Diploma Thesis

Explosive spalling of concrete under thermal load - state of knowledge

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Diplomarbeit

Das explosive Abplatzen von Beton bei thermischer Belastung - Stand des Wissens

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Kurzfassung

Diese Masterarbeit beschäftigt sich mit dem explosiven Abplatzen von Beton bei thermischer Belastung. Die erste schriftliche Aufzeichnung dieses Themas stammt aus dem Jahre 1854. Seit diesem Zeitpunkt haben unzählige Forscher und Experten versucht herauszufinden, was der tatsächliche Auslöser dieses Verhaltens ist.

Um diesen langen Prozess der Forschungsarbeit besser verstehen zu können, sind die wichtigsten Erkenntnisse und Ereignisse der letzten 170 Jahre in dieser Arbeit beschrieben. Explosives Abplatzen ist ein sehr komplexes Thema. Aus diesem Grund wurde auch essenzielles Grundlagenwissen für das bessere Verständnis der beschriebenen Szenarien inkludiert.
Verschiedenste Theorien und Modelle wurden im Laufe der Jahre entwickelt, um den Prozess des explosiven Abplatzens besser zu beschreiben. Die heutzutage noch anerkannten Theorien werden im Detail beschrieben, um die Komplexität des Themas darzustellen.

Der letzte Teil dieser Arbeit beschäftigt sich mit einem der größten Probleme dieser Thematik, nämlich dem Hochskalieren der Ergebnisse von Experimenten im kleinen Maßstab auf das Verhalten von größeren Probekörpern. Die Unbekanntheit dieses Skalierungsfaktors führt dazu, dass die Vorhersage des Verhaltens realer Bauteile herausfordernd und unsicher ist.
Die Ergebnisse verschiedenster Forschungsprogramme wurden analysiert, um ein Muster zwischen den Testergebnissen zu finden. Dies ist mit dem gewählten Ansatz nicht gelungen.

Abstract

This master thesis deals with explosive spalling of concrete under thermal load. The first written account of this phenomenon was made in 1854. Since then, many researchers from all over the world have tried to elucidate the governing mechanisms behind this behaviour.

First, the most important findings and events concerning the explosive spalling of concrete over the last 170 years are described for a better understanding of this long knowledge-building process. As explosive spalling is a very complex process, essential knowledge about the basics of this research field is also included in this section. Various theories and models were developed over the years to describe the process of explosive spalling but leave gaps in understanding the leading causes of this phenomenon. The theories that are still considered a possible explanation today are then described in more detail and underline the topic's complexity.

The last part of this thesis presents one of the outstanding issues in this field, namely upscaling the small-scale laboratory experimental results to the behaviour of large-scale elements, making the prediction of real-life structures' behaviour challenging and uncertain. The results of different research programs were analysed to identify a pattern amongst the various test results to describe explosive spalling behaviour, but the chosen approach showed none.

Contents

Abbreviations

BLEVE Boiling Liquid Expanding Vapour Explosion

CTIF International association of fire and rescue services

EC Eurocode

HGV Heavy Goods Vehicles

HHR High heating rate

HPC High-performance concrete

HSC High-strength concrete

LHR Low heating rate

MIP Mercury Intrusion Porosimetry

NMR Nuclear Magnetic Resonance

NSC Normal-strength concrete

PP-fibres Polypropylene fibres

SCC Self-compacting concrete

SEM Scanning Electron Microscopy

UHPC Ultra-high performance concrete

Chapter 1

Introduction

Concrete is one of the most used materials in this world – second only to water. It is a composite material made of water, cement and aggregates. Sometimes admixtures are added to the concrete mix to enhance specific properties of the fresh or hardened concrete. They can improve the workability, accelerate the early strength of concrete or bring other improvements. With the addition of reinforcement in the form of reinforcement steel or various forms of fibres, it is possible to enhance the ductility and tensile strength of the concrete. All these properties make it possible to use concrete for various building projects such as skyscrapers, residential buildings, bridges and roads.

This thesis focuses on the topic of explosive spalling of heated concrete. Explosive spalling is not a new topic for concrete research, it was first mentioned about 170 years ago. What exactly triggers and influences the explosive spalling behaviour in concrete is still a controversial topic and many different approaches to solve this puzzle have been taken over the years.

But what exactly is explosive spalling? When concrete is heated, an internal mechanism is triggered that leads to the ejection of concrete pieces from the heated surface with a high velocity and a loud explosion noise. Various theories have been introduced over the years as to what the main trigger is. The main theories attribute the behaviour to either pore pressure, thermal stresses or a combination of those two.

To support a better understanding of the origins of the different theories, the second chapter of this work gives an overview of the history of explosive spalling. Starting in the middle of the 19^{th} century with the first written account of the phenomenon, the most important discoveries and approaches to the topic are described. As many of the more modern discoveries like the unique void and moisture distribution in every concrete member, or the ability to measure pore pressure, weren't available for a long time, some smaller theories that have since then been disproved are also mentioned in this chapter. Fire accidents that triggered severe explosive spalling in concrete constructions are also included to give a better understanding of the importance of the topic. The endangerment of human life and the huge economic costs for renovation or demolition that come with explosive spalling behaviour show the importance of understanding this problem.

In the third chapter, various important components of the explosive spalling thematic are described. As concrete loses some of its mechanical properties through heating, the physico-chemical changes of the concrete when it is exposed to fire are described. Explosive spalling is influenced by many different factors. Researchers and scientists all over the world are still trying to find out which of these parameters influence the explosive spalling behaviour, in what way and how much. These parameters are introduced with a short explanation as to how they influence explosive spalling and in some cases why their effect is still not clear. Another section of chapter three deals with the topic of result presentation. In later chapters, various experimental programs of different researchers are analysed. Therefore it is important to know how the effect of explosive spalling is quantitatively assessed in different articles. In section 3.4 a statistical method called the z-score is introduced. This method is used to show the distribution of the explosive spalling tests more clearly and it can also be used to define outliers in a dataset. The last section of chapter 3 gives a short introduction to the various proposed solutions to mitigate explosive spalling occurrence.

As mentioned before, over the years, many different theories about the mechanisms behind explosive spalling behaviour were introduced by various researchers. Chapter 4 describes the concepts of these theories and the scientific reasoning for them. The main reason behind explosive spalling is in most cases attributed either to pore pressures, thermal stresses, or a combination of those two. But even among the scientists who believe in the pore pressure theory, the exact way of how they believe pore pressure influences the explosive spalling behaviour differs. This applies analogously to the thermal stresses theory.

Explosive spalling of concrete is a phenomenon that is challenging to predict. Two factors that influence that behaviour are the so-called size effect and its stochastic tendencies. Their effect on the spalling behaviour is studied in chapter 5 by analysing data from various research programs. The size-effect and its consequences are described in chapter 5.1. It addresses the advantages and disadvantages of experimenting on small-scale specimens and gives an overview of the opinions of different researchers that addressed this topic in their work. As experimenting on small-scale specimens is both cheaper and more time efficient than the tests of large-scale specimens, it is important to know if the results of those "small" experiments are representative of actual building structures.
In chapter 5.2, the stochastic tendencies of the explosive spalling behaviour are discussed. Many researchers have difficulties finding the true catalyst of explosive spalling due to large variability during tests: when identical specimens are tested under heat exposure, some spall very violently while others only have a very minor or no reaction at all. Other researchers think that this random behaviour can be attributed to the unique void and moisture distribution in each concrete specimen. For a better understanding of this topic, experimental programs that tested more than two identical specimens under the same condition are analysed in more detail. Statistical methods are applied to find out if these "random" results are truly outliers or if they should be included in the final result set.

Chapter 6 summarises all conclusions reached in this work and refers to important research work that might be able to solve some of the mysteries surrounding explosive spalling in the future.

Chapter 2

Historical overview

2.1 Important events and discoveries about the explosive spalling behaviour over time

Concrete is not the same material as cement, although those two words are often mixed up with each other. Concrete is typically made out of 10 to 15 percent of cement, additives, fillers and aggregates (both mm-size (sand) and cm-size aggregates). The predecessor of cement was already used as early as 6500 BC in southern Syria and northern Jordan. Although this mixture is probably not comparable to modern concrete mixtures, the first use of some kind of concrete was already in use during the Roman Empire in 300 AD. But with the fall of the Roman Empire in 476 AD, the recipe for concrete was lost, and it wasn't used anymore for many years to come. From the 16^{th} century until the end of the 18^{th} century, no remarkable developments regarding concrete were made until John Smeaton rediscovered how to make "Roman cement" in 1793. In 1824 Joseph Aspdin invented the formula for Portland cement, an essential ingredient of concrete.[68]

1854 While exploding spalling of concrete under thermal load isn't exactly a new problem, it wasn't documented until 1854 when Mr Tite discovered that using flint as an aggregate in concrete leads to "splitting and yielding" under the influence of fire [1]. Concrete usage wasn't as common then as it is today, with the real high-rise of concrete usage only starting at the beginning of the 20^{th} century.

1866 In 1866 Ingle [2] 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. In addition to this conclusion, he also presented a solution to this new problem. Adding dried gypsum instead of limestone to the concrete mix would prevent this problem. Unfortunately, it is not possible to say with certainty if these spalling events were of the explosive kind or if it was only surface spalling. [2]

1878 1878 was the year the American inventor Thaddeus Hyatt got granted a patent for reinforced concrete. One year before that, he published the book *An Account of some Experiments with Portland-Cement-Concrete* ([3]), in which he describes experiments performed on Portland-cement-concrete. He was one of the first people who performed large-scale fire tests on reinforced concrete beams. He compared two materials: the Portland cement of the time and a newly developed Portland cement. One of his many experiments involved heating Portland cement bricks for six hours and then partially plunging them into water. In the case of the old Portland cement, the part of the brick that came into contact with the water instantly fell to pieces. In another experiment, he let the bricks, made of the same old Portland cement mix as before, slowly cool down in the open air. Those bricks disintegrated within six to forty-eight hours. Fortunately, the same experiments with bricks made from the new Portland cement didn't have the same consequences. Those specimens didn't disintegrate and only showed signs of a few fire-cracks after the procedure.

1887 When in 1887, roof tiles exploded while a house was on fire in Switzerland, there was quite a lot of commotion among the population. The roof tiles exploded loudly, while large fragments were shot through the air scaring and endangering people. After investigating the incident, it was found that the dense structure of the tiles, made of one part cement and one part sand, caused this commotion. Older tiles, made from the same material, didn't react the same way as fine hairline cracks had already developed on their surface and the pressure wasn't "trapped" inside the tiles. [7]

1903 Until 1903 there were no standardized time-temperature curves for the fire-testing of building parts. Until then, every laboratory used its own specifications. In figure 2.1, the timeline of the development of the standardized time-temperature curve is displayed. For more details, see the works of Babrauskas [22] and Gales et al. [70]. At the International Fire Prevention Congress in 1903, Sachs presented his time-temperature curve, which was adopted as a new standard. It was a simple table where three endurance classes were established: full, partial and temporary protection. A slightly compressed version of the table can be seen in table 2.1. In the U.S., the first standardized test conditions were implemented in New York in 1899, and nationwide standards were first implemented in 1907. [22]

In figure 2.2, you can see the standard fire curve (or cellulosic curve) compared to earlier test curves. The fire curves that are used today are pictured in chapter 3.1.3. Time-temperature curves define what temperature profile should be used during experiments to test the resistance of concrete to different fire scenarios.

Tab. 2.1: Fire test standard of the British fire prevention committee 1903 as published in [22]

CLASSIFICATION	SUB-CLASS	DURATION OF TEST	MINIMUM TEMPERATURES	LENGTH OF HOSE STREAM TEST	FLOORS		PARTITIONS		DOORS	
					Load	Minimum Area	Maximum thickness	Minimum Area	Maximum Thickness	Minimum Area
		[min]	[°C]	[min]	[kg/m²]	[m²]	[m]	[m²]	[m]	[m²]
Temporary	A	45	816	2	not required	9,3	0,051	7,43	0,051	1,86
	B	60		2		18,6	not limited		not limited	
Partial	A	90	982	2	547	9,3	0,063	7,43	0,063	1,86
	B	120		2	820	18,6	not limited		not limited	
Full	A	150	982	2	1094	9,3	0,063	7,43	0,018	2,32
	B	240		2	1367	18,6	not limited		not limited	

1911-1918 M. Gary [5, 7, 4, 6] was the head of the department of the royal material testing office in Germany. He performed important research and numerous experiments from 1911 to 1918 on reinforced concrete slabs, walls, columns, beams, stairways, and even whole buildings. During his experiments, he varied the tested specimens' aggregate type and dimensions. With regard to these experiments, he defined different kinds of spalling to differentiate between the destructive and the non-destructive ones. The main categories were as follows:

Explosive surface spalling When the dimensions of the spalled surfaces measure between 100 cm^2 and several square meters. This type of spalling was mainly observed on walls and columns under pressure. After the spalling, the reinforcement steel was partially exposed. The cause of this spalling type was traced back to water vapour stress in relatively moist concrete by Gary [4].

Explosive corner spalling This type of spalling was observed at the corners of beams, columns and steps, also partially exposing the reinforcement steel. The reasons for this spalling type were explained by the water vapour stresses and the temperature stresses that developed due to the two-sided heat exposure.

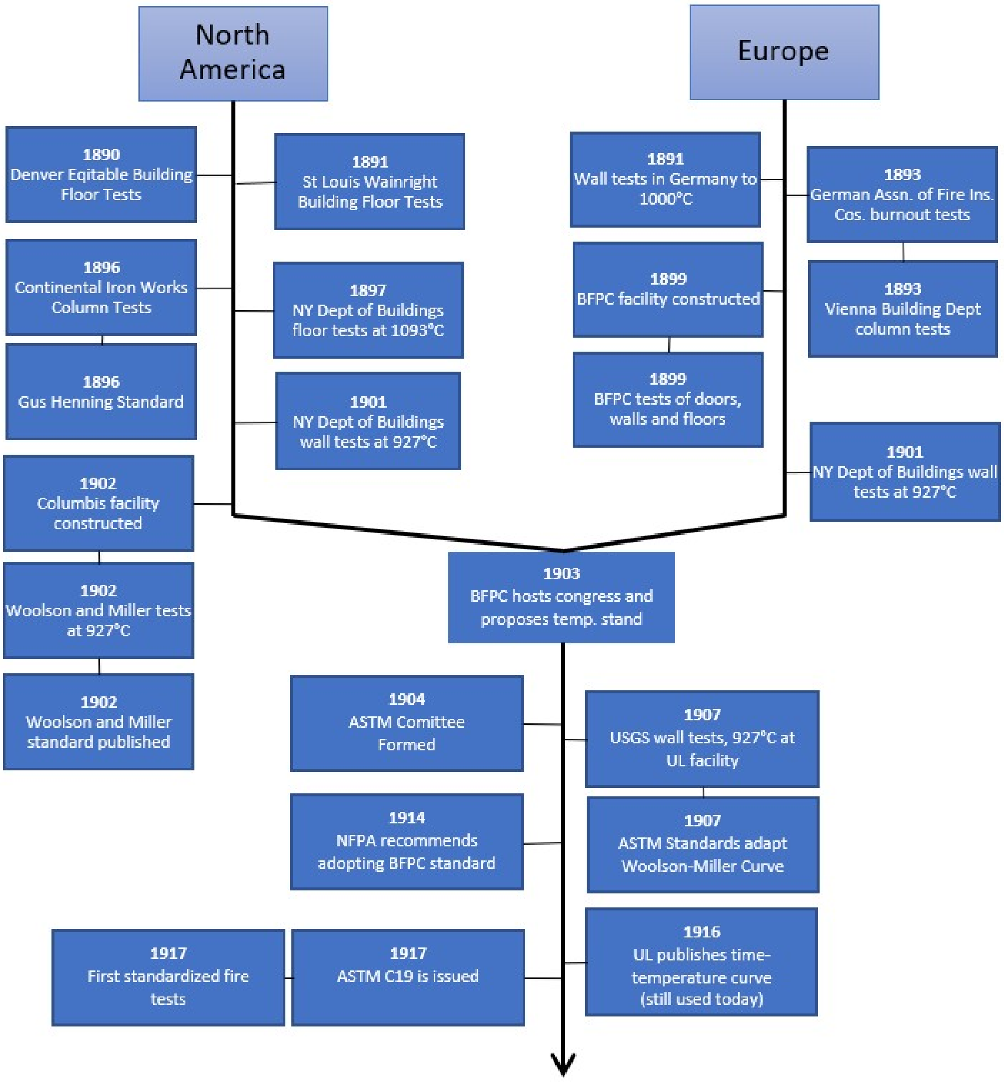


Fig. 2.1: Timeline of the development of the standard time and temperature curve from 1890-1917 with focus on North America and Europe (adapted from [70])

Explosive spalling of walls Up to one square meter big pieces of walls were ejected violently. The room enclosure was lost, but the load-bearing capacity of the walls was maintained. Gary [7] ranked this spalling type as the most dangerous one, but he had no explanation for the cause of it.

In [7], Gary describes fire tests conducted on whole buildings. There were two houses in total with the same dimensions but built with similar yet different concrete mixes. The walls were 8 cm thick with a reinforcement mesh in the middle.

House 1 From now on, referred to as H1. As an aggregate, "Meißner" granite was used.

House 2 From now on, referred to as H2. As an aggregate, Basalt was used.

The buildings were tested on two different days. A few days before H1 was set on fire, it rained. The differences between the results from the fire tests on the two houses were extreme. While H2 didn't show any kind of spalling behaviour, H1 suffered from severe explosive spalling at both

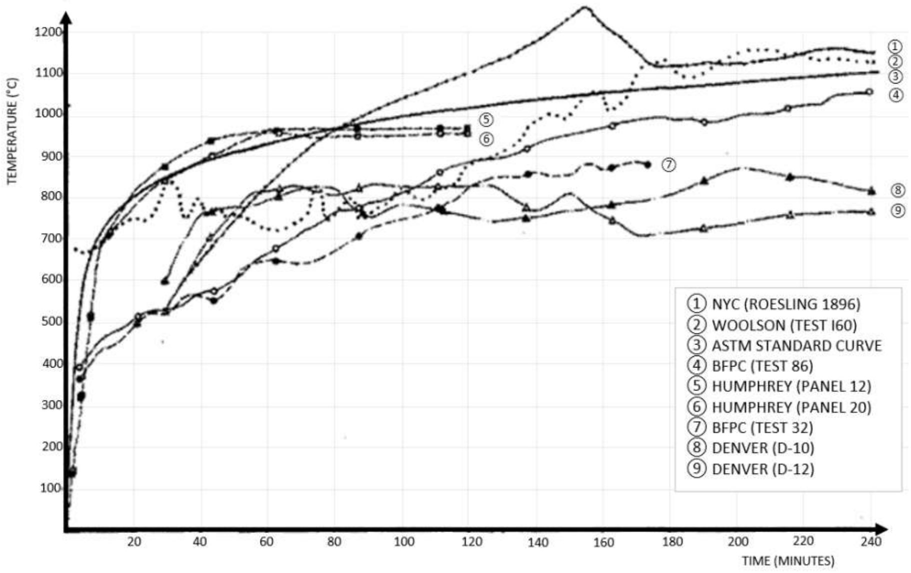


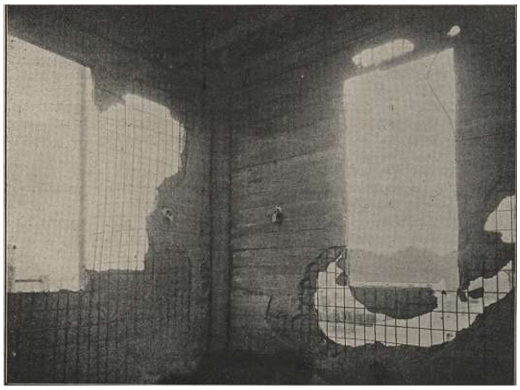
Fig. 2.2: The Standard ASTM curve compared to some earlier test curves as displayed in [22]

the inner and outer layers of concrete. Those layers were blown off and thrown up to 40 meters through the air when the explosions occurred. The destroyed houses can be seen in figure 2.3. The explosions happened approximately 33 minutes after the experiment was started, at a fire temperature of 630°C to 700°C. No explosive spalling occurred on the ground floor, but after 18 minutes, water escaped through the resulting cracks to the outside.

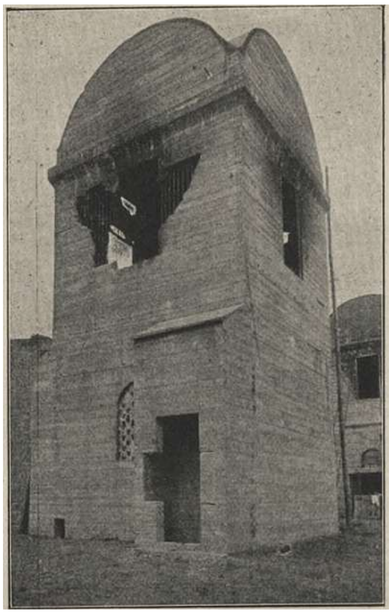
At first, the scientist thought that the additional moisture from the rain caused the violent reaction in H1. To test this theory, H2 was wetted with water and set on fire again. There was no spalling during the second attempt either, but the cracks from the first experiment were enlarged slightly. Investigations regarding the pore distribution of both concrete mixtures showed that it was very different.

It was discovered that the "Meißner" mixture H1 had a dense surface with the majority of its pores trapped on the inside. The H2 mixture, on the other hand, had a lot of pores with an opening towards the surface of the concrete, creating a pathway for the moisture from the inner concrete regions to the surface. One theory developed was that this fact made it harder for the moisture of H1 to escape from the structure. The sudden vaporization of the water led to the spalling of the surface layers to relieve the inner stresses.

Extensive investigations were carried out to ensure that the mineral components or mineral inclusions (crystal water, carbonic acid) of the “Meißner” granite weren’t responsible for the explosive spalling event. The examinations revealed that neither the petrographical nor the mineral nature of the “Meißner” granite was responsible for the violent explosive spalling behaviour. The third suspicion as to the trigger of the violent behaviour was the weathered feldspar inside the “Meißner” granite, which causes a dense surface layer through which the vapour cannot escape when the heating rate is fast. To prove this suspicion, they heated reinforced concrete slabs of the same mixture one-sided, and their reaction was compared to slabs made from different concrete mixtures. It was found that different kinds of aggregates could also cause spalling in concreteThe conclusion was that either the trapped moisture, the trapped air, or a combination of both triggered the explosive spalling. The dense surface of the concrete structure additionally influenced that behaviour in a negative manner.



(a) North-west corner of the house from the inside after fire



(b) South-west side of the building after the fire on the first floor

(c) North-east side of the building after the fire on the first floor

Fig. 2.3: Concrete building made with granite after a damaging fire in which exploding spalling occurred [7]

1925 Hull and Ingberg [8] concluded that the type of aggregate used in the concrete mix causes explosive spalling. While some aggregates expand slowly and gradually when heated, others only expand gradually until a specific temperature is reached and then exhibit a sudden increase in volume. For example, quartz and granite reach this point of sudden expansion at approximately 575 °C. It was concluded that using a “non-spalling” aggregate, such as diabase, is enough to prevent explosive spalling and ensure the necessary fire resistance of concrete. Diabase expands gradually, even heated up to 1000 °C and doesn’t suffer from sudden volume increases like granite and quartz. Another prevention measure proposed was to protect the structure by other means if a “spalling” aggregate is used. In other words, avoiding a core temperature of more than 500°C in the concrete would solve the problem also.

1935 Hasenjäger [9] describes the cause of spalling behaviours in his work from 1935.

- rapid heating of the concrete
- exceeding the tensile strength of the concrete due to one-sided strain
- sudden structural changes and sudden increase of the volume of the aggregates
- pressure effect of released water vapour and released gases in the aggregate and cement stone

He also recommended specific procedures to reduce the risk of spalling in concrete structures. For example, one way to lower the risk is to use concrete with low thermal expansion or a concrete mix with good thermal conductivity in combination with high tensile strength and good elasticity. Another one is using aggregates with low structural changes and low volume changes in combination with sufficient strength. The solution regarding the aggregate type is similar to the one of [8].In addition to the low volume changes, they shouldn't release any gases and vapours when heated, according to [9]. Unfortunately, no more details were given on how to reach those goals.

1956 Malhotra [10] suspected spalling is caused by large temperature differentials between the surface and the centre of the tested concrete specimens.Their investigation aimed to find the effect of temperature on the crushing strength of concrete. However, spalling was not desired in their experiments, and they avoided it by controlling the heating rate so that the temperature gradient across the cross-section of the specimen never exceeded 100 °C.

1961 G.W. Shorter and T. Z. Harmathy [11] published a theory about the cause of explosive spalling in 1961. According to them, the primary cause of explosive spalling during a fire is the moisture content of the concrete. This conclusion was reached by performing a series of tests on concrete walls in the Fire Research Laboratory for the National Research Council of Canada. Their theory is explained in detail in chapter 4 under the name “Moisture clog theory”, but in short they explained the behaviour by the movement of the moisture away from the heated surface. Rising resistance to moisture movement, sharp temperature gradients across the dry layer of the concrete, and with it high vapour pressures are developed until the dry layer detaches and is ejected at high velocity from the specimen. Shorter & Harmathy [11] also proposed that there must be a critical moisture content under which concrete is no longer at the risk of explosive spalling and that concrete which has already aged several years is not at risk anymore for the same reason. They also mentioned that it might be possible for sharp temperature gradients to cause explosive spalling all on their own. However, this idea was discarded because spalling had never been observed in completely dry samples.
Nevertheless, other researchers pointed out that moisture alone could not be solely responsible for the explosive spalling behaviour of concrete and that a combination of mechanisms was likely at play.

1966 Only five years after Shorter and Harmathy published their pore pressure theory, Saito [13] released his thermal stress theory. In Saitos' 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's compressive strength. His solution to the problem was adding a fireproof covering to the concrete members or adding aggregates to the concrete with only a small thermal expansion coefficient.
Gustaferro investigated the general fire resistance of concrete in his work [12]. While explosive spalling is not mentioned in this publication, it is stated that a higher amount of moisture in the

concrete is better for the overall fire resistance. But, as mentioned before, additional moisture would increase the risk of explosive spalling.

1971 Sullivan and Zaman [16] published an article about "Explosive spalling of concrete exposed to high temperatures" 1971. Here they describe the various experiments they used to investigate the explosive spalling behaviour of concrete. During their work, they studied the influence various parameters have on explosive spalling, like curing conditions, age and maturity of the concrete, heating rate, temperature gradient and the size of the concrete specimens. They also came to the conclusion that the "Moisture clog theory" ([11]) can only partially explain the explosive spalling behaviour of concrete. In their opinion, explosive spalling happens due to three different effects: the formation of the moisture clog, the build-up of pressure in the smaller pores and the presence of thermal stresses. The sum of these stresses causes cracks to appear in the concrete when the limiting tensile strength is reached, which leads to a sudden release of energy and causes explosive spalling. More detail regarding this theory is given in chapter 4.
The high build-up of pore-pressure they observed during their experiments was still low enough for the concrete to contain it. Regarding the influence of size on the explosive spalling behaviour, it was observed that smaller specimens weren't as inclined to spall as larger ones. The reason for this behaviour was explained by the less severe temperature gradient in the smaller samples. However, their work pointed out that other researchers didn't reach this conclusion.

1972 Meyer-Ottens studied the behaviour of normal-strength concrete under fire exposure for his master thesis [19] published in 1972. He gives three different causes for the destructive spalling behaviour in concrete:

1. spalling due to the mineralogical structure of the aggregates used in the concrete mix
2. spalling due to temperature stresses
    a) internal stresses as a result of different expansions under non-uniform temperature distribution in the cross-sectional areas of the concrete members
    b) Restrained / forced stresses as a result of different expansions of the concrete and the reinforcement steel
3. spalling due to the moisture content of the concrete

He also found that either a greater moisture content, greater pressure due to external loads or restraint, or smaller distances between the reinforcement would cause a bigger spalling area. Meyer-Ottens also refuted that explosive spalling is caused by the transformation from low-quartz to high-quartz, as proposed in [8], and states that, in his opinion, quartz does not cause more spalling than other aggregate types. Through various calculations, Meyer-Ottens also showed that it is impossible for explosive spalling to happen because the compressive strength of the concrete was exceeded, thus disagreeing with the believes of [13] and others.
Dougill [17] also published a paper in 1972 in which he further developed Saito's theory [13] about explosive spalling behaviour. According to him, destructive spalling most often occurs in concrete members with small cross-sections and when the specimen's thermal expansion is somehow restricted. He approved of Saito's theory but disagreed with the part where thicker cross-sections are more likely to spall than smaller ones. His theory regards explosive spalling as a form of instability, not as a compression failure like Saitos. More about Dougill's theory can be read in chapter 4.

1976 Kordina et al. made it known in their work [18] from 1976 that the fluctuation in results of high-temperature experiments is at least partially due to the size of the chosen specimens. They mention how it is a problem that there are no standardized sample sizes and that every researcher chooses their own experimental setup. With the example of a column and a frame, they proposed a way of calculating the fire resistance of concrete without practical experimentation.Up until this point, the fire resistance in Germany was always determined by experimentation, and this new way would save time and money. The ultimate goal was to find a calculation method to determine the fire-resistance of whole buildings, as testing those is exceptionally complicated and costly. As the deformation behaviour of concrete is highly complicated under transient thermal stresses, the material equations at this time were insufficient to completely describe the performance of concrete under thermal load. According to the authors, this was only the first attempt to predict the behaviour of concrete under fire mathematically, and much further research has to be done. Explosive spalling wasn't mentioned in their work.

1982 Schneider [24] concluded in his work from 1982 that while the moisture content of concrete strongly influences the explosive spalling behaviour of concrete, the moisture distribution is only of minor importance. He thought the moisture content was the main trigger, while the heating rate played a secondary role. Not only is it important how fast or slow the heating rate is, but also if the heat-exposure is unilateral or multilateral. Other deductions of Schneider were that the more sides are heated, the higher the risk of explosive spalling and that high compressive stresses due to external loads or prestressing increase the spalling risk also.

According to Schneider, other factors that increase the risk of spalling are high reinforcement concentration, flint, gneiss, and slate in the concrete mix, and a combination of increasing porosity and decreasing pore radius. In figure 2.4, the connection between the thickness of the concrete member, external stresses and the likeliness to spall can be seen for two-sided heated specimens. The boundary visualizes that using thicker concrete members decreases the risk of spalling.

1984 Hertz [25] deals with the topic of dense concrete with high strength and its susceptibility to heat-induced explosive spalling. This concrete made with silica fume often has a compressive strength of more than 150 N/mm^2 and a high mechanical and chemical resistance. While testing small cylinders of this concrete mix, some samples exploded with such force that the furnace was damaged. After doing some investigations into the moisture content of these cylinders, it was discovered that the moisture loss when heated at a low temperature of 150 °C for seven days was less than 50 percent of that of normal-strength concrete. It was concluded that the chemically bound water, which is released at about 250 °C, plays an essential part in the explosive spalling, which happens at around 300 °C. Furthermore, the author states that this means that the decrease of risk with the increase of concrete age will not be applicable to this kind of concrete. The conclusion of Hertz was that this dense concrete made with silica fume should not be used in structures where a heating rate of more than 1 °C per minute can be expected. Furthermore it was discovered that adding steel fibres to the concrete mix didn't lower the risk of explosive spalling, but the temperature at which it occurred was higher.

1995 In 1995, Connolly [27] describes in his work how even oven-dried concrete specimens may explosively spall if they are uniaxially loaded, although their free moisture content is nominally zero. This led to the conclusion that the theory about pure pore pressure spalling by Meyer-Ottens may be wrong, as he stated in his work that there is a lower threshold of moisture content under which explosive spalling cannot occur. Connolly concludes in his work that no concrete is safe from explosive spalling and that if the combination of load, thermal stresses, and pore

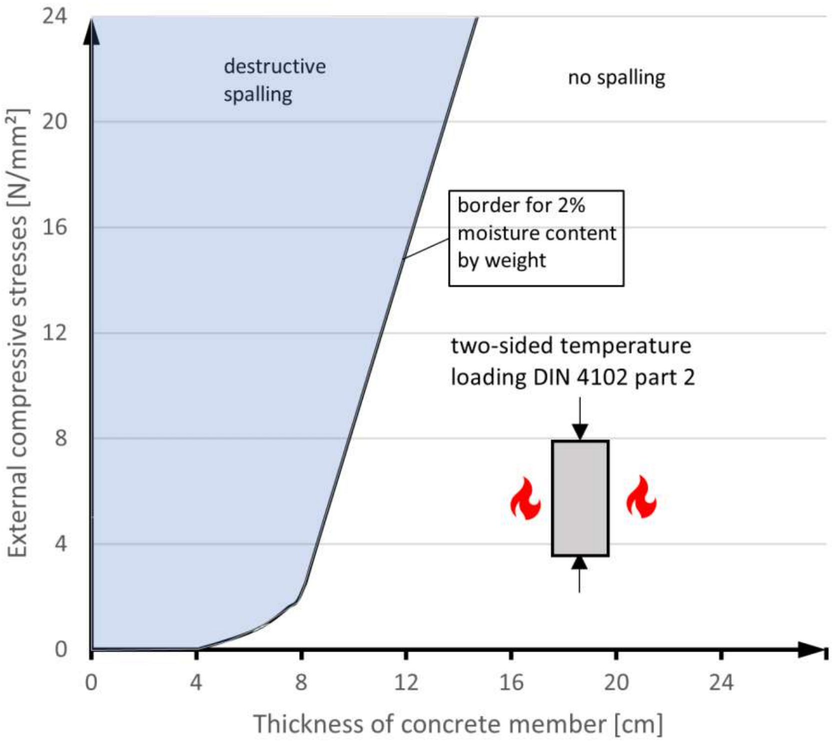


Fig. 2.4: Influence of member thickness and compressive stress on the spalling behaviour of two-sided heated concrete according to [24]

pressure is right, every concrete can suffer from thermal stress induced spalling. Pore pressure spalling is influenced by the water/cement-ratio of the concrete, which in turn influences its compressive strength, permeability, and thermal expansion. He further states that high-strength concrete (HSC) is only more likely to spall than normal-strength concrete (NSC) in terms of pore pressure spalling but is not as risky concerning thermal stress spalling because of its higher tensile strength. He came to the same conclusion regarding specimen thickness as Schneider [24], namely that thinner concrete sections are more likely to spall than thicker ones. Also, the higher the loading level, the higher the risk of spalling.

To summarize, Connolly believed that explosive spalling is due to either pore pressure induced spalling or thermal stress induced spalling. In the case of pore pressure spalling, it is possible to counteract it with low levels of applied loads, as this kind of spalling behaviour mainly happens in unloaded or lightly loaded concrete members or in smaller specimens. If the explosive spalling is due to excessive thermally induced stress, then the imposed load stresses combined with the thermal stresses cause a violent, destructive failure of the concrete member. In theory, this should make higher strength concrete less likely to spall, but the low permeability increases the risk of spalling again.

1996 In 1996, a train that carried heavy goods vehicles (HGVs) caught fire before it entered the Channel Tunnel. The plan was to let the train cross the tunnel until it reached the station on the British side, where the fire could be safely extinguished. Approximately 19 kilometres into the tunnel from the French side, the train came to an unplanned stop, and the fire took its

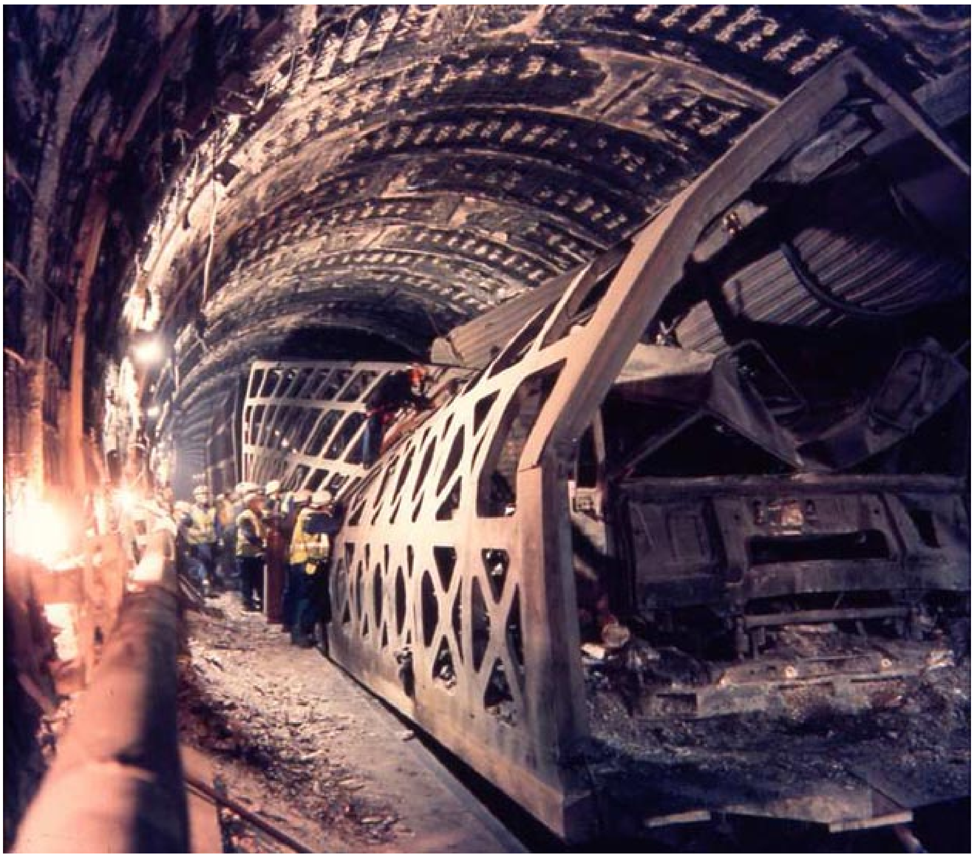


Fig. 2.5: Damage to the concrete lining of Channel tunnel after the fire in 1996 (picture by Eurotunnel)

course. The fire considerably damaged about 480 m of the tunnel, with the most severe damages spanning over an area of 50 m. In this area, the 40 cm thick reinforced tunnel lining was reduced to 17 cm in large parts, and in the most extreme cases, only 2 cm of tunnel lining remained (see figure 2.5). In addition to the 480 m, 240 m were damaged with spalling depths between 5 cm and 20 cm. The steel reinforcement was exposed over a length of 290 m, although the less damaged areas didn't need replacement. The investigations revealed that the temperatures inside the tunnel reached about 800 °C, with 1100 °C to 1300 °C in the most affected areas. The loss of income and the repair costs amounted to 298 million euros. [28]

1997 Bazant [29] gives two possible reasons for explosive spalling in his work from 1997. The first one references the "moisture-clog" theory that Ashton and Bate [11] already mentioned in their work. In this case, a high pore pressure which is produced by the oversaturation of a concrete layer (=moisture clog), leads to violent spalling. The second reason for explosive spalling, according to Bazant, is a brittle fracture of the concrete. The author describes that the potential energy of thermal stresses is stored in the structure, and a sudden unstable release of this energy leads to failure. He further points out that while the high pore pressure undoubtedly plays an important role in the spalling process as only wet concrete seems to suffer from this phenomenon, it remains only a triggering role. Bazant [29] explains his theory as described below:

If high pore pressure is developed at a certain distance from the heated surface, it creates a crack. This crack provides a specific volume for water vapour and liquid. The moment the crack starts opening, this volume increases by several orders of magnitude, forcing the water to expand enormously. If pore pressure were the main reason for explosive spalling, the water of the surrounding concrete would have to flow into the opening crack in a fraction of a second, as this is the time it takes for explosive spalling to occur. As this is not possible, the pore pressure must drop immediately to zero as soon as the crack starts opening up. Therefore Bazant [29] concludes that pore pressure only triggers the crack, but it doesn't have the ability to force the crack wide open. Another supply of energy must be responsible for that. This required energy is available as the potential energy of the thermal stresses.

2000 Ichikawa [35] set himself the goal of predicting the spalling behaviour of concrete with the help of numerical models. He was of the opinion that the main trigger of explosive spalling due to rapid heating is the build-up of pore-pressure, which leads to increased tensile stresses and then to explosive spalling when the tensile strength of the concrete is exceeded. He studied the prediction of pore pressure and the heat and moisture transfer leading to spalling. In his work, he identified three different types of spalling:

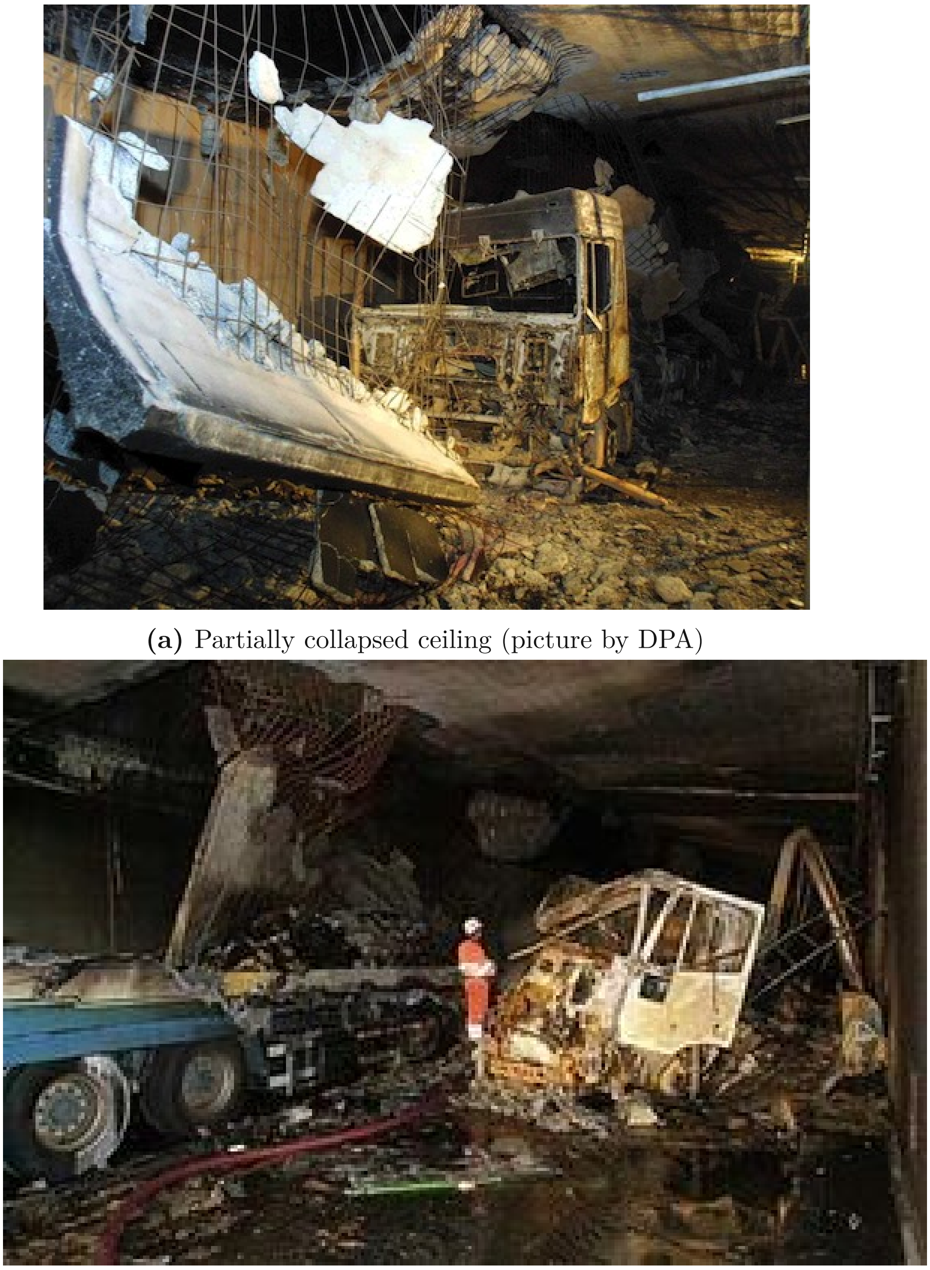
1. high pressures due to dry vapour (D-type)
2. high pressures due to saturated pores (W-type)
3. high pressures due to pressurised water (S-type)

The third type – spalling due to pressurized water – is the most destructive one as it can happen at relatively low temperatures, and the spalling point is located in the saturated zone. More about this type of explosive spalling can be read in chapter 4 in the chapter BLEVE.

2001 In 2001 a truck crashed into an oncoming lorry in the Gotthard Tunnel. As a result of the accident, both vehicles started to burn, and as they were both loaded with tyres and plastic materials, the fire spread quickly under a lot of smoke. In total, six cars, four vans, and 13 trucks burned out in the course of the fire. The false ceiling (see 2.6), which separates the driving area and the air ducts, collapsed over a length of 200 to 250 m due to the fast heating rate and the high temperatures. The effects the fire had on the concrete element can be seen in figure 2.6. [34]

2003 The Hengzhou building in China was an eight-store reinforced concrete frame supported masonry structure. The ground floor was dedicated as market space, while the upper floors were used as living space for tenants. When the market closed, the ground floor was used as storage for chemical materials. Those materials were highly flammable and had a high heat release. When the fire started, it spread quickly through the ground floor while the upper floors weren't affected at first. In figure 2.7, the temperature profile of the fire can be seen. In the high-temperature zones, temperatures from around 800 °C up to more than 1300 °C were developed. This caused explosive spalling in columns E2 and D9. Both columns collapsed due to the buckling of the exposed longitudinal reinforcement and compressive failure. This failure, in turn, caused two beams (8-E/F and 10-D/E) to collapse. The beams also suffered from spalling depths deeper than the concrete cover. The failure of these structural elements triggered the collapse of the whole east side of the building. The primary reason for the initial damage to the structural elements was the extremely high fire load due to the stored flammable materials, for which the building was not designed. The collapse was caused by this and the spalled-off concrete cover, as well as constructional errors in the reinforced concrete frame. In figures 2.8 and 2.9, the collapsed beams and columns are pictured. [57]

Li et al. [57] did a numerical simulation of the collapse process using FEM to understand the collapse mechanisms better. As the simulation of the spalling process is extremely complicated



(a) Partially collapsed ceiling (picture by DPA)

(b) Partially collapsed ceiling and burned out truck (picture by Ti Press)

Fig. 2.6: Damaged and partially collapsed ceiling of the Gotthard tunnel after the fire in 2001

and complex, it was investigated separately from the other factors. The simulation model used was that by Kodur et al. [40]. According to this model, the spalling started at a temperature of 350 °C. As this was simulated separately, the loss of strength and stiffness due to spalling was not included in the main model, but the researcher could conclude that the collapse progress was nearly identical whether spalling occurred or not. It was, however, found out that the amount of time it took the building to collapse was accelerated by 10 minutes due to the spalling of the concrete. As the used spalling model is a relatively simple one, the effect of moisture transfer, boundary conditions, vapour pressure and concrete stress were not included in the simulation.

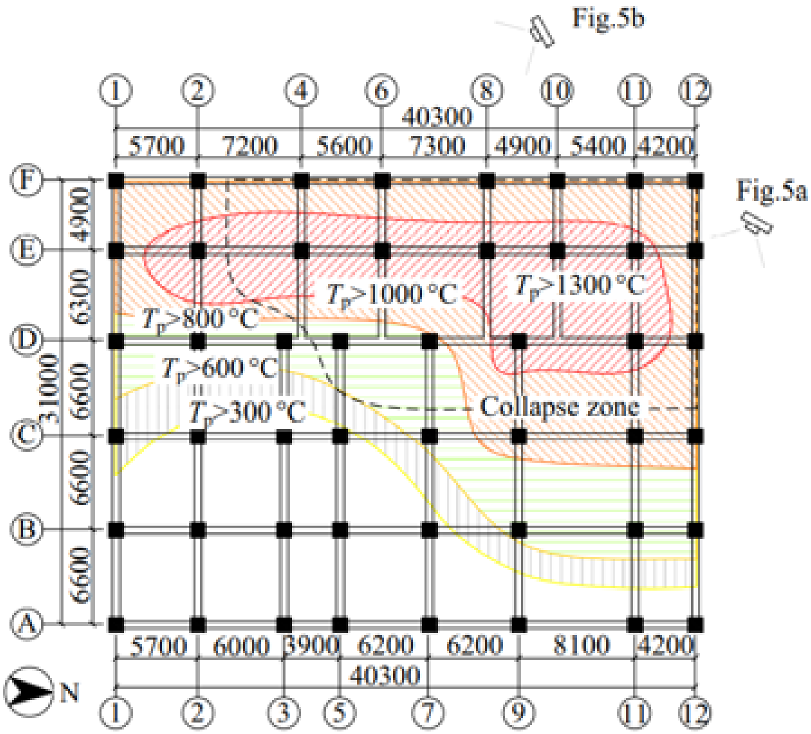
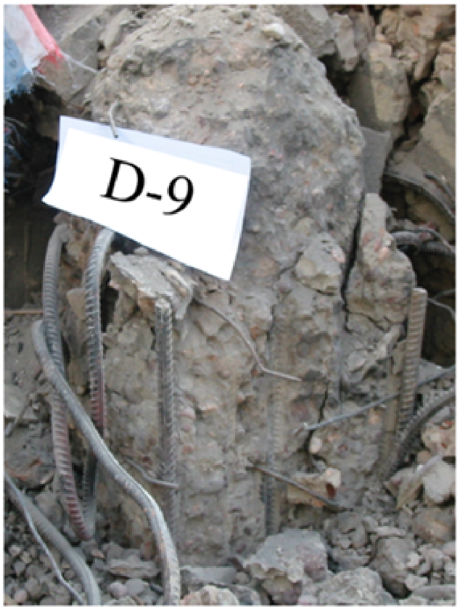


Fig. 2.7: Temperature distribution in the Hengzhou Buidling at the height of the fire by [57]

2009 In 2009 the use of the Eurocode (EC) became mandatory in Austria (see also figure 2.10). According to EC [46, 48] explosive spalling should either be avoided or its influence on the performance requirements (loss of stability (R) and/or EI) should be taken into account. If the moisture content by weight is lower than 3 percent explosive spalling is unlikely to occur. If it is higher, then the moisture content, aggregate type, heating rate and permeability of concrete should be considered. The limit for the maximum moisture content of 3 percent is only a recommendation and can be further specified in the national documents. If the concrete members are designed for the exposure classes X0 or XC1, it can automatically be assumed that the moisture content is between 2,5 and 3 percent by weight. Regarding beams, slabs and tensile members with more moisture content than the specified limit, the loss of stability (R) may be assessed by assuming that the concrete cover is lost over one reinforcing bar (or bundle of bars) in the cross-section and then calculating the reduced load-bearing capacity of the member. Falling off of concrete debris/parts has to be avoided in the early and late stages of fire exposure or it has to be taken into account when considering the load bearing ability (R), the integrity (E) and the thermal insulation (I). All of these rules also apply to high-strength concrete with a concrete grade between C 55/67 to C 80/95 and as long as the amount of silica fume is less than 6 percent by weight of cement. For higher concrete grades or more silica fume content, it is written that spalling may happen in any situation where the concrete is directly exposed to fire. In that case, four recommendations are given, of which at least one should be applied:

1. Reinforcement mesh with at least 15 mm concrete cover and a nominal cover greater than 40 mm for the main reinforcement. The diameter of the wires should be greater than 2 mm and the pitch smaller than 50 x 50 mm.

(a) Collapsed column E-2



(b) Collapsed column D.9

Fig. 2.8: Destroyed columns photographed after the collapse of the Hengzhou Building [57]

(a) Collapsed beam 8-E/F

(b) Collapsed beam 10-D/E

Fig. 2.9: Destroyed beams photographed after the collapse of the Hengzhou Building [57]

2. Usage of a concrete type for which it has been proven by experimentation or local experience that no spalling occurs under the influence of fire.

3. Application of protective layers which prevent spalling under fire exposure

4. Inclusion of more than 2 kg/m^3 of monofilament propylene fibres in the concrete mix.

In Austria, the moisture content by weight, under which it is safe to assume that no explosive will happen, is set as 2 %. For high-strength concrete or a higher fire exposure than the standard fire curve in the first ten minutes, one of the methods (2) to (4) must be applied. [48]

2011 Fu and Li [49] used numerical models and simulations to investigate the spalling behaviour. They suggest that explosive spalling happens due to thermal cracking and high pore pressure.

2014 Bosnjak [53] did various experiments regarding explosive spalling and concluded that very high levels of compressive strength in combination with high pore pressure were the cause sometimes.

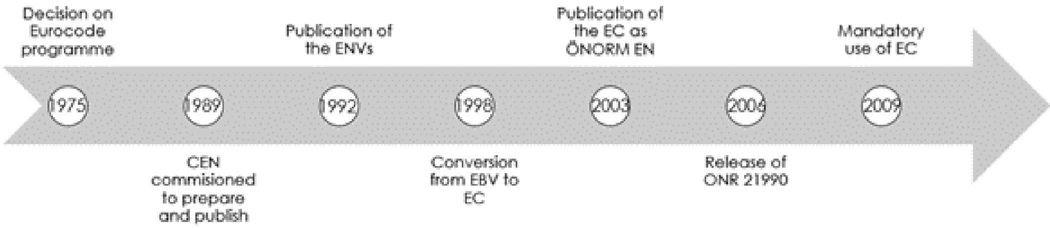


Fig. 2.10: The implementation of the Eurocode in Austria with information from [55]

In these cases, the thermal stresses in combination with the pore pressure were not high enough to cause explosive spalling until the compressive stress was increased by mechanical loading. Therefore the critical combination of compressive stress and pore pressure can lead to explosive spalling in some cases, while in other cases, different stress combinations cause the spalling. Bosnjak defines permeability as the main factor influencing explosive spalling behaviour.

2018 Liu et al. [63] address the three main theories about explosive spalling in their work (pore pressure spalling, thermal stress spalling and combined pore pressure and thermal stress spalling) and propose a spalling theory of their own. They categorize fire-induced spalling by its driving mechanisms into three types:

1. thermo-hygral spalling
2. thermo-mechanical spalling and
3. thermo-chemical spalling.

The first type is what, in this thesis, is regarded as explosive spalling. In the case of [63], it is described as a combination of moisture clogging and pore pressure build-up inside of the heated concrete specimen. The temperature range at the spalling location is given as 220 °C to 320 °C. Type 2 and 3 are types of spalling that don't happen in such a violent way as explosive spalling and are not part of this thesis.

2020 Liu and Zhang [69] developed an ANN (artificial neural network) model to predict the explosive spalling behaviour of concrete. This machine learning approach has a prediction rate of 82,1 % and shows a lot of potential in classifying concrete mixes as resistant or non-resistant to explosive spalling.

This artificial intelligence system is fed with existing sample data and automatically learns from this information without explicit programming. The complex and non-linear behaviour of explosive spalling is challenging to predict with traditional FEM models, and this approach seems to perform quite well. The ANN model used eleven input parameters: water/binder-ratio, GGBS/binder-ratio, fine aggregate/binder-ratio, coarse aggregate/binder-ratio, moisture content, heating rate, maximum exposure temperature, characteristic length of the sample and the maximum aggregate size. 265 test results from various studies were used to feed the model with the initial information. The results are given as a binary classification, 0 meaning no explosive spalling will happen and 1 meaning explosive spalling will occur. To verify the model, 28 sets of 3 small cylinder specimens were tested. The reason for using three specimens for each parameter-set is the stochastic tendencies (randomness) of explosive spalling behaviour. If one of these three cylinders spalled during the fire test, the concrete mix was regarded as "vulnerable to spalling".

The computer model was able to predict the outcome of 23 of these 28 cases correctly, which translates to a total accuracy of 82,1 %. Under a heating rate of 1 °C/min, the accuracy was 100 %, while it was only at 64,3 % for a heating rate of 5 °C/min.
If more initial data is fed to the ANN model it should become even more precise in predicting the outcome. One of the reasons for the inaccuracy of the model is given as the missing moisture content on the day of experimentation in many experimental studies. As this parameter has such a strong influence on the spalling behaviour, it is crucial to collect this data prior to testing.

2021 Hwang et al. [71] studied the behaviour of HSC under fire exposure and came to the conclusion that while slower heating rates lead to explosive spalling, higher heating rates (ISO 834) lead to continuous surface spalling in HSC. This seems to be in accordance with observations from other researchers as well. More details about this conclusion and its effects are given in chapter 3.

2.2 Summary

The long history of concrete, its uses and application limits began already in 6500 BC and is still not completed. During the last 170 years, the behaviour of concrete upon exposure to fire or high temperature has been studied extensively. A dramatic consequence of the material's 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 that occurs when concrete suffers from elevated heat exposure. The exact reasons for this phenomenon have not been entirely discovered yet, but most people believe it is either due to high pore pressure, high thermal stresses or a combination of both of these things inside the concrete.
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 was the cause of the problem. Extensive research programs show that while it has some influence on the behaviour, it is by no means the main trigger. Unfortunate occurrences like the house fire in 1887 in Switzerland led to the discovery that a densely structured concrete surface significantly impacts the explosive spalling behaviour of concrete, as liquid water and water vapour cannot escape easily from the structure. 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 by Sullivan and Zaman. Over the following decades, numerous different 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 behaviour. The development of such models is still being expanded in the hope that the accurate prediction of explosive spalling behaviour may soon be possible.
Rules and regulations were added to the Eurocode in 2009 to make building structures safer in regard to explosive spalling. With modern building practices, the requirements for the durability and strength of concrete have increased. This led to new forms of concrete being developed. As each new type of concrete (HSC, UHSC, ...) reacts differently to heat exposure, explosive spalling research has to be adapted for each case.

Chapter 3

Basic knowledge about explosive spalling behaviour

3.1 Necessary knowledge about the inner workings of concrete

3.1.1 The material concrete

Concrete is a composite material made of water, cement, coarse and fine aggregates, air, and, if necessary, admixtures. Cement is the binder of concrete. When ground clinker and water are mixed, a chemical reaction takes place – the hydration process, that results in cement paste. The cement paste is responsible for binding the aggregates (sand, gravel, crushed stones) into a solid mass as the paste hardens. The end product of this is concrete. [50]
The two major products of this hydration process are calcium-silicate-hydrate (C-S-H) and calcium hydroxide (CH). CH is also sometimes referred to as portlandite. When C_3S and C_2S hydrate, C-S-H is produced, following (3.1) and (3.2) [44]. The excess CaO reacts with water to produce CH. C-S-H is primarily responsible for the strength of cement-based materials.

$$\boldsymbol{C_3S} + (1.3 + x)\boldsymbol{H} \Rightarrow \boldsymbol{C_{1.7}SH_x} + 1.3\boldsymbol{CH} \tag{3.1}$$
$$\boldsymbol{C_2S} + (0.3 + x)\boldsymbol{H} \Rightarrow \boldsymbol{C_{1.7}SH_x} + 0.3\boldsymbol{CH} \tag{3.2}$$

$\boldsymbol{C_3S}$	Ca_3SiO_5	tricalcium silicate
$\boldsymbol{H}$	H_2O	liquid water
$\boldsymbol{C_{1.7}SH_x}$	$1.7CaO \cdot SiO_2 \cdot xH_2O$	calcium-silicate-hydrate
$\boldsymbol{C_2S}$	Ca_2SiO_4	dicalcium silicate
$\boldsymbol{CH}$	$Ca(OH)_2$	calcium hydroxide

3.1.2 Concrete pores

The four main types of pores inside concrete are

- Gel pores: micropores; characteristic dimensions: 0.5-10 nm (most common: 1.5-2 nm)
- Capillary pores: mesopores, average radius: 5 - 5000 nm
- Macropores due to
  - deliberately incorporated air
  - inadequate compaction

Gel pores affect the creep and shrinkage behaviour of concrete but don't negatively impact the concrete strength. On the other hand, capillary pores and macropores influence the strength and elasticity of concrete. [38]
According to Gao et al. [56], the pore structure of the cement paste influences concrete properties such as compressive strength, permeability, and durability. This pore structure mainly consists of gel and capillary pores. Felix et al. [30] state that about 25 % of the total volume of C-S-H are pores smaller than 20 nm.
Klingsch [54] points out in his work that a minimum water/cement ratio of 0.4 is required to reach complete hydration of the cement paste. Approximately two-thirds of this water is chemically bound in the C-S-H-phases, while the remaining water is physically bound in the gel pores. If the w/c-ratio is greater than 0.4, the remaining water remains as free water inside the larger capillary pores (d=10nm-100μm). If the w/c-ratio is lower than 0.4, only very little water remains free. On the other hand, the amount of unhydrated cement is very high, which results in very dense concrete with high compressive strength.

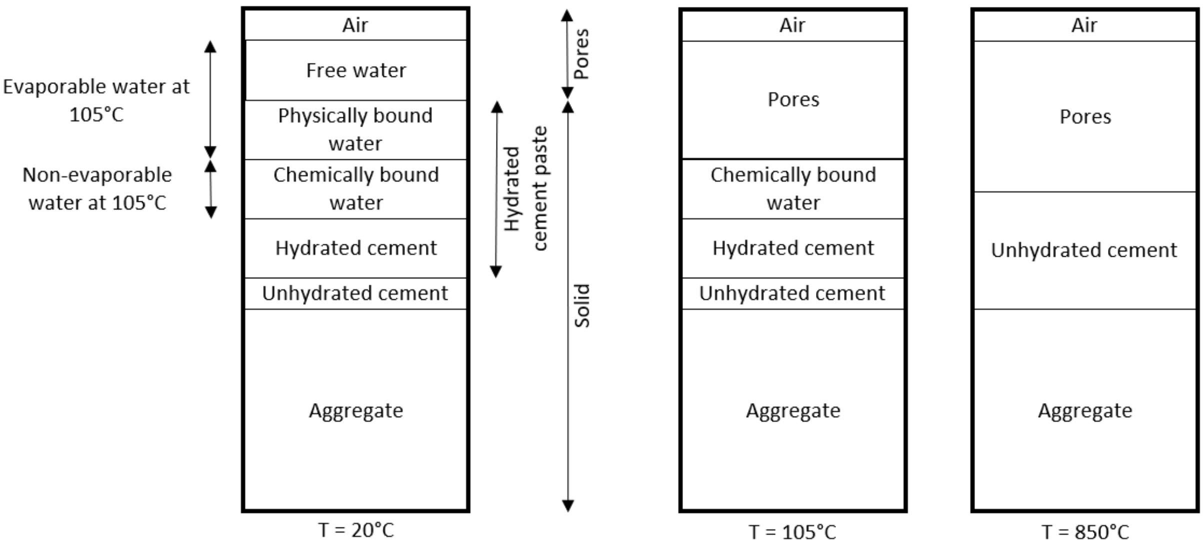


Fig. 3.1: Types of water inside concrete at different temperatures [54]

In figure 3.1, the different types of water inside concrete can be seen at different temperature levels.

3.1.3 Heated concrete

Exposing concrete to heat has various influences on the material. While high heating rates may lead to explosive spalling, it also changes the mechanical properties of the concrete because the chemical composition and the physical structure don't stay the same. Figure 3.1 gives an overview of the reactions inside concrete depending on the temperature.

Tab. 3.1: Influence of heat on concrete

Temperature	**Reactions in concrete**
50°C - 100°C	- Small increase in concrete strength [43]
100°C	- Evaporation of free water (at about 1 bar) - Part of the physically bound water evaporates - Loss of chemically bound water starts [32]
> 100°C	- Most of the physically bound water evaporates
120°C-150°C	- Decomposition of C-S-H-phases [54]
180°C	- Removal of chemically bound water - Dehydration of the cement gel
> 300°C	- Noticeable increase of microcracks an porosity [54] - Compressive strength of concrete decreases significantly
400°C	- Calcium hydroxide in the cement begins to dehydrate, causing a significant reduction in physical strength [41]
400°C-600°C	- Dissociation of calcium hydroxide $Ca(OH)_2 \rightarrow CaO + H_2O$ [54]
535°C	- Highest peak of calcium hydroxide decomposition [54]
~ 575°C	- Quartz-based aggregates undergo mineral transformation, causing an increase in volume [41]
600°C	- Decomposition of C-S-H, resulting in further strength loss [59]
600 - 800°C	- Calcareous aggregates undergo a decarbonation reaction -> leads to increased permeability
~ 800°C	- Limestone aggregates begin to decompose [41] - Chemically bound water is fully evaporated [54]
> 850°C	- Concrete loses its structural performance [66]
> 1200°C	- Concrete starts to melt [54]

Some reactions in the concrete further enable explosive spalling. Reduced strength means there is even less resistance to explosive spalling than before. According to Monte et al. [64], the first spalling occurs when the exposed surface temperature reaches between 300 and 350 °C. This temperature range also leads to microcracks throughout the material, allowing more vapour and moisture movement, and thus reducing the risk of explosive spalling. Other researchers found out since then that explosive spalling may start as soon as the concrete temperature exceeds 200 °C, which is about the temperature at which the second evaporation state happens.

When the temperature exceeds 500 °C, most changes in the concrete become permanent. To better understand the heat exposure of concrete in a fire, the most common fire curves used for fire testing concrete are displayed in figure 3.2. As seen in the figure, each of these curves exceeds the temperature of 500 °C. This is because those curves represent actual fire scenarios depending on the environment in which they could occur. The cellulosic curve is based on the burning rates of common building materials, while the hydrocarbon curve applies to fire scenarios in which small petroleum fires (car fuel, chemicals) occur. The RABT fire curve is used for tunnel fires. In the case of a tunnel fire, a chimney effect occurs, leading to very high temperatures in a short amount of time. This is why those curves reach 1200 °C in only five minutes. The RWS curve is based on a particular fire scenario, where a 50 m^3 tanker (fuel, oil or petrol) catches fire. It presupposes a fire load of 300 MW and is also used for road tunnels. The summary of the concrete reactions in table 3.1 also makes it quite clear why the temperature range of the fires described in chapter 2 was quite so destructive to the concrete structure.

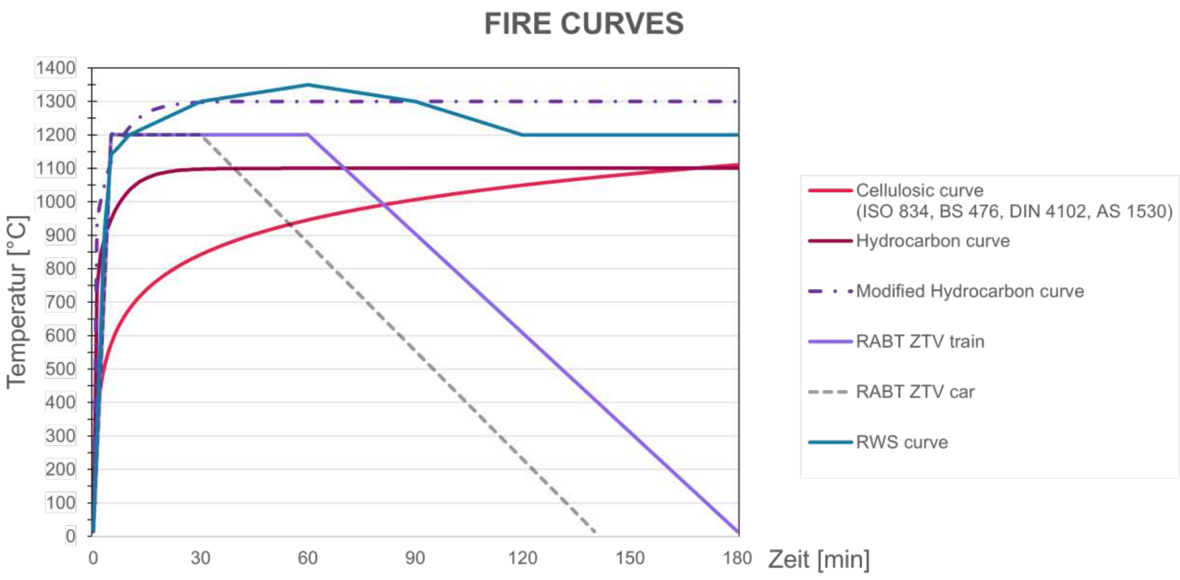


Fig. 3.2: Most common fire curves used for fire testing concrete in accordance with the standards

After a fire incident, building structures need to be assessed for damages. Depending on the degree of destruction, the damage can either be repaired or the building has to be demolished. While high heat exposure reduces the mechanical properties of concrete and encourages failure, explosive spalling may uncover the reinforcement steel inside the concrete, leading to an even faster collapse of the structure or building part.

3.1.4 Temperature distribution inside a concrete specimen

In the case of a fire, the exposed concrete surface suffers the most from heat exposure since the concrete temperature is at its highest here. The temperature inside the concrete specimen decreases significantly just a few centimetres away from the surface. To better illustrate this behaviour, temperature measurements from two different studies are described in the following paragraphs.

Nguyen et al. [61] exposed NSC and HSC walls to the standard fire curve and the hydrocarbon fire curve. Additionally to the fire exposure, the walls were eccentrically loaded. All specimens were tested in a vertical position, supported at the top and bottom only. Seven thermocouples were secured into the specimens as shown in figure 3.3. In the bottom left graphic, you can see the temperature gradients of the first three thermocouples (1,0 cm, 2,5 cm, and 4,0 cm away from the heated surface), while on the bottom right, the temperature measurements for the thermocouples 4, 5, 6, and 7 are shown. The measurements indicate that HSC walls are more temperature sensitive than the NSC walls. At a furnace temperature of about 800°C, the temperature taken 2,5 cm away from the heated surface was ∼300 °C for the HSC specimen and ∼220 °C for the NSC specimen. The difference in temperature between the two concrete types decreases with distance from the heated surface (see figure 3.3).

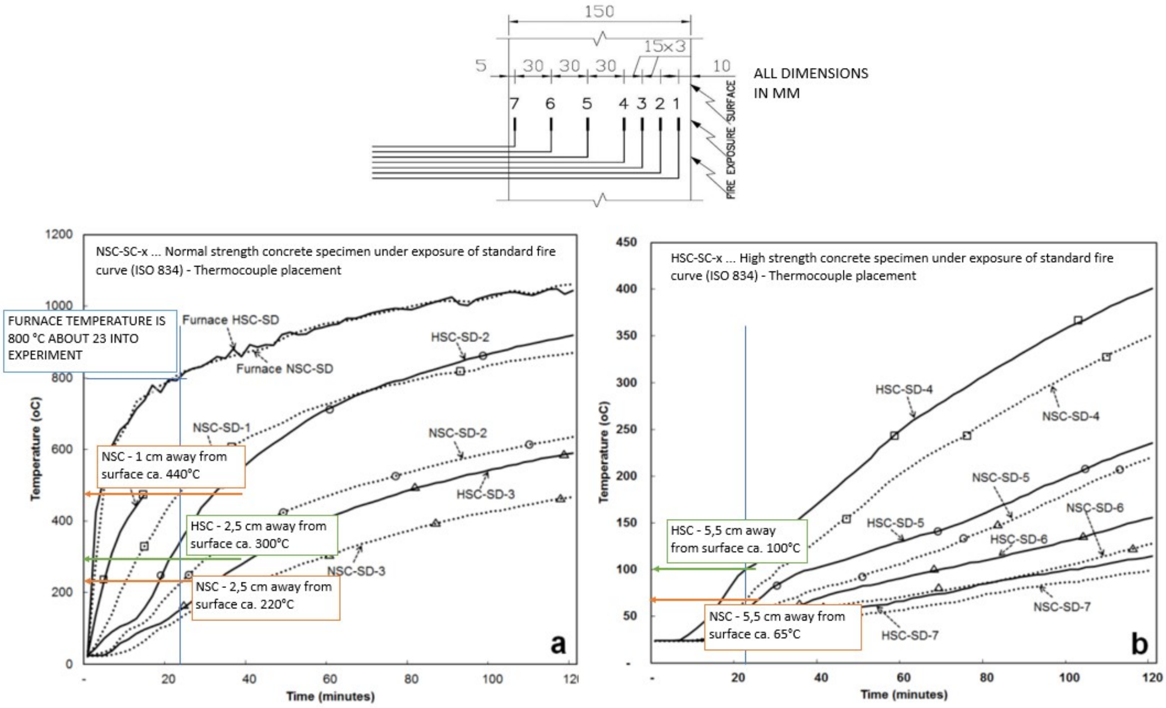


Fig. 3.3: Temperature measurement for the standard fire curve in NSC and HSC specimens as published in [61]

Kim et al. [66] conducted fire simulations to study the effects of fires caused by HGVs. A reinforced concrete specimen was exposed to the RABT fire curve for trains to simulate the tunnel fire. The test specimens measured 1400 mm in length and 1000 mm in width. Only the bottom surface was exposed to the fire. Thermocouples were installed at 0, 20, 40, 60, 80, and 100 mm from the heated surface to measure the temperature at different points. Figure 3.4 shows the experimental results. The International Tunnelling Association (ITA) specifies that the maximum critical temperature for concrete is 380 °C, and for reinforcement bars, it is 250 °C. The two red dashed horizontal lines show these temperatures in the figure.

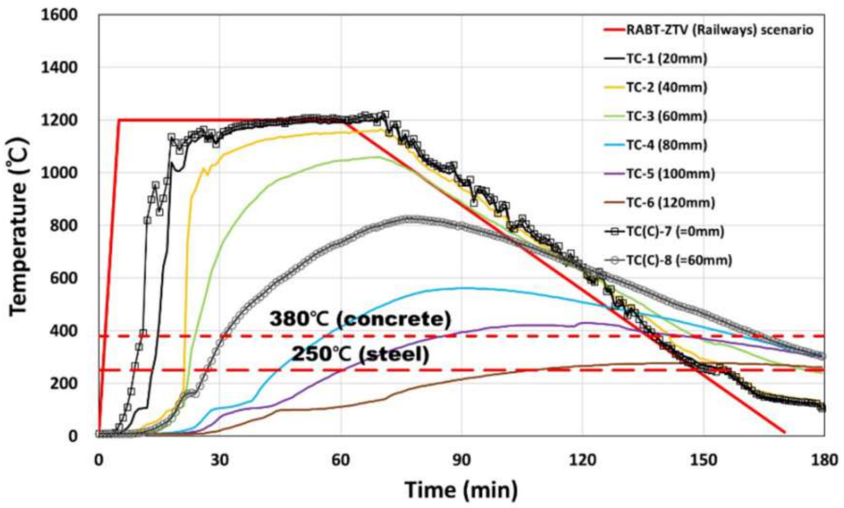


Fig. 3.4: Temperature measurement for the RABT-ZTV (Train) fire curve as published in [66]

3.2 Parameters

The explosive spalling behaviour of concrete is influenced by external factors, geometry, concrete composition, and many other parameters. The following list gives an overview of the known factors:

External factors:

- mechanical loads
- mechanical restraint
- severity of thermal exposure
- number of fire-exposed sides

Geometry:

- size of the heated specimen
- cross-section
- heated area

Concrete mix:

- moisture content
- aggregate type
- aggregate size
- denseness of the concrete
- fibre content
- age of concrete
- permeability
- water/cement-ratio
- water/binder-ratio

Concrete type:

- NSC/HSC/HPC,...
- compressive and tensile strength
- steel reinforcement
- dense surface layer

As seen in the list above, numerous parameters influence concrete's explosive spalling behaviour. However, the scale of their influence on the phenomenon is not clear in most cases, as many researchers give different amounts of importance to them. Another fact worth mentioning is that many of these variables are interrelated, and their simultaneous action may impact spalling in one direction or another in a non-linear way.

3.2.1 Moisture content and concrete age

Moisture was identified as having a dramatic influence on spalling of concrete. The more moisture by mass is present in the concrete, the more likely the concrete is to spall explosively. This is also the reason why in Eurocode [46, 48], it is recommended to keep the moisture amount below 3 % to reduce the risk of spalling. The national documents can further reduce this recommendation. While this is a good first step to improving fire safety in concrete structures, high-strength concrete is known to spall even if the moisture content is far below that (see [65]). Deeply intertwined with the moisture content of concrete is the concrete age. While an increasing concrete age means that the moisture content is reduced, it also means that the denseness of the concrete is increased. More dense concrete has fewer pores and voids with fewer pathways for the water to escape in case of heat exposure. This fact is often mentioned regarding HPC, UHPC or similar concrete mixes, which are believed to be more prone to explosive spalling than normal strength concrete.

3.2.2 Aggregate type and size

The aggregate type was once believed to be the primary source of explosive spalling (see also chapter 2). In the course of the last 170 years, this has been disproven. While the type and size of aggregate have some kind of influence on the spalling behaviour, it is by no means the cause of it, at least regarding modern types of aggregates. Quartz gradually expands during heat exposure until a temperature of approximately 575 °C is reached. At this point, a phase change occurs (α-β-transition), resulting in a sudden volume expansion. The same rule applies to granite [8]. In many fire tests where the temperature of the specimens is measured, it was found that most spalling started at a core temperature of about 230°C, which would negate the involvement of this aggregate behaviour in the explosive spalling process.

3.2.3 Heating rate

The heating rate is one parameter that significantly influences explosive spalling behaviour. The temperature rate seems to have a greater influence than the maximum reached temperature itself. By studying numerous scientific articles, it becomes more evident that this factor affects different types of concrete in different ways. Especially in cases where 2 or more specimens per data set were tested, it is often seen that HSC reacts more violently to lower heating rates than NSC. Like with all the other parameters, the stochastic tendencies of explosive spalling and the influence of so many variables make it difficult to prove this fact definitely. In this case, Hwang et al. [71] introduced a theory to explain this connection between heating rate and HSC spalling behaviour. A higher heating rate leads to a larger temperature difference between the concrete surface and the inner regions which in turn causes the moisture clog to form more closely to the heated surface. Under a slower heating rate, the moisture clog forms further inside the concrete specimen, while the temperature is more evenly distributed, and the stress slowly increases. They tested this theory only for HSC specimens while heating them with either a slow heating rate of about 1 °C/min or the higher heating rate of the ISO 834-fire curve.

3.2.4 Permeability

The permeability of concrete is one factor that influences the spalling behaviour. This is one of the main reasons why it is believed that high-strength concrete is more susceptible to spalling than normal-strength concrete. Ali [37] experimented on full-scale columns to determine if this claim is valid. His research and test results show that the HSC specimens showed a lower spalling degree under axial restraint than the NSC samples. Under external load without axial restraint, the spalling degree of the HSC was slightly higher than the NSC. More about these experiments can be read in chapter 5.2. As the tensile splitting strength of the concrete also influences the spalling behaviour, the author concluded that the high tensile strength of HSC overcomes the low permeability effect.

3.2.5 Concrete type

Concrete is a building material made from a mixture of paste and aggregates in its simplest form. The paste consists of cement and water, while the aggregate can be sand, gravel and sometimes grit. While the earliest use of concrete can be dated back to 6500 BC, modern concrete is a high-tech building material which is constantly getting further developed as there are greater demands on building height and durability. In the course of this work, various concrete types are mentioned. For better understanding, a small overview of the different types is given in the next paragraph with information from Thienel [62].

NSC Normal Strength Concrete. Describes all concretes with a compressive strength class between C 8/10 and C 50/60

HSC High Strength Concrete. Describes concrete with a compressive strength class between C 55/60 and C 100/115

HPC High-Performance Concrete. As mentioned in the description above, HSC is defined through the compressive strength of the concrete. HPC describes concrete based on its performance criteria, like high workability, high durability and high strength. In some literature, the terms HPC and HSC are used synonymously, as HPC has the compressive strength of HSC with additional qualities.

UHPC Ultra High-Performance Concrete. It has a compressive strength than can surpass 200 N/mm^2 and a bending tensile strength of more than 20 N/mm^2.

HSC is increasingly used for high-rise buildings, bridges and offshore structures. As fire safety is one of the main concerns in building designs, this raised the question of how this kind of concrete would react when exposed to heat. Many studies show that HSC reacts differently to fire than NSC. As HSC has a lower porosity than NSC, it is often believed to be more susceptible to explosive spalling, as the vapour pressure cannot escape as easily. On the other hand, the higher tensile strength of HSC works in favour of the resistance to spalling behaviour.

Hwang et al. [71] made an interesting observation while experimenting on single-sided heated ring-restrained HSC specimens. They varied the heating rate and observed that the lower heating rate (1°C/min) leads to explosive spalling while the higher ISO 834 heating rate leads to continuous surface spalling.

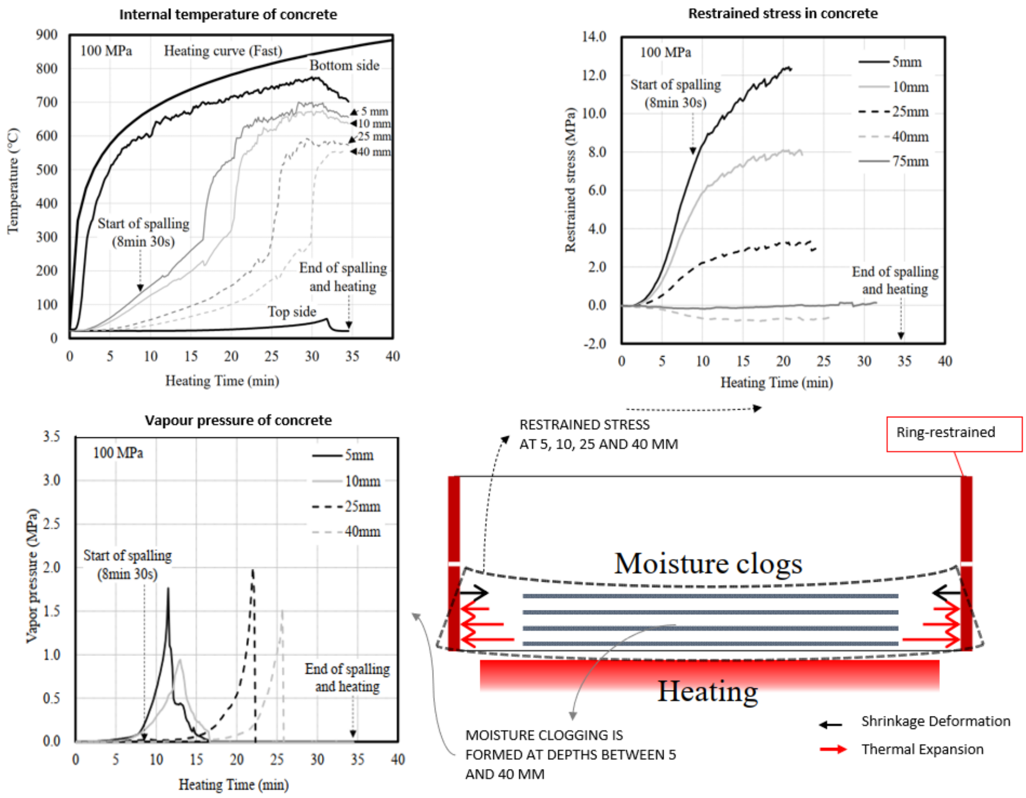


Fig. 3.7: Internal temperature, restrained stress and vapour pressure of a single-sided heated ring-restrained HSC specimen under the influence of the ISO 834 fire curve (by [71])

Figures 3.7 and 3.8 show the internal temperature, the restrained stress and the vapour pressure inside a single-sided heated ring-restrained HSC specimen. At a furnace temperature of 500 °C, the heated concrete surface reached a temperature of ∼350 °C under the ISO 834 curve and ∼430 °C when exposed to the heating rate of 1 °C/min. The temperature of the unexposed surface corresponded to the room temperature of about 24 °C under ISO 834, while it reached about 145 °C when the slower heating rate was applied.
On the bottom left of the graphics, you can see the vapour pressure measurements of the concrete specimens. Under the influence of the fast heating rate, a maximum vapour pressure of 2,0 MPa was observed. When comparing the temperature and the vapour pressure, it is recognizable that the vapour pressure peaked at each measurement point when a temperature of about 130 °C was reached. The measurement points are located 5 mm, 10 mm, 25 mm, and 40 mm from the heated surface. Additional measurements were taken at the specimen's bottom and top surfaces. When exposed to the slow heating rate, a maximum vapour pressure of 7,6 MPa was reached at the 40 mm point, indicating that the moisture clog was formed here.
The restrained stress in the ring-restrained concrete specimens is shown in the top right corner of figures 3.8 and 3.7. It is calculated by using the deformation of the steel ring, which is shown by the dashed black line. Under the ISO 834 fire curve, the restrained stress was higher towards the heated surface due to the high-temperature difference inside the concrete. Hwang et al. further explain in their work that thermal expansion at depths of 5 to 25 mm causes shrinkage deformation in the fast heated specimens. When exposed to the slow heating rate, the restrained stress slowly increased as the temperature difference inside the concrete was small compared to that of the fast heating rate.

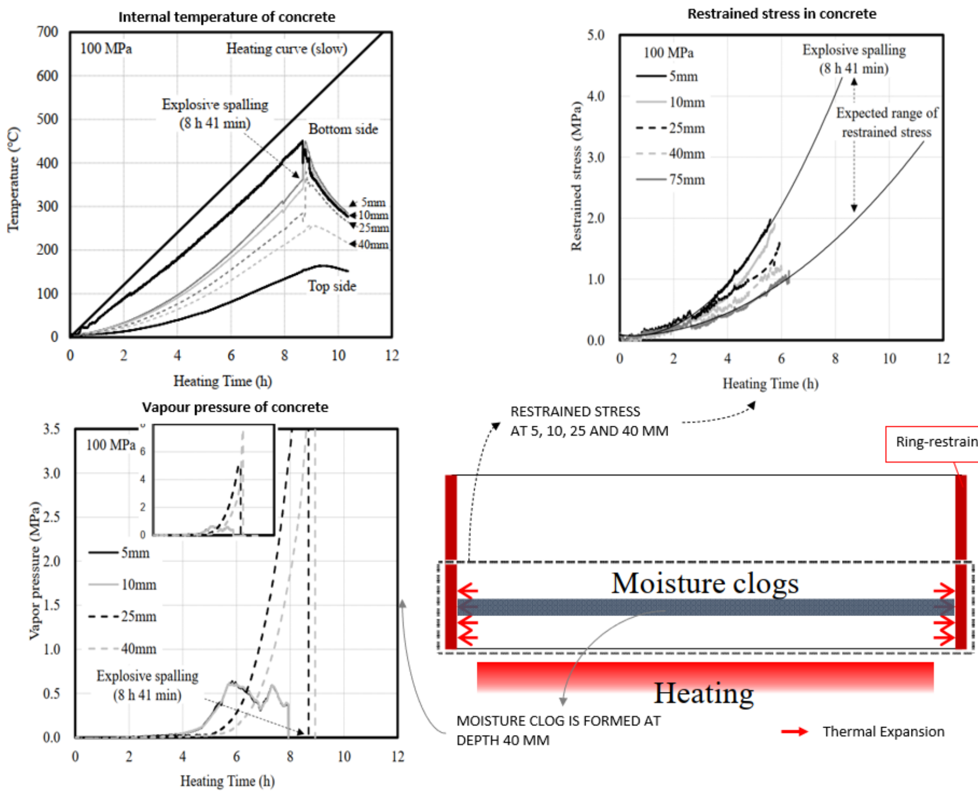


Fig. 3.8: Internal temperature, restrained stress and vapour pressure of a single-sided heated ring-restrained HSC specimen under the influence of the slow heating rate (1°C/min) (by [71])

For a better understanding, you can find a schematic of the above-explained processes in the bottom right corner of the figures.

3.3 Magnitude of explosive spalling damage

Different researchers use different formulas to present their results. Most of the time, the outcome is quantitatively given in a table as spalling degree. This spalling degree gives the mass ratio of the specimen destroyed by spalling. So a spalling degree of 30 % means that about one-third of the original specimen was lost/detached in the experiment. Another way to judge how severe the explosive spalling was is the spalling depth. The maximum spalling depth represents the depth of the most affected point of the specimen, while the average spalling depth gives the average depth over the whole affected area. There are different ways to measure the spalling depth. One way is to use a tachymeter as described in [58]. This tool records the depth of spalling along the width and height of the specimen at specific points, for example, every 15 mm. It can then be used to develop 3D contour maps of the spalling damage. Another option for measuring spalling depth is a handheld 3D scanner as described in [72]. The nominal spalling depth was introduced by Ali et al. [58] in 2017. In this case, the spalling depth is averaged only over the fire-exposed area.

3.3.1 Spalling degree

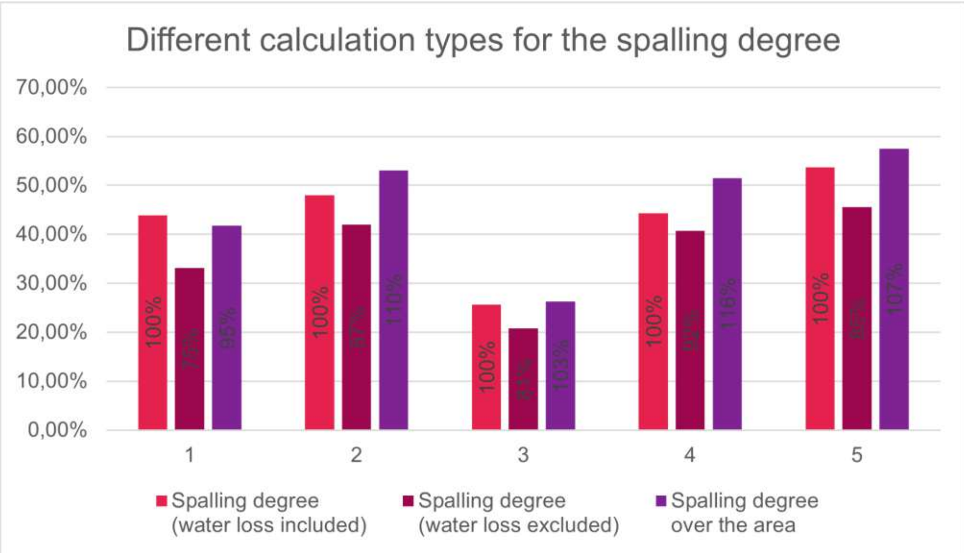


Fig. 3.9: Spalling degree results for 5 full-scale tunnel lining experiments under hydrocarbon fire curve. The first column gives results from [65], formula (3.3). The second and third column give the spalling degree, when calculated with formulas (3.4) and (3.5).

Figure 3.9 shows the results of an experimental study done by Guerrieri and Fragomeni [65]. Five full-scale tunnel linings were tested under heat exposure, and the results of these experiments were given by the spalling degree. The spalling degree always gives the percentage of the specimen mass lost due to spalling.
While this is always true, different ways are used to calculate said spalling degree. When concrete is exposed to heat, it loses mass. Some of this mass loss is due to moisture loss through evaporation and the movement of the moisture clog, while another part is due to solid mass loss because of spalled-off debris. The measurement of the moisture loss due to heating is complicated, so not all scientists include it in their experiments. Three different calculation methods for the spalling degree are given by the formulas (3.3), (3.4) and (3.5).

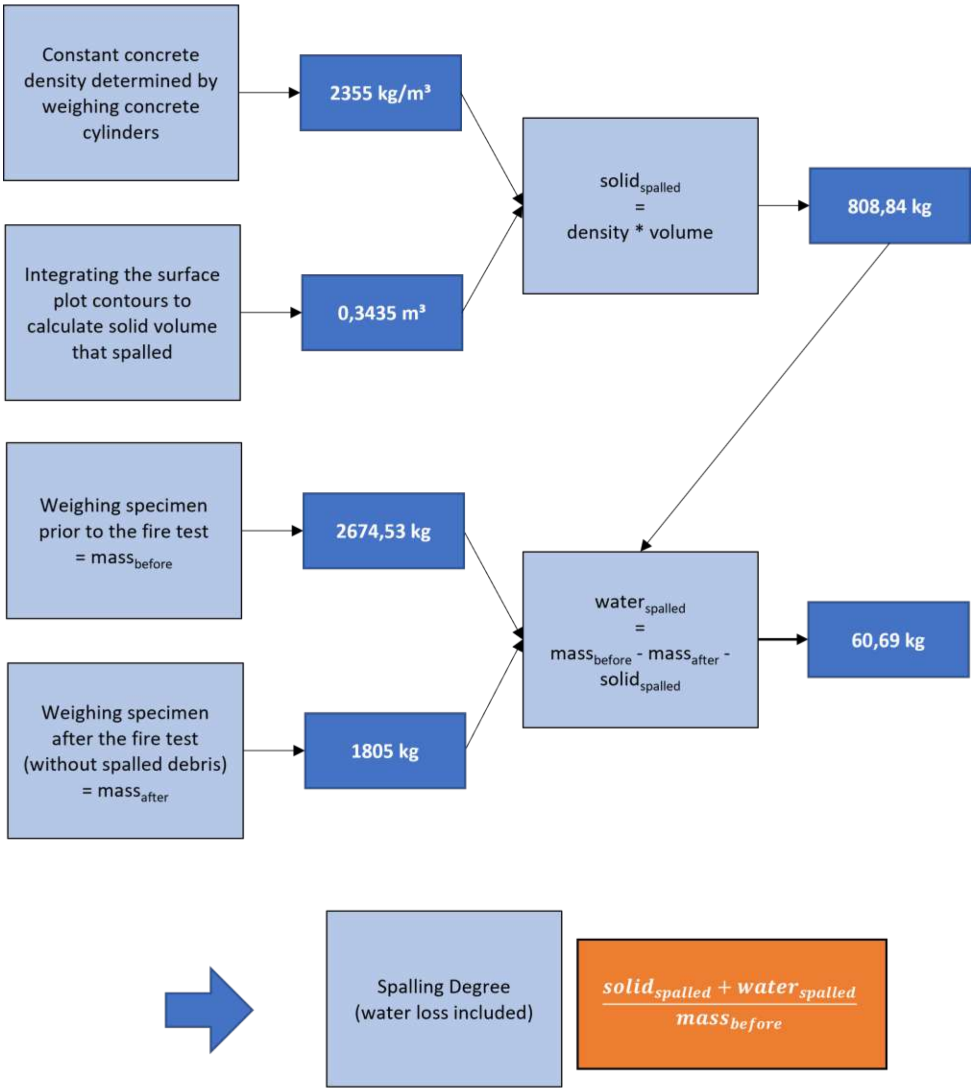


Fig. 3.10: Schematic illustration of the calculation of the spalling degree (water loss included) as dony by Guerrieri and Fragomeni [65]

$$\text{Spalling Degree with water loss} = \frac{w_L + w_W}{w_C} \quad (3.3)$$

$$\text{Spalling Degree without water loss} = \frac{w_L}{w_C} \quad (3.4)$$

$$\text{Spalling Degree over the area} = \frac{S_L}{S_C} \quad (3.5)$$

$w_L \ldots$	Mass of concrete lost due to spalling
$w_W \ldots$	Mass of water lost due to spalling
$w_C \ldots$	Initial mass of test specimen
$S_L \ldots$	Lost area due to spalling
$S_C \ldots$	Cross-sectional area

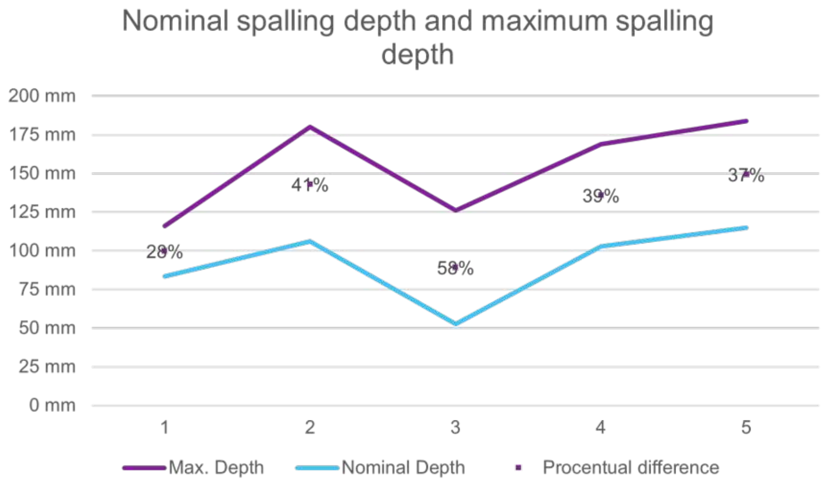
Guerrieri and Fragomeni [65] calculated the spalling area in their work by calculating both the mass lost due to water and the solid mass loss. The procedure Guerrieri and Fragomeni used to calculate the spalling degree, including water loss, is shown in figure 3.10. A uniform constant concrete density is determined by weighing concrete cylinders. After the experiment, the fire-exposed concrete surface is scanned, providing surface plot contours. The total volume spalled from the specimen surface is calculated with volume integration. The solid mass loss is calculated by multiplying the density by the spalled volume. The tested specimen is weighed before and after the experiment. The specimen mass after the experiment and the solid spalled mass is deducted from the specimen's initial mass resulting in the spalled water's mass.

In figure 3.9 we attribute 100 % to the calculation method including the water loss. This makes it possible to compare the different methods with each other. If the spalling degree is calculated without considering the water loss (formula (3.4)), the results are lower. For the five specimens in figure 3.9, the mass loss due to water was between 16 % ± 8 %. As this is quite an extensive range, it is essential to know how the spalling results are calculated when looking at test results from other researchers. Thinking the water loss was included in the results when it is not could lead to overestimating the explosive spalling resistance of a concrete specimen by quite a bit.
The spalling degree over the area (see formula (3.5)) is, for example, used by Qin et al. [73] to calculate the spalling degree of two-sided heated beams. In the case of figure 3.9, it was adapted for the tunnel lining specimens. The results differ from the "spalling degree including water loss" by a maximum of 16 %.

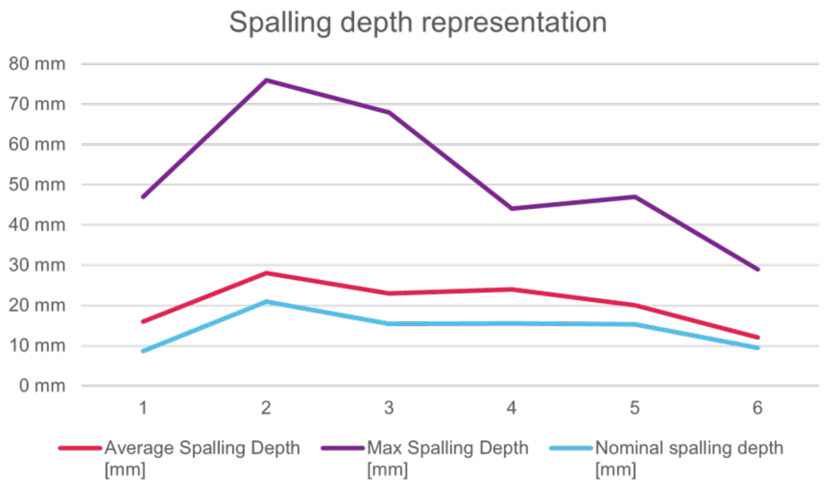
3.3.2 Spalling depth

While the spalling degree gives information about the percentage of the spalled-off debris, the spalling depth is important to assess the damage done. The maximum spalling depth gives the depth at the point of the most severe damage. Suppose this length is greater than the concrete cover. In that case, the reinforcement steel is exposed and directly subjected to the heat source, leading to the weakening of the steel and possible structural collapse of the concrete member.
The nominal spalling depth was first used by Ali et al. [58] to better assess the damage done by explosive spalling. It also makes it possible to compare the test results of different-sized specimens or specimens subjected to different heating conditions (unilateral, multilateral). The nominal spalling depth is calculated using formula (3.6) and has been used by other scientists and researchers since its introduction.

$$d_{SP} = \frac{V_{SP}}{A_{Fi}} \tag{3.6}$$



(a) Nominal spalling depth and maximum spalling depth for full-scale experiments under hydrocarbon fire curve [65]



(b) Nominal spalling depth, maximum spalling depth and average spalling depth for small-scale experiments under hydrocarbon fire curve done by [72]

Fig. 3.11: Comparison of different representations for the result of the spalling depths

d_{SP} ...	Nominal spalling depth
A_{AP} ...	Lost volume due to spalling
A_{Fi} ...	Heated area of the test specimen

The difference between the average and nominal spalling depth is that the former refers to the whole heat-exposed side, while the second only regards the fire-exposed area. As shown in figure 3.11 the difference between the two is low in the experiments of Maluk et al. [72].
A low nominal or average spalling depth in combination with a high spalling degree indicates severe damage in localized areas, while the rest of the specimen wasn't damaged at all or only very lightly. The closer those results are to each other, the more evenly the damage is distributed.

3.4 Z-score

A z-score is a simple way to measure the distance between a data point and the population mean using the standard deviation. How exactly the z-score for a data point is calculated can be seen in equation (3.7). The usage of z-scores makes it possible to :

- earn a better understanding of where exactly a data point fits into a distribution
- identify outliers for the observed population
- compare observations between different variables [60]

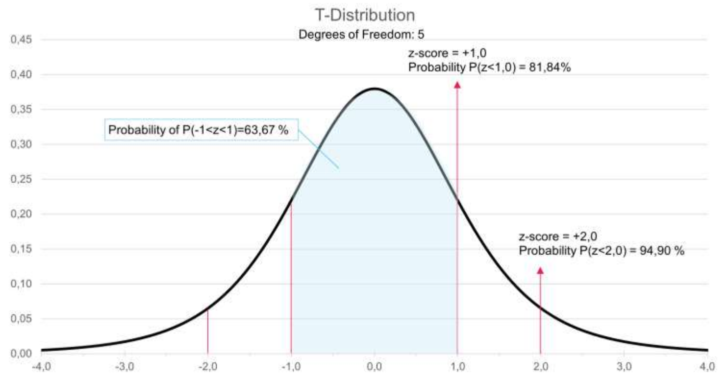
It is also possible to calculate the probabilities and percentiles using the standard normal distribution. As explosive spalling behaviour does not follow this distribution this is not possible in our case.

$$z = \frac{X - \mu}{\sigma} \tag{3.7}$$

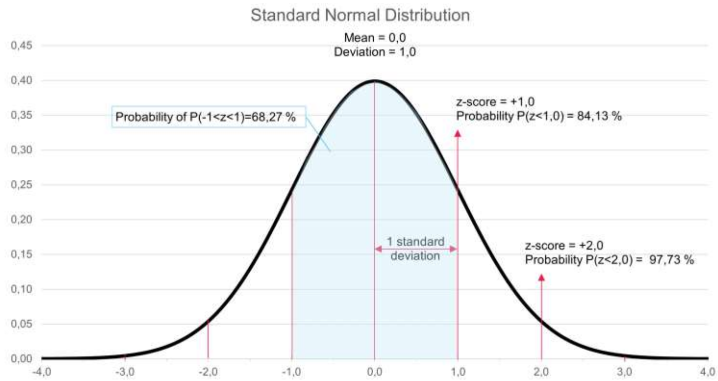
$X \ldots$	Data point
$\mu \ldots$	Population mean
$\sigma \ldots$	Population standard deviation

The calculated z-scores follow the same distribution as the original data. The data does not necessarily need to follow the normal distribution if z-scores are to be used, but the meaning of the results is different for each distribution. For a better understanding, the meaning of z-scores for a T-distribution and a standard normal distribution is shown in figure 3.12. If the data is not following the standard normal distribution, z-scores can still be calculated, but the z-score can't be directly connected to a percentile without knowing the distribution. For the normal distribution, a z-score of less than 2 is reached with a probability of 97.73 %, while for a T-distribution with five degrees of freedom, the probability would be 94.9 %.

The z-score is used to identify and describe the exact location of every score in a distribution. A positive z-score means the score is located above the mean, while a negative score is located below the mean. The number describes the distance between the score and the mean in terms of standard deviation. A z-score close to zero signifies that the score is close to the population mean and representative of the set. For the standard normal distribution, a z-score greater than +2 or smaller than -2 indicates that it is noticeably different from the other results and, therefore, an outlier.



(a) T-distribution with 5 degrees of freedom



(b) Standard normal distribution for a mean of 0 and a standard deviation of 1

Fig. 3.12: Probabilities for z-score values depending on the distribution of the data

3.5 Summary

Exposing concrete to elevated temperature causes various changes in the mechanical properties and the chemical composition of concrete until, at about 1200 °C, the crystalline phases begin to melt. Most cases of explosive spalling have been observed at temperatures between 200 and 350 °C.

Many different parameters concerning external factors, such as concrete mix/type and geometry, influence the explosive spalling behaviour of concrete. How significant the impact of the individual parameters is on the explosive spalling behaviour is still being researched all over the world. For example, higher moisture content increases the risk of explosive spalling while a higher concrete age decreases it, although older concretes have a lower moisture content than younger concretes. Increasing concrete age also leads to a higher density with fewer pores and voids, which has been discovered to raise the risk of spalling in HPC and UHPC. Aggregate type and size have some influence on spalling behaviour. But the sudden volume changes, for example, in quartz at about 575 °C, have been disproven to be the main trigger of explosive spalling. There is the belief that a lower permeability increases the risk of explosive spalling, making HSC more prone to spalling than NSC. Some studies show a lower spalling degree in HSC specimens than NSC specimens. The reason for this may be the higher tensile strength of the HSC and the fact that HSC and NSC are influenced differently by the chosen heating rates. While rapid heating rates lead to extreme reactions in NSC specimens, HSC tends to react more aggressively under the influence of lower heating rates.

The result of a spalling test is generally given as either the spalling degree or the average spalling depth. As there are various options to calculate the spalling degree, it is essential to check the methods used before comparing the experimental results of different researchers. The z-score is a simple way to measure the distance between a data point and the population mean. It can be used to find outliers in a data set and to compare observations between different variables.

Chapter 4

Theories

4.1 Pore pressure theory

Pore pressure theory states that pore pressure is the main trigger for explosive spalling behaviour. The classic approach for the pore pressure theory is the "Moisture clog model" by Harmathy and Shorter [11]. The complete mechanisms behind spalling remain a matter of controversy, but the existence of the moisture clog itself has been visualised by splitting spalling concrete slabs during a fire test (see figure 4.1).

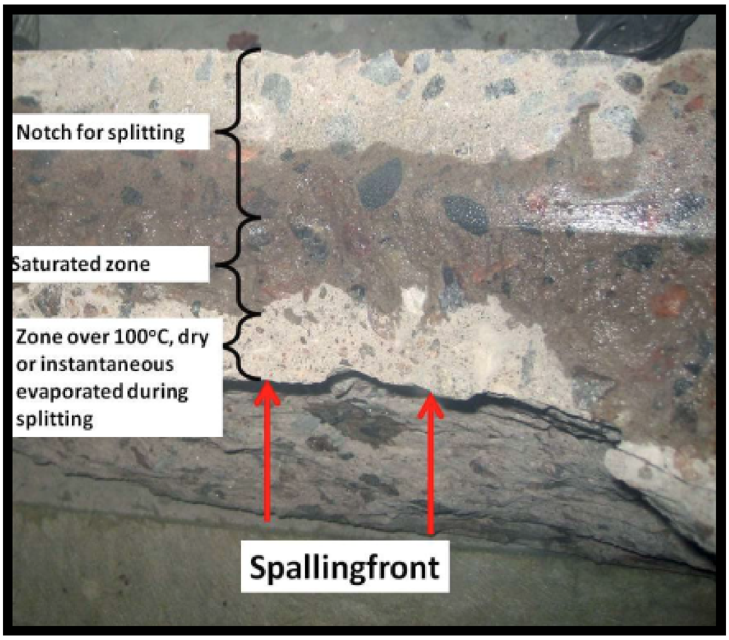


Fig. 4.1: Moisture Clog visualized by splitting a 600x500x200mm^3 concrete slab during a fire test [51]

4.1.1 Moisture clog theory - Harmathy & Shorter

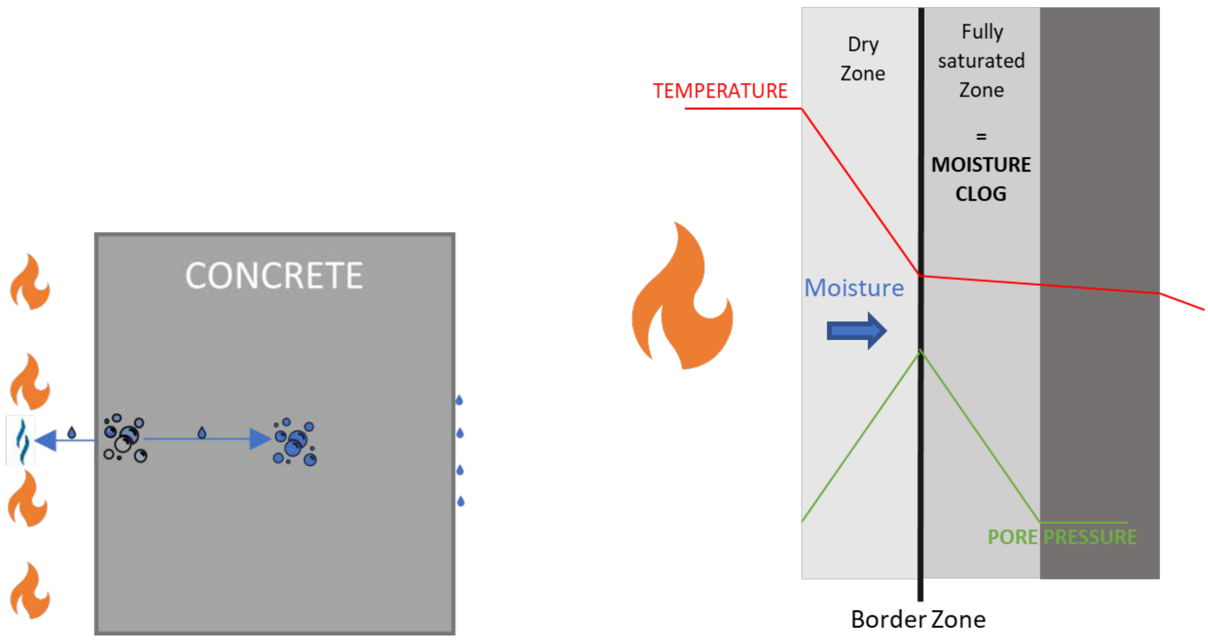
When concrete is exposed to temperatures above 100 °C, the water in concrete tries to expand, causing its migration towards less confined environments. The moisture movement goes in two opposite directions:

- One part moves in the direction of the heat 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 vapour 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 vapour starts this movement toward the colder regions. Upon getting filled, the pores restrict the vapour 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 vapour movement grows too. Concurrently, a steep temperature gradient is developed across the dry layer. According to Harmathy & Shorter, this stems from the fact that at an outside temperature of 500 °C, the temperature just 1.5 cm into the concrete is considerably lower (see also chapter 3.1.4). According to Harmathy & Shorter [11] this temperature gradient has two effects:

1. A high heat flow through the dry concrete layer causes high vapour pressure in the border zone. The high vapour pressure, in turn, influences the rate of vaporization. (See also figure 4.2)
2. Thermal stresses reach high values

If stresses generated by the large pressure drop coming from the hydraulic resistance to vapour 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. High enough vapour pressures to induce explosive spalling are only generated at temperatures considerably higher than 100 °C.



(a) Schematic representation of the moisture movement in heated concrete

(b) Schematic representation of the moisture clog model by Shorter & Harmathy

Fig. 4.2: Simplified schematics to show the moisture clog model with information from [11]

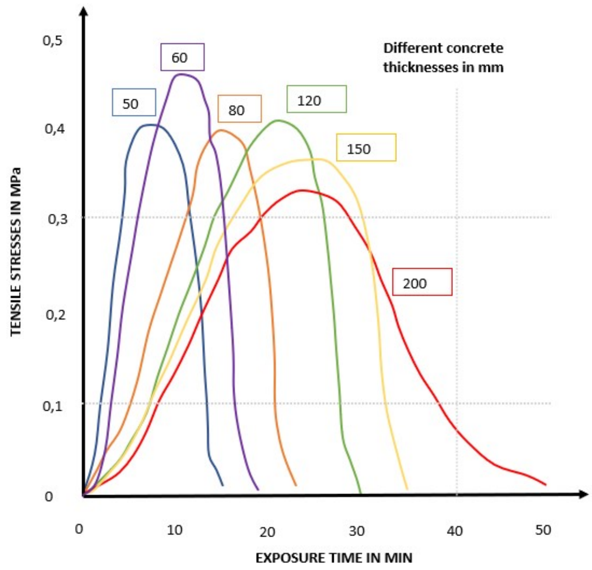


Fig. 4.3: Tensile stresses as a result of water vapour movement predicted in two-sided heated concrete for different widths of the concrete cross section between 50 mm and 200 mm according to Meyer-Ottens [19]

4.1.2 Frictional forces from vapour flow theory

The "Frictional forces from vapour flow theory" concept was introduced by Waubke [14] and then further investigated by Meyer-Ottens [19] in 1972. It is also sometimes mentioned as the "High vapour drag forces theory" in some literature. It also belongs to the category of pore pressure theories.

According to Meyer-Ottens, friction between the pore walls and the outflowing vapour creates tensile stresses in the capillary system of the concrete. If those tensile stresses exceed the tensile strength of the concrete, explosive spalling occurs. The calculation of these tensile stresses depends on the distance between the concrete surface and the moisture clog, the permeability of the concrete, the velocity of the 100-degree isotherm[1] and the moisture content of the concrete. Meyer-Ottens based his studies on two-sided heated concrete specimens with an average moisture content of 3 %. Friction is generated by the vapour 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.

Contrary to Shorter & Harmathy's theory [11], which describes that the build-up pore pressure drives the moisture clog into the concrete, Meyer-Ottens believed that the build-up of pore pressure drives the vapour towards the heated surface of the concrete [27]. Meyer-Ottens placed the moisture clog in the location of the 100-degree isotherm.

The theory of Meyer-Ottens was never experimentally verified, and it is questionable if the moisture inside of the concrete is enough to generate such a continuous vapour stream necessary to cause these stresses. Also, the permeability and other material-related properties are not incorporated in this theory, although they have a direct effect on the moisture movement and, in turn, the probability of explosive spalling.

Figure 4.3 shows the tensile stresses Meyer-Ottens calculated with his model for two-sided heated concrete specimens with 3 % moisture content by weight. The stresses are calculated from the

[1] Isotherms are lines of the same temperature

hydraulic resistance of water vapour movement and are only produced in the first minutes of heat exposure. The time at which explosive spalling happened in Meyer-Ottens experiments is nearly consistent with the time at which the maximum tensile stresses are reached in the calculation. The thinner a specimen's cross-section is, the sooner the maximum tensile stresses are reached.

4.1.3 Idealized spherical pore model

Sullivan and Zaman [16] noticed in their experiments that water-stored concrete specimens are more likely to spall. When concrete is heated, the water inside the concrete evaporates, leading to steam pressure which causes stress inside the concrete. Sullivan and Zaman created a simplified model, which represents the entire volume of voids of the concrete specimen. A schematic drawing of the idealized spherical pore model can be seen in figure 4.4. 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.

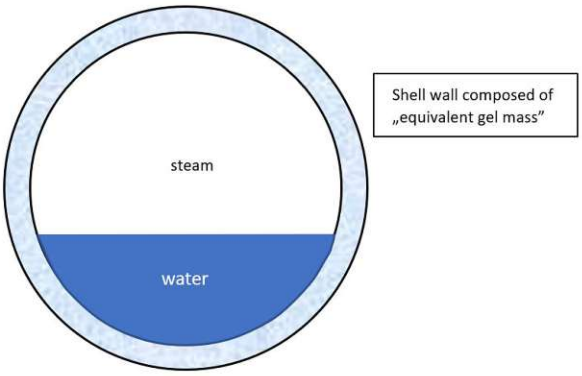


Fig. 4.4: Idealized spherical pore model according to Sullivan and Zaman [16]

To better understand the model, one has to know what each element represents. The "equivalent gel mass" is equal to the total mass of the fully hydrated cement paste for the considered concrete age. The volume of solids includes the aggregate volume, the equivalent gel mass and the unhydrated cement particles. The remaining volume consists of free water and air voids.
The hollow sphere in figure 4.4 represents the entire amount of voids in the test specimen but not the ones within the aggregate itself. The shell wall confines the water and steam present in the specimen during heating. The air in the pores is forced out during the initial evaporation process at about 100 °C and is therefore not included in the model. During the second evaporation stage at around 200 °C, hoop stresses begin to develop because the internal pressure increases.
This simplified model should only be applied to very young concrete, as the moisture content of older specimens is not high enough to cause the necessary amount of pore pressure to induce explosive spalling. Additionally, one should remember that no moisture migration information is included in this model. Most likely because there was next to no knowledge about pore size distribution and total porosity in 1971 when this model was created. [27]

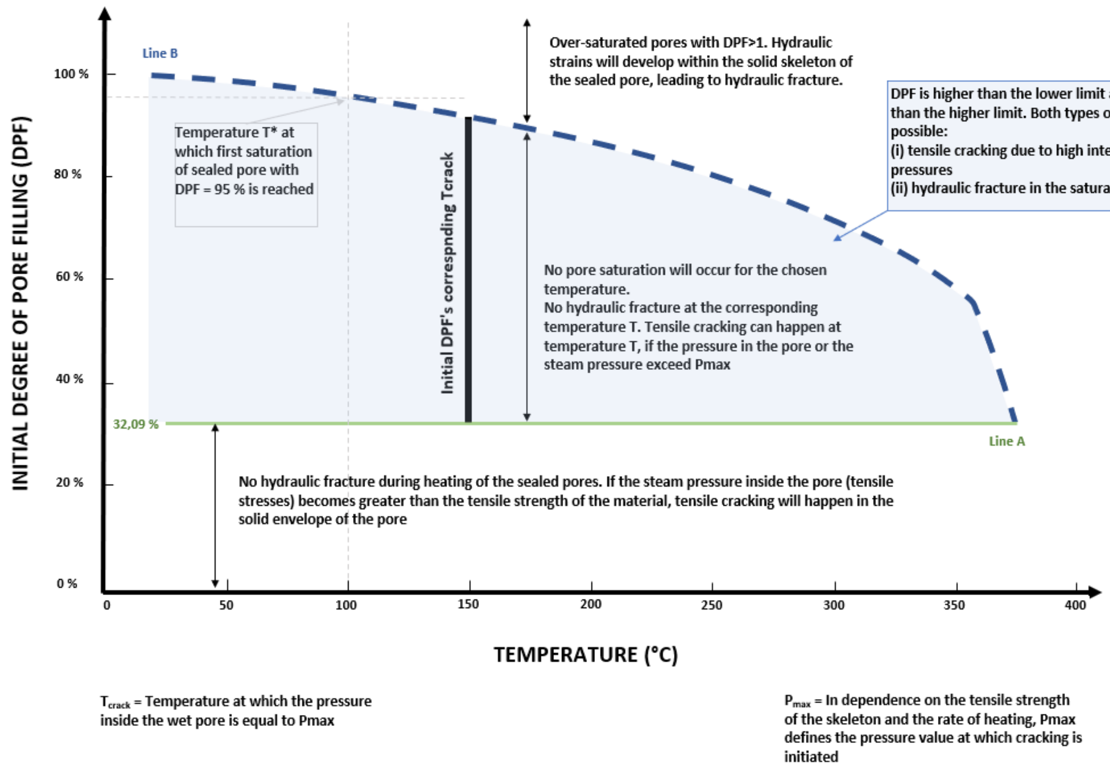


Fig. 4.5: Upper and lower boundaries for initial DPF in an inert porous material defining the type of failure during exposure to fire according to [31] with additional information

4.1.4 Fully saturated pore pressure theory

Figure 4.5 gives an overview over this theory developed by Khoylou [31]. If the DPF (Degree of Pore Filling) of a sealed wet pore is less than 32 percent, the pore cannot become saturated during heating, no matter which temperature is applied. Indeed, its free water completely vaporizes during heating. This threshold value for the DPF was calculated using a series of formulas that exceed the scope of this work. For further details, please see the work of Khoylou [31], pages 152-155. No hydraulic fracturing[2] takes place as there is no additional straining due to expanding liquid. In figure 4.5, this addresses the area below the green line A. 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 percent, then a specific temperature T* exists at which the saturation of the pore occurs during heating. This temperature T* can be found in the figure 4.5 by finding the crossing point between the initial DPF and line B. 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. For the area between line A and line B, both of the following failure modes are possible for wet pores :

1. tensile cracking due to high internal pressures
2. hydraulic fracture in the saturated pores

[2]Hydraulic fracturing: If a pore is physically saturated, additional tensile strains are generated in the solid skeleton surrounding the pore. If this doesn't lead to fracture, high tensile stresses and hydraulic pressures are created in the pores. As the pores are interconnected, water can escape from the saturated pores to dry or only partly filled pores. If the flow rate of the migrating water is not fast enough, tensile stresses are built up in the skeleton, quickly exceeding the fracture strength concrete. This is an example of hydraulic fracturing.

Which kind of failure occurs depends on the tensile strength of the skeleton and the heating rate. The area above line B describes over-saturated sealed pores (DPF>1 for corresponding temperature T). Increasing the temperature for a specific initial DPF leads to an increase in the oversaturated pore's DPF and also to increasing tensile strains within the skeleton. This results in the spalling of the concrete.
McNamee [67] and Jansson [51] compare this theory to the mechanism used in sprinklers with bulb activation. A glass container filled with water and a bubble is used so that when the temperature rises beyond a specific point, the water expands and the air is forced into solution with the water until the whole bulb is filled and breaks due to the build-up of hydraulic pressure. Whether or not the fully saturated pore theory is correct is hard to say, as it is nearly impossible to prove in practice.

4.1.5 BLEVE-Theory

Ichikawa [35] 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 papers (Chapman [23] and Khan [26]). He then performed 16 numerical case studies and presented the location, time, and temperature at which concrete spalls.
Ichikawa [35] identifies three types of spalling in his work from the year 2000:

- D High pore pressure due to dry vapour: The spalling occurs in a dry zone, and the state of the water is superheated
- W High pore pressure due to saturated vapour: The spalling occurs in a wet zone, and the state of the water is a mixture between liquid water and water vapour
- S High pore pressure due to pressurised water (i.e. water-filled pores): The spalling occurs in the saturated zone and the state of the water is compressed liquid water only.

The S-type spalling is the most destructive one of these three types 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 [35] states that most cases of explosive spalling are created by S-type spalling at temperatures above 100 °C. The compressed water inside the pores of HSC is at a temperature above the vaporisation 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 vaporisation of the superheated water in the form of BLEVE[3] and to explosive spalling.

Rapid Expansion of superheated water This theory is similar to the above one and was created by Petrov-Denisov et al. [20] in the year 1972. 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. [67]
For a better understanding the general steps of a BLEVE are shown in figure 4.6.

[3] BLEVE stands for "Boiling Liquid Expanding Vapour Explosion"

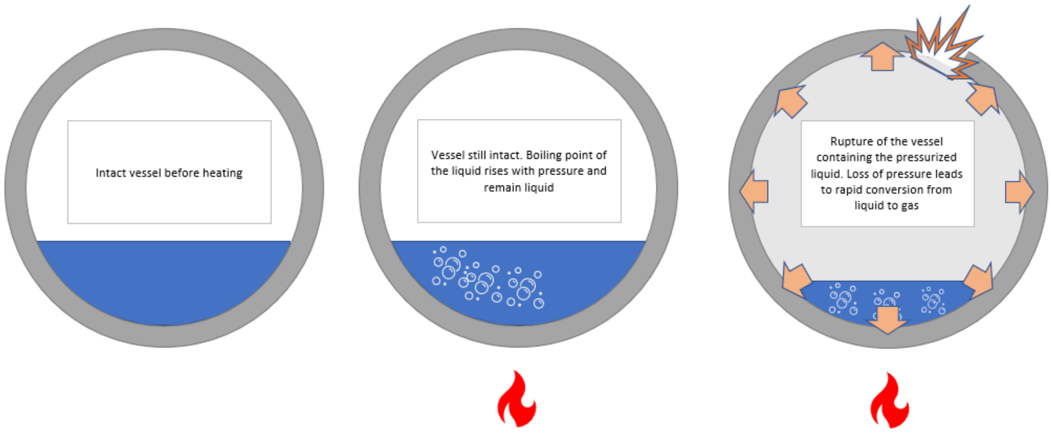


Fig. 4.6: Simplified representation of a BLEVE

4.2 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's matrix. With its low thermal diffusivity and high density, concrete suffers from high thermal gradients close to the heated surface. An 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 [67].
Both Saito [13] and Dougill [17] were defenders of the thermal stresses theory. Saito published his theory in 1966 and based his work on the findings of Hasenjäger [9]. Dougill based his work on that of Saito but regarded spalling as a different kind of failure. Both theories are described in the following paragraphs in more detail.

4.2.1 Saito's theory

Saito [13] regarded explosive spalling as a kind of compression failure at the heated surface of the concrete. During his studies, he noticed that the temperature gradients within the cross-section of the heated concrete lead to thermal stresses because of the non-uniform temperature distribution near the surface.

According to Saito, every point of the concrete specimen's 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 $\epsilon_{s,thermal}$, a curvature $1/\rho$ and the thermal strain $\epsilon_{thermal}$, as pictured in figure 4.7. Compressive stresses (green area) are generated close to the heated surface because of the restrained thermal deformation and the unexposed side. Tensile stresses (orange area) are developed in the cold central regions of the concrete specimen. When concrete is heated beyond a specific temperature, it suffers from a loss of concrete strength, thus further increasing the risk of spalling. The maximum stress at the heated surface is reached within the first 30 minutes of heat exposure. 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.
If the concrete can withstand the maximum thermal stresses generated, it is safe from explosive

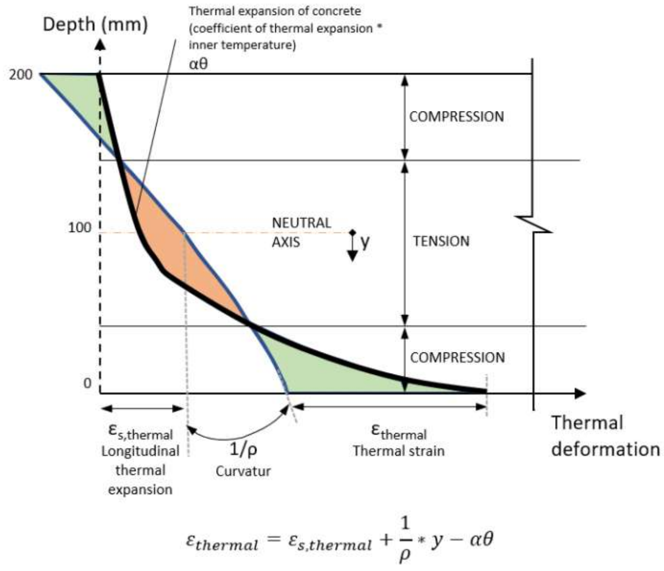


Fig. 4.7: Resulting thermal strains in heated concrete according to [13]

spalling. In Saito's opinion, higher moisture content leads to higher thermal gradients, thus influencing the spalling behaviour.
One shortcoming of this theory is that the explosive spalling risk increases with the specimen's thickness, contrary to numerous experiments that have shown that specimens with smaller cross-sections are more likely to spall than larger ones. As explained next, this is one of the adaptions Dougill [17] made in his model.

4.2.2 Dougill's theory

Dougill [17] based his thermal stress theory on that of Saito [13]. 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 [13]. 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. The stiffer the specimen, the stiffer the testing machine. Through this adaption to Saito's model, the specimen's 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 material behaviour. But as lightweight concrete with similar material properties has almost no spalling risk, it is highly probable that this theory only applies to highly loaded 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. But Akhtaruzzaman [21], Sullivan and Zaman [16] and some others showed through experiments that this is not the case. [27]

4.3 Combined compressive strength and pore pressure theory

Bosnjak [53] studied the interaction between compressive stresses and pore pressures in concrete cubes of 150 x 150 mm. These cubes were heated to 230 °C so that the pore pressures could develop and were then loaded in compression. When the concrete cubes were only exposed to the temperature for a short time, they suffered from compressive failure in the second stage of the experiment. 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 specimens changes from non-explosive to explosive due to the presence of pore pressure. This led Bosnjak [53] to conclude that a critical combination of compressive stress and pore pressure can result in explosive spalling of concrete. In these experiments, the combination of thermal stresses and pore pressures was not critical until the compressive load was applied. Therefore, in Bosnjak's scenario, pore pressure can be considered as the main trigger of explosive spalling. He further points out that this scenario does not account for all types of explosive spalling.

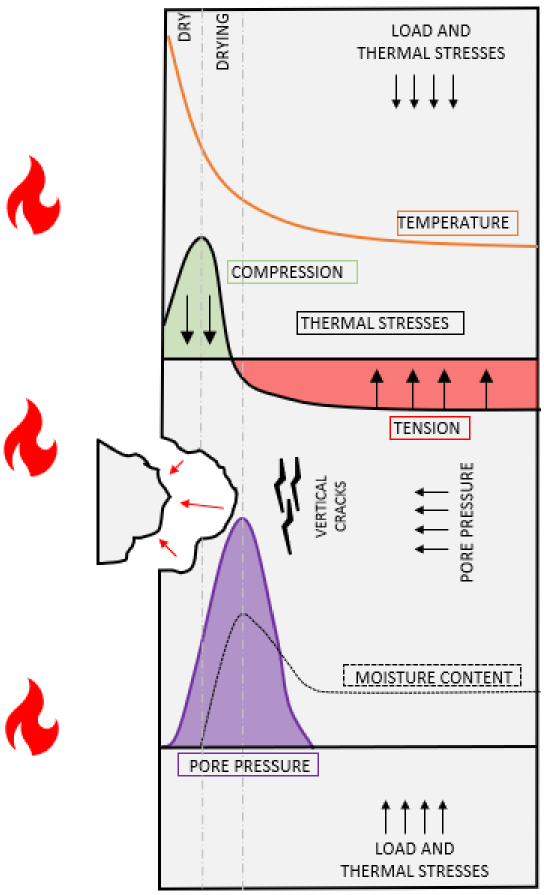


Fig. 4.8: Explosive spalling caused by combined thermal stresses and pore pressure [15]

4.4 Combined thermal stresses and pore pressure theory

Zhukov [15] was the first person to recognize the possibility 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. Figure 4.8 gives an overview of the stresses in the heated concrete specimen. 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. [53] Zhukov used a model similar to that of Meyer-Ottens [19] to calculate the pore pressure induced stresses. In his model of outflowing vapour, the tensile stresses due to drag forces of the outflowing vapour are calculated. In heavy, dense concrete with 8 % moisture content by weight, those stresses reach a value of 15 N/mm^2, which is a relatively large value. This would explain why relatively small pore pressure generates stresses greater than the tensile strength of concrete. According to Zhukov, his spalling predictions were proven by experiments on 35 concrete slabs, but no further information or references were given. [27]

4.5 Summary

All the theories behind the explosive spalling behaviour that were not disproved can be divided into four categories: pore pressure theory, thermal stress theory, combined pore pressure and thermal stresses theory, and combined compressive strength and pore pressure theory.
The pore pressure theory includes the moisture clog theory from Harmathy & Shorter, the frictional forces from vapour flow theory from Waubke and Meyer-Ottens, the idealised spherical pore model from Sullivan and Zaman, the fully saturated pore pressure theory from Kyoylou, and the BLEVE-theory from Ichikawa. These theories and models all have in common that pore pressure is considered the main trigger of explosive spalling behaviour.
The moisture clog theory describes the process where rising temperatures lead to increased pore pressure in the concrete, which forces the evaporated water not only outwards but also towards the colder regions of the concrete. As a result, the water vapour condensates once it reaches those colder regions, filling pores and voids with water and so creating a fully saturated concrete layer, the so-called moisture clog. This moisture clog restricts the following moisture movement until the vapour pressure reaches such values that explosive spalling happens. During a fire test, Robert Jansson [51] visualised the moisture clog by splitting a concrete slab. The frictional forces from vapour flow theory are also mentioned under the name of high vapour drag forces theory in some literature. It was never experimentally verified, and it is quite questionable if the moisture inside the concrete is available in such an amount that continuous vapour streams, which lead to bursting stresses, can be generated. The idealised spherical model is a simplified model to calculate the hoop stresses caused by pore pressure inside the concrete voids. It should only be applied to very young concrete. The fully saturated pore pressure theory describes the failure mode of sealed wet pores regarding the initial degree of pore filling (DPF) and the temperature, also depending on the tensile strength of the pore skeleton and the heating rate. Depending on those parameters, there will be either no hydraulic fracture, tensile cracking due to high internal pressures, or hydraulic fracture in the saturated pores. As this theory is nearly impossible to prove in practice it is still unsure if it is correct or not. The BLEVE theory describes explosive spalling as a failure mode where compressed water inside the pores of HSC reaches a temperature above the vaporisation temperature at atmospheric pressure. This causes an immediate vaporisation of the superheated water in the form of BLEVE when the initial fracture of the pore happens.
The thermal stresses theory includes Saito's and Dougill's theory. While Saito regarded explosive spalling as a compression failure at the concrete's heated surface, Dougill regarded it as a form of instability. Dougill's theory was based on that of Saito, but he solved some of the earlier complications where thicker specimens seemed more prone to spalling than thinner ones.
Bosnjak introduced a theory where a critical combination of compressive strength and pore pressure leads to the explosive spalling of concrete. Thermal stresses and pore pressure only led to an explosive failure when the compressive load was applied to the specimen. It is a particular form of explosive spalling where pore pressure is the main trigger, but according to Bosnjak, it is not the only way explosive spalling may be triggered.
The combination of pore pressure and thermal stresses as the cause of explosive spalling was first recognised by Zhukov. Today it is the most widely accepted theory. The sum of thermal stresses, pore pressure and load-induced stresses are superimposed onto each other until the resulting sum exceeds the concretes strength and explosive spalling is induced.

Chapter 5

Complications in predicting the results of explosive spalling experiments

Explosive spalling is a very complex topic with various parameters influencing the behaviour to various degrees. As part of this master thesis, two factors, the size effect and the stochastic tendencies of explosive spalling are explored in more detail to study if parallels between different experimentation setups can be found.
The z-score system introduced in chapter 3 is used to make the results of the individual tests more comparable.

5.1 Size effect

The "size effect" is a widely discussed topic in this research field. Experimenting on smaller specimens is cheaper, easier and generally a lot faster as various specimens can be tested at once. But the question remains: Are those results representative of the real-sized or large-scale specimens used in practice?

Sullivan and Zaman [16] experimented on small-scale specimens of different length but with the same cross-section (see figure 5.1).

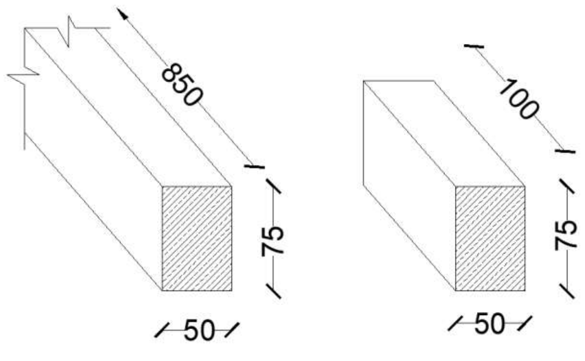


Fig. 5.1: The used specimens by [16]. All dimensions in mm.

In total, 26 of the larger specimens and eight of the smaller ones were tested. The specimens were not loaded or restrained but simply placed inside the electrically heated furnace. Heating elements were placed along the sides of the furnace. Depending on the chosen heating rate, all or just some were switched on. None of the smaller specimens showed any signs of explosive spalling, while many of the larger specimens exploded violently at various heating rates. The specific number of exploded specimens was not published in the study. However, the authors assumed that the smaller specimens stayed intact due to the less severe temperature gradient along the length of those specimens.

Connolly [27] and Meyer-Ottens [19] both concluded that specimens with a reduced thickness are more prone to explosive spalling than thick specimens. Connolly believed that the stresses which influence the failure process, like pore pressure, have a larger magnitude in thinner specimens.

Zhao and Sanjayan [45] subjected concrete cylinders with a diameter of 150 mm and 300 mm height to a surface exposure test and cylinders with a 100 mm diameter and 200 mm height to a gas fire test. The goal was to present a new method with which it is possible to carry out spalling tests on small-scale specimens with a commonly available electric furnace. The lateral confinement of the small-scale specimens is used to simulate the behaviour of full-scale structural members. The "vertical exposure test method" triggered more severe spalling in HSC than in NSC cylinders. According to Zhao and Sanjayan, this is consistent with previous research findings and proves that this test method is suitable for investigating the spalling risk of HSC specimens. The experimental program of Ali et al. ([33],[37],[39]) that is discussed in chapter 5.2 however shows much lower spalling degrees for HSC specimens than for NSC specimens, if axial restraint and loading is applied. For a quick overview of the test results in the study of Ali et al. see figure 5.11 on page 69. While Zhao and Sanjayan studied the behaviour of concrete cylinders in different test setups, no medium or large-scale experiments were performed to confirm the results. To fully determine the effectiveness of this new test method, the results should be compared to those of large-scale specimens.

Jansson and Boström [52] point out in their study from 2012 that the experimentation on unloaded small-scale specimens (cylinders or cubes) is not suitable for studying the spalling behaviour of full-scale concrete members as there is almost always some kind of restraint or load present in real structures. The experimental program was conducted on 20 slabs (1800 x 1200 x 200 mm), 4 beams (3200 x 600 x 200 mm) and 154 small slabs (600 x 500 x 200 mm). All specimens were made out of 52 different mixes of self-compacting concrete (SCC). Extensive result tables for this experimental program were published in report [42]. Specimens were exposed to three different kinds of heat exposure from only one side, the standard fire curve, the hydrocarbon fire curve, and a slow heating rate of 10 K/minute. Loads were applied to the specimens through poststressing. After the tests, the spalling depth and the weight loss (without the water loss due to evaporation) were measured. A comparison of the large and small slabs showed a considerable smaller spalling depth in the smaller specimens, even when the load level was the same. According to the authors, this may be due to the more dominant boundary conditions in the smaller specimens, stress release by more cracks in the smaller specimens, and reinforcement of the larger slabs, which restricted the development of cracks in the larger specimens.

Jansson [51] observed that the test results of small loaded slabs don't represent the spalling degree of larger loaded slabs with the same thickness and load level. This is also why Jansson believes that explosive spalling behaviour should not be regarded as a material property. He further states that the unknown scaling factor for explosive spalling leads to the conclusion that only full-scale fire tests or well-documented real fire scenarios are reliable ways to confirm the fire resistance of concrete members or whole structures.

5.1.1 Analysing test results of different sized specimens

To find out if small-scale specimens are representative of large-scale specimens, the results of Boström and Jansson [42] have been analysed in more detail. The dimensions of the used specimens are displayed in figure 5.2. All specimens were exposed to the fire from one side only. The fire-exposed area amounts to 88 % of the surface area for the large specimens and to 67 % for the smaller specimens.

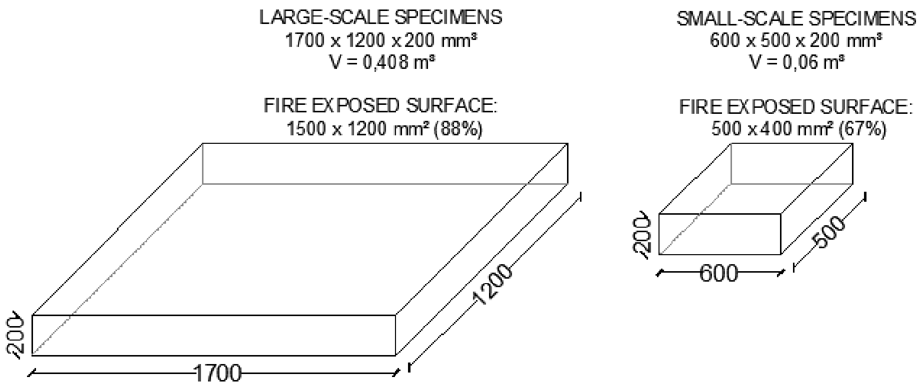


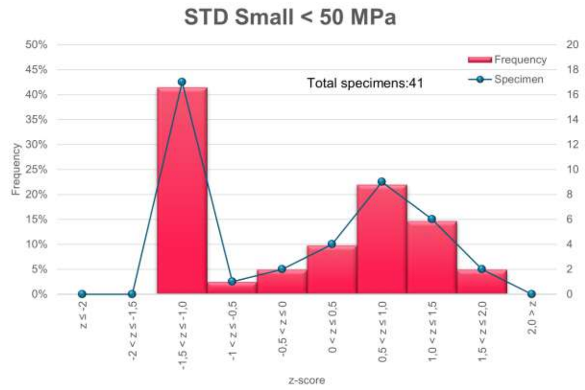
Fig. 5.2: The used specimens by [42]. All dimensions in mm.

To make the results more comparable, they were divided into four groups per specimen size.

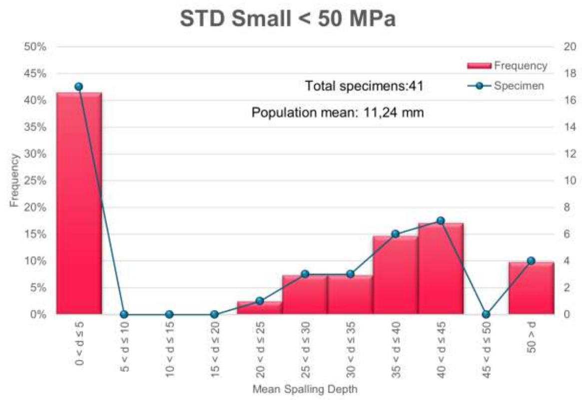
- Standard heating curve (STD) and compressive strength below 50 MPa
- Standard heating curve (STD) and compressive strength greater or equal to 50 MPa
- Hydrocarbon curve (HC) and compressive strength below 50 MPa
- Hydrocarbon curve (HC) and compressive strength greater or equal to 50 MPa

As only 2 large specimens were tested under the hydrocarbon curve with compressive strength below 50 MPa, a comparison would not have been helpful in this case.

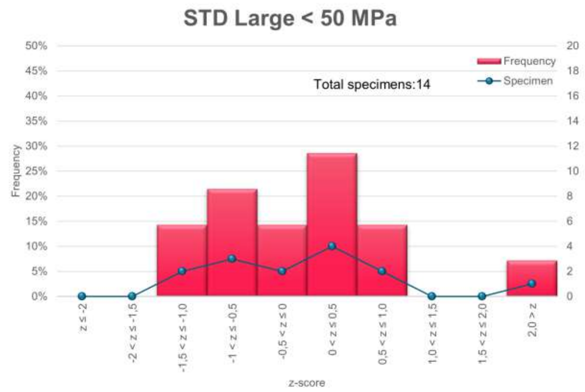
The next step was determining each group's population mean, standard deviation and z-score. Histograms with the same step wide were generated for the large and small specimens for a better comparison. These diagrams can be found in figures 5.3 to 5.5.



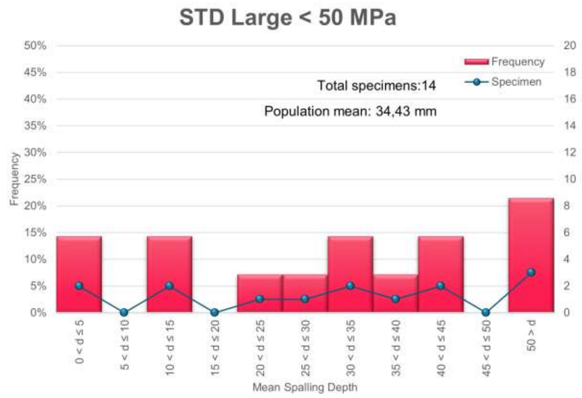
(a) Small-scale specimens - Z-score



(c) Small-scale specimens - Mean spalling depth



(b) Large-scale specimens - Z-score

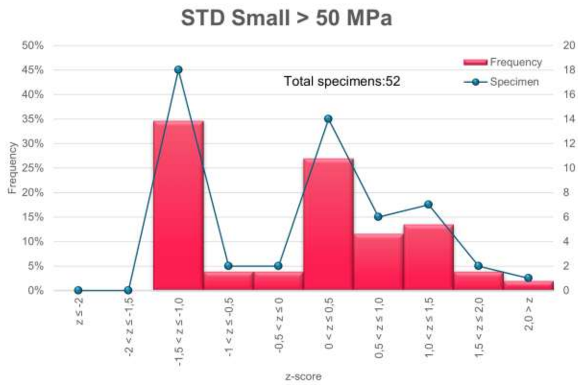


(d) Large-scale specimens - Mean spalling depth

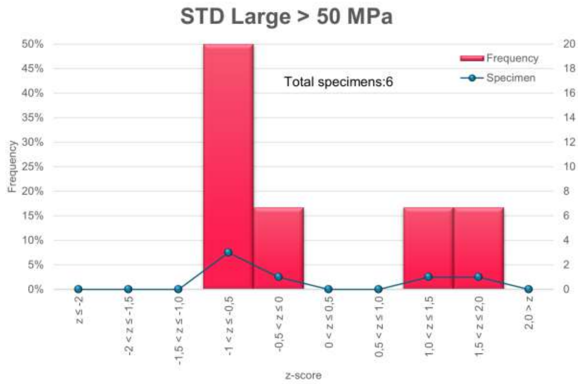
Fig. 5.3: Evaluation for the standard heating curve and compressive strength below 50 MPa

In figure 5.3, the frequency of the test results for the small and large-scale specimens under the influence of the standard heating curve is displayed. The results are shown on the left side with the z-score system, while the mean spalling depth is used on the right side. This comparison shows only specimens with compressive strength below 50 MPa.

In total, 41 small and 14 large specimens were tested under the above conditions. About 41 % of the smaller specimens showed no or next to no sign of spalling damage, while only about 14 % of the larger specimens reacted non-destructively. As this is the test group with the most large-scale specimens, an attempt was made to find a scaling factor between the large and the small specimens. But as shown in the histograms, the distributions of the different sizes are not comparable. The mean spalling depths of the larger specimens are almost evenly distributed across all classes. The distribution is skewed to the right in the case of the smaller specimens. The population mean of the mean spalling depth is about three times higher for the larger specimens, while the fire-exposed surface is 9 times bigger. No scaling factor could be identified with the available data.



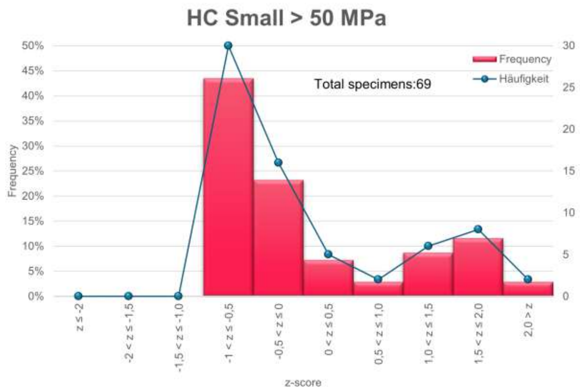
(a) Small-scale specimens



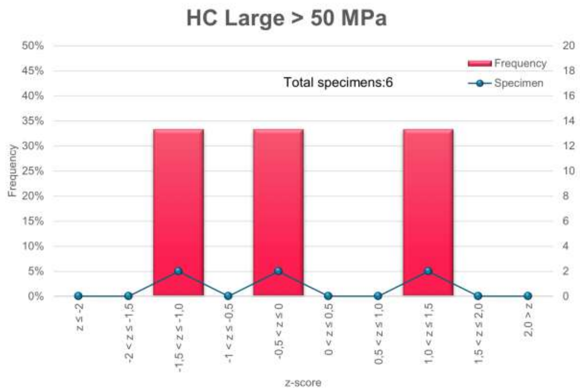
(b) Large-scale specimens

Fig. 5.4: Evaluation for the standard heating curve and compressive strength greater or equal to 50 MPa

In figure 5.4, the z-score results for specimens under the influence of the standard heating curve and with compressive strength greater than 50 MPa are displayed. In this case, there were only six large specimens experimented on, while 52 smaller specimens were tested. This difference in the number of tested specimens means the comparison between the two sizes is not very meaningful.



(a) Small-scale specimens



(b) Large-scale specimens

Fig. 5.5: Evaluation for the hydrocarbon curve and compressive strength greater or equal to 50 MPa

In figure 5.5, the results for the specimens tested under the hydrocarbon fire cure and with compressive strength greater than 50 MPa are plotted. Here 69 small specimens and 6 large specimens were tested. As mentioned before, the difference in tested specimens makes no sensible comparison possible.

As shown in those diagrams, no clear trend is visible in the groups of identical-sized specimens or between the smaller and larger specimens. In case of the standard heating curve and compressive strength below 50 MPa, the results for the larger slabs seem to be distributed more evenly. Nearly 45 % of the smaller specimens didn't spall at all, while only about 14 % of the larger specimens showed no destructive reaction to the heat exposure. As this is also the group the most large-scale specimens were tested on, histograms showing the distribution of the mean spalling depth were also generated. No scaling factor could be identified to translate the behaviour of the smaller specimens to that of the larger ones.

5.2 Stochastic tendencies

As mentioned in the previous chapters, explosive spalling behaviour is influenced by different parameters and factors. An extensive list of all these parameters can be found in section 3.2 on page 33. Most researchers and scientists who study this phenomenon varied some of these factors to better understand the inner dynamics of explosive spalling. But regardless of the parameters they are actively examining, there is often a reference to the stochastic tendencies of explosive spalling included in their work.

The term "stochastic tendencies" refers to the problem that those inconsistent test results are not outliers but the norm. The applied characteristic loads that structural design engineers use have a 95 % probability of not being exceeded, while the characteristic material strength has a 5 % probability of being overestimated. This approach is possible because it is assumed that those values follow the Gaussian distribution. According to extensive research, no probability distribution that fits the explosive spalling behaviour could be found. Therefore, it is not yet possible to assign a reasonable probability to the outcome of an explosive spalling experiment. The terms stochastic tendencies, random behaviour, or erratic test results refer to this lack of pattern in spalling tests.
Some researchers believe that the high variance in the spalling results is due to specific properties (non-homogeneity, cracking behaviour,. . .) of concrete. They would define the results, which are too unlike the others in their opinion, as outliers and ignore them. Defining outliers and excluding them from the final results leads to a more uniform overall result. Different mathematical methods of defining outliers require a relatively large set of initial data, which is usually unavailable for spalling experiments. This approach doesn't attribute stochastic tendencies to explosive spalling behaviour, as the outliers are not considered in the result distribution. The following paragraphs give an overview of the opinion of different researchers on the matter of stochastic tendencies.

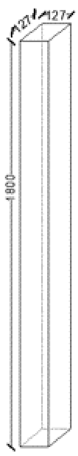


Fig. 5.6: Dimension and geometry of the test specimens in the experimental program published in [39, 33, 37]. All dimensions in mm.

Sullivan and Zaman [16] did experiments on two differently sized beam specimens, as pictured in figure 5.1. In this experimental program, 26 of the larger beams and 8 of the smaller ones were tested. None of the smaller beams suffered from explosive spalling, while many of the larger ones exploded violently. No detailed results for the larger beams were presented in this work.

Khoury [32] believes that the prediction of explosive spalling is a "rather imprecise empirical exercise". He attributed the randomness of the experimental results to the complex microstructure of concrete and to the multiphase nature of heated concrete. This is, according to Khoury, what makes the developing of an analytic model so difficult. He is, however, optimistic that this is becoming possible thanks to the development of thermo-hydromechanical non-linear finite element models, which can predict pore pressure.

Hertz [25] experimented on DPS (Densified Systems containing homogeneously arranged ultra-fine particles), which are concrete mixes made with silica-fume cement paste. The resulting concrete is very dense, with a high compressive strength between 150 MPa and 280 MPa. When small cylinders were heated in an electric oven, some exploded so violently that the oven was considerably damaged, while others didn't explode at all. For every maximum test temperature, three specimens were tested. For the maximum temperature of 350 °C, one of three cylinders exploded; at 450 °C and 650 °C, two of three specimens exploded each. No opinions about the variation in those results were offered in their work.

Connolly [27] did extensive research about explosive spalling and conducted an experimental study himself. One of his conclusions was the importance of the probability associated with explosive spalling. In his opinion, this random behaviour is one of the reasons why developing a detailed computer model to predict explosive spalling behaviour is so tricky. The explanation Connolly proposes for the erratic stochastic tendencies of exploding spalling behaviour is the following: Both the permeability and the tensile strength of heated concrete are very sensitive to the cracking behaviour of concrete. Cracking behaviour is influenced quite strongly by many different parameters like aggregate shape and distribution. This influence makes the manner in which concrete cracks random for each test specimen. As the explosive spalling behaviour is strongly affected by both permeability and the tensile strength of the concrete, this would be a possible explanation for the random behaviour.

Khoylou [31] states the reason why the mechanisms, limits and conditions that cause spalling behaviour are not understood yet is that spalling was found to be a random phenomenon.

Ali et al. [39, 33, 37] believes that the outliers in the test results of identically tested specimens are only due to the non-homogeneity of concrete. Non-homogeneity means that the void and moisture distribution in each sample is unique. He proceeded with removing those outliers from the result set and thought that the problems about the inconsistent spalling behaviour could be solved by always testing three identical samples and removing the inconsistent results. More about this experimental study can be read in section 5.2.1.

Phan et al. [36] states in his work from 2001 that spalling in HPC specimens seems to happen randomly, as from a large badge of identically tested samples, some spalled, and some didn't. He further states that this erratic behaviour of HPC specimens is the reason why predicting an explosive spalling event is so difficult.

Majorana et al. [47] mentioned in his work from 2010 that although samples of the same concrete mix were tested under identical circumstances, some spalled and some didn't. In this case, no further information about the test environment and the used samples was given.

Bosnjak [53] experimented on small slab specimens (700 x 700 x 350 mm) with and without PP-fibres. Three specimens made of the same concrete mix were placed on top of the oven and heated one-sided under the ISO 834 fire curve. Bosnjak states in his work that while all three specimens spalled explosively, no pattern in the position of explosive spalling or the size of the spalled-off surface could be observed. The same applies to the three identical specimens tested under the ZTV-ING fire curve.

All of these examples above show that the stochastic tendencies of explosive spalling are a widely discussed topic. While some people think it is simply stochastic in nature others think that there are specific reasons for the inconsistent results in spalling tests. On the other hand, in many scientific publications about explosive spalling, the random behaviour in which it occurs is not mentioned at all. When no detailed test results are published in these articles, it is hard to say if the specimens behaved in a uniform manner or if erratic behaviour was found but not deemed important enough to mention.
There are many reasons why it is so hard to find out if explosive spalling has stochastic tendencies. The main reasons are:

- The tested concrete mix varies in almost every study.
- The test procedures and conditions to determine explosive spalling behaviour are not standardised. Test set-up, furnace type, heating rate and the kind of furnace (gas, electrical, flame) varies in almost every study.
- The shape and size of the specimens are different
- In some cases, the description of the test results is incomplete, or it is only given as a very general result (for example: 2 of 5 specimens explosively spalled) without explanation to what happened with the specimens that didn't explosively spall.
- Not enough specimens tested for one set of test conditions.

In order to find out more about the stochastic tendencies of concrete, studies with at least three test specimens per condition set and extensive information about the test results were further analysed. The discoveries and conclusions are presented in the following sections.

5.2.1 Study on half-scale concrete columns

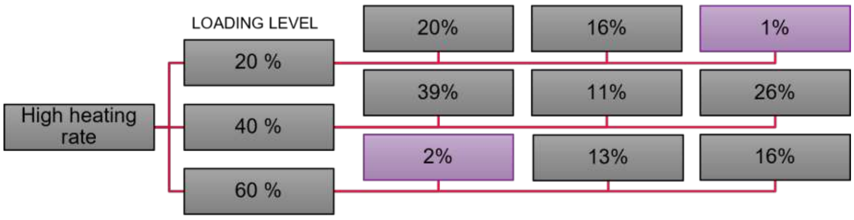
Ali et al. started an extensive experimental program on half-scale concrete columns in 2001 and published their findings in three articles [39, 33, 37]. The dimension and form of the test specimens are pictured in figure 5.6.

In the course of their study, the heating rate, concrete type (NSC, HSC), loading level and axial restraint were varied. All results for the spalling degree are given as described in formula (3.4). This means the water loss was not included in the calculation, and the total spalling loss was higher in reality than in these results. For further information about this thematic, please see section 3.3.1 on page 38.

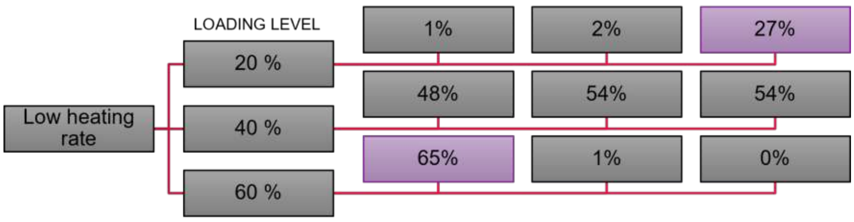
5.2.1.1 Variation in heating rate and loading level

In figure 5.7, the different testing conditions and spalling results for each parameter set are pictured.

Two different heating rates were used here. The high heating rate corresponds to the BS 476 fire curve, which means the concrete specimens are heated to 600°C in 6 minutes. Under the low heating rate, it takes 40 minutes to reach a temperature of 600°C. The exact course of the BS 476 fire curve is pictured in 3.2 on page 31. Ali et al. [33] believes that the variation in



(a) High heating rate (BS 476) - 100°C/min



(b) Low heating rate - 15°C/min

Fig. 5.7: Overview of the spalling degree results for HSC half-scale columns as described in [33] for different heating rates and loading levels

the test results is caused by the non-homogeneity of concrete resulting in the unique void and moisture distribution in each test specimen. Because of this conclusion, it was decided to strike the coloured results (=outliers) in figure 5.7 from the result set.
The diagram in figure 5.8 shows the average spalling degree results for the test specimens described in figure 5.7. The "modified average" describes the adjusted result set, while the other results represent the whole set (including the outliers).

Whole result set When looking at all the results without excluding any outliers, the standard deviation for the high heating rate varies between 6 % and 11,4 %. For the low heating rate, the standard deviation fluctuates between 2,8 % and 30,4 %. Overall it seems like the specimens exposed to the higher heating rate behave more uniformly than the ones under the low heating rate.

Modified result set Like mentioned before, Ali et al. [33] defined four of his experimental results as outliers and excluded them from the result set. This means that the standard deviation for the lower heating rate is below 3 % for all three test sets and the standard deviation for the higher heating rate varies between 1,5 % and 11,4 %.

Defining of outliers The only reason Ali et al. [33] mentioned for excluding those results is the non-homogeneity of concrete. The paper did not discuss their reasoning behind which results are to be excluded. To better understand this decision, the results were examined using the z-score (see chapter 3.4).

The first step was determining the population mean and standard deviation for every test set. Every line in figure 5.7 describes one individual test set. In the next step, the z-score was calculated by using formula (3.7). If every test set is considered separately, there are no z-scores

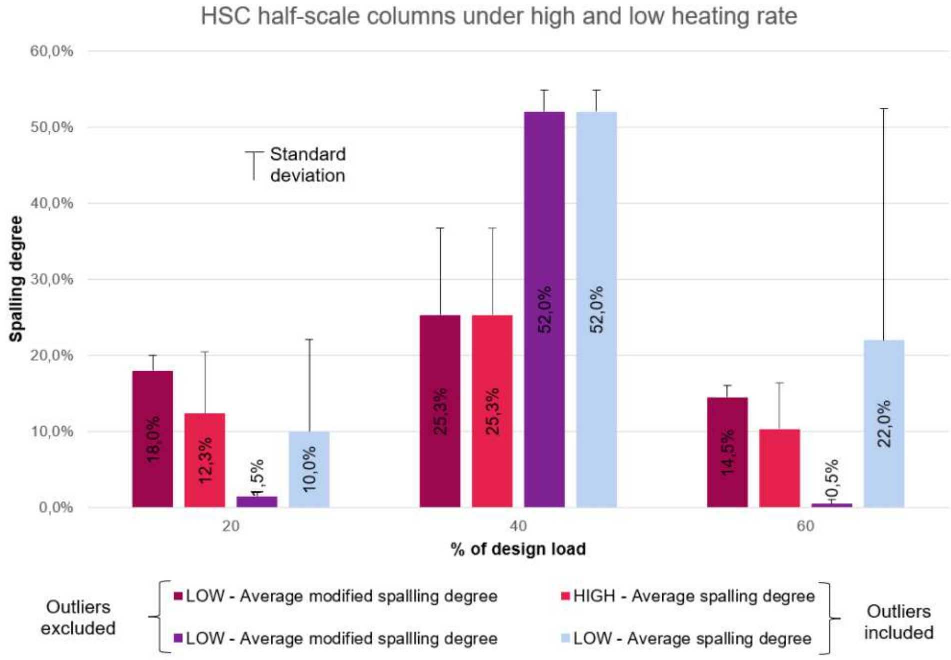


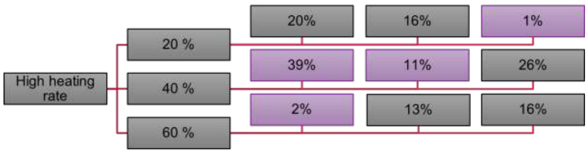
Fig. 5.8: Averaged spalling degree results for HSC half-scale concrete columns in study [33] with the representation of the standard deviation for the complete and the adjusted result set.

beyond the $\pm 2,0$ border which means non of the results would be regarded as outliers in the case of a normal distribution. As our dataset with only three specimens is very small compared to most statistical datasets and our results don't follow the standard normal distribution, different borders were also looked at. In this case, the limit was lowered to $\pm 1,0$. In figure 5.9 and 5.10, this is referred to as the "restricted outer limit". In this scenario, seven test results are identified as outliers - 4 specimens under the high heating rate and 3 under the low heating rate. A problem with this approach is that for the high heating rate (HHR) group with a loading level of 40 %, only one specimen remains in the corresponding result set.

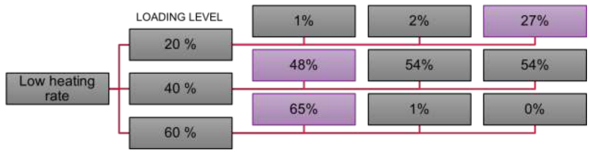
The next step was to look at each group of heating rates together, meaning there were nine specimens in each dataset with various loading levels. For the specimens subjected to the high heating rate, this brings better results. As pictured in figure 5.10 a limit of $\pm 1,0$ detects one outlier per group, making it a total of three outliers for the HHR. A limit of $\pm 2,0$, on the other hand, only results in one outlier overall for the HHR. For the group tested under the low heating rate, a limit of $\pm 2,0$ results in zero outliers, while a limit of $\pm 1,00$ defines 4 outliers, and an additional 3 specimens are situated precisely on the border. In the last case, all results under the 60 % loading level would be removed from the result set, leaving zero usable data.

5.2.1.2 Variation in concrete axial restraint and loading level

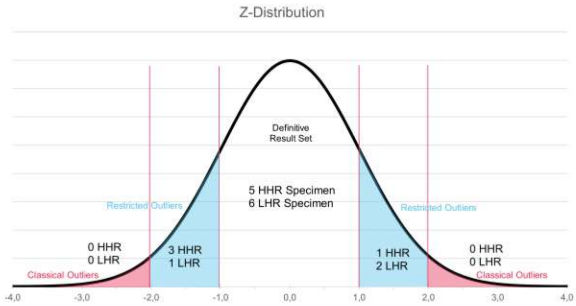
In the next part of the experimental program by Ali ([39, 33, 37], HSC and NSC half-scale columns were tested under different levels of axial restraint and various loading levels. Figure 5.11 gives an overview of how many specimens were tested under which conditions. The axial restraint is calculated by dividing the structure's axial stiffness by the column's axial stiffness. The loading level gives the percentage of the design load applied to the half-scale columns.



(a) HHR - Outliers according to z-score, if groups of three are looked at separately and the limit is defined as $\pm 1,0$



(b) LHR - Outliers according to z-score, if groups of three are looked at separately and the limit is defined as $\pm 1,0$

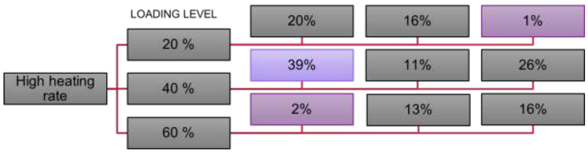


(c) Z-Distribution with the amount of results for each area

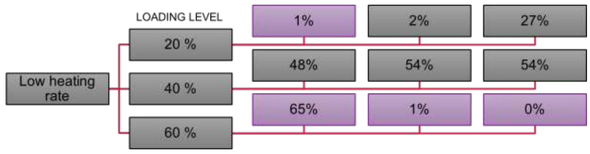
(d) Z-Score for HSC half scale columns under low and high heating rate - every dataset calculated individually

Fig. 5.9: Z-Distribution and z-Score for HSC half scale columns. The evaluation is carried out for groups of three specimens separately. (experimental results from [33])

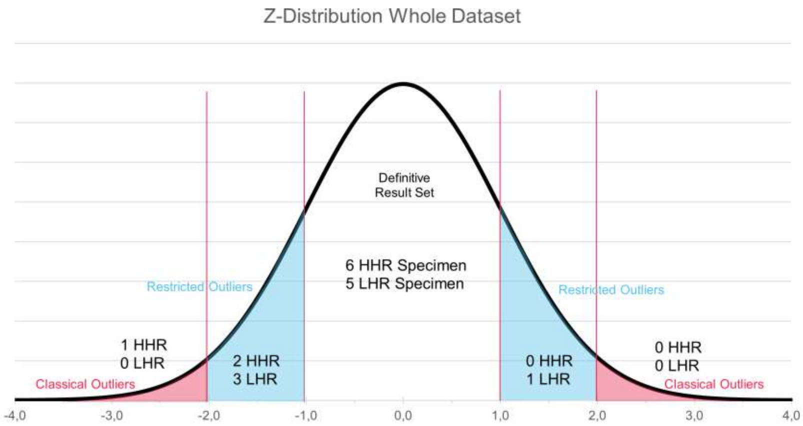
In figure 5.11, the NSC specimens that were excluded from the result set by the responsible author are shown in colour. For a better understanding, the z-scores for the results are shown in figure 5.12 - once for all NSC columns together and once for each individual dataset. The before-mentioned outliers are shown in yellow. It is stated by Ali [37] that the apparent variance in the results is due to the non-homogeneity of concrete. According to him, the result of 0 % in the first dataset is excluded because it isn't as close to the other two results in this test group (16 % and 32 %) as these are to each other. A more detailed look at figure 5.12 shows that if you



(a) Outliers according to z-score, if all specimens under the high heating rate are looked at together and the limit is defined as $\pm 1,0$



(b) Outliers according to z-score, if all specimens under the low heating rate are looked at together and the limit is defined as $\pm 1,0$



(c) Z-Distribution with the amount of results for each area

(d) Z-Score for HSC half scale columns under low and high heating rate - validated for HHR and LHR separately

Fig. 5.10: Z-Distribution and z-Score for HSC half scale columns. The evaluation is carried out for the 9 specimens - depending on the used fire curve. (experimental results from [33])

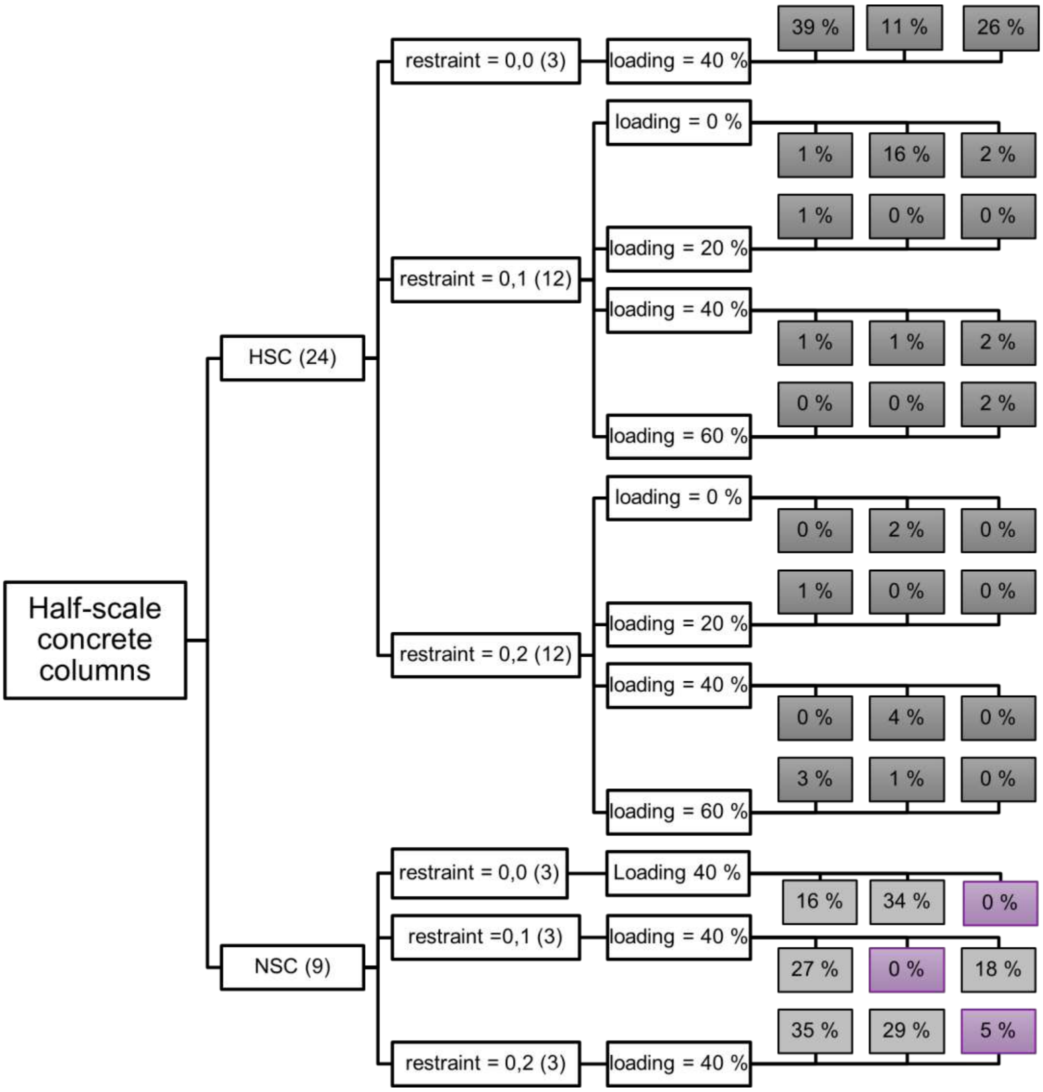


Fig. 5.11: Overview of the testing conditions and the spalling degree results for [39, 37]. The coloured results were defined as outliers by the author Ali.

set the excluded results as a limit for your outlier detection, two of the higher spalling degree results would be excluded from the respective dataset also. In fact, in the case of the individual datasets, the result of 34 % is further from the mean than the result of 0 %. But it should still be mentioned that in the case of the NSC columns, the excluded results lead to a safer end result because the average spalling degree is higher without them than with them.

The high-strength concrete columns behaved much more uniformly than the NSC columns. The only exceptions are the groups tested under no axial restraint with 40 % load and the group tested under an axial restraint of 0.1 and no load. This also seems to be in accordance with the theory of Hwang et al. [71], that HSC specimens are not as prone to explosive spalling under a high heating rate as NSC specimens. In terms of stochastic tendencies, there doesn't seem to be a large variance in the results if the test parameters (loading conditions and axial restraint) correspond to reality.

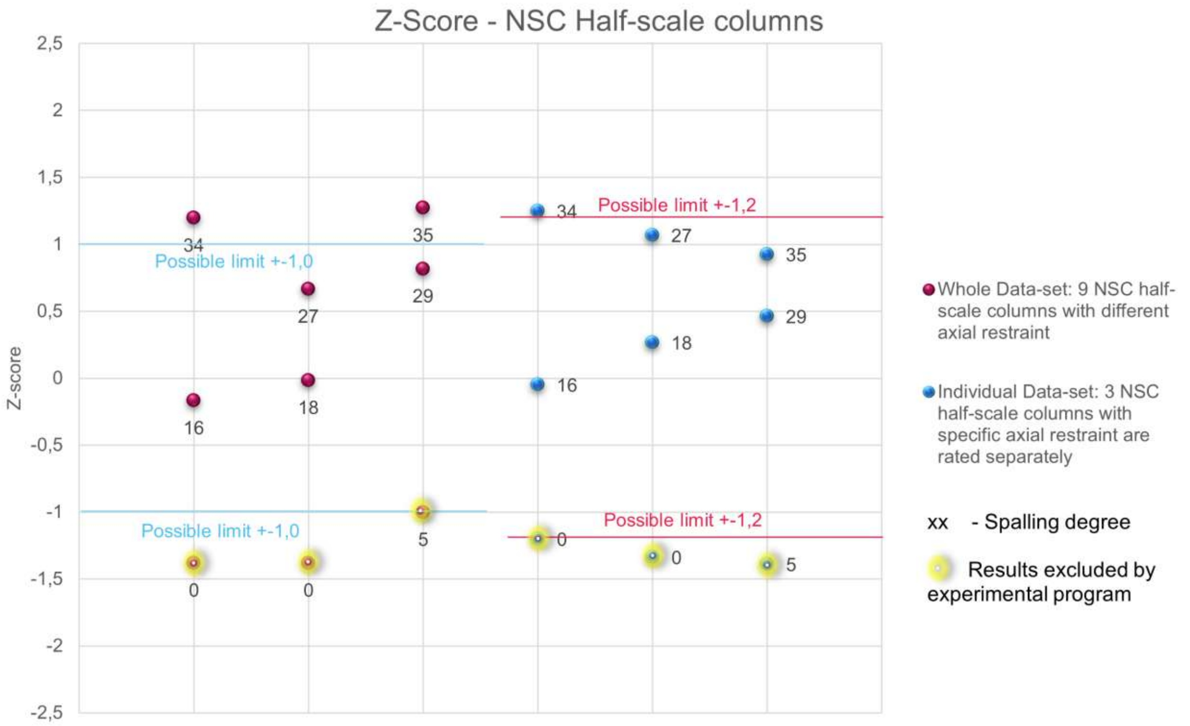
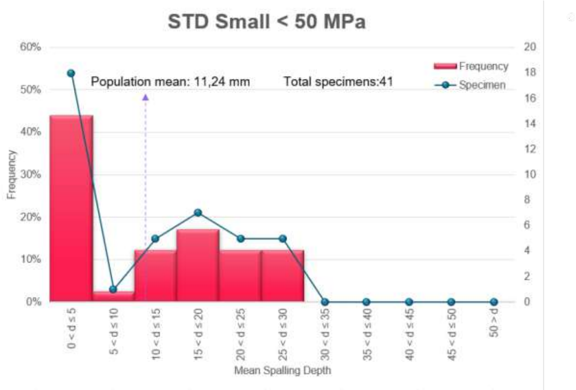


Fig. 5.12: Z-scores for the NSC test specimens in the study of Ali [37]. Calculated for the whole set of 9 half-scale columns disregarding the different axial restraints, and separately for each set of three columns.

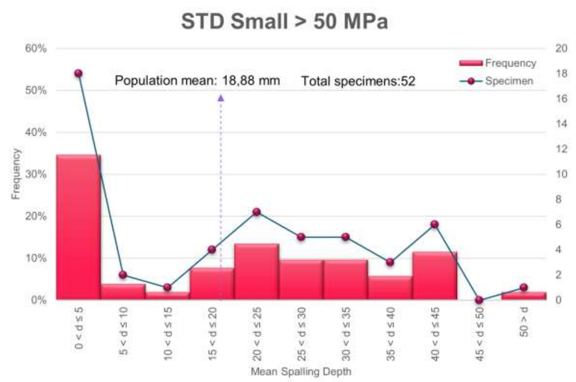
5.2.2 Study on SCC

The experimentation program of Boström and Jansson [42] was already discussed in chapter 5.1.1 on page 57 to find out more about the connection in the behaviour of small and large-scale specimens. To study the stochastic tendencies of explosive spalling, those test results were again analysed to see if there is a pattern to be found.

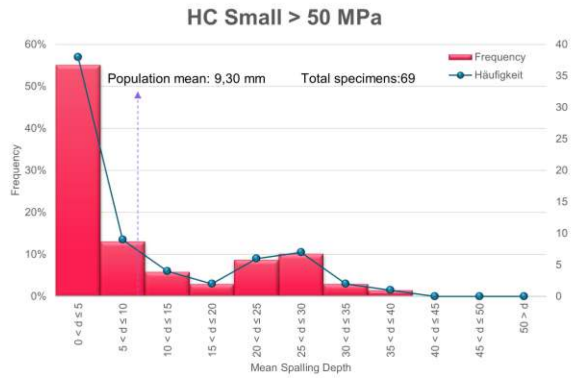
In figure 5.13, the mean spalling depth results are shown for the small-scale samples. Every test group has between 40 and 69 specimens, and the results are placed in different categories depending on their value. All three test groups show a skewed right distribution, as respectively, between 35 % and 55 % of the specimens showed no or only minor spalling damage. The results seem to differ the most for the specimens with compressive strength below 50 MPa, either showing no damage or a spalling depth of more than 20 mm with increasing probability for higher damage. In the case of the higher strength specimens, the right tail of the distributions is more even, but no clear pattern is still visible.



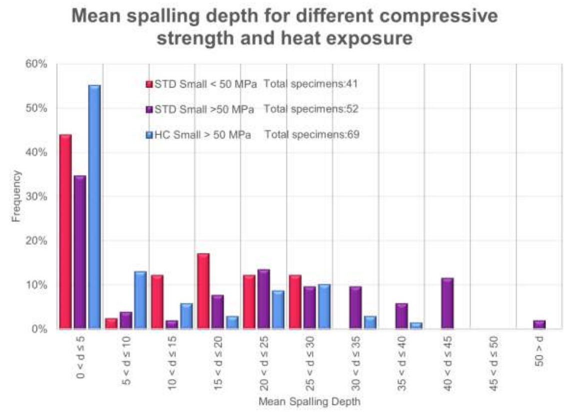
(a) Small-scale specimens with compressive strength less than 50 MPa subjected to the standard heating curve



(b) Small-scale specimens with compressive strength greater or equal to 50 MPa subjected to the standard heating curve

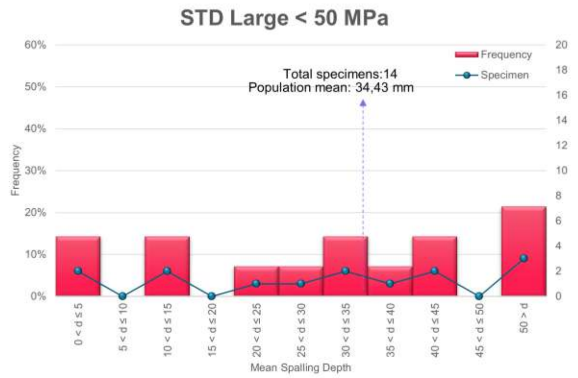


(c) Small-scale specimens with compressive strength greater or equal to 50 MPa subjected to the hydrocarbon curve

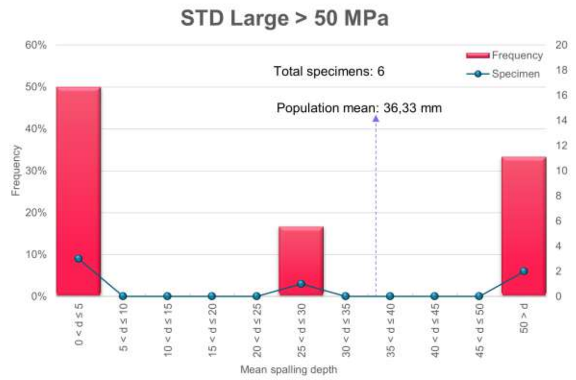


(d) Comparison of mean spalling depth for different test groups

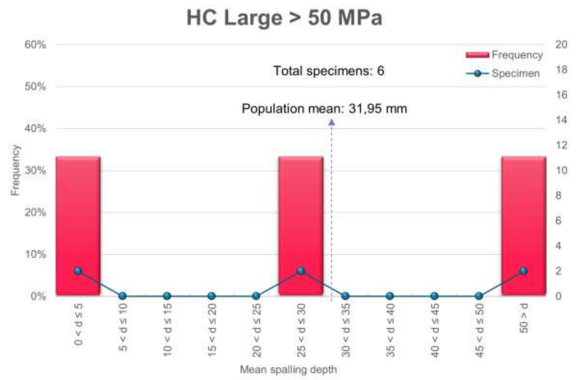
Fig. 5.13: Distribution of mean spalling depths for small-scale slabs under the influence of the standard heating curve and the hydrocarbon heating curve in relation to their compressive strength



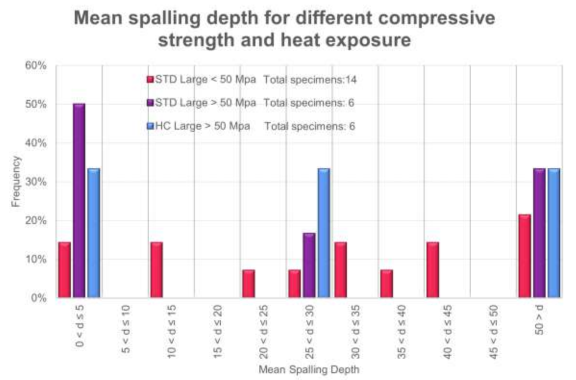
(a) Large-scale specimens with compressive strength less than 50 MPa subjected to the standard heating curve



(b) Large-scale specimens with compressive strength greater or equal to 50 MPa subjected to the standard heating curve



(c) Large-scale specimens with compressive strength greater or equal to 50 MPa subjected to the hydrocarbon curve



(d) Comparison of mean spalling depth for different test groups

Fig. 5.14: Distribution of mean spalling depths for large-scale slabs under the influence of the standard heating curve and the hydrocarbon heating curve in relation to their compressive strength

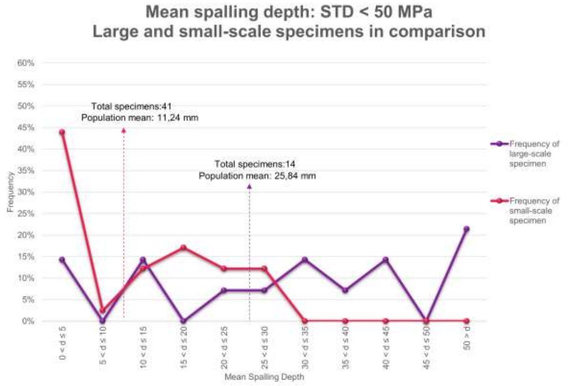
5.3 Summary and discussion

The purpose of chapter 5 was to show in more detail why it is so hard to make unambiguous statements regarding the reaction of concrete to heat exposure. While many different factors influence the explosive spalling behaviour of concrete, the size effect and the stochastic tendencies of the phenomenon are two of the more discussed factors. Conflicting opinions are common among the various experts.

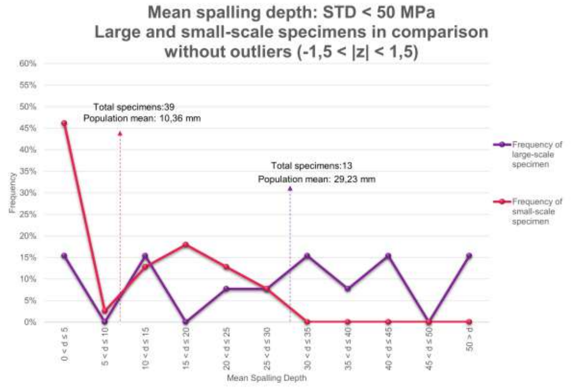
The size-effect describes the problems in concluding the behaviour of an actual-sized structural element from experiments done on small-sized specimens. Trials with small specimens are easier to carry out and a lot cheaper. Therefore these are the kinds of experiments where test results can be found in abundance. The experimentation on medium to large-scale specimens is generally more expensive, partly due to the more complicated test set-up necessary to perform these experiments. The detailed analysis of one of these research programs showed that the finding of a scaling factor is challenging and, in the case of the discussed experimentation, not possible. Part of the problem is that the number of tested full-sized specimens only was between 8 % and 34 % of the amount of tested small-scale specimens. In the group where the large specimens amounted to about one-third of the small specimens, it was still impossible to find a connection between the two sizes. It is possible that this is not only due to the difference in sizes but also the difference in boundary conditions.

The aforementioned size-effect and the fact that test procedures, conditions, concrete mixes, the geometry of the specimens, and the number of tested specimens vary between the different research programs make it difficult to say for sure if explosive spalling shows stochastic tendencies or not. Many researchers state that explosive spalling happened randomly in their experiments, and different opinions on why exist. Khoury [32] thinks that the randomness is due to the complex microstructure of concrete. Conolly [27] states in his work that the permeability and tensile strength of concrete are very sensible to the cracking behaviour of concrete, which is different in each case. As those two parameters also strongly influence the explosive spalling behaviour, this could explain the stochastic tendencies of this phenomenon. Ali et al. took another approach to the problem. According to them, the variance in the test results is due to the non-homogeneity of concrete and the resulting unique void and moisture distribution. Their solution was always to test at least three different samples per condition set and to remove the inconsistent results as they were defined as outliers. The outcome of this procedure is that the explosive spalling results appear to be much more evenly distributed than they actually are.

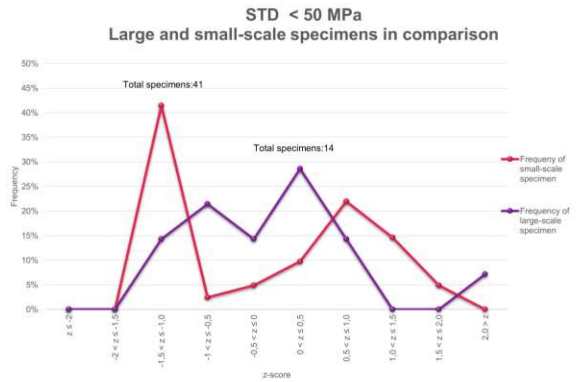
Ali et al. [39] experimented on HSC half-scale columns. For each test set, three identical specimens were tested. Three loading levels and two different heating rates were applied, resulting in 18 samples and six test groups. As mentioned above, the decision was made to exclude specific results from the end results because of the non-homogeneity of concrete. In this work, an attempt was made to find a way to define those outliers based on a mathematical approach. For this, the z-score system was applied. The first step was calculating the z-score for each test set individually, meaning the standard deviation and mean were calculated from three test results in each case. Adapting the outlier limit showed that this was not the desired approach, as either no or too many outliers were defined this way. The next step was to calculate the z-score for all specimens exposed to the same heating rate. Meaning the standard deviation, the population mean, and the z-score was determined for a set of nine samples disregarding the different loading levels. While this approach showed the desired outcome for the HSC specimens exposed to the high heating rate, the results for the specimens exposed to the low heating rate were not sensible. For



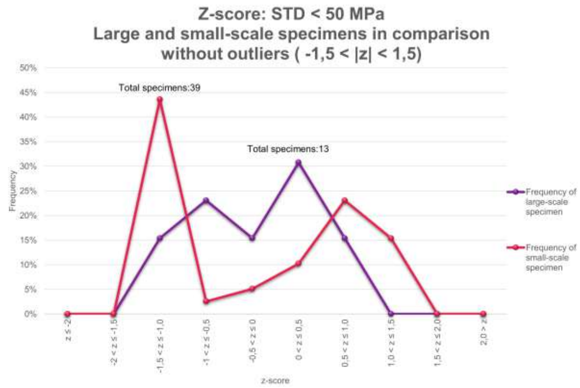
(a) Comparison of small and large-scale specimens with compressive strength less than 50 MPA subjected to the standard heating curve using the mean spalling depth



(b) Comparison of small and large-scale specimens with compressive strength less than 50 MPA subjected to the standard heating curve using the mean spalling depth. Results with a z-score lower then -1,50 or higher than +1,5 are excluded



(c) Comparison of small and large-scale specimens with compressive strength less than 50 MPA subjected to the standard heating curve using the z-score system.



(d) Comparison of small and large-scale specimens with compressive strength less than 50 MPA subjected to the standard heating curve using the z-score system. Results with a z-score lower then -1,50 or higher than +1,5 are excluded.

Fig. 5.15: Comparison of small and large-scale specimens with compressive strength less than 50 MPA subjected to the standard heating curve. Results from [42]

the low heating rate, the results varied so strongly that either no outliers at all were defined or all results from a group were excluded. This might be a clear indication that high-strength concrete reacts a lot more erratically to low heating rates than to high heating rates.
The same approach as described above was taken for the study of Ali in which normal strength concrete columns were experimented on. In this case, there were three test groups with different axial restraint and loading levels resulting in a total of nine tested samples. The calculation of the z-score for the individual test groups resulted in the same outcome as before. Either no outliers were defined, or too many test results were excluded at once. The z-score system where all 9 specimens were considered at once led to similar results. These results could be another sign that explosive spalling shows signs of extremely random behaviour.

The research program of Boström and Jansson [42], which was analysed to find a scaling factor, was again consulted to find a pattern in the results of the small-scale specimens. The only similarity between the different test groups is that all distributions are heavily skewed to the right, as between 35 % and 55 % of the test specimens showed no sign of explosive spalling. No clear pattern could be determined in the distributions. The results of the large-scale specimens were even more randomised. No pattern at all could be seen in those distributions.
As large-scale tests are more expensive and complicated, only 28 specimens were experimented on, of which 26 were analysed by their average spalling depth. The graphs in figure 5.14 show the results for those test groups. In the case of the first group (figure 5.14a), the results seem to be almost evenly distributed between the chosen categories, while in the other two groups, no pattern at all could be found. It has to be mentioned that in groups of higher compressive strength, only 6 specimens were tested respectively, while 14 slabs were experimented on in the first group.

To better visualize the discussed problems, a direct comparison between the small and large-scale specimens for "STD < 50 Mpa" is shown in figure 5.15. In the upper left corner of the figure, the mean spalling depths of the two groups can be seen. As to be expected, the mean spalling depths of the small specimens are generally lower than those of the large specimens. 100 % of all small specimens show a smaller mean spalling depth than 30 mm. However, the distribution across the classes is more variable for the large specimens. 43 % of all large specimens have a mean spalling depth below 30 mm, while the remaining 57 % suffered more severe spalling damage.
In the two figures on the right side, outliers $(-1,5 < |z| < 1,5)$ were defined and excluded from the result set. Unfortunately, this did not lead to a significant improvement in the results. It was not possible to determine a scaling factor using this approach.
The bottom diagrams show the comparison between the two sizes using the z-score-system. These figures confirm the stochastic behaviour of explosive spalling and that the probability distribution for small and large specimens is very different.

Chapter 6

Discussion and further research

Analysing all the different experimental programs discussed in this work has shown the necessity to test at least three specimens under the same conditions, although more is always better. The problem with this approach is that the testing of half-scale and large-scale specimens is much more complicated, time-consuming and expensive than the experiments performed on small-scale specimens. While the experimentation on multiple small-scale specimens simultaneously is relatively simple, the fact that no "scaling factor" has yet been found makes this approach not always helpful. Detecting a scaling factor would make it possible to translate the behaviour of small-scale specimens to that of actual structural members used in practice. However, the question remains whether it is even possible to find such a factor while testing small unloaded or unrestrained specimens. The discussed study of Boström and Jansson [42] in chapter 5.1 with loaded small-sized specimens showed that even with the addition of loading, the behaviour of large-scale specimens could not be foreseen. This problem was even more true for specimens with higher compressive strength.

Another aspect that makes defining a scaling factor very difficult is the stochastic tendencies of explosive spalling. Especially for normal strength concrete under the influence of high heating rates or high strength concrete under the influence of lower heating rates, the results vary quite strongly even when the same conditions are applied to all tested specimens. The z-score was used in chapter 5.2 to attempt to define outliers in a test set. No sensible limit could be found with this approach. For a given limit, the number of outliers for groups of three specimens varied between 0 % and 100 %. This extreme variation may also be because only three specimens were tested per condition set in the experimentation of Ali et al. [33]. Most statistical methods are usually applied to much larger test groups.

Some researchers put the erratic behaviour of explosive spalling down to the non-homogeneity of concrete ([33], [37], [39]). In contrast, others believe that it may at least partly be due to concrete's random cracking behaviour ([27]). While these parameters surely influence the stochastic tendencies it seems unlikely that they lead to such high differences in the spalling degree quite so often.
Decisions to remove individual test results from the final result set should be made very carefully as this distorts the expected values quite heavily, making the end results seem safer or unsafer than they might actually be. This is also because most test sets only consist of three or fewer specimens, and removing one means removing at least one-third of all available results.

The difference in the behaviour of high strength and normal strength concrete was found in many different studies. After analysing various experimentation results, it becomes more likely that the earlier belief that HSC is principally more likely to spall than NSC may not be valid. Under lower heating rates or with the addition of loads and restraint, larger HSC specimens seem to behave less randomly than NSC specimens in many studies. It might be possible that

HSC is simply influenced differently by the parameters than NSC, thus sometimes showing much more violent spalling behaviour when the surrounding parameters are right.

Conclusions:

- It is essential to find a factor which makes it possible to translate the results of small-scale specimens to that of large-scale structural members. This might only be possible if the boundary conditions of those smaller specimens are adapted to represent the actual behaviour of structures used in practice. This, in turn, would make those small-scale experiments more time-consuming and expensive but could save costs in the long run if large-scale experiments are no longer necessary.
- The development of a numerical model that can anticipate the explosive spalling behaviour of concrete should be of utmost importance. The approach of Liu and Zhang [69] using an artificial intelligence system seems very promising. Although the model only predicts if spalling will or will not happen at the time of writing this thesis, it may be possible to adapt and develop it further, so a prediction about the expected spalling degree becomes possible.

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