Fire-Induced Spalling Behavior of Concrete: A Review

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ABSTRACT
Small fragments of concrete can get dislodged and cause spalling when exposed to fire. By reducing the structure's remaining mechanical qualities and durability, this phenomenon is one of the most detrimental impacts that can lead to damage or even failure of the concrete members during or after a fire. The true process of spalling remains poorly understood despite several experimental and numerical investigations. This is mostly because the phenomena are unpredictable and the concrete buildings are not uniformly built. This study reviews the fire-spalling behavior of concrete and differing opinions on the governing variables influencing this phenomenon to provide a clearer picture of the accomplishments in this field.

KEYWORDS: *Fire-induced spalling, Elevated temperatures, Concrete, Fibers, Structural Concrete.*

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I. INTRODUCTION

High temperatures are known to have extremely negative effects on the structural integrity and properties of concrete structural elements, both in the mesostructured and microstructure. Concrete constructions' structural performance will decrease and their serviceability and longevity will be shortened in the event of a fire due to the spalling behavior of the concrete cover and the exposure of the reinforcement to high temperatures, figure 1 [1]. Severe loading conditions are imposed by fire and high temperatures, especially on critical facilities like tunnels, where extreme fire situations can result in temperatures as high as more than 1000^{o}C. Concrete components can withstand extremely high temperatures and still retain the necessary mechanical performance and structural integrity. High temperatures, however, cause concrete to deteriorate. Furthermore, there are three types of concrete degradation caused by fire: (i) there is thermo-hygral damage, which occurs pore pressure caused by moisture restriction in concrete at 220 – 320^{o}C; (ii) there is thermos-chemical deterioration, which is resulted by the breakdown of CaO at about 700^{o}C; and (iii) there is thermos-mechanical deterioration by high temperatures, which is resulted by temperature gradients and external stresses between 430 – 660^{o}C [1-4].

Figure 2, which depicts a concrete wall that was heated from a single side, illustrates thermos-hydraulic spalling. The area around the concrete's fire-exposed side experiences a temperature difference because of fire exposure. Fire-induced pore pressure builds progressively because of the hydration gel's water and chemically bound water being released into the micropores of concrete and becoming free water. The concrete system experiences internal stress within its pores due to a pressure gradient generated by varying pore saturation levels and temperature differences. Moisture is driven in opposite directions by the pressure gradient: into the deeper, colder zone, and towards the hot face. This leads to the formation of three zones: wet, dry, and saturated. Therefore, bursting failure happens when the stress brought on by the pressure of water inside the pores is greater than the maximum flexural strength of the concrete. The moist area, or saturated zone, is in the front of where the pressure is highest. The pore pressure in the wet zone is equivalent to the sum of the partial pressure of dry air and the saturated vapour pressure. The water in the wet zone is a mixture of vaporised water and liquid [4-6].

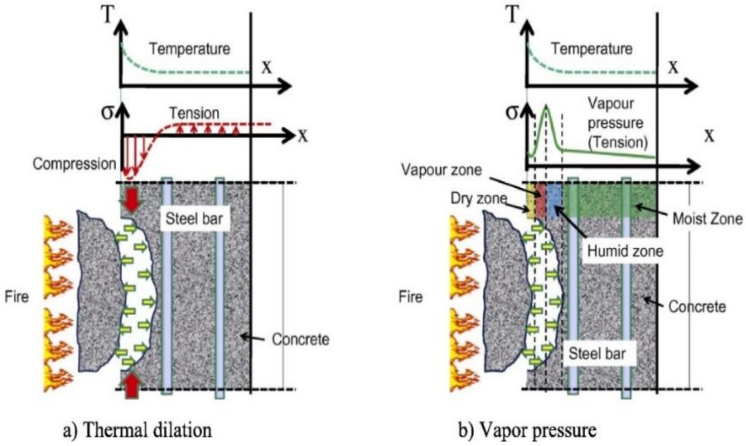

Figure 1: Spalling Mechanism [1]

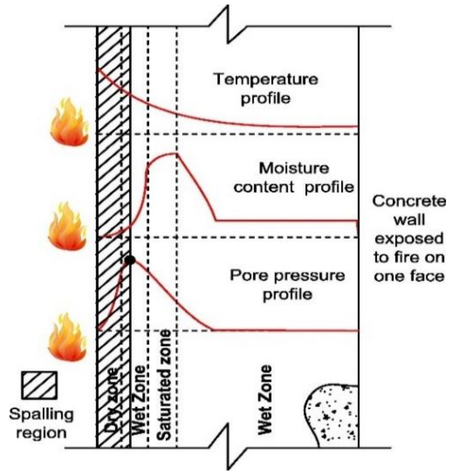

Figure 2. Spalling region of concrete wall exposed to fire on one face [5].

It is commonly recognized that the term "spalling" refers to a variety of destructive processes that occur in concrete buildings following a fire. These events are caused by a number of processes, such as a) an increase in pore pressure with rising temperature; b) the separation of the heated surface as a result of the developed compression brought on by the thermal gradient in the concrete sections; c) the possibility of interior cracks resulting from differences in thermal expansion and deformation between the aggregate and cement matrix; e) the breaking of concrete and reinforcing bars due to differences in deformation and thermal expansion; and f) fire resulting in chemical changes that weaken the concrete strength [7-10]. When small portions of concrete (30 – 50 mm) are separated from the concrete surface due to explosive nature, it is referred to as concrete spalling in a fire. Usually occurring 15 to 30 minutes after the fire begins, spalling is thought to be the most critical time for combating the fire and reducing its impact. The deterioration occurred by the spalling has been explained by a number of theories by researchers, which are outline as: i) Aggregate and cement matrix are incompatible due to their different temperatures; 2) pressure damage caused by moisture; 3) physicochemical changes of aggregates; and 4) aggregate thermal degradation [1, 11].

Primarily, it emerges at the 250 - 400^{o}C temperature range, which is attainable through fire. There are three types of spalling: surface spalling (which is when concrete bursts or splits apart from structural element), sloughing-off/corner spalling (which is when the concrete falls off the edges of beams or columns), and aggregate spalling (which is when the aggregates split). The heating rate is the decisive factor for the first two categories, while the highest temperature is the crucial component for sloughing-off spalling/corner spalling. Another way to categorize spalling is by origin, where it can be further divided into two categories: explosive and gradual spalling. Concrete fragments sliding out of the structural element is a characteristic of progressive spalling, often referred to as sloughing-off. In contrast, explosive spalling is characterized by the sudden separation of concrete pieces accompanied by an instantaneous escape of energy. Since explosive spalling causes the most damage to concrete elements, most studies are concentrated on this kind of spalling [12-14]. Damage resulting from spalling to concrete structures can modify the calculations used in fire-safety design, causing the calculations to be inaccurate and reducing the margin of safety significantly in a fire scenario. It is therefore imperative that (i) effective and economical strategies to reduce or eliminate explosive spalling in concrete structural elements be developed, (ii) the environmental and socio-economic impacts of spalling be accurately assessed, and (iii) the foundations of fire-induced spalling in concrete structural elements be thoroughly understood [12].

Predicting the mechanism and degree of spalling during the design phase is particularly challenging due to the interaction of numerous unique materials and structural elements. It is also challenging to generate complete knowledge of the phenomenon. It is not new for fire to cause spalling in concrete. Fire-induced spalling of concrete has long been linked to this concern. In general, the applied load, system permeability, heating rate, and initial pore saturation level are the main factors influencing spalling. High-strength concrete is more prone to explode than nominal-strength concrete. This results from the material's decreased ductility as well as the higher pore pressures that fire-induced reduction in permeability causes in the material. This is caused by the material's decreased ductility as well as the higher pore pressures that result from the material's decreased permeability when heated. Further variables that come into play include the cross-sectional size and shape, the age of the concrete, the heating profile, the kind, size, and fibers of the aggregates, the reinforcement bars, and the presence of cracks. Specific chemical or physical conditions cause different types of concrete spalling.

a. As water expands and evaporates at high temperatures, pore pressure increases.
b. The heated surface compresses as a result of a temperature difference in the concrete elements.
c. Internal cracking resulting from variations in the thermal expansion of the aggregate and cement paste.
d. Dissimilarities in thermal distortion between the concrete and reinforcement bars that cause cracking.
e. As a result of internal cracking, pore pressure, and temperature gradients.
f. As a result of internal concrete matrix cracking and chemical deterioration during the heating process, which results in a loss of strength.
g. As a result of the combination of pore pressure and thermal gradients in the cross-section of the members, as well as various thermal distortions of the concrete and the key reinforcement at the concrete elements corner, the member's cross-sections exhibit cracking patterns.
h. As a result of chemical transition-induced strength loss and internal cracking occurred on by varying aggregate thermal expansions.

II. INFLUENCING FACTORS OF FIRE-INDUCED SPALLING

2.1 Post cooling spalling

Concrete spalling has been documented, however not during the heating stage. Post-cooling spalling is the term used to describe this kind of spalling. The 44% volume increase that followed the rehydration of calcium oxide after cooling may have been the reason [15, 16]. When concrete has access to moisture, this rehydration process occurs. Neither the pore pressure nor the thermal stress spalling [17].

2.2 Size of concrete elements

Large concrete cylinders treated to a heating rate of 1^{o}C/min showed explosive spalling [18]. Explosive spalling was, however, avoided when the cylinder size was reduced by either 75% or 50%. Concrete's risk of thermal spalling was investigated [19]. While the temperature gradient in small examples was comparable to that in large specimens, he noticed that spalling only happened in large specimens when the heating rate and same concrete mixture were used. The notation of heat gradient-induced spalling was contradicted by these experimental results. The phenomena of thermal stress spalling caused by restricted thermal dilation could not be explained by the fact that the concrete specimens under test were unloaded and constrained. The pore pressure spalling idea, however, could provide a plausible explanation for this. When compared to larger specimens, smaller specimens allow moisture to exit the concrete more quickly, which lowers the pore pressure. Consequently, as specimen size drops, the chance of spalling is decreased [20, 21].

2.3 Duration of Spalling

Harmathy's, [22] observations showed that in the event of an ASTM E119 fire, concrete spalling often happened in 10 to 25 minutes. Within the first 10 to 25 minutes of the ISO fire test, Mindeguia et al., [23] found that thermal spalling had taken place on an unrestrained, empty concrete slab. Within 10 minutes after ISO 834 (equivalent to ASTM E119) elevated temperature. Ko et al., [24] found that spalling happened in unrestrained and unloaded concrete slabs. The pore pressure spalling mechanism states that when the heated concrete's tensile strength is exceeded by the tensile stress caused by the internal vapour pressure, spalling usually results. Concrete spalling is understandable in the initial stage of fire since it takes a few minutes of duration for the concrete cover to be exposed and to reach this crucial temperature. The pore pressure spalling process, however, is unable to account for instances of spalling concrete that occur at a later stage of a fire [24, 25]

2.4 Steel fibers

Various conclusions were reached on the ability of steel fibers to reduce concrete spalling during fire. Kodur et al. tested the fire resistance of HSC columns, they discovered that steel fibers improved the fire resistance of HSC columns and decreased the spalling behaviour [26]. When steel fibers were added to unrestrained and unloaded concrete for thermal spalling testing, Klingsch, [16] discovered that the risk of explosive spalling was not decreased by the inclusion of fibers. The steel fibers included are 42 kg/m^3 [16] and 192 kg/m^3 [26] of steel fibers, respectively.

2.5 Thermal gradient

The thermal stress spalling theory states that a low thermal gradient results in a low probability of spalling and a high danger of spalling. As a result, concrete heated at a higher pace is more prone to spalling than heated at a lower rate [27-28]. But Noumowe et al., [27] discovered that even at a heating rate of $0.5^oC/min$, concrete experienced severe spalling. Klingsch, [16] investigated how the duration of heat affects the likelihood of thermal spalling. To reduce the thermal stress caused by the thermal gradient, low heating rates were employed. Additionally, it was discovered that the concrete specimens spalled by $0.5^oC/min$. The results did not support the spalling mechanism generated by thermal gradients. However, it was found that there are two different ways that thermal spalling in concrete can occur: at low heating duration (insulated with a thermal barrier or $0.5\text{-}1^oC/min$), concrete elements explode violently, producing a loud sound; at a higher level of heating rates, however, concrete elements can crack gradually with popping sounds [16].

2.6 Pore pressure and porosity

The movement of liquid mass via the pores causes repression. According to Hertz, dense concrete has a smaller porosity than ordinary concrete, making it more likely to spall [20]. The vapour pressure produced in the pores of concrete with low gas permeability is the prime factor affecting the fire-induced spalling of concrete, according to numerous experimental studies to evaluate the spalling risk of concrete exposed to fire. The water in the pores evaporates when the temperature rises, and it then dissolves in free water until the pores are completely saturated. The inability of pores to hold both water and vapour at this point results in a significant increase in internal pressure. However, some researchers indicate that increasing porosity does not always result in less spalling [29]. Increasing porosity will increase the amount of free water in the concrete, which will increase the amount of vapour and, in turn, the pore pressure. This is presuming that there is a lot of free water in the pores. The increase of porosity in those air-filled pores results in an increase in internal air volume, which lowers the thermal conductivity of concrete. A decrease in thermal conductivity causes the internal heat gradient and tension to rise in concrete, which may intensify the spalling process [30].

2.7 Concrete mixture

The likelihood of spalling in concrete exposed to fire was said to be increased by the expansion and quick changes in the volume of aggregates such as limestone filler and quartz. The filler densifies the concrete, which prevents the internal pressure from the concrete from releasing and may lead to spalling [30, 31]. However, a few researchers have rejected the idea that the type of aggregate governs the amount of fire spalling. They reasoned that aggregate expansion, like that found in quartz, causes microcracks in the concrete and results in slight deterioration but not spalling. Additionally, when aggregates and concrete expand at different rates, fissures are created that could let in vapour and free water and lessen the severity of spalling [20, 33]. It is thought that selecting the right aggregate could improve the performance of the concrete fire, despite differing opinions regarding how the concrete mixture affects the amount of spalling. To improve their compatibility with the cement paste and improve the integrity of the concrete, for instance, high thermal stability and low thermal expansion aggregates can be used. The bond between aggregates and paste is stronger when the surfaces are angular. Reactive silica is also used to strengthen the chemical connection with the paste [34, 35]. At high temperatures, magnesium carbonate breaks down and carbonate aggregates absorb heat to release CO_2. Concretes containing these kinds of aggregates will have better fire resistance because these processes are endothermic, which means they absorb heat and slow down the rate at which the temperature inside the concrete rises [36, 37].

2.8 Age of Concrete

Bostrom & Jansson's [38] experimental work demonstrates that, despite early expectations of a decline in spalling in aged concrete, spalling persists even after years of concrete production. Furthermore, it was demonstrated that the age of the concrete had little bearing on low-permeability concrete and large concrete specimens [38]. Given that various varieties of concrete eventually struggle to reach the humidity equilibrium with their surroundings. Therefore, there is not any solid data to support the idea that getting older concrete will reduce the likelihood of spalling. As a result, it is rather challenging to pinpoint the precise age at which concrete will not spall [16, 38].

III. DISCUSSION ON FIRE-INDUCED CONCRETE SPALLING

In a fire, two main mechanisms lead to damage to concrete: (i) thermal expansion is directly proportional heating rate, and (ii) vapour pressure is related to the liquid phase of concrete mass transfer. When shear stresses are applied to a structure, the concentration of beam shear cracks reduces as the proportion of shear reinforcement increases; as a result, flexure becomes the predominant driving force of the fracture pattern instead of shear. Similar trends can be seen in fiber-reinforced concrete structures, where the fibres increase the resistance to flexure and shear resistance.

Under fire situations, three forms of fire-induced spalling can be distinguished based on the driving mechanisms: thermo-mechanical spalling, thermo-chemical spalling, and thermo-hygral spalling. The temperature ranges of three forms of fire-induced spalling are presented in the figure 3 [5, 39]. Damage resulting from spalling to concrete structures can modify the calculations used in fire-safety design, causing the calculations to be inaccurate and reducing the safety in a fire scenario. The physical characteristics of fire-induced spalling are presented in the table 1 [34]. The measures for reducing different types of fire-induced spalling are presented in the table 2 [5]. Transient moisture in concrete is turned to vapour by high temperatures. The vapour can flow in any direction because of the pressure and temperature differences created in the concrete section. Depending on the concrete's permeability, some of the vapour escapes through the fire-exposed surface and the remaining vapour flows in the concrete through colder interior layers. The saturated layer will form at a particular distance from the fire-exposed concrete surface, because of the moisture migration, concrete drying, and vapour condensation processes repeating as the fire exposure period increases. It is called the moisture clog phenomenon [5, 34, 40]. Gases are prevented from migrating any further towards the cooler interior by the saturated layer, which serves as an impenetrable barrier. Pore or vapour pressure builds up in the vicinity of the concrete surface exposed to fire. Tensile stresses in the elements are produced as pore pressure builds up.

Table 1. Physical characteristics of fire-induced spalling [14]

Spalling type	**Nature**	**Time of occurrence (min)**	**Influence**	**Sound**	**Main influences**
Surface	Violent	7-30	Can be serious	Cracking	F_t, P, H, W
Corner	Non-violent	30-90	Can be serious	None	R, F_t, A, T
Aggregate	Splitting	7-30	Superficial	Popping	W, D, S, A, H
Explosive	Violent	7-30	Serious	Loud bang	Z, W, S, R, Q, P, O, L, G, F_s, S, A, H
A = thermal expansion of aggregate, O = heating profile, D = thermal diffusivity of aggregate, P = permeability, F_s = tensile nature of concrete, Q = element shape, G = age of concrete,R = reinforcement, H = heating rate, S = aggregate size, L = loading, T = highest/maximum temperature, W = moisture content in concrete, Z = element size.					

Table 2. Measures for reducing different types of fire-induced spalling [44].

Type of spalling	**Methods**	**Protective measures**
Thermo-chemical spalling	• Lower the temperature • Limiting the quantity of cement • Aggregate selection	• Use thermal barrier • Preventing use of excessive cement content • Avoid calcareous aggregates usage.
Thermo-mechanical spalling	• Overcome brittleness • Lower the temperature • Decrease initial load stress • Aggregate selection	• Inclusion of steel fibres • Use thermal barriers • Reduce loading levels • Instead of siliceous aggregates, use calcareous aggregates.
Thermo-hygral spalling	• Aggregate selection • Reducing heating rate • Increase permeability	• Not a single flint or comparable aggregates • Use a thermal barrier • Inclusion of air-entraining agent, raw rice husk, jute fibres, PVA fibres, PP fibres, etc.

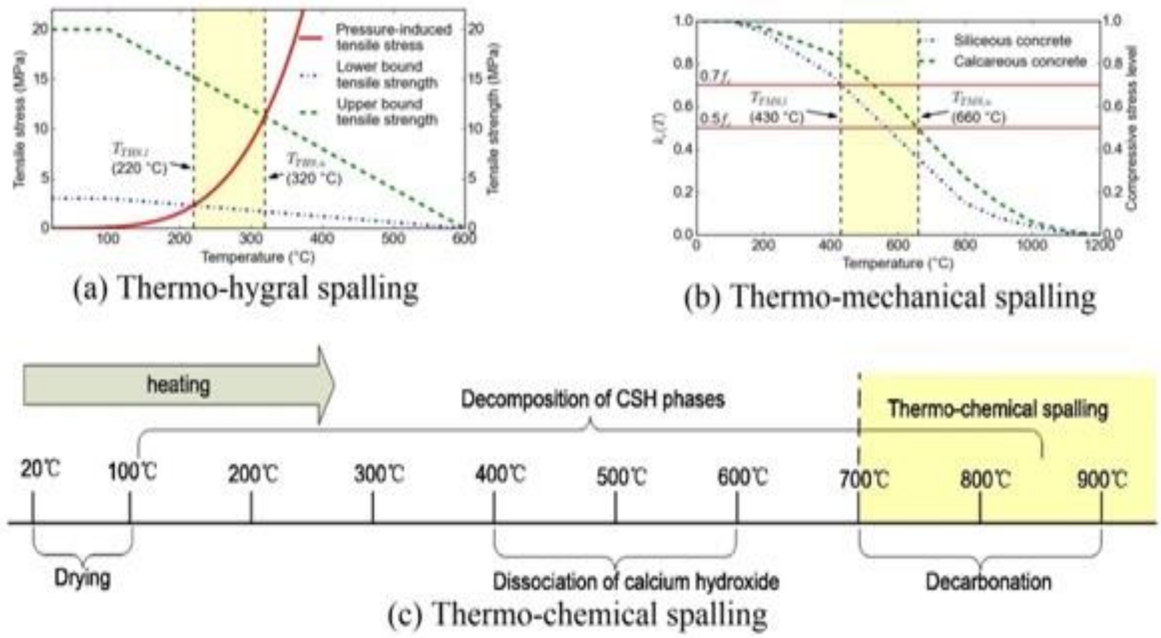

Figure 3. Temperature ranges of different types of fire-induced spalling [44].

Spalling will happen if the temperature rises and the fire-induced strains are greater than the concrete's tensile strength. Darcy and Fick's rules govern the movement of moisture in concrete. Increased pressure and pressure gradient are observed in low-permeable materials because of the moisture-clog layer forming sooner and closer to the concrete's lower porosity. Although high-performance concrete (HPC) has a higher tensile strength than normal Portland concrete (NPC), it is more prone to explosive spalling because of its poorer permeability and consequently greater pore pressure developed due to fire. Furthermore, in thin HPC elements subjected to fire, several spalling events occur because of the pore pressure peak in HPC appears closer to the element's surface [7, 41-43]. Two distinct methods are usually cited to explain concrete spalling caused by fire [44]:

(a) The primary cause of spalling by pore pressure mechanism is the thermal-hydraulic nature that occurs in the fire-induced concrete. Moisture migration and heat transfer cause the micropores' pore pressure to progressively increase. Spalling happens when the tensile tension brought on by pore pressure exceeds the tensile strength of fire-induced concrete.
(b) There are two kinds of thoughts about the spalling by thermal stress mechanism. While some studies believe that compressive stress caused by constrained thermal dilatation causes spalling, others maintain that thermal stress resulting in thermal gradient is the primary cause of spalling.

The pore pressure that builds up in concrete as a result of the water inside it vaporizing. Concrete has two types of water: interlayer water in CSH and free chemically bounded water linked to calcium hydroxide (CH). Initially, the matrix's pore pressure started to rise at about 100^{o}C, when free water started to evaporate. The chemically bounded water and CSH gel's interlayer started to dehydrate when the temperature rose from 300 to 400^{o}C. At 400-500^{o}C, the CH started to dehydrate, which led to the shrinkage of concrete and the loss of a considerable amount of its strength. At about 900^{o}C, the CSH gel would finally completely break down. Free and chemically bounded water in the concrete pore structure evaporates when the temperature rises [45-47]. Some of the vaporized water escapes to the heated surface, but the majority of the vaporized water migrates to the center of the concrete, where it condenses due to the lower temperature there. The vapour is prevented from traveling towards the inner concrete after a given amount of time by the formation of a saturated layer inside the concrete. Instead, to enter the atmosphere, the vapour widely flows towards the direction of the concrete's surface [42, 48].

Using concrete pore pressure and temperature field measurements, Kalifa et al., [42] have verified the pressure of a quasi-saturated layer that exists before the drying front. Furthermore, concrete that has a reduced permeability develops a saturated layer more quickly and nearer the heated surface when exposed to high temperatures, and it also experiences a higher-pressure gradient and pore pressure [42]. The second factor is thermal strains induced by temperature gradients, which can cause concrete to crack. A thermal gradient, sometimes known as "thermal shock", is created when high temperatures or fires combine with the inside of the concrete. Furthermore, perpendicular to the fire-induced concrete's surface, tensile stress develops in the concrete. As soon as the compressive tension is greater than the tensile stress, concrete explodes. The heterogeneity of concrete components will also result in significant thermal cracking at the interface because of the various behaviours of the components at increased temperatures [49, 50]. Uncertainty exists on how steel fibres might impact concrete's ability to withstand explosive spalling in the event of fire or extreme heat. The inclusion of steel fibers doesn't lower the danger of disintegration or explosion, according to Hertz's analysis of experimental data, and specimens with the highest amount of steel fibres had greater explosive-spalling nature. Steel fiber addition, however, may be able to lessen the spalling nature of concrete at elevated temperatures, according to other studies [51]. The incorporation of steel fibres increased the amount of heat that could enter the concrete, which decreased the temperature gradient within the concrete, the heating surface, and thermal shock, as per the findings of [29, 52]. Pore pressure buildup and temperature gradient-induced thermal stress are the primary causes of spalling behaviour in fire-induced concrete specimens. Adding steel fibers to concrete can improve its tensile qualities, decrease its pore pressure at elevated temperatures, and increase its thermal conductivity, all of which can lower the risk of an explosion [53, 54]. Some of the suggested techniques to lessen/avoid spalling caused by fire are presented in the table 3 [54].

Table 3: Suggested techniques to lessen/avoid spalling caused by fire [54]

Techniques	Advantages	Disadvantages
Choosing the section geometry approximately	• Diminish the damages caused by spalling in thicker parts (especially crucial for I-beams and ribbed sections)	• Because of the larger section, it is no longer economical.
Use of additional reinforcement	• Minimize the damages caused by spalling in older concrete buildings	• Difficult to use in constrained spaces
Application of reinforcement	• Diminish the losses caused by spalling. • Restrict the spread of the damages caused by spalling.	
Regulating the compressive strength	• Lower the possibility of explosive spalling	• Not economical because of the enlargement of the portion
Appropriate choice of aggregate size and type	• Aggregates in small sizes are efficient. • High thermal expansive aggregates cause more cracks, poor resistance, and less spalling. • Additional fire protection in the event of lightweight concrete with low moisture content.	• In situations with a high moisture content, encourage the violent spalling. • Controlling the water content is difficult.
Use of thermal barrier coatings (TBCs)	• Incredibly effective at improving HPC's fire spalling behaviour. • Lower the concrete temperature. • Increasing fire resistance.	• Expensive. • The specifications for the concrete should be the basis of designing the layer thickness.
Lowering the amount of moisture	• Lower the pressure inside the vapour chamber.	• Challenging to acquire.
Air-entraining agent	• Effective substitute to improve the concrete's pore structure and lower pore pressure.	Decreases the concrete strength
Inclusion of textile fabrics	• Improves concrete's tensile strength when it's exposed to high temperatures	• Severe degradation in the concrete's workability
Inclusion of hybrid fibres	• Enhance HPC's mechanical properties. • Lowers core pore pressure. • Enhance concrete's thermal resilience at high temperatures. • Reduce the spalling behaviour.	• Can perhaps make the concrete less workable. • Maybe ineffective in stopping spalling in large-scale UHPC. • Severe degradation in the concrete's workability.

Inclusion of steel fibres	• Enhancing concrete's mechanical characteristics, such as it's ductility and flexural strength.	• Failure to outlaw spalling
Inclusion of PP fibres	• Incredibly effective in reducing spalling, even with HPC. • Lowers pore pressure.	• Decreases workability, particularly with self-compaction concrete. • Decreases concrete strength. • Unable to lower the temperature. • In UHPC, unable to stop spalling.

IV. CONCLUSIONS

In recent decades, there has been a notable increase in research focus on fire-induced spalling in fires, which poses a real risk to structural concrete. The two main factors that led to explosive spalling were thermal stress and water vapor from the high-temperature differential inside the concrete. There are no established guidelines that permit the design of concrete mixtures to prevent spalling, and there are no standardized, internationally accepted, repeatable testing protocols that precisely gauge or confirm the resistance to spalling of a particular mix in a particular application. Consequently, there are currently no models available that are accurate enough to predict spalling for use in design. According to the majority of research, the risk of explosive spalling in concrete was decreased by adding steel fiber. Furthermore, insufficient research has been done on the impact of steel fiber diameter and length on violent spalling. To determine whether they could reduce concrete spalling, fibers and aggregates are still being investigated. In addition to lower temperature gradients, bridging microcracks inside the concrete, and increasing tensile strength, steel fiber can slow the buildup of steam pressure inside the concrete. As a result, even though the behavior of concrete at elevated temperatures has been thoroughly studied, fires are volatile and complicated. To fully realize the potential of fire-resistant structures, more experiments and studies are therefore necessary.

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