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Spalling of concrete in fire – an overview and local relevance

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Concrete has traditionally been considered as a material with favourable fire resistance. The development of modern concretes with low permeability has, however, resulted in the increased occurrence of spalling when exposed to fire. Recent fire damage in South Africa during the riots in July 2021 resulted in such damage.

This paper presents an overview of explosive spalling of concrete in fire, recent local observations, and developments in the field. It is shown that various (often interrelated) factors influence the susceptibility of concrete to spall in fire, and that much research is still needed to fully understand the phenomenon and, specifically, how to accurately predict its occurrence. Recent observations in South Africa support conclusions in the literature that, as an accidental loading case or as life-safety performance criteria, overall structural integrity is rarely compromised. However, as the use of higher concrete grades increases, the relevance of this risk should be considered by practising engineers.

Keywords: fire exposure, pore pressure, explosive spalling, reinforced concrete

List of symbols

b	Biot's coefficient (-)
E	Young's modulus of concrete (Pa)
f_t	tensile strength of concrete (Pa)
$f_{t,20}$	tensile strength of concrete at ambient temperature (Pa)
$f_{t,\theta}$	tensile strength of concrete at temperature θ (Pa)
k	moisture content (%)
p_{atm}	atmospheric pressure (Pa)
p_x	pore pressure at depth x (Pa)
T_f or θ	fire (gas) temperature (°C)
T_s	concrete surface temperature (°C)
T_x	concrete temperature at depth x (°C)
$W_{rupture}$	rupture strain energy (J)
W_x	strain energy in direction x (J)
ε_x	strain in direction x (-)
ν	Poisson's ratio (-)
σ_ℓ	applied compressive stress (Pa)
σ_p	pore pressure (Pa)
σ_t	thermal stress (Pa)

INTRODUCTION

Fires in structures pose a significant threat to occupants and property owners. Structural engineers are responsible for limiting the probability of injury, loss of life and damage to property to acceptable levels. Traditionally, concrete has been considered as incombustible, chemically stable, and as a material with favourable insulating properties, performing well during a fire (Buchanan & Abu 2017). A gradual decrease in compressive strength does, however, occur with increased concrete material temperature. A marked reduction in strength is associated with the 300°C isotherm, which is often accompanied by a discolouration of the cement matrix (Albrektsson *et al* 2011). Such thermal degradation can impair the continued service of reinforced concrete elements after a fire, but will seldom prevent safe evacuation during a fire for normal concrete grades. As an accidental load case then, such damage might be considered as detrimental to structural integrity, but low hazard.

Spalling of concrete is known to occur in some cases of fire exposure. This typically leads to a loss of concrete cover, resulting in a loss of thermal insulation to reinforcement and increased thermal degradation of the confined concrete core and high temperature exposure of reinforcement steel. In severe cases, spalling depth can extend into the confined core of reinforced concrete elements which, together with high-temperature exposure of reinforcement, can lead to collapse.

Various types of fire-induced spalling have been defined to date, as summarised in Table 1. The earliest forms of spalling are surface spalling, aggregate spalling, and explosive spalling, of which explosive

Table 1 Characteristics of the different types of fire-induced spalling (Khoury 2000)

Spalling type	Time of occurrence	Nature	Sound	Influence
aggregate	7 – 30 min	splitting	popping	superficial
corner	30 – 90 min	non-violent	none	can be serious
surface	7 – 30 min	violent	cracking	can be serious
explosive	7 – 30 min	violent	loud bang	serious

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Figure 1 Examples of recent fire-induced spalling damage during a fire damage assessment by the author following the July 2021 riots in South Africa: (a) explosive spalling of the steel-fibre-reinforced concrete floor, (b) spalling to the soffit and drop panel of an office building, (c) spalling to the top of an exposed slab, and (d) corner spalling of a column

spalling is considered the most violent. Due to the early, violent and often extensive nature of explosive spalling, it is considered as the greatest hazard to reinforced concrete structures if the extent is substantial.

Partial collapse of reinforced concrete building structures as a result of fire has been observed in the past. In many cases, however, reinforced concrete slabs are able to maintain structural integrity after spalling has occurred. Bailey (2002) concluded that this is most likely due to slabs acting in compressive membrane action following thermal expansion, although reduced loading benefits response as well.

The development of concrete with increased strength and reduced permeability, such as high-strength concrete (HSC) and self-compacting concrete (SCC), holds many advantages, such as increased durability and reduced element sizes. These advantages lead to its increased use in high-rise buildings, tunnel linings and warehouse floors. However, the low permeability of such compact modern concrete types leads to an increased risk of explosive spalling during fire exposure (Mindeguia *et al* 2013). This makes the assessment of spalling susceptibility of concrete, the possible extent of damage that might prevent safe evacuation during a fire, ways of preventing its occurrence, and the repair of such damage, increasingly relevant to structural engineers. Recent local observations illustrate this point.

Recent observations of fire-induced spalling of concrete in South Africa

The July 2021 riots in South Africa resulted in extensive fire damage to a warehouse structure in Durban. In addition to partial collapse of the steel superstructure, extensive fire-induced spalling of concrete elements resulted, as shown in Figure 1.

Severe explosive spalling of the steel-fibre-reinforced concrete floor occurred in isolated locations (Figure 1(a)) to depths of up to half of the floor thickness. Similarly, extensive spalling resulted to slab soffits of the adjacent office building, exposing bottom reinforcement (Figure 1(b)). Such spalling around columns has been shown to drastically reduce punching shear resistance (Lu *et al* 2018). Localised fires in reinforced concrete structures inside the warehouse space showed substantial spalling of the top of slabs, as well as cases of corner spalling of columns, exposing reinforcement to fire (Figures 1(c) and 1(d)).

PROPERTIES INFLUENCING SPALLING

Numerous parameters influence the susceptibility of concrete to spall in fire, ranging from material production to construction and operational conditions. Properties can be grouped into the following four categories (Van der Merwe 2019):

Concrete mixture composition

The *aggregate type* is said to influence spalling susceptibility, with siliceous aggregate concretes often reported as being more susceptible to spalling (Fib Bulletin 38: 2007). Substantial thermal damage can result due to the difference in the thermal expansion coefficient of aggregate and the surrounding cement paste. Quartz in siliceous aggregates is generally associated with a phase change at high temperatures that results in a rapid increase in volume and subsequent thermal damage to concrete (Bažant & Kaplan 1996).

Although some contradictory results have been reported in the literature, there appears to be general agreement that a larger *coarse aggregate size* reduces spalling susceptibility. Experimental results by Pan *et al* (2012) support this, suggesting the cause to be related to an increased characteristic length of the fracture process zone that is associated with larger aggregates, although increased permeability is likely an additional contributing factor (Van der Merwe 2019).

High *cement and silica fume content* is also said to increase spalling susceptibility, correlating with lower permeability and a subsequent higher internal pressure build-up potential (e.g. Klingsch 2014; Kodur & McGrath 2006).

Material properties of hardened concrete

It has often been stated in the literature that greater *compressive strength* is often associated with increased spalling susceptibility (e.g. Majorana *et al* 2010). General consensus is that this is due to the compact microstructure that is associated with greater compressive strength. A strong correlation has been shown to exist between the compressive strength of concrete and its intrinsic permeability (Van der Merwe 2022c), suggesting that higher concrete grades can be expected to be associated with higher pore pressure build-up during fire exposure. Related to such a compact microstructure is the *permeability* of concrete, which governs pore pressure build-up potential (Bažant & Kaplan 1996). Since the permeability of concrete can be reduced without increasing compressive strength, Hertz (2003) concluded that permeability is a more relevant indication of spalling risk than compressive strength.

In addition to permeability, the *moisture content* determines pore pressure build-up during fire exposure, and is therefore considered by many as a crucial parameter related to spalling susceptibility (e.g. Hertz 2003). In addition to its influence in pore pressure build-up, increased moisture content can be expected to increase the thermal stress gradient (Fib Bulletin 38: 2007). Latent heat during the phase change from liquid water to vapour is associated with an increased specific heat of concrete, with a subsequent slower increase in temperature away from the heated surface and a resulting increase in thermal stress. Similarly, *thermal properties* that affect thermal stress development are also associated with spalling risk, including the specific heat and thermal conductivity of concrete.

Since *fracture energy* determines the specific energy required for crack propagation, lower fracture energy is associated with increased spalling risk. Bažant and Prat (1988) concluded from experimental results that the fracture energy of concrete gradually decreases with increased temperature, thereby making concrete gradually more susceptible to spalling with increased temperature.

Structural properties

Previous investigations have shown that the spalling susceptibility of concrete generally increases (i) with increased *element size* (Boström *et al* 2007), (ii) where structural *geometry* results in stress concentration at sharp corners (Khoury & Anderberg 2000), and (iii) where *thermal restraint* prevents expansion of concrete during heating (Majorana *et al* 2010).

Loading

It is generally accepted that an increased *heating rate* increases spalling susceptibility due to increased thermal stress development (Kodur & Phan 2007). Experimental observations have also shown that moderate *compressive stress* increases spalling susceptibility (Carré *et al* 2013). Moderate compressive stress adds to the overall internal stress state, but has also been shown to reduce the intrinsic permeability of concrete (Van der Merwe 2022b), which in turn can result in increased pore pressure development.

PLAUSIBLE MECHANISMS OF SPALLING

Various mechanisms for explosive spalling have been proposed, and some academic debate in this regard continues to date. Shorter and Harmathy (1961) and Harmathy (1965) proposed that **pore pressure** build-up in the concrete matrix at elevated temperatures is the main mechanism responsible for spalling. Once moisture evaporation starts, the resulting pressure gradient forces part of the moisture to the heated surface, whilst the direction of heat flux forces the remainder to the cooler inner region. Here condensation is said to result in a region of increased moisture content. As heating continues, two distinct zones result – a dry region near the heated surface, and a saturated zone (moisture clog) deeper in the concrete section (Figure 2). The low permeability in this moisture clog results in gradually increasing pore pressure and finally in spalling when the high-temperature tensile strength of concrete is exceeded.

Despite such a moisture clog having been experimentally shown to develop, it is widely accepted that pore pressure alone cannot be responsible for spalling since the mechanism does not account for increased spalling risk due to confinement (Jansson & Boström 2012) and since resulting pore pressure is usually well below typical ranges of concrete tensile strength (Bažant & Thonguthai 1979).

The high heating rate imposed during fire exposure results in a high temperature gradient over the depth of a concrete section which, in turn, leads to the development of **thermal stress**. The compressive stress state that results near the heated surface was proposed by Saito (1966) as a mechanism of explosive spalling. It was suggested that such compressive stress induces cracks that separate a surface layer. Thermal buckling of this weakened delaminated layer is the proposed cause of spalling. Experimental observations have shown, however, that spalling can occur in some concretes at heating rates much lower

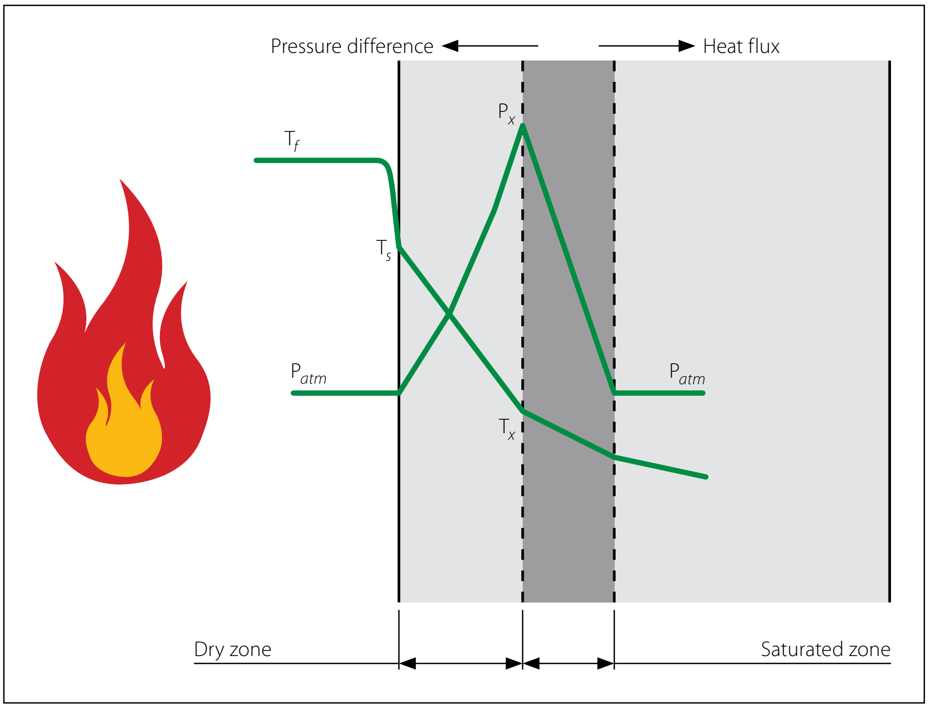

Figure 2 Pore pressure spalling mechanism proposed by Harmathy (adapted from Harmathy 1965)

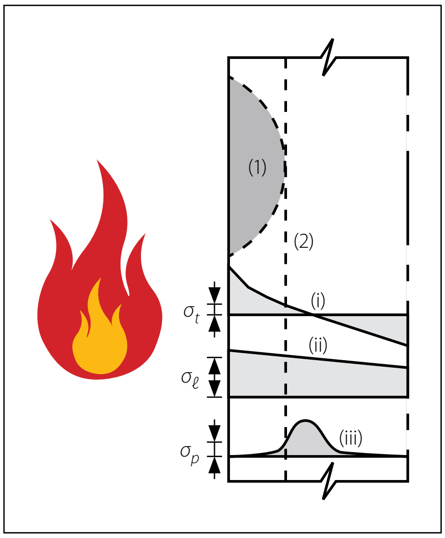

Figure 3 The combined stress state mechanism suggests that spalling of concrete (region 1) occurs when the concrete tensile strength is exceeded (at depth shown by 2) and a crack opens due to a stress state resulting from the combined effect of (i) thermal stress (σ_t), (ii) applied compressive stress (σ_ℓ) and (iii) pore pressure (σ_p) (adapted from Zhukov 1976)

that those that would impose meaningful thermal stress, suggesting that thermal stress alone cannot be a mechanism of spalling (Klingsch 2014).

The most widely accepted mechanism is the combined stress state mechanism proposed by Zhukov (1976). With reference to Figure 3, this mechanism suggests that explosive spalling occurs when the combined effect of thermal stress, pore pressure development and level of applied compressive stress exceeds the temperature-dependent tensile strength of concrete.

Considering the total strain in the direction of spalling (Equation 1), pore pressure (σ_p) acts directly in this direction, whilst Poisson effects from thermal stress (σ_t) and applied compressive stress (σ_ℓ) add to this effect.

$$\epsilon_x = \frac{1}{E}\cdot[\sigma_p + \nu\cdot(\sigma_\ell + 2\cdot\sigma_t)] \qquad (1)$$

Explosive spalling is said to occur when the strain energy (W_x, Equation 2) exceeds the rupture strain energy ($W_{rupture}$, Equation 3).

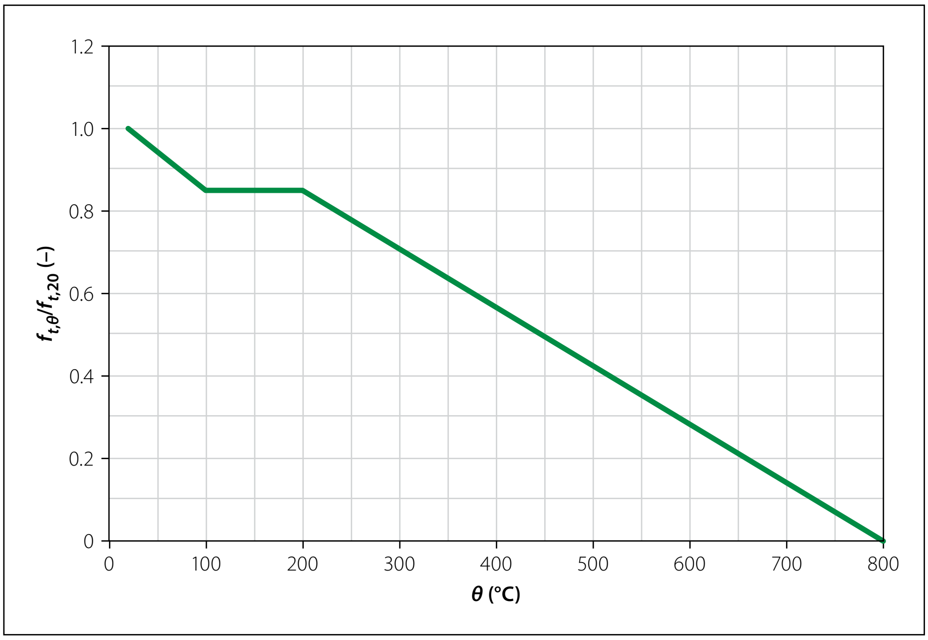

Figure 4 Tensile strength of concrete has been shown to gradually decrease with increasing temperature (adapted from Van der Merwe 2022a); within the temperature range typically associated with spalling (Fib Bulletin 46: 2008), a tensile strength reduction of up to 50% can be expected

$$W_x = \frac{1}{2}\cdot\epsilon_x\cdot\sigma_x = \frac{\sigma_p}{2\cdot E}\cdot[\sigma_p + \nu\cdot(\sigma_\ell + 2\cdot\sigma_t)] \qquad (2)$$

$$W_{rupture} = \frac{1}{2\cdot E}\cdot f_t^2 \qquad (3)$$

Combining Equations 2 and 3, it follows that explosive spalling is initiated when the combined internal stress state exceeds the tensile strength of concrete, as shown in Equation 4. With increased material temperature, the tensile strength of concrete can be expected to gradually decrease as shown in Figure 4.

$$f_t^2 = \sigma_p^2 + \nu\cdot\sigma_p\cdot(\sigma_\ell + 2\cdot\sigma_t) \qquad (4)$$

PREDICTIVE MODELS

Numerous attempts have been made to develop a means of predicting the occurrence of explosive spalling of concrete in fire, ranging from nomograms, analytical models and numerical models. To date, however, none of these have been validated as a reliable means of predicting this phenomenon.

Moisture clog theory

Harmathy (1965) proposed analytical expressions for the movement of a moisture clog in concrete. Based on these expressions, he proposed a limit criterion for the pore saturation associated with

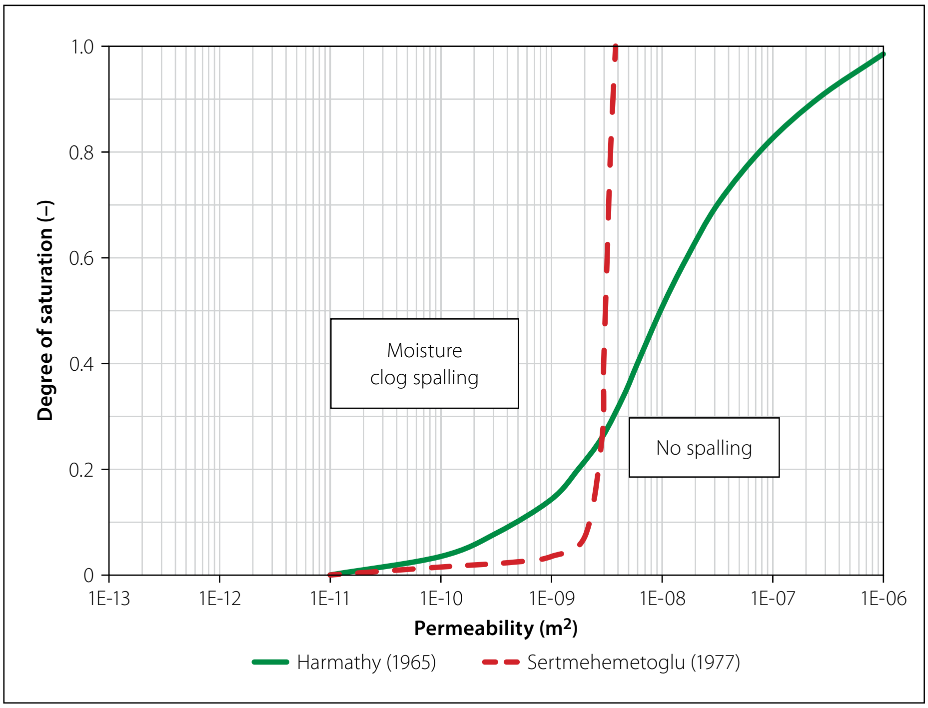

Figure 5 Nomograms proposed by Harmathy (1965) and Sertmehemetoglu (1977) for spalling risk considering concrete permeability and the degree of saturation (adapted from Harmathy 1965 and Sertmehemetoglu 1977)

fire-induced spalling. His proposed nomogram (Figure 5) provides a graphical means of evaluating the risk of explosive spalling based on a limit value for pore saturation with permeability. This model was modified by Sertmehemetoglu (1977) to account for the difference in permeability, viscosity, and pressure between the moisture clog and the heated surface. Comparing these two models in Figure 5, shows that the modified model suggests a narrower range of permeability associated with spalling susceptibility, which can be expected to shift to higher or lower permeability values depending on the concrete tensile strength.

Level of compressive stress and element thickness

Based on experimental results by Meyer-Ottens (1972), Sertmehemetoglu (1977) proposed a nomogram for spalling susceptibility based on the level of applied stress and the thickness of a concrete element heated from two sides (Figure 6). An adapted version of this nomogram was later incorporated in Eurocode (EN 1995).

Numerical models

Each of the two nomograms described above clearly accounts for parameters known to be associated with explosive spalling, but neglects other known contributing parameters. Numerical models have been proposed to account for all known effects that contribute to explosive spalling. Gawin *et al* (1999) proposed a hygro-thermal model which, amongst others, accounts for the effect of moisture movement and heat flux. Their model for the high-temperature development of intrinsic permeability was subsequently considered by Dwaikat and Kodur (2009) to propose a hydrothermal model for the assessment of spalling risk. The model accounts for temperature variation, pore pressure and moisture movement that are considered as coupled equations to be solved numerically. Spalling is then identified when the pore pressure exceeds the high-temperature tensile strength of concrete. Elaborating on this model to account for pore pressure in all directions, and for Biot's coefficient, which determines the extent to which pore pressure affects the internal stress state of the concrete matrix, Lu (2015) proposed the numerical model shown in Equation 5.

$$\sqrt{(1-2\nu)\cdot b^2\cdot{\sigma_p}^2+\nu\cdot(b\cdot\sigma_p)\cdot(\sigma_\ell+2\cdot\sigma_t)}\geq f_t \tag{5}$$

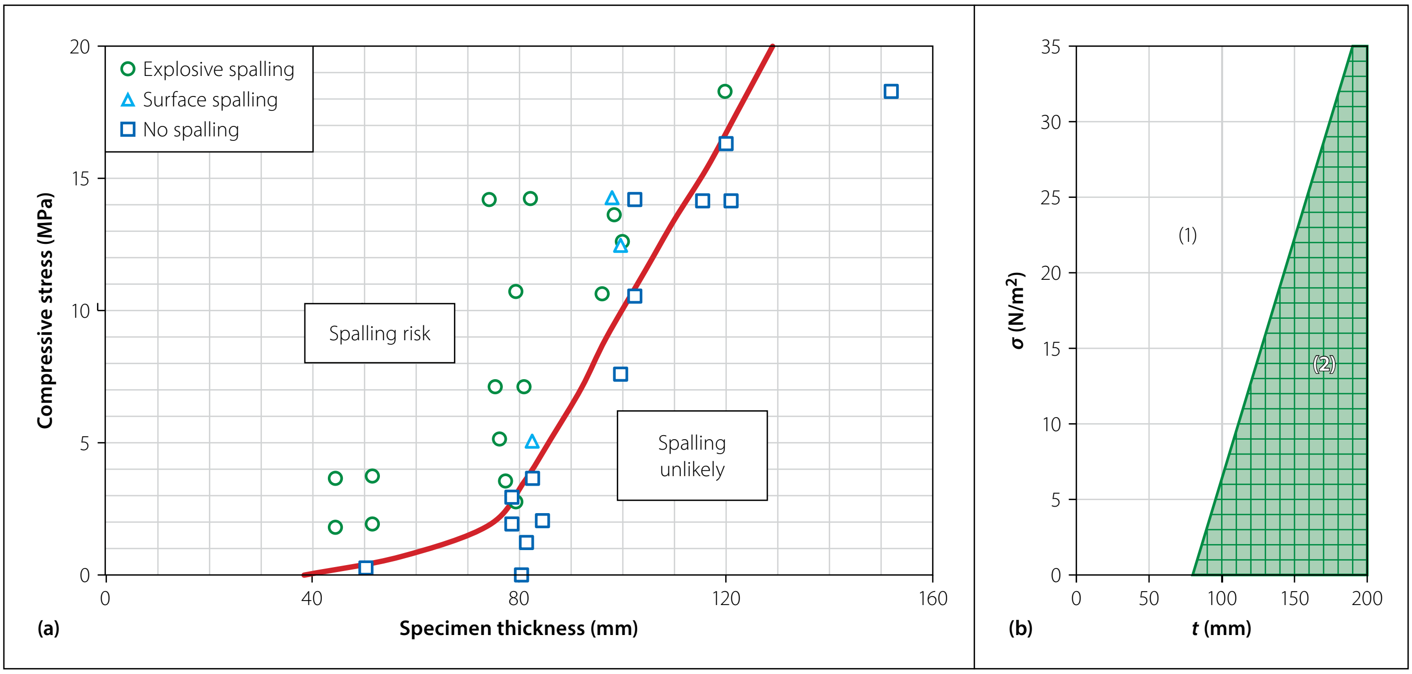

Figure 6 The nomogram for spalling risk proposed by Sertmehemetoglu (adapted from Sertmehemetoglu 1977) proposed a means of assessing spalling risk based on the thickness of a concrete element and the level of applied load; an adapted version of this nomogram was included in an earlier version of Eurocode (adapted from EN 1995)

Considering a 150 mm thick concrete slab exposed to fire on one side, and with a reference concrete tensile strength of 2.5 MPa, Lu (2015) proposed a boundary intrinsic permeability value of 2×10^{-17} m^2. The correlation between concrete tensile strength and intrinsic permeability investigated by Van der Merwe (2019) suggests that such intrinsic permeability values are, however, unlikely for the concrete tensile strength assumption.

GENERAL METHODS OF PREVENTION

Experimental observations of explosive spalling have shown the occurrence of this phenomenon to be complex and often erratic. Fib Bulletin 38 (2007) reports a test series of ten similar specimens where five samples spalled, whilst five did not. Elsewhere this observation is supported, mentioning that, for concrete samples from the same batch and under identical curing and testing conditions, some samples would spall whilst others would not (Connolly 1995; Majorana *et al* 2010). To this extent, Bisby *et al* (2014) recommend that "*… attempts should be made to avoid spalling … in practice, since spalling introduces uncertainties that are very difficult to rationally account for in design.*" Where a risk of spalling is therefore suspected, or where the consequence of explosive spalling is expected to have a substantial effect on structural integrity or the safe evacuation of occupants, preventative methods should be considered.

Addition of fibres

In addition to improving ductility, the addition of *steel fibres* to concrete increases its tensile strength. Since it is generally believed that spalling occurs when the high-temperature stress state in concrete exceeds its tensile strength, steel fibres can be expected to increase the resistance to explosive spalling. Nevertheless, contradicting experimental observations of its beneficial effect have been reported, with some tests showing improved spalling resistance (Kodur *et al* 2003), whilst others notice no substantial improvement (Klingsch *et al* 2013). Moreover, the addition of steel fibres has been noted to increase the violent nature of explosive spalling in some cases due to the release of a greater build-up of energy accommodated by the increased tensile strength (Fib Bulletin 38: 2007). This supports recent observations of a steel-fibre-reinforced concrete warehouse floor (Figure 1a).

It is widely agreed that the addition of *polypropylene fibres* (PP-fibres) reduces the risk of spalling. Explosive spalling of concrete with compressive strength of up to 150 MPa has been found to be avoided when adding 0.05 – 0.10% PP-fibres (Fib Bulletin 38: 2007). Most conclusions in literature seem to agree that the observed benefit of adding PP-fibres is related to increased permeability and improved moisture transport, thereby reducing pore pressure build-up (e.g. Heo *et al* 2012; Klingsch *et al* 2013; Maluk *et al* 2017). Increased entrained air during the concrete mixing process, and poor adhesion between fibres and the surrounding concrete matrix have been proposed as potential mechanisms for the beneficial effect of adding PP-fibres, but the formation of continuous channels after fibres melt, and differential thermal expansion are the two most widely argued mechanisms. Following experimental tests of HSC with PP-fibres, Kalifa *et al* (2001) studied test samples with a scanning electron microscope. They concluded that molten PP-fibres are absorbed into the surrounding porous cement matrix. The interconnected channels created in this manner are said to increase permeability and, subsequently, reduce pore pressure. Another proposed mechanism suggests that there exists a difference in thermal expansion between PP-fibres and the surrounding concrete matrix, resulting in micro cracks that increase overall permeability and, subsequently, reduce pore pressure. Zhang *et al* (2018) investigated ultra-high performance concrete with PP-fibres after heating to elevated temperatures at 5°C/min. A subsequent review of samples with a scanning electron microscope revealed micro cracks in the concrete matrix between fibres prior to melting, suggesting that the thermal expansion mismatch between fibres and the cement matrix is responsible for the reduced spalling risk. Despite the variation in conclusions, it is clear that PP-fibres reduce the risk of explosive spalling by increasing permeability. It is argued here that the interconnectedness of increased porosity that is required to increase permeability, is more likely to result from the formation of microcracks than absorbed molten fibres.

Protective barriers

The aim of protective barriers, be they panels, mortar or intumescent paint, is to minimise heat transfer to concrete in the event of a fire. No design criteria are currently available for the use of these measures to avoid explosive spalling. As such, careful experimental validation of protective barriers is typically required. Reviewing a series of fire tests by Klingsch *et al* (2013), Lu (2015) concluded that the provision of an insufficient protection layer can, in some cases, increase the violent nature of explosive spalling. Figure 7 compares

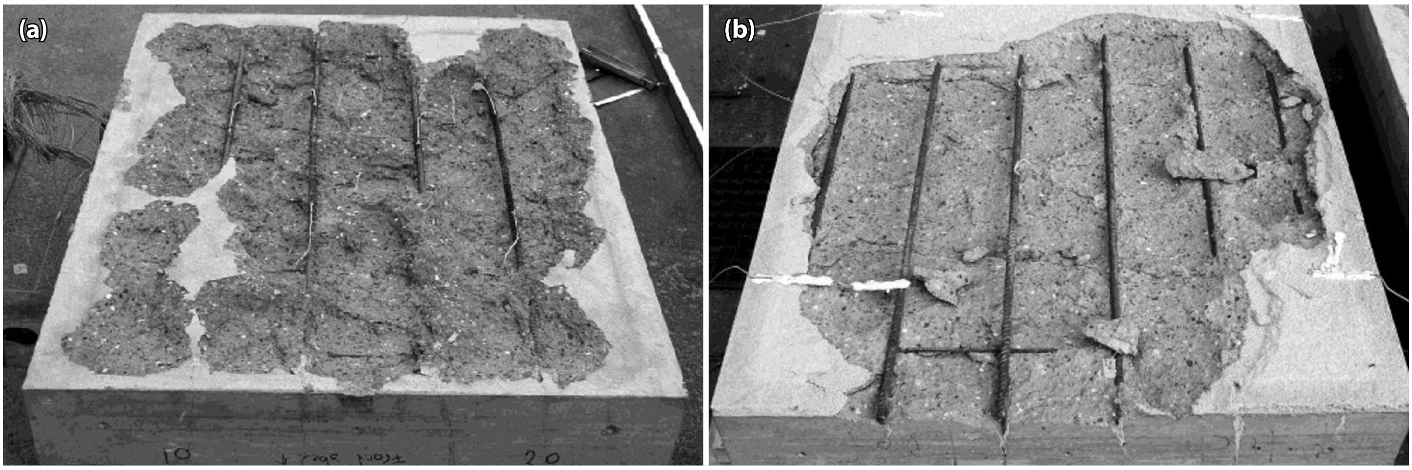

Figure 7 HSC slabs after fire testing: (a) without a protective lining, explosive spalling started after 15 minutes and continued gradually to a depth of 100 mm after stopping the test, (b) where a 10 mm protective lining was provided, spalling occurred with a single load explosion after 119 minutes to the same depth (Klingsch *et al* 2013 – ETH Zurich, open-access source for non-commercial use)

explosive spalling of a slab with and without a protective lining (Klingsch *et al* 2013). Although the protective lining delayed the occurrence of spalling, damage occurred to the same depth. Moreover, compared to the gradual, layer-by-layer spalling observed for the slab without a protective layer, spalling occurred with a single loud explosion where the protective layer had been applied.

Reinforcement details

A series of experimental and numerical investigations of the behaviour of reinforced concrete columns in fire were conducted by Kodur and McGrath (2006), and Kodur and Phan (2007). They concluded that transverse confinement reinforcement details that are typically recommended in regions of seismic hazard are well suited to improve the explosive spalling resistance of columns. The detail calls for (i) a reduced transverse reinforcement diameter with decreased vertical spacing instead of larger diameters at greater spacing, (ii) the provision of cross ties, and (iii) anchorage of tie ends into confined concrete, i.e. a 135° hook instead of the more common 90° hook (Figure 8).

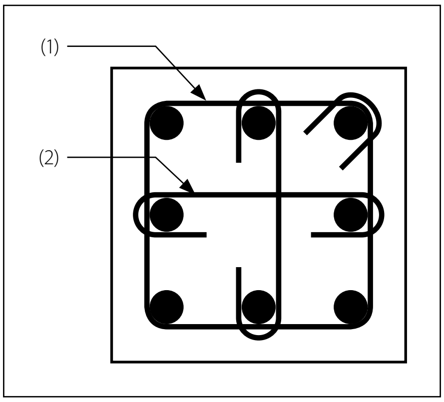

Figure 8 **Experimental observations by Kodur and McGrath (adapted from Kodur & McGrath 2007) suggest that improved confinement detailing of stirrups to columns improves the spalling resistance of columns: (1) ends of stirrups should be anchored into the confined core, and (2) cross ties should be provided**

CURRENT REGULATIONS AND GUIDELINES

Eurocode 2 (EN 2004) addresses the fire design of concrete structures and is perhaps the most suitable current reference, since the suite of SANS standards does not include similar clauses. This standard recommends that the occurrence of spalling should either be prevented, or that the engineer should consider the consequences of spalling on the structural capacity of elements. Spalling is addressed separately for normal strength concrete (NSC) and high strength concrete (HSC). It is suggested that spalling of NSC is unlikely to occur if the initial free moisture content is less than 3%. An earlier version of this standard (EN 1995) mentioned that this moisture content would most likely not be exceeded if a concrete element is subjected to internal exposure. Where this limit is exceeded, the risk of spalling should be more carefully investigated, considering (i) the moisture content, (ii) aggregate type, (iii) concrete permeability, and (iv) the expected (or design) heating rate. It does, however, give no guidance as to how these factors should be reviewed to assess spalling susceptibility. Nevertheless, the standard recommends that no further in-depth spalling assessment is necessary if the tabulated concrete material property data and the recommended reinforcement details are considered by the engineer.

HSC up to class C80/95 with a silica fume content of less than 6% of the cement mass, is treated as NSC. For higher concrete classes, or where the silica fume content exceeds 6%, four possible methods are recommended to prevent the occurrence of spalling:

(A) providing mesh reinforcement near the exposed concrete surface
(B) prescribing concrete that has been proven (experimentally or by experience) not to be susceptible to spalling
(C) providing a protective layer that has been shown to prevent spalling
(D) including a minimum of 2 kg/m^3 monofilament polypropylene fibres.

However, even when adhering to regulations, spalling can still occur. A full-scale fire test was performed on a seven-storey reinforced concrete building in Cardington in 2001 (Bailey 2002). Adhering to prescriptive rules, Eurocode recommendations suggest that spalling should not occur and that its occurrence can be ignored. Nevertheless, severe spalling did occur. The outcome highlights our poor understanding of the phenomenon of explosive spalling, and the limited means available to practising engineers to assess the spalling susceptibility of concrete.

DEVELOPMENTS

Recent findings are set to influence the evolution of Eurocode provisions pertaining to the susceptibility of concrete to spall explosively in fire. Eurocode (EN 2004) mentions that spalling should not occur if the moisture content is below k% by weight, with $2.5 \leq k \leq 3.0$% and a recommended value of 3%. Although the moisture content of concrete is undoubtedly an important parameter affecting the propensity of concrete to spall during fire exposure, it is difficult to predict what the moisture content of a concrete element will be, and equally hard to influence its value.

Moreover, spalling has been observed at lower moisture content levels (e.g. Zheng *et al* 2010). Results from various studies suggest that the relevance of moisture content as a parameter affecting spalling susceptibility depends on the type of aggregate, cross-sectional shape of the element, level of compressive stress, concrete mixture and heating rate (Jansson 2013). It has been suggested that such a moisture content limit be replaced by a list of concrete conditions known to result in a high moisture content and limited drying (Jansson 2013). These can include concrete exposed to saturated conditions or with permanent formwork that prevents drying.

CONCLUDING REMARKS

Although less severe types of fire-induced spalling might affect normal concrete strength grades to a limited extent, the susceptibility of concrete to spall explosively in fire is likely to become an increasingly relevant risk to be considered by structural engineers as the use of denser concretes and higher concrete grades increase in South Africa. This paper highlighted some key considerations, but also showed that, to a large extent, this phenomenon remains poorly understood. Much research is still needed in order to more accurately assess this risk. To date, the only accurate method of assessing the susceptibility of concrete to spall explosively in fire, is to perform fire tests of representative concrete elements. Since both the size and geometry of a concrete element influence the risk of spalling, small-scale samples, such as standard concrete cubes or cylinders, should not be considered as representative (e.g. Boström *et al* 2007). Due to the great cost of such fire tests, various studies attempted to develop a numerical means of assessing spalling susceptibility. Significant progress has been made towards such a numerical means of assessment (Lu 2015; Lottman 2017), but fundamental input parameters for such models have not been the focus of many studies (Van der Merwe 2019). Considering results reported to date, the most effective method of prevention is to include polypropylene fibres to a concrete mixture.

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