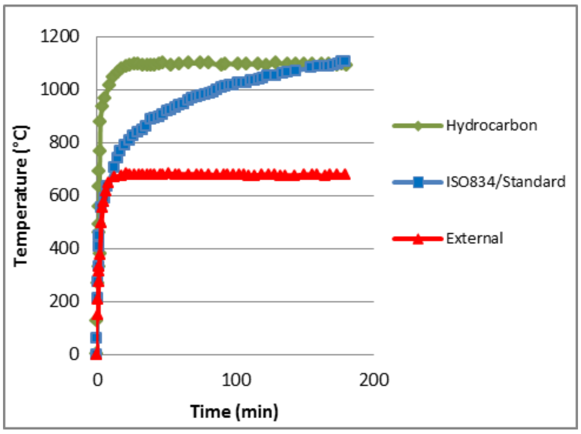

Figure 1: Fire curves used for design of structural members

2.2.2. **Eurocode-2** [10]

Eurocode-2 is a European standard that presents features of the thermal and mechanical properties of concrete and reinforcing steel bars when they are exposed to fire. The main aim of this code is to prevent integrity failure, insulation failure and thermal radiation in concrete members exposed to fire by measuring parameters such as integrity, insulation and load bearing of the exposed members. This code deals specifically with explosive spalling (section4.5 for NSC and section 6.2 for HSC). For NSC with moisture content higher than 3% by weight, assessment of moisture content, type of aggregate, permeability of concrete and heating rate is suggested. In case of HSC the following methods are suggested: using a reinforcement mesh with a nominal cover of 15 mm, using a type of concrete that experimental studies have shown that no spalling will happen for it, using protective layers and using more than 2 Kg/m^3 of PP fibres in the concrete mix

3. Preventive strategies of concrete fire spalling

To mitigate fire spalling in concrete members, researchers have considered some factors influencing this phenomenon.

3.1. Addition of Polypropylene fibres in concrete mix

Many experimental studies claim that using PP fibres could decrease and in some circumstances cancel the fire spalling of the concrete members [6,8,9]. Microscopic study on the behaviour of PP fibres in concrete shows that by exposing concrete to fire, these fibres start to expand, melt, and then shrink at around 170° [13]. The void spaces occur in the concrete referring to melting of PP fibres can be considered as weak points inside concrete. Increasing the heat causes cracks at the edges of the voids. These cracks act as micro gateways around fibres, from which water vapour can pass through by the aid of either capillary forces or the pressure difference. Hence the vapour pressure built-up in the concrete and then the magnitude of spalling could be reduced [3].

Jansson [14] also reported that due to the behaviour of PP fibres in concrete during a fire some additional void spaces are produced in the concrete, which may decrease the durability of the member at first steps of exposing to fire. These voids may be converted in to micro cracks and may become places for stress concentration inside the concrete at temperatures up to 175°C [15]. Therefore, using PP fibres could have some disadvantages on workability of the concrete. Utilizing optimum amount of PP fibres in concrete mix to improve the spalling behaviour as well as durability of concrete members is the matter of importance in this area.

3.2. Reducing water content

To improve the fire spalling performance, pre-drying the concrete is suggested [3,16]. Euro code also suggests decreasing the amount of free water in concrete to less than 3% by weight to reduce the amount of vapour inside concrete at high temperatures. On the other hand, some researchers have reported the occurrence of fire spalling in concretes with low water content [16] . In addition, it was also claimed that even bounded water in high strength concrete could be enough to cause severe spalling [17].

To improve the concrete behaviour in terms of moisture content, efforts need to be made on finding out the optimum amount of moisture, the moisture distribution in different types of concrete and the effect of saturated water inside concrete members on fire performance of concrete [17].

3.3. Utilizing thermal barrier

Referring to some problems that addition of PP fibres could cause, including reduction of mechanical residual strength of concrete exposed to fire, utilizing external thermal barrier or using them in combination of the fibres is suggested [15,16]. Some researchers [5,17] believe that thermal barrier, blocking the heat transfer to the concrete structure, is the most effective but expensive way to improve the fire spalling behaviour of HSC.

4. Experiments

To investigate the effect of the main governing factors on spalling behaviour of concrete walls, experimental analyses have been implemented on NSC and HSC specimens exposed to fire in a furnace. The specifications of the specimens are shown in Tables 1 and 2.
Figure 2 shows a schematic view of a wall specimen exposed to fire. As can be seen, hydraulic jack impose line load on top of the wall. Some sensors are also located on the surface of the wall to measure the temperature and displacements of different parts of the wall. The fire performance of each specimen could be seen through windows located on the furnace.

After testing, the specimens were cooled over two days. Following this, the depth of spalling on the wall surface exposed to fire was measured using a hard net, which is a hard wood panel (1200×2400mm) drilled with net holes (20×20mm net). The depth of spalling was measured via these holes.

Table 1: Concrete mixes ($1m^3$)

Component	NSC	HSC
Cement PC50 (kg)	320	600
Aggregate (kg)	828 (size 10-20 mm)	1029 (size: 5-10 mm)
Elkem Microsilica Fume (kg)		70
Sand (kg)	925	586
Water (litre)	189	140
Superplasticizer Glenium 51		8.5
Water/Binder Ratio	0.59	0.235
Slum (mm)	17.65	18.92
Initial moisture (%)	8.4	5.7

Table 2: Fire resistance test details of concrete wall specimens

	NSC	HSC
Dimension (meter)	2.4 (H) ×1.5 (W)× 0.15 (D)	2.4 (H) × 1.5 (W)× 0.15 (D)
Compressive strength of concrete	30-32 MPa	80-85 MPa
Type of fire	standard	Standard /hydrocarbon
Applied Load using hydraulic jacks	485 KN (eccentricity:10 mm)	485 KN (eccentricity:10 mm)
Reinforcements Strength	400MPa	400MPa
No and size of longitudinal steel	8Y16-300	8Y16-300
No and size of lateral steel	8Y14-300	8Y14-300
Concrete cover	25mm	25mm

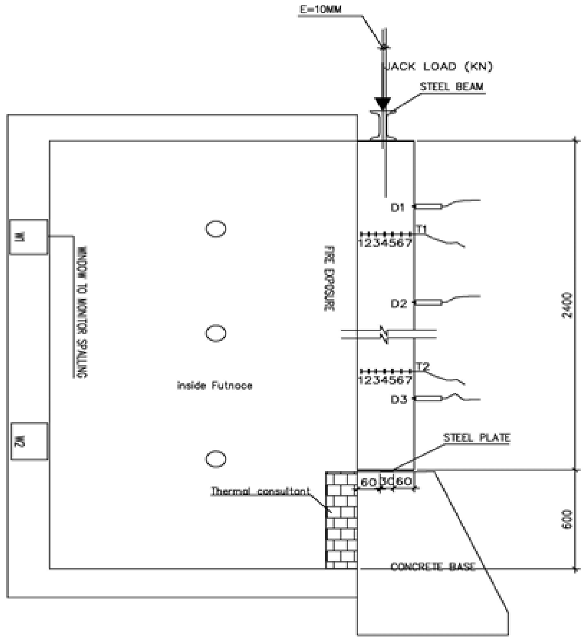

Figure 2: Section of the wall specimen set up in the furnace [21]

5. Results and discussion

Figures 3-5 show the effect of the influencing factors on fire spalling behaviour of concrete walls.

5.1. The effect of concrete porosity on fire spalling

Experimental results comparing fire behaviour of NSC and HSC exposed to standard fire indicate that spalling depth in HSC is larger comparing with NSC (Figure 3) due to the low porosity of HSC.
One of the main reasons affecting the spalling behaviour of concrete is the vapour pressure generated in the pores of a concrete with low gas permeability during fire. By increasing the temperature, water in the pores evaporates and then

solves in free water until the pores become fully saturated. At this stage, pores cannot contain water and vapour at the same time, which cause the pressure inside them to increase considerably. When the pressure surpasses the tensile strength of concrete, spalling happens. Hence it seems that low permeability of concrete impedes internal pressure to escape from concrete and could increase the spalling risk [22]. This could be the reason that HSC materials are more susceptible to spalling than NSC.

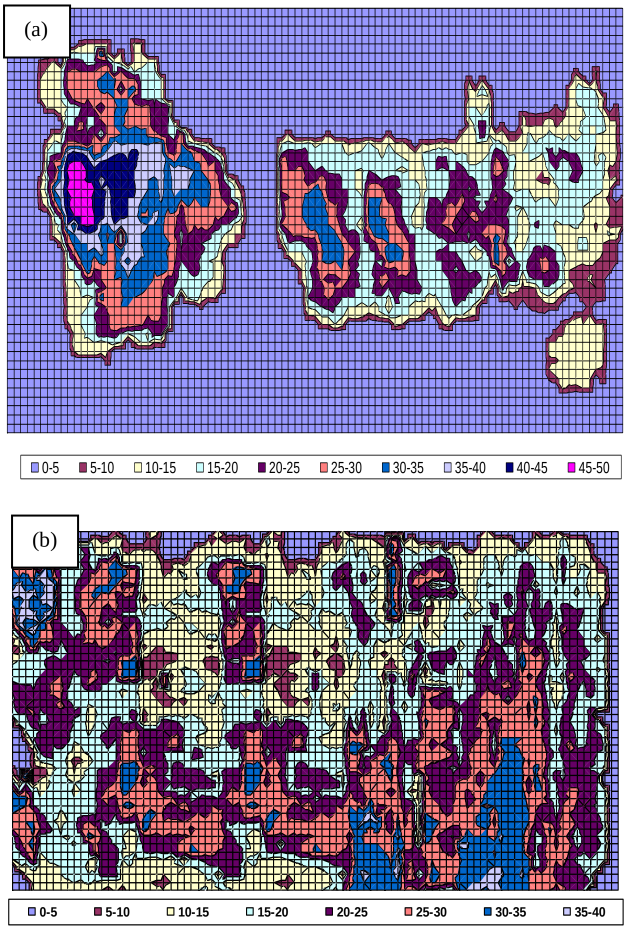

Figure 3: Comparing the spalling depth of (a) NSC and (b) HSC

5.2. The effect of thermal stress and type of fire on fire spalling

Rapid heating gives rise to both temperature and moisture gradient, which leads to higher build-up of pore pressure and tensile stress and then larger spalling [3,20]. Figure 4 shows the experimental results comparing the effect of exposure of hydrocarbon fire with standard fire on spalling depth of HSC. The results indicate that hydrocarbon fire with rapid rise of temperature imposes more thermal gradient and thermal stress, resulted in significant explosive spalling in HSC wall.

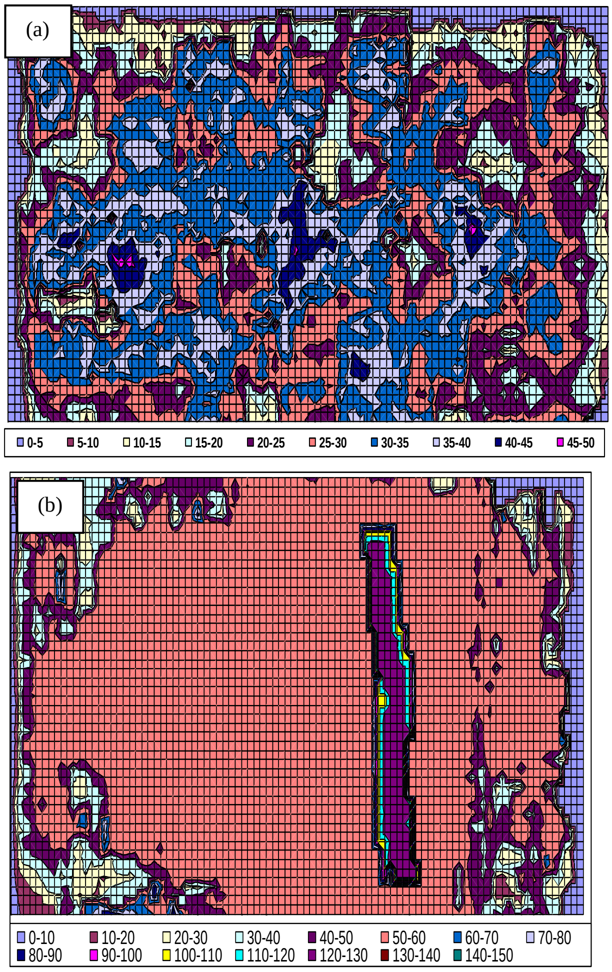

Figure 4: Comparing the effect of type of fire on spalling; (a) Standard Fire, (b) Hydrocarbon fire

5.3. Effect of adding PP fibres in concrete mix on fire spalling

Figure 5 shows the effect of adding PP fibres to HSC mix. As expected, the surface of the HSC without PP fibres is much higher degraded than the one with these fibres. Melting the fibres at high temperatures generates some voids inside the concrete. These voids could act as get ways for the internal vapour pressure. Therefore, reduction of the vapour pressure can mitigate the magnitude of spalling.

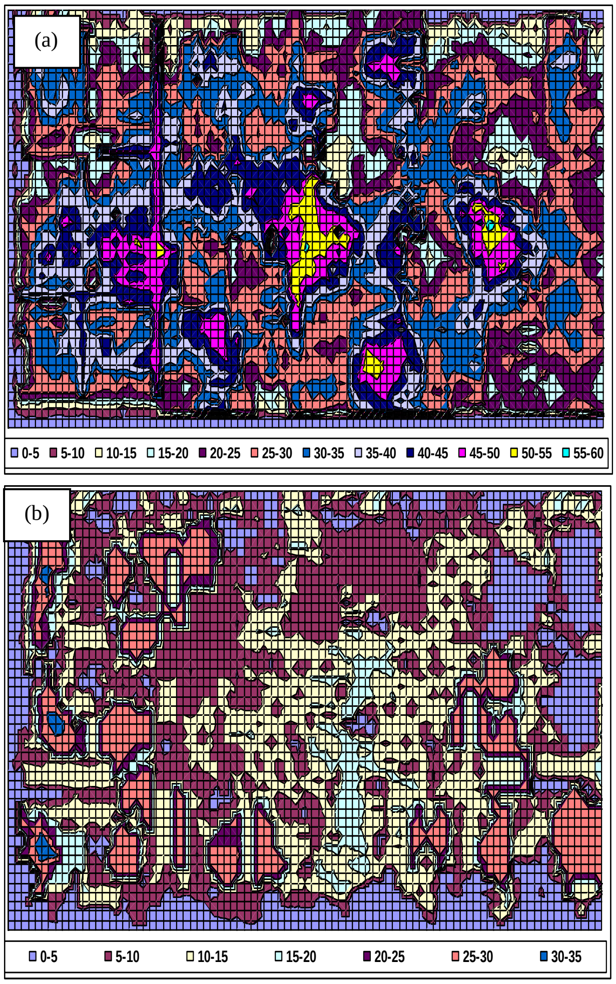

Figure 5: Comparing the effect of adding PP fibres (a) HSC without PP fibres, (b) HSC adding PP fibres

6. Conclusion

Reviewing the previous studies shows that the exact origin of the concrete fire spalling and the physics involved is not yet understood. Continuity of fires, increasing usage of HSC in construction and the susceptibility of these materials to explosive spalling have necessitated more investigations in this area [6]. Since now some influencing factors on the magnitude of fire spalling of concrete and some prevention methods have been found out; which are not comprehensive. To simulate the spalling behaviour of concrete members and figure out the real mechanism of this phenomenon, a comprehensive research program is currently underway at the University of Melbourne.

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