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A new perspective on nature of fire-induced spalling in concrete

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HIGHLIGHTS

- A unified fire-induced concrete spalling theory is proposed.
- Fire-induced spalling is categorised into three types according to their distinct governing mechanisms, viz., thermo-hygral, thermo-mechanical and thermo-chemical spalling.
- The spalling temperature range, influencing factors and the protective measures for each type of spalling are discussed.
- A design concept of 'multiple defense line against fire-induced concrete spalling' is introduced based on the unified fire-induced concrete spalling theory.

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ABSTRACT

Spalling of concrete is a great potential threat to fire resistance of concrete structures. Understanding the underlying mechanism is important to predict and mitigate this unfavorable phenomenon. Currently, there are two main mechanisms to explain the fire-induced concrete spalling: viz. spalling due to (a) pore pressure buildup or (b) thermal stress. The relative importance of these two mechanisms has been a subject of intense debate in the research community over the past few decades. This paper presents a critical review of conflicting and concordant points on concrete spalling at high temperature and proposes a unified and coherent fire-induced concrete spalling theory. Therein, the authors propose three types of thermal spalling depending on the governing mechanisms: thermo-hygral spalling, thermo-mechanical spalling and thermo-chemical spalling. The criteria to forecast each type of spalling are established and the spalling temperature range for each of them is analysed. The spalling pattern, influencing factors and preventive measures for each type of spalling are also discussed in this paper.

1. Introduction

Fire-induced spalling is a phenomenon which occurs in concrete under fire. It is characterised by violent and non-violent dislodgement of pieces or chunks of concrete from heated concrete surface. Spalling results in loss of concrete section, reduction in loading-capacity and consequently fire resistance of concrete members.

Understanding the physics behind this phenomenon is significant for prediction of spalling and advancement in protective measures against spalling. So far mainly two theories have been proposed to explain thermal instability of concrete. The first theory deems that concrete spalling is mainly caused by the buildup of pore pressure, known as pore pressure spalling [1–8]. The second assumes that concrete spalling is mainly caused by thermal stress, known as thermal stress spalling [9–12]. There is also a third school that combines the effects of thermal stress and pore pressure to account for concrete spalling [13–16]. However, no consensus has been reached on fire-induced concrete spalling mechanism to date.

This paper compiles conflicting and common views from previous research works on fire-induced concrete spalling. Based on the analyses of these contradictory and concordant test results, a unified and consistent spalling theory is proposed. According to the driving mechanisms, fire-induced spalling can be categorised into three types: thermo-hygral spalling, thermo-mechanical spalling and thermo-chemical spalling. The mechanisms of these three types of spalling are explained and the criteria to forecast each of them are established in this paper. They are found to occur within different temperature ranges. The factors that influence them, solutions to prevent them and interactions between them are also discussed.

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Nomenclature

β_t	is the scaling factor
$\sigma_{c,a}$	is the axial compressive stress
$\sigma_{c,c}$	is the circumferential compressive stress
$\sigma_{p,t}$	is the tensile stress caused by peak pore pressure
$\sigma_{t,ni}$	is the tensile stress normal to interface between the concrete cover and core
ϕ	is the porosity of concrete
f_c	is the compressive strength of concrete
$f_t(T)$	is the temperature-dependent tensile strength of concrete
$k_c(T)$	is the compressive strength reduction factor of concrete
p_p	is the peak pore pressure
T	is the temperature of concrete
$T_{TCS,t}$	is the threshold temperature for thermo-chemical spalling of concrete
$T_{THS,l}$	is the lower bound temperature for thermo-hygral spalling of concrete
$T_{THS,u}$	is the upper bound temperature for thermo-hygral spalling of concrete
$T_{TMS,l}$	is the lower bound temperature for thermo-mechanical spalling of concrete
$T_{TMS,u}$	is the upper bound temperature for thermo-mechanical spalling of concrete

2. Conflicting views regarding current work on fire-induced concrete spalling

2.1. Spalling mechanism

Fire spalling of concrete is commonly explained by two different mechanisms:

(a) Pore pressure spalling mechanism is mainly associated with thermal-hygral process inside the heated concrete. Pore pressure builds up gradually in the micro-pores as a result of heat transfer and moisture migration. When the tensile stress induced by pore pressure is greater than the tensile strength of concrete, spalling occurs [3,7,8].
(b) Concerning thermal stress spalling mechanism, there are two kinds of views. Some researchers believe that spalling is induced by thermal gradient-induced thermal stress [9,17], while others insist that spalling is caused by compressive stress resulting from restrained thermal dilation [12].

2.2. Influence of factors

2.2.1. Degree of restraint (DOR)

Many experimental results have shown that unrestrained and unloaded concrete specimens experienced explosive spalling under high temperature. The DOR in these tests is zero. According to the theory that concrete spalling is induced by restrained thermal dilation, there should be no spalling in these unrestrained concrete specimens. This inference is obviously contradicted by the experimental results. Therefore, it can be concluded that compressive stress generated from restrained thermal dilation is not a necessary condition for occurrence of spalling in concrete at high temperature.

2.2.2. Thermal gradient

According to thermal gradient-induced thermal stress spalling theory, a high thermal gradient leads to a high spalling risk, and similarly, a low thermal gradient leads to a low spalling probability [18,19]. Hence, concrete under a higher heating rate should be more prone to spalling that concrete under a lower heating rate.

However, Noumowe et al. [18] found severe thermal spalling occurred in concrete at a heating rate as low as 0.5 °C/min. Klingsch [20] studied the influence of heating rate on the occurrence of thermal spalling. Low heating rates were used to minimise the thermal gradient-induced thermal stress. The concrete specimens were also found to spall at a heating rate of 0.5 °C/min. These experimental facts were not in favor of thermal gradient-induced thermal stress spalling mechanism.

Furthermore, concrete with certain amounts of polypropylene fibre (PPF) subject to extreme higher heating rate was observed to be free from thermal spalling [2,21]. In contrast, explosive spalling occurred in concrete without PPF even at 0.5 °C/min. Kanéma et al. [1] found that spalling degree of high strength concrete was greater than ordinary strength concrete, although in their tests, thermal gradient in high strength concrete specimens was lower than that in ordinary strength concrete specimens. These experimental results could not explained by thermal gradient-induced thermal stress spalling mechanism.

On the other hand, thermal spalling in concrete was observed to occur in different manners: at low heating rates (0.5–1 °C/min, or insulated with thermal barrier), concrete specimens could explode violently characterised by a loud bang [20,22], whereas at high heating rates (such as in a hydrocarbon fire), concrete specimens could scale off progressively accompanied by popping sounds [23-25]. It would be far-fetched to rely on thermal gradient-induced thermal stress spalling theory to explain two different spalling patterns exhibited by concrete under different heating rates.

These aforementioned experimental results were in conflict with the theory that the thermal spalling in concrete was governed by thermal gradient-induced thermal stress. Therefore, thermal gradient-induced thermal stress is not a critical factor contributing to spalling of concrete under heating.

2.2.3. Steel fibres

Different conclusions were made about the effectiveness of steel fibres in mitigating spalling of concrete under fire. Klingsch [20] conducted thermal spalling tests on unrestrained and unloaded concrete cylinders with steel fibres and found that steel fibres had no beneficial effect in minimizing the risk of explosive spalling. However, Kodur et al. [26] conducted fire endurance tests on high strength concrete columns and found that steel fibres reduced spalling in concrete columns and enhanced fire endurance of HSC column. The amounts of steel fibres used in the concrete mixes of [20] and [26] are 195 kg/m^3 and 42 kg/m^3, respectively.

2.2.4. Time of spalling

Observations by Harmathy [27] indicated that spalling of concrete tended to occur within 10–25 min in the case of ASTM E119 fire. Mindeguia et al. [28] observed that thermal spalling occurred in unrestrained and unloaded concrete slab between 10 and 20 min of ISO fire test. Ko et al. [29] observed that spalling occurred in unrestrained and unloaded concrete slabs within 10 min of ISO 834 (similar to the ASTM E119) fire heating.

However, Franssen and Dotreppe [30] observed surface spalling in concrete columns between 20 and 60 min of fire test. Kodur and Mcgrath [31] observed significant spalling at the corners of