Explosive spalling of concrete under fire load - A review of spalling theory development

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Abstract

In this work, we will present the most important findings and events concerning the explosive spalling of concrete since its first written account in 1854. As explosive spalling is a very complex process, essential knowledge about the basics of this phenomenon will be discussed. When concrete is heated, it undergoes numerous physical and chemical modifications. Over the years various theories and models have been developed to describe explosive spalling but leave gaps in understanding the leading causes of this phenomenon. Spalling is considered to be a result of a combination of thermo-mechanical and thermo-hydro changes which trigger the formation of cracks. The theories still considered plausible today will be described in more detail and underline the topic complexity.

Today, spalling of concrete due to fire is still topical due to the development of alternative binder systems and additives that may change the microstructure of concrete which therefore may show a different behavior under high temperatures.

Keywords: *concrete, spalling, fire load, permeability, moisture*

1 INTRODUCTION

Concrete is one of the most used construction materials in the world. Compared to steel, which is vulnerable to loss of strength at high temperatures, and wood, which is combustible, concrete can withstand higher temperatures. However, concrete can show the phenomenon of spalling. Spalling is associated with the flaking, breaking off, or in severe cases, instantaneous loss of cross sections. The latest is called "explosive spalling" which can rapidly reduce the load bearing capacity of the structure, thus, resulting in collapse [1],[2].

2 HISTORICAL OVERVIEW

Some important events and discoveries about explosive spalling behaviors over time are listed below:

1854: Presumably the first documentation of explosive spalling of concrete under thermal load. Mr. Tite discovered that using flint as an aggregate in concrete leads to "splitting and yielding" under the influence of fire [3].

1866: Ingle [3] discovered and wrote about improving fire safety by using concrete. He also stated that concrete spalls when water is used on a heated concrete surface. Reductions in concrete strength and loss of its cohesion due to rapid cooling were also mentioned in his work.

1887: Roof tiles exploded while a house was on fire in Switzerland, causing commotion among the population. The roof tiles exploded loudly, while large fragments were shot through the air endangering people. It was found that the dense structure of the tiles, made of one part cement and one part sand, caused this powerful explosion. Older tiles, made from the same material, didn't react in the same way because fine cracks had already developed on their surface and the water vapor wasn't "trapped" inside the tiles [5].

1905: Woolson [6] first recorded the flow of water out from the cold side of a concrete sample during fire tests on floor slabs. This illustrates the fact that, during fire exposure, a continuous crack system is present throughout the cross-section of the specimen.

Miller discovered [7] that when fire testing of concrete is performed soon after manufacturing, important quantities of water are still present in the concrete and must be driven off, leading to disintegration by rapid water/steam expulsion from the specimen. The time allowed for setting before performing fire tests therefore deserves some attention.

1911-1918: M. Gary [5],[8],[9],[10] performed research and experiments on reinforced concrete slabs, walls, columns, beams, stairways, and whole buildings. During his experimental campaign, the concrete aggregate type and dimensions were varied. His results lead to the definition of various types of spalling to differentiate between the destructive and the non-destructive ones, including aggregate spalling, explosive surface spalling, explosive corner spalling and explosive spalling of walls.

1916: In the Far Rockaway fire in the U.S., five of the eight levels of the concrete building were exposed to fire. The 4th floor collapsed during the fire and extensive spalling was found in the building. The reason for the severe spalling behavior was, according to Woolson [11], the use of quartz gravel from the New York vicinity.

1935: A new description of the main factors leading to fire spalling was given by Hasenjäger [12]. He summarized the factors leading to fire spalling:

- Rapid heating of concrete
- Exceeding the tensile strength by unilateral strain
- Rapid structure and volume change in the aggregate
- Pressure from liberation of water vapor and gases from the aggregate and the cement paste.

The main types of stresses identified by Hasenjäger were thermal stress and pressure from moisture.

1961: According to Shorter and Harmathy [13], the primary cause of explosive spalling during a fire is the moisture content of the concrete. The findings gained fame under the name "Moisture clog theory".

1966:. In Saitos’ [14] opinion, it is not the steam pressure of the heated water that is responsible for the explosive spalling but the thermal stress of the concrete near the surface. Explosive spalling occurs when the thermal stress exceeds the concrete compressive strength.

1966: The "frictional forces from vapor flow theory" concept was introduced by Waubke [15] and then further investigated by Meyer-Ottens [16] in 1972. It is also known as the "high vapour drag forces theory" in literature.

1997: According to Khoylou [17], the probable cause of fire spalling of concrete is the occurrence of fully saturated pores. He showed that if 32% of a closed pore is initially filled with water, the water expansion during heating will force the trapped air into solution resulting in a fully saturated pore at elevated temperatures (see below).

2000: The BLEVE (Boiling Liquid Expanding Vapor Explosion) theory can, according to Ichikawa [18], play an important role in the spalling process of high strength concrete. Petrov-Denisov et al. [19] also present a theory that accounts for the rapid expansion of super-heated water. Hertz [20] points out that a progressive breakdown of the microstructure can result.

2020: Liu and Zhang [21] developed an ANN (Artificial Neural Network) model to predict the explosive spalling behavior of concrete. This machine learning approach and shows potential in classifying concrete mixes as resistant or non-resistant to explosive spalling.

3 SPALLING THEORIES

3.1 Pore pressure theory

The pore pressure theory states that pore pressure is the main trigger for explosive spalling behavior. The most important aspects of this theory are briefly presented below.

3.1.1 Moisture clog theory by Harmathy & Shorter [13]

When concrete is exposed to temperatures above 100 °C, the water may undergo a phase transition associated with large expansion, causing its migration towards less confined environments. The moisture movement goes in two opposite directions:

- One part moves in the direction of the heated side, to the outside, and evaporates there.
- The other part moves towards the colder, inner regions of the concrete specimen.

The moisture travels mostly through cracks in the concrete structure, as the hydraulic resistance is low there. When the vapor reaches colder regions inside the concrete, it condenses, slowly filling the pores towards the inner concrete surface with water. The higher the temperature rises, the higher quantity of vapor starts this movement toward the colder regions. Upon getting filled, the pores restrict the vapor movement towards the colder regions. The migration of water in both directions leads to a dry layer of concrete behind the exposed side of the concrete specimen, while resistance against the vapor movement grows too. Concurrently, a very steep temperature gradient is developed across the dry layer. This temperature gradient has two effects:

1. A high heat flow through the dry concrete layer causes high vapor pressure in the border zone. The high vapor pressure, in turn, influences the rate of vaporization.
2. Thermal stresses reach high values

If stresses generated by the large pressure drop coming from the hydraulic resistance to vapor movement become greater than the limit tolerated by the material, a layer with approximately the thickness of the dry zone will be violently spalled off from the specimen.

3.1.2 Frictional forces from vapor flow theory

According to Meyer-Ottens, friction is generated by the vapor movement within the porous material and subjects the concrete to tensile stresses. When these tensile stresses exceed the tensile strength of the concrete, explosive spalling happens.

3.1.3 Idealized spherical pore model

Sullivan and Zaman [22] noticed in their experiments that water-stored concrete specimens are more likely to spall. They created a simplified model, which represents the entire volume of voids of the concrete specimen. The volume of the sphere is related to the entire void space within the concrete, except for the voids in the aggregate itself. The basic mechanism of the model is as follows: The pressure development inside the pores follows the vapour saturation pressure curve. When the pore pressure builds up, hoop stresses are created inside the pores. If these hoop stresses become greater than the tensile strength of the concrete, explosive spalling will happen.

3.1.4 Fully saturated pore pressure theory

This theory was developed by Khoylou [17]. If the DPF (Degree of Pore Filling) of a sealed wet pore is less than 32 %, the pore cannot become saturated during heating, no matter which temperature is applied. Indeed, its free water completely vaporizes during heating. No hydraulic fracturing takes place as there is no additional straining due to expanding liquid. If the steam pressure inside the pore reaches the pressure limit of the solid pore envelope, tensile cracking occurs. If, however, the DPF of the pore is more than 32 %, then a specific temperature T* at which the pore reaches saturation during heating exists. The temperature at which tensile cracking occurs in these sealed pores depends on the tensile strength of the pore skeleton and the volume of water inside the pore.

3.1.5 BLEVE-Theory (Boiling Liquid Expanding Vapor Explosion)

Ichikawa [18] created a mathematical and computational model for heat and moisture transfer in concrete during heat exposure. To validate his model, he compared the numerical results with the experimental data from two other studies (Chapman [23] and Khan [24]). He performed 16 numerical case studies and presented the location, time, and temperature at which concrete spalls. Ichikawa identified three types of spalling:

D High pore pressure due to dry vapor: The spalling occurs in a dry zone, and the state of the water is superheated

W High pore pressure due to saturated vapor: The spalling occurs in a wet zone, and the state of the water is a mixture between liquid water and water vapor

S High pore pressure due to pressurized water (i.e. water-filled pores): The spalling occurs in the saturated zone and the state of the water is pressurized liquid water only.

The S-type spalling is the most destructive as the pressure of the compressed water rapidly increases with the rising temperature. It can happen at relatively low temperatures, from below 100 °C to an upper limit of 320 °C. D-type spalling, on the other hand, occurs at higher temperatures between 320 °C and 540 °C because the pressure of the superheated steam only gradually rises with the temperature. These spalling temperatures are predicted by using the results of the numerical analysis. Ichikawa states that most cases of explosive spalling are created by S-type spalling at temperatures above 100 °C, where water inside the pores is a pressurized liquid (at a temperature above the vaporization temperature at atmospheric pressure). This compressed water causes the initial fracture process of the saturated pores, thus exposing this water to atmospheric pressure. This exposure, in turn, leads to immediate vaporization of the superheated water in the form of BLEVE and to explosive spalling.

A similar theory was created by Petrov-Denisov et al. [19]. There are closed pores filled with superheated water next to open pores with lower pressure. The pressure difference between these two types of pores leads to the destruction of the dividing pore walls, and then to a progressive breakdown of the microstructure [20].

3.2 Thermal stresses theory

The two main components of concrete, cement paste and aggregates, expand and contract differently when under the influence of heat. This difference leads to stresses and microcracks in the concrete matrix. With its low thermal diffusivity and high density, concrete suffers from high thermal gradients close to the heated surface. The area close to the heated surface wants to expand while at the same time, the inner, colder region of the concrete restricts this growth, creating thermal stresses during the heating of concrete [25].

3.2.1 Saito’s theory

Saito [14] regarded explosive spalling as a kind of compressive failure at the heated surface of the concrete. He noticed that the temperature gradients within the cross-section of the heated concrete led to thermal stresses because of the non-uniform temperature distribution near the surface. According to Saito, every point of the concrete specimen cross-section is subjected to a thermal deformation proportional to its temperature. He concluded that the thermal deformation is made of the longitudinal thermal expansion, a curvature and the thermal strain. Compressive stresses are generated close to the heated surface because of the restrained thermal deformation and the unexposed side, while tensile stresses are developed in the cold central regions of the concrete specimen. If those compressive stresses exceed the compressive strength of the concrete, explosive spalling will happen. Additional loads and pre-stresses also increase the compressive stress and, thus, the risk of explosive spalling.

3.2.2 Dougill’s theory

Dougill [26] based his thermal stress theory on that of Saito [14]. But while Saito regarded explosive spalling as a compression failure of the heated surface, Dougill regarded it as a form of instability. Dougill compares heated concrete to a concrete specimen in a very stiff testing machine. If a tensile splitting test is done, the outer regions of the concrete are in compression while the inner parts are under tension. This part of the theory is identical to that of Saito, but here, the stress zones change with the heat exposure time and the geometry of the tested sample. Dougill developed stress-strain relationships in the form of a stiffness matrix and took strain-softening into account. Through this adaption to Saito’s model, the specimen thickness is considered. The influence of the higher heating rate is explained by taking strain-softening into account. According to Dougill, HPC and UHPC specimens are more likely to spall due to their brittle behavior. Dougill noted that lightweight concrete with similar material properties had almost no spalling risk, concluding that his theory only applies to certain specimens, where critical stresses are developed due to load and temperature. The influence of moisture is not addressed in this theory: Water-cured concrete specimens should be less susceptible to explosive spalling because of the higher hydration on the surface and, thus, their better ability to cope with thermal stresses, according to Dougill's theory, contradicting a large body of experimental evidence (Akhtaruzzaman [27], Sullivan and Zaman [22] ,[28]).

3.3 Combined compressive strength and pore pressure theory

Bosnjak [29] studied the interaction between compressive stresses and pore pressures in concrete cubes. These cubes were heated to 230 °C so that the pore pressure could develop, and then were loaded under hydrostatic compression. When the concrete cubes were only exposed to the temperature for a short time, they suffered from compressive failure during the compressive test. Cubes that were allowed a longer heat exposure time spalled very explosively once loaded in compression. The specimens that weren't loaded (just exposed to the heat) didn't spall explosively.

The failure mode of the specimen changes from non-explosive to explosive due to the presence of pore pressure. This led Bosnjak to conclude that a critical combination of compressive stress and pore pressure can result in explosive spalling of concrete. In Bosnjak's scenario, pore pressure can be considered as the main trigger of explosive spalling. She further points out that this scenario does not account for all types of explosive spalling.

3.4 Combined thermal stresses and pore pressure theory

Zhukov **Fehler! Verweisquelle konnte nicht gefunden werden.** was first to recognize that explosive spalling could be caused by superimposition of thermal stresses and pore pressure. He came to this conclusion after observing that concrete with higher moisture content was more susceptible to spalling and that risk of spalling is higher in dense concrete than in normal strength concrete. The load and thermally induced stresses act parallel to the heated surface, while the pore pressure acts at a right angle towards the heated surface. Explosive spalling will occur if the sum of all these stresses exceeds the concrete strength. Zhukov used a model similar to that of Meyer-Ottens [16] to calculate the pore pressure induced stresses.

4 CONCLUSION

During the last 170 years, the behavior of concrete upon exposure to fire or high temperature has been studied extensively. A dramatic consequence of the material response has been called explosive spalling, which refers to the violent ejection of small and large debris from the concrete surface with a high velocity. All the information we have today about the inner proceedings of explosive spalling comes from numerous trials and errors over the past century and a half. For a long time, it was believed that the type of aggregates used in the concrete mix were the cause of the problem. Extensive research programs show that while it has some influence on the behavior, it is by no means the main trigger. The house fire in 1887 in Switzerland led to the discovery that a densely structured concrete surface significantly impacts the explosive spalling behavior of concrete, as liquid water and water vapor cannot escape easily from the structure. Gary [5],[8],[9],[10] never used the expression of permeability, but he already noticed that vapor transport processes inside the heated concrete contribute to spalling. The beginnings of the pore pressure theory and the thermal stress theory were published in the 1960s and the combination of those two theories was first made public in 1971. Over the following decades, numerous additional theories were put forward, and some have already been disproven. The digital revolution made it possible to create complex numerical models to investigate the spalling behavior. This phenomenon has still not been entirely explained yet, but nowadays most authors believe spalling is a result of a combination of thermo-mechanical and thermo-hydro changes, that trigger the formation of cracks. The development of models is being expanded targeting a more precise prediction of explosive spalling behavior. Simultaneously, new binder systems and concrete types are being developed, which react differently to heat exposure and require further explosive spalling research.

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