

A Comprehensive Review of Spalling and Fire Performance of Concrete Members

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ABSTRACT: Spalling of concrete in fire is due to dislodgement of small pieces of concrete. This phenomenon is one of the most detrimental effects causing damage or even failure of the concrete members during or after a fire by decreasing the residual mechanical properties and durability of the structure. In spite of many experimental and numerical studies, the real mechanism of spalling is still not well understood, which is mainly due to the erratic nature of this phenomenon and inhomogeneity of the concrete structures. To establish a more clear view of the achievements in this area and also the areas in need of more investigations, this paper critically reviews the latest findings on concrete performance during heating in general and specifically the fire spalling behaviour of concrete members and different views on governing factors that affect this phenomenon.

Keywords: fire, spalling, concrete, high strength

1 INTRODUCTION

Spalling” is defined as a thermal instability that occurs when concrete is exposed to fire. Many experimental results indicate that when exposing the surface of a concrete member to fire some micro-cracks are generated both within and on the surface of the element as a result of increase of pore pressure within the concrete mass [1]. With the increase of temperature, the cracks develop further and some pieces of concrete dislodge from the exposed surface. Depending on the type of fire and the material properties of the element, the failure mechanism can be localised and/or explosive. Fire spalling of concrete, exposure of steel reinforcements to high temperatures and reduction of concrete section results in capacity loss of the structural elements and eventual failure of the entire structures [2], [3].

In general, spalling of concrete can be categorized into four different stages, among which, spalling steps (a) and (b) are more severe and need more attention to be controlled [4], [5]:

a. Dismantlement of large pieces of concrete from the surface during the first 15-30 minutes after exposure to fire. It could cause serious problems such as exposure of reinforcements to fire and reducing the cross-section. Figure 1, shows monitoring of concrete spalling after about 12, 19 and 27 minutes when the fire starts [6].

b. Dislodgement of considerable amount of small pieces of concrete from the surface during 30-60 minutes after the fire starts.

c. Minor dislodgement of the surface and edges 60 minutes after the fire starts.

d. Gradual reduction of the surface layers called “sloughing off” at very high temperature, which may continue even after fire stops [7], [8].

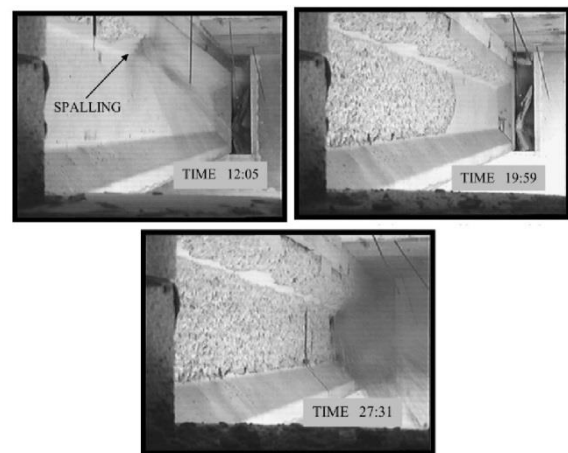


Figure 1: Loaded pre-stressed beam exposed to ISO 834 fire after 12:05min (a), 19:59 min (b) and 27:31 min (c) [6].

Bazant and Kaplan [9] defined general physical and chemical performances happen inside a concrete exposed to fire as follows:

1. Starting the evaporation of free water inside concrete paste and aggregates at 100°C.
2. Beginning of dehydration of cement gel at 180°C.
3. Decomposition of Ca(OH)₂ at about 500°C.
4. Physical transportation of α-quartz to β-quartz in quartzite and basalt aggregates at about 570°C.
5. Commencing of decomposition of CSH at about 700°C.

6. Decarbonation of calcium carbonate in limestone aggregates at about 800°C.
7. Beginning of melting the cement paste and aggregates at about 1200°C.

There are ample literatures published on the basis of experimental and numerical analysis to investigate the spalling of concrete subject to fire. They are broadly categorised into material level characterisation considering the thermodynamic aspects explaining the chemistries involved. The focus of these investigations, mostly known as thermo-hydral process [10], is on migration of water and vapour inside concrete [4], [11]–[13], the accumulation of water at certain depth of concrete called moisture clog [4], [10], [13]–[19], heat transfer inside the concrete [13], [14], [20]–[22], dehydration of free water and chemically bond water [13] and also thermal decomposition of cement paste and aggregates at high temperatures [23]–[25].

The second category includes investigations treating thermo-mechanical properties of concrete when subject to fire [16]. Thermo-mechanical processes describe the deterioration of mechanical properties [23], [26], [27] and thermal expansion of concrete exposed to fire leading to both biaxial compressive stresses on the regions parallel to heated surface and tensile stresses in perpendicular directions [4], [13], [20], [27], [28].

The third category includes investigations considering the combined material-structural aspects. Thermo-hydro-mechanical or thermo-hygro-chemo-mechanical processes are some of the examples. These processes are mainly using numerical analysis to simulate the stress evolution within fire-loaded concrete [25], [26], [29]. The aim of these investigations are to discuss the behaviour of concrete elements at macro-scale, broadly reporting on the failure patterns, cracking initiation and criterion and progression of spalling.

The fourth category includes studies mostly relying on the second and third categories in order to propose methods of reinforcing structural concrete with metallic and non-metallic materials, in an attempt to reduce the effects of spalling on concrete damage. Utilizing Polypropylene (PP) fibres, steel fibres or their hybrid to mitigate the magnitude of fire spalling in concrete members are some of the solutions extracted from these type of analysis [22], [26], [30]–[34].

Finally, there are numerous review papers published addressing concrete subject to fire [27], [35]–[38] but very few has specifically treated fire spalling of concrete members and discussed controversial views on the effect of governing factors.

In spite of many implemented studies, researchers have not yet achieved a consensus agreement on the relative contribution of the influencing factors on the

fire spalling phenomenon. Also, no certain results have led to unique established code and design guidance for fire spalling [39]. The gap that has been reported is mainly due to the erratic nature of spalling phenomenon. Other reasons include non-homogenous structure of concrete material, large number of factors that influence spalling and their interdependency. Weak understanding of the origin of fire spalling in concrete members can bring about the following problems:

- it slows down the developments on technological solutions to mitigate the magnitude of spalling and embeds achieving predictive calculation of the risk of this phenomenon;
- due to increasing usage of HSC susceptible to higher risk of fire spalling in many engineering applications, it has become a major challenge for concrete designers [40].

The focus of this paper is to present a comprehensive report on concrete spalling as a result of a fire exposure, aiming at contributing to understanding of the origin of the phenomenon. It starts with showcasing the major fire events worldwide where spalling of concrete have been reported to affect the structural integrity of the structures causing damage to life and/or property. It will then resort to explore the extent to which, if any, the major codes and design standards are considering fire spalling of concrete. It is noted that spalling of concrete due to fire is stated as important but no comprehensive design consideration is given. Thereafter, the influencing factors on spalling of concrete subject to elevated temperatures are reviewed in light of more recent investigations and findings. This includes the physical phenomenon and the effect of very high temperatures on thermal and mechanical properties of concrete. It is noted that due to their reduced pore size, high strength concrete (HSC) behave differently to that of normal strength concrete (NSC).

1.1 *Concrete spalling and contributing factors*

In order to provide a comprehensive account of the research to date and the type of research, a list of 100 references were compiled with a listing of their research aims, see Table 1.

Referring to the reviewed papers, it is well established now that heating a concrete element creates two moving fronts: heat and moisture front and that the probability of explosive spalling of concrete increases under higher heating rates [41]. Therefore two parallel interlinked processes are involved: thermo-mechanical and thermo-hydral. Like any other material, concrete has a thermal expansion coefficient and deforms when heated. If it is restrained, say, due to self-weight or the restraint imposed by the adjacent elements, thermal stresses develop. For a

concrete element that is heated non-uniformly, the process produces more thermal dilatation gradients (thermo-mechanical). The thermo-mechanical process is directly associated with the temperature field in the concrete element [42].

The second process is the thermal-hydral process which is associated with the transfer of mass water in liquid and vapour phases and air within the porous medium. Rightly, since concrete is porous this process is facilitated by a network of pores (air, vapour and water). With the rise of temperature, the vapour pressure (also referred to as pore pressure) increases and the water particles are transferred through the pore networks. Whether one or the other processes is dominant depends notably on the thermal solicitation. Therefore, spalling results from a thermo-hydro-mechanical coupling process [42].

The thermo-hydro-mechanical coupling is best described in terms of parameters related to each of the processes. However, both of those depend on the type of fire, the heating rates, and the rate of thermal dissipation in the concrete. There are a number of other properties at material level such as density, porosity, moisture content, type of aggregates and strength properties that affect the type and extent of spalling. In addition, undoubtedly, the geometry, the boundary conditions and the extent of external mechanical action on the concrete element affect spalling. Each of these parameters is further discussed in section 4 in light of the latest published work.

1.2 Past events

A historical overview of fire spalling of concrete between the mid-1800s through to modern time has been presented in reference [43]–[45]. In the paper, the observations and progression of the theory of spalling is clearly outlined. Special interest in the mechanism of concrete spalling due to high temperatures was gained after 1996 when fire occurred in three European tunnels (Figure 2). Since then a number of other fire events took place with costly consequences to the asset owners. Table 2 indicates the details of some of the fire events in tunnels and buildings [11]–[13]. In some of the cases listed, spalling of concrete has been reported as the contributing factor towards the collapse of the building [45], [46].

2 CODES AND STANDARD GUIDELINES

The standards and codes related to fire design are reviewed in this section.

2.1 Australian guidelines

- AS3600, Concrete Structures Standard [47]: Section 5 of the standard discusses design criteria such as fire resistance period, fire resistance level, fire-separating function, insulation and integrity of reinforced and pre-stressed concrete members including beams, slabs, columns and walls. To enhance the fire resistance of concrete members tabulated data including the minimum dimensions of the members are suggested.

- AS1530 [48]: Methods for fire tests on building materials, components and structures: This standard deals with fire test procedure including sampling, preparing test specimens and apparatus, necessary settings and suitable test methods. Also, methods of calculations and reporting the final results are presented.

2.2 New Zealand guidelines

- NZS3101, Concrete Structures Standard [49]: Similar to the Australian Code, the New Zealand Building Code categorises the fire-resistance ratings of concrete elements for a period of 30-240 minutes according to three criteria: stability, integrity and insulation. The tabulated data in the standard show suitable dimensions of the members including beams (simply supported or continuous), slabs (one-way or two-way), columns and walls. For improving the fire resistance of concrete members following the structural tables and dimensions or using insulating materials is suggested.



(a) (b) (c)

Figure 2: Fire spalling in (a) Mont Blanc tunnel, France/Italy, 1999, (b) Tauern Tunnel, Austria, 1999, (c) Gotthard road tunnel, Switzerland, 2001 [50]

2.3 American guidelines

ASTM E119 [50]: This code suggests a standard time-temperature curve for testing. This fire curve is a representation of the maximum fire temperature that may occur in buildings and not in a real fire situation. The fire curve generally covers variously fire load situations and has contributed to define the maximum fire severity, which may occur during a real life building fire.

Table 1: Summary of of articles studied on fire spalling behaviour of concrete and the governing factors

No	Ref	Concrete	age	moisture content	cement mixture	heating rate	vapor pressure	thermal gradient	concrete density/permeability	specimen geometry	compressive strength	Tensile strength	Loading level/boundary conditions	Significant results
1	[51]	HPC												For inside applications 50 mm of gypsum is the best and most economical way to protect any material from fire.
2	[23]	HSC		Y	Y									Spalling degree decreased drastically when the water to binder ratio level increased in the mixture containing Silica Fume.
3	[26]	HSC												Addition of 2kg/m ³ PP fibres can significantly promote the residual mechanical properties of HSC.
4	[52]						Y	Y						Spalling is due to a sudden unstable release of the potential energy of thermal stresses stored in the structure and vapour pressure is not the main reason of spalling.
5	[53]	HSC		Y	Y	Y			Y	Y.not main	Y			FEM showed that concrete mixture is not the main factor affecting spalling.
6	[30]	HSC					Y							Mixing high melting point with low melting point fibre in HSC greatly improves the properties exposed to fire.
7	[54]						Y	Y						Presence of steel reinforcement impedes moisture movement and produces quasi-saturated moisture clog zones that lead to the development of significant pore pressure. These zones alter the flow of heat into the system and tend to attenuate the rise of internal temperature. Hence thermally induced stresses in concrete are related not only to the external thermal loading but also to moisture flow, reinforcing steel placement, and thermal processes such as evaporation.
8	[55]	HSC					Y							Reinforced concrete slabs strengthened with textile concrete have improved resistance in fire. The key mechanisms contributing to the outstanding fire resistance capability presented are: superior crack control of the textile reinforce concrete and load redistribution between textile and steel reinforcement as well as primary load transfer into the slabs.
9	[19]	HSC		Y			Y			Y				For concrete with spherical shape, a fibre content of 1 kg/m ³ is sufficient to prevent spalling.
10	[56]	NSC					Y	Y						Adding steel fibres along with PP fibres can reduce the degree and severity of spalling comparing with concrete containing PP fibres only.
11	[57]													Spalling is a form of instability and happens when the internal pressure reaches the compressive strength of concrete.
12	[58]					Y			Y			Y		Using textiles as concrete reinforcements to improve fire performance of concrete. Relative humidity has marginal effect on spalling.
13	[59]	HPC					Y	Y						Fire spalling behaviour is monitored by acoustic emission techniques and modelled with a fully coupled thermo-hydro-mechanical codes.

No	Ref	Concrete	age	moisture content	cement mixture	heating rate	vapor pressure	thermal gradient	concrete density/permeability	specimen geometry	compressive strength	Tensile strength	Loading level/boundary conditions	Significant results
14	[2]	NSC & HSC					Y	Y		Y	Y			Spalling is caused by the combination of thermal stresses and pore water pressure build-up. The degree and magnitude of spalling is governed by a number of inter-dependent factors including panel size, thickness and compressive strength.
15	[31]	HSC					Y	Y		Y				To mitigate the spalling of HSC, a thermal barrier would be the most effective way to reduce both thermo-hygral and thermo-mechanical process at the same time by blocking the heat flow into the substrate concrete. One disadvantage of this method is an increase of costs. Addition of PP fibres is also effective. PP fibres have a more significant influence on pore pressure spalling than on thermal stress spalling. Addition of combined fibre (PP and Nylon) is also recommended. The effectiveness of the combined fibre is dependent on the size and the boundary condition of the specimens and is the most effective in the columns and that in the beam is next. The slab had the worst results. The major cause of these different results is probably the thermal gradient that is dependent on the size and the boundary condition of concrete structures.
16	[8]	densed C						Y	Y					For super dense concrete the crystal water can be sufficient for causing an explosive spalling and no thermal or external stresses are needed. For other dense concrete compressive stress from load or hindered thermal expansion are necessary for spalling.
17	[11]			Y			Y							Vapour pressure is considered the main reason of spalling.
18	[60]	SCC	Y		Y					Y			Y	It is claimed that moisture content is not the main cause of fire spalling.
19	[61]			Y			Y							Vapour pressure is involved in the redistribution of moisture during fire exposure, but it is not the main reason of it. The spalling reducing function of PP fibers is based on the presence and movement of moisture.
20	[6]	HSC	Y	Y			Y			Y			Y	Moisture plays an important role in fire spalling behaviour of concrete.
21	[25]	NSC,H SC					Y	Y		Y				Thermal gradient is not the only factor affects spalling, vapour pressure is also a primary factor.
22	[4]						Y	Y						The risk of spalling increases in concrete with lower permeability and can be improved by adding PP fibres or applying thermal barrier.
23	[62]			Y		Y	Y	Y	Y				Y	The mechanism of fire spalling in concrete could be due to thermal gradient, pore pressure or the combination of these two.
24	[63]													The application of fire protection coatings as a preventive measure, is a relatively simple construction method that is effective in protecting tunnel structures from collapse. However, the coating materials currently available are rather expensive and have low compressive and tensile strengths. Low strengths of coating materials can lead to fatigue failure and spalling of the tunnel linings. So a newly developed coating material (bottom-ash-based cementitious) is presented which is low in cost and high in strength.

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25	[64]							Y						Thermal conductivity has influence on spalling.
26	[65]			Y			Y		Y					Moisture content is the factor affects spalling.
27	[33]	HSC												By using a combination of NY and PP fibres the same level of spalling protection is achieved using half as much fibre content as that when PP or NY fibre is used alone. The synergic effect of the combined NY and PP fibre on spalling protection is explained by both the comparably low melting point of PP fibre at the early stage of a fire and a larger number of fibres available due to the thinner diameter of NY fibre, which allows 11 times more channels than that of PP fibre at a later stage of a fire, improving the spalling protection by providing connections between pores with low fibre content.
28	[66]								Y					With melting of PP fibres, no significant increase in total pore volume is obtained. However, the connectivity of isolated pores increases leading to increase of gas permeability. So the connectivity of pores (below 300°C) as well as the creation of micro cracks are the major factors which determine the permeability after exposure to high temperatures.
29	Lottman 2011						Y							Fire spalling behaviour of concrete is modelled based on fracture mechanics approach.
30	[67]	HPSCC		Y		Y	Y	Y	Y					Combining the SAP with a low amount of PP fibres is beneficial for the fresh properties of the HPSCC.
31	[17]		Y	Y	Y	Y	Y	Y	Y	Y				A fully non-linear micro structure modelling of concrete behaviour exposed to fire is presented on the basis of mechanical and thermodynamical theory.
32	[68]	HSC,SCC		Y			Y	Y						Adding PP fibres can reduce the magnitude of fire spalling in concrete members.
33	[39]	NSC,HSC				Y	Y		Y					Type of fire and strength of concrete have effect on fire spalling behaviour of concrete members.
34	[3]	NSC,HSC		Y			Y	Y	Y					Pore gas pressure cannot be the only physical origin for concrete spalling.
35	[69]	HSC					Y		Y		Y			Spalling of small scale specimens was analysed. A relationship between maximum pore pressure, concrete strength and fibre geometry was presented. As a result for HSC, a threshold relative maximum pore pressure of 0.92 Mpa has been suggested above which spalling is likely to occur.
36	[70]						Y	Y						Fire spalling is modelled numerically. Referring to the results, the vapour pressure is usually the main factor of explosion spalling; but the effect of thermal stress may become predominant under the constraint boundary condition.

No	Ref	Concrete	age	moisture content	cement mixture	heating rate	vapor pressure	thermal gradient	density/permeability	specimen geometry	compressive strength	Tensile strength	Loading level/boundary conditions	Significant results
38	[34]	HPC					Y							For fibre concrete, although residual strength was decreased by exposure to high temperatures over 400°C, residual fracture energy was significantly high than that before heating. Incorporating hybrid fibre (steel and PP) seems to be a promising way to enhance resistance of concrete to explosive spalling.
39	[71]						Y							Pore pressure during ISO fire is largely higher than during HC fire. This tendency is explained by an increase of concrete permeability related to an increase of cracking during HC fire.
40	[29]						Y	Y						A coupled thermo-hydro-mechanical model shows that thermal expansion affects spalling.
41	[5]	HSC		Y										To improve fire spalling behaviour of HSC suggestions such as reduction of concrete covers, using sacrificial steel with small concrete covers and adding PP fibres are suggested.
42	[72]	GC						Y						The strength loss in the concrete was mainly due to the difference between the thermal expansion of geopolymer matrix and the aggregates.
43	[73]	NSC, SCC					Y							Addition of PP fibres increases the spalling resistance of SCC mixtures. However they had negative effect on concrete's residual mechanical properties since they significantly decreased the residual compressive strength and tensile strength of concrete. It is therefore recommended to use PP fibres as part of a total spalling protection design method in combination with other materials such as external thermal barriers.
44	[74]			Y	Y				Y					Recommendations for required amount of PP fibres for different cases are presented.
45	[10]			Y					Y					The moisture transport in concrete subjected to fire is one of the most important processes with respect to fire spalling.
46	[12]	NSC		Y		Y	Y		Y					A new method (Nuclear magnetic resonance) was set up to study the moisture migration inside concrete. Results show that pressures close to the tensile strength of concrete can be generated by vaporization processes alone. Hence, moisture is one of the key parameters for understanding fire spalling. Heating rate, permeability and pore size distributions determine the position of the drying front with respect to the 100°C front. If the drying front lags behind the 100°C front the water is superheated, which results in an increased pressure.
47	[22]			Y			Y	Y	y. the main					Adding PP fibres can improve fire spalling behaviour of concrete.
48	[75]						Y	Y						A coupled thermo-hygro-chemo-mechanical code simulating the stresses resulted from both thermo-hygro and thermo-mechanical process is presented.
49	[16]						Y	Y						A fully coupled thermo-hydro-chemo-poro mechanical model is presented to simulate the spalling behaviour.
50	[76]						Y	Y						The presence of vapour pressure makes concrete fail in a more brittle manner. Thermal gradient is the main governing factor.
51	[24]	HPC						Y						Explosive spalling is not caused by moisture clog, but by the thermal stress in the central region of the specimen.
52	[77]	PC		Y				Y	Y		Y	Y		Results show that both tensile and compressive strength have significant effect on the spalling behaviour of concrete; while moisture content has minor effect on this phenomenon.

No	Ref	Concrete	age	moisture content	cement mixture	heating rate	vapor pressure	thermal gradient	concrete density/permeability	specimen geometry	compressive strength	Tensile strength	Loading level/boundary conditions	Significant results
53	[78]				Y		Y	Y					Y	PP fibres and thermal barriers can reduce the magnitude of spalling. The higher the water saturation level at fire exposure, the higher the risk of spalling.
54	[74]	HSC			Y	Y					Y			If the heated area is relatively small compared with the thickness of the vermiculite slab, a temperature shade effect can occur, which may reduce the temperature increase of the surface. The thermal stresses decrease as a result of lower temperature gradients for tests with smaller unheated areas. The temperature distribution of a specimen is strongly dependent on the size of the heated area. The relative increase of the fragments' masses is attenuated with larger heated areas. Macro cracks were observed along the shortest paths from the geometric centre to the edges of the specimens. No or more-shallow spalling occurs at these paths. A secondary lime slaking can lead to a decomposition of cement stone several weeks after fire testing. The volume distribution of the spalled fragments determined after a secondary lime slaking is independent of the heated area.
55	[60]	HSC		Y										The presence of moisture can reduce the strength and intensify the fire spalling.
56	[15]	SCC		Y			Y							Pressure in the capillary system is not the driving force for spalling during fire. Moisture movement is the influencing factor. Pressure is involved in redistribution of moisture inside concrete at high temperatures.
57	[79]	HSC				Y								Explosive spalling is due to expansion, so no spalling takes place in contraction phase.
58	[80]													Experimental tests conducted on medium size specimens. Because medium to large scale experiments consider structural effects such as loading and boundary conditions; While experimental studies on small scale specimens provide information on material response to fire. This study presented some guidelines for optimal test conditions, equipment and specimen instrumentations.
59	[42]	HPC, NSC		Y : moisture clog			Y	Y						An original device is designed to measure both the pressure and temperature of concrete during a fire. A coupled thermo-hydro mechanism is considered for spalling. Also, results highlighted the effect of moisture clog on spalling.
60	[32]													The effect of adding hybrid fibres on fire spalling is investigated. Results show that the combination of Nylon (9mm length) and PP (19mm) fibres provide the most optimum results.
61	[81]	HSC												Two supervised Artificial Neural Networks are developed to simulate the fire spalling.
62	[82]	HSC, NSC					Y	Y						Addition of PP fibres has significant influence of mitigating the magnitude of spalling.
63	[14]	HSC		Y			Y	Y						A finite difference method is applied to simulate the coupled heat and mass transport in heated concrete. Results show that the presence of steel reinforcements impeded moisture movement and causes moisture clog zone inside concrete. Moisture clog increases both the vapour pressure and internal temperature.
64	[13]			Y					Y					Coupled transient differential equations governing heat, mass transfer and pore pressure in heated concrete is presented.
65	[83]			Y	Y				Y				Y	Monofilament PP fibres with 32 micron diameter and 12 mm length and dosage of 1 and 2 kg/m ³ have the highest ability to control spalling.

No	Ref	Concrete	age	moisture content	cement mixture	heating rate	vapor pressure	thermal gradient	concrete density/permeability	specimen geometry	compressive strength	Tensile strength	Loading level/boundary conditions	Significant results
66	[84]			Y	Y	Y			Y		Y			Cover of reinforcements in concrete affect the temperature distribution in concrete while heating. The higher the cover, the more fire resistance in reinforcements. By increasing the compartment size and reducing the openings, the fire temperature can be controlled; Hence the required cover thickness can be reduced.
68	[85]	HPC												Addition of PP fibres has positive influence of spalling behaviour except for loaded walls.
69	[86]	HSC					Y		Y					In HSC even the chemically bound water is enough to cause explosive spalling.
70	[87]	RC		Y					Y					Finding a critical moisture content level below which spalling will not happen, is very difficult.
71	[88]	HSC				Y	Y							A one dimensional numerical model based on pore pressure calculation is presented to predict fire spalling in concrete.
72	[89]	NSC				Y								Thermal gradient increases at hydrocarbon fire comparing with standard fire.
73	[90]						Y							A mathematical model of hygro-thermo-mechanical system for heated concrete is presented. Preventive strategies such as using Witec reflective layer, protective layer, PP fibres were presented.
74	[91]									Y				Addition of hybrid fibres (Nylon+PP fibres) to large scale concrete specimens is suggested to mitigate the magnitude of spalling.
75	[92]						Y	Y						Thermal spalling is due to chemical de-cohesion (strength degradation) and not to chemical softening (rigidity reduction).
76	[93]				Y	Y		Y	Y	Y		Y		Addition of PP fibres and improvement in tie configuration are the most effective preventive strategies for fire spalling in HSC.
77	[94]	HSC			Y		Y		Y					In the tested HSC, the probability of spalling was reduced by drying the surface region (0-30 mm). Some influencing factors on spalling are related to moisture transfer including heat conduction and vapour pressure
78	[95]													The number of fibre per unit volume is a better option than the fibre volume percentage or fibre weight per unit volume. Also the length and melting point of fibres are important factors.
79	[96]	FR HPC					Y	Y					Y	Steel fibres are not beneficial in reducing spalling, while addition of PP fibres or a combination of PP and steel fibers could reduce spalling. Vapour pressure is the leading factor that affects spalling.
80	[97]													Results show that 3.5 kg/m ³ of the 20 mm PP fibres is required to prevent the spalling of a low W/C lightweight concrete subjected to hydrocarbon fire.; but only 1.65 kg/m ³ of the finer fibres (12.5 mm) would be sufficient.
81	[98]	HSC												Addition of Polyvinyl acetate fibre didn't have significant effect on spalling due to its high melting point. Spalling didn't happen in specimens containing more than 0.1% PP copolymer fibre.
82	[99]	HSC												Air bubble network were beneficial in improving spalling.

No	Ref	Concrete	age	moisture content	cement mixture	heating rate	vapor pressure	thermal gradient	concrete density/permeability	specimen geometry	compressive strength	Tensile strength	Loading level/boundary conditions	Significant results
83	[100]	HPC					Y							1-2 kg/m ³ of PP fibres can improve spalling behaviour of concrete. A heat treatment to 150°C is the most suitable way to protect the current concrete structures.
84	[101]	HP-SRC												Steel fibres are beneficial in reducing spalling and increment of porosity.
85	[102]	HPC												Influence of fibre parameters including total surface area, total length and total number of PP fibres were examined. Results show that spalling happened when at least one of these parameters were relatively low, while none of them seems to be determinant in the effectiveness of fibre on spalling.
86	[103]						Y	Y						Spalling depends on many interacting parameters. For considering the mechanism of spalling, both thermo-hydral and thermo-mechanical process needs to be considered.
87	[104]			Y		Y					Y		Y	A model for evaluating concrete fire spalling risk is presented on the basis of fuzzy pattern.
88	[105]	NSC,HSC		Y	Y	Y								It is believed that the mechanism of explosive spalling is different with normal spalling. Normal spalling is considered to be a ductile failure happens when the ultimate tensile strength of concrete exposed to fire is reached; while explosive spalling a brittle failure and is caused by the stresses imposed on the gel structure of the concrete.
89	[106]	HPC												Spalling didn't happen in concretes containing higher dosage of 0.05% by volume of PP fibres. A metal fabric showed beneficial effects on spalling; while glass or carbon fabrics do not show the same effect.
90	[107]	HPC					Y							The results show that steel fibre has a beneficial effect on spalling.
91	[108]	HSC					Y							Amount of silica fume has a significant effect on spalling.
92	[109]						Y	Y						Vapour pressure cannot be the only reason of spalling. Thermo-mechanical stress could also increase the risk of spalling.
93	[110]						Y	Y						Results indicate that low permeability and high initial moisture content increase the magnitude of internal pore pressure and simultaneously increase the spalling risk.
97	[111]	UHPC												Steel fibres were not effective in reducing the spalling. PP fibres with dosage of 0.1% by volume were effective for reducing this phenomenon.
95	[112]	SCC												The best dosage of PP fibres to reduce spalling was 0.5 kg/m ³ of PP fibres with 6 mm length.
96	[113]									Y			Y	External compressive loading increases the spalling. Using pre-stress bars or wires could reduce the spalling. The spalling around the edges were less than centre parts.

No	Ref	Concrete	age	moisture content	cement mixture	heating rate	vapour pressure	thermal gradient	concrete density/permeability	specimen geometry	compressive strength	Tensile strength	Loading level/boundary conditions	Significant results
97	[114]	HPC		Y			Y	Y						Results show that fire resistance is highly dependant on the moisture and void content of concrete. A thinner specimen with a higher air void content shows better fire performance.
98	[115]	RC					Y	Y						To improve the spalling behaviour of concrete, adding 0.1 vol% of PP fibres were suggested. It is claimed that the proposed temperature formulas and graphs can be used to design PP-fiber-mix reinforced concrete slabs against fire.
99	[116]			Y			Y	Y	Y					Results show that thermal stresses play the primary role in spalling; while the pore pressure is considered to play the secondary role in this phenomenon.
100	[117]	HSC												Fly ash concrete column behave similarly with conventional HSC during heating.
101	[118]	NSC					Y	Y						Addition of PP fibres has benefit on increasing compressive strength and spalling performance of concrete.

*HSC: High strength concrete, NSC: Normal strength concrete, HPC: High performance concrete, RC: Reinforced concrete, SCC: Self compacting concrete, UHPC: Ultra high performance concrete, HP-SRC: High performance steel reinforced concrete, FR HPC: Fibre reinforced high performance concrete, PC: Prestressed concrete, GC: geopolymers concrete, SF: Silica Fume, FEM: Finite element methods

Table 2: Details of some of the past fire disasters since 1996

Year	Location	No. of injured people	No. of dead people	Estimate Cost (\$million)	Description of the Disaster
1996	Channel tunnel, UK/France	30	-	100	A truck fired on the freight train in the tunnel. Fire duration was 7 hours. The tunnel is approximately 51 km long. Most part of the tunnel was lined with precast high strength reinforced concrete with thickness of 400 to 800 mm. During the fire, 500 meters of tunnel had burnt and explosive spalling happened in the roof lining. The spalling depth was up to 35cm. It took about 6 months to repair the tunnel [43]–[45], [119]
1999	Mont Blanc tunnel, France/Italy	34	39	52	A truck fired in the tunnel. Fire duration was 53 hours. Damage was mainly on tunnel roof and road pavement. The tunnel was made of reinforced concrete. The spalling was mainly due to the dehydration of concrete. Due to spalling a certain part of the roof collapsed and exposed the rock layer. Spalling depth was up to 40 cm [120].
2003	Daegu subway station fire, South Korea	148	192	0.1	A subway train made of reinforced concrete was set on fire with gasoline, destroying two trains. Fire duration was 3 hours. The spalling happened in the roof [46].
1999	Tauern tunnel, Austria	49	12	8	The spalling depth was up to 35 cm [121].
2001	Gotthard road tunnel, Switzerland	-	11	1.3	The spalling depth was up to 35 cm and it caused collapsing of the ceiling. The required time to repair the tunnel was about two months [121].
2005	The Windsor tower, Madrid, Spain			32.5	The 32-storey building was made of reinforced concrete with waffle slabs supported by internal RC columns and steel beams with perimeter steel columns which were unprotected above 17 th floor. The fire was due to a short-circuit on the 21 st floor. The total fire duration was about 18-20 hours. A large portion of the floor slabs above the 17 th floor collapsed [122].
2008	Channel tunnel, UK/France			93	The tunnel is 51 km long. This fire was large and similar to the one that happened in 1996. Major spalling and structural damage was reported in the tunnel [121].
2009	Beijing television cultural centre	7	1	0.05	On the Chinesees new year festivals, the uncompleted Beijing building caught fire because of unauthorised fireworks. It took 5 hours to extinguish the Fire [44].
2013	Moscow psychiatric hospital	-	38	NA	A fire resulted from faulty electric wiring and a short circuit ignited on the second floor of the two-story hospital. After a few minutes fire spread over the second floor and caused collapsing on the first floor. It took 3 hours to extinguish the fire [45].
2014	Docklands apartment, Australia			5	The fire, which affected more than 10 stories, forced hundreds to evacuate and caused ignition of the façade [123].

2.4 European guidelines

Eurocode-1[124]: EN 1992-1-1 presents standard fire curves, which are designed on the basis of real fire experiences to show a more accurate estimate of fire severity using time-temperature curves. These curves are used in testing, analysis and designing to simulate the behaviour of building elements exposed to fire in both experimental and numerical analysis. Referring to different reasons causing a fire, specific time-temperature curves are introduced.

- Standard fire

The fire curve is the most popular one for predicting the fire resistance of building elements. Most standards around the world, including the Australian Standard follow this time-temperature relationship. Mathematically, the fire curve is defined via the following equation:

$$T = T_0 + 345 \log_{10}(8t + 1) \quad (1)$$

Where t is time (minutes), T_0 is ambient temperature ($^{\circ}\text{C}$) and T is Temperature ($^{\circ}\text{C}$).

- Hydrocarbon fire

The fire curve is defined as follows:

$$T = T_0 + 1080(1 - 0.325e^{-0.167t} - 0.678e^{-2.5t}) \quad (2)$$

Where t is time (minutes), T_0 is ambient temperature and T is temperature ($^{\circ}\text{C}$). In hydrocarbon fire curve the temperature rise is significantly more rapid when compared to a standard fire.

- External fire

The external fire curve, which is defined via the following equation, presents the time-temperature relationship for members outside the fire compartment. External member is defined as “structural member located outside the building that may be exposed to fire through openings in the building enclosure” [125].

$$T = T_0 + 660(1 - 0.687e^{-0.32t} - 0.313e^{-3.8t}) \quad (3)$$

Where t is time in minutes, T_0 is ambient temperature ($^{\circ}\text{C}$) and T is Temperature ($^{\circ}\text{C}$).

- Eurocode-2 [125]: EN 1992-1-2, presents features of the thermal and mechanical properties of concrete

and reinforcing steel bars when exposed to fire. The main aim of this code is to prevent integrity failure, insulation failure and thermal radiation in concrete members exposed to fire by measuring parameters such as integrity, insulation and load bearing of the exposed members. The code deals specifically with explosive spalling (section 4.5 for NSC and section 6.2 for HSC). For NSC with moisture content higher than 3% by weight, assessment of moisture content, type of aggregate, permeability of concrete and heating rate is suggested. In case of HSC the following methods are suggested to reduce spalling: using a reinforcement mesh with a nominal cover of 15 mm, using a type of concrete that experimental studies have shown that no spalling will happen for it, using protective layers and using more than 2 kg/m^3 of PP fibres in the concrete mix.

2.5 International guidelines

- ISO 834 [126]: The type of fire is considered to be cellulose materials such as wood, paper, etc. Mathematically, the fire curve is defined via the following equation:

$$T = T_0 + 345 \log_{10}(8t + 1) \quad (4)$$

Where t is time (minutes), T_0 is ambient temperature ($^{\circ}\text{C}$) and T is Temperature ($^{\circ}\text{C}$).

Figure 3, compares some of the fire curves presented in guidelines, used for designing the structural members.

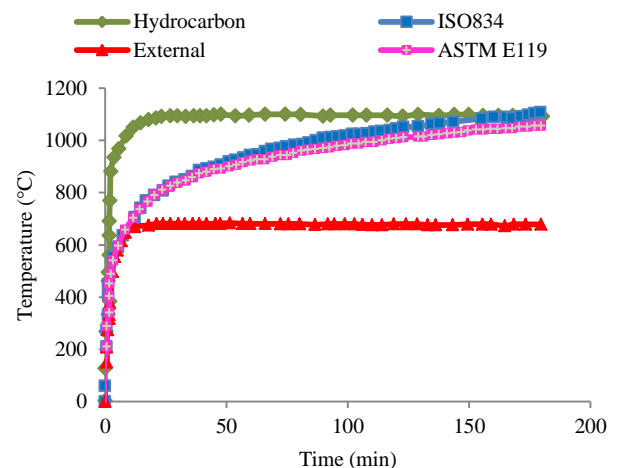


Figure 3: Fire curves used for design of structural members

Table 3, compares different national and international guidelines addressing design methods for improving fire performance of concrete. As can be seen in the table very few standards cover design methods specifically for fire spalling.

Table 3- Fire design methods in codes and standard guidelines

NO	Guideline	Design method
1	European guidelines (Eurocode-2): EN 1991-1-2 : General actions on structures exposed to fire [125]	<p><u>General:</u> Eurocode-2 is a European standard that presents features of the thermal and mechanical properties of concrete and reinforcing steel bars when they are exposed to fire. The main aim of this code is to prevent integrity failure, insulation failure and thermal radiation in concrete members exposed to fire by measuring parameters such as integrity, insulation and load bearing of the exposed members. For these purposes the standard, investigates the material properties inside concrete, thermal and physical properties of concrete with siliceous and calcareous aggregates and thermal elongation of reinforcing and prestressing steel. The design procedures consist of simplified calculation method (temperature profile, reduced cross-section and strength reduction) and advanced calculation methods (thermal response, mechanical response and validation of advanced calculation models).</p> <p><u>Spalling:</u> This code deals specifically with explosive spalling (section 4.5 for NSC and section 6.2 for HSC). For NSC with moisture content higher than 3% by weight, assessment of moisture content, type of aggregate, permeability of concrete and heating rate is suggested. In case of HSC the following methods are suggested: using a reinforcement mesh with a nominal cover of 15 mm, using a type of concrete that experimental studies have shown that no spalling will happen for it, using protective layers and using more than 2 Kg/m³ of monofilament fibres in the concrete mix. In addition, general design rules to increase fire resistance of concrete have been presented in tabulated data for parameters such as axis distance of reinforcements and section size of concrete. The data are investigated separately for columns, walls, beams and slabs and it is claimed that "when using tabulated data no further checks are required concerning spalling, except for surface reinforcements."</p>
2	American guidelines: ASTM E119: Standard test methods for fire tests of building construction and materials [50]	<p><u>General:</u> This standard presents test methods to measure the fire-resistive properties of materials and assemblies and doesn't specifically talk about design methods.</p> <p><u>Spalling:</u> -</p>
3	Australian standard: AS3600: Concrete structures [47]	<p><u>General:</u> General design performance criteria has been discussed for a concrete member (slab, wall, column or beam separately) for structural adequacy, integrity and insulation of not less than the required fire resistance level including: Increasing in axis distance for prestressing tendons, dimensional limitations to achieve fire-rating, adding joints between members or between adjoining parts, minimizing the chases, Increasing FRP by the addition of insulating materials. Also for achieving fire resistance periods for each concrete member, tabular data is available.</p> <p><u>Spalling:</u> Some general observations on spalling behaviour of concrete members is mentioned have been recently added to the standard as follows: "The tendency for spalling is high when: - the element is made of HSC rather than normal strength concrete (NSC); - the cover to the reinforcement is increased, especially more than about 40 mm- the moisture content of the concrete is high; - the temperature rise of the fire is rapid and concrete is subjected to a high thermal gradient; - the concrete is subjected to compressive stress; or- when concrete is subjected to a hydrocarbon fire compared to a standard fire."</p> <p>In AS3600, referring to the experimental results, adding Polypropylene fibres (PP) with a dosage of 1.2 kg/m³ and 6 mm length is recommended to reduce the magnitude of spalling.</p>
4	British guidelines: Structural use of concrete, Part 2: Code of practice for special circumstances: BS 8110-2:1985 [124]	<p><u>General:</u> In this standard, three different methods for determining the fire resistance of concrete members are presented: Tabulated data, fire test and fire engineering calculations. In each of the three methods the factors that influence the fire resistance of concrete elements are mentioned as follows: size and shape of elements, disposition and properties of reinforcement or tendon, the load supported, the type of concrete and aggregate, protective concrete cover provided to reinforcement or tendons and conditions of end support. In this standard, the Fire engineering calculations allow interaction between these factors to be taken into account.</p> <p><u>Spalling:</u> The standard claims that rapid rates of heating, large compressive stresses or high moisture contents (over 5% by volume or 2-3% by mass of dense concrete) can lead to spalling of concrete cover at elevated temperatures, particularly for thicknesses exceeding 40 -50 mm. Also, it is mentioned that concretes made from limestone aggregates are less susceptible to spalling than concretes made from aggregates containing a higher proportion of silica, e.g. flint, quartzites and granites. Concrete made from manufactured lightweight aggregates rarely spalls. Acceptable measures to protect spalling are: an applied finish by hand or spray of plaster as a fire barrier, the provision of a false ceiling as a fire barrier, the use of lightweight aggregates, the use of sacrificial tensile steel. Welded steel fabric as supplementary reinforcement is sometimes used to prevent spalling. It is then placed within the cover at 20 mm from the concrete face. There are practical difficulties in keeping the fabric in place and in compacting the concrete; in certain circumstances there would also be a conflict with the durability recommendations of this standard.</p>

5	International guidelines (ISO 834) [127]	General: Iso 834, under the general title of fire resistance tests, consists of different part including: specific requirements for loadbearing vertical and horizontal separating elements, specific requirements for beams and columns, specific requirements for non-loadbearing vertical separating elements and ceiling elements. <u>Spalling</u> : -
NO	Guideline	Design method
6	New Zealand guidelines: NZS3101 [49]	<u>General</u> : Similar to the Australian Code, the New Zealand Building Code categorises the fire-resistance ratings (FRR) of concrete elements for a period of 30-240 minutes according to three criteria: stability, integrity and insulation. The tabulated data in the standard show suitable dimensions of the members including beams (simply supported or continuous), slabs (one-way or two-way), columns and walls. For improving the fire resistance of concrete members following the structural tables and dimensions or using insulating materials is suggested. <u>Spalling</u> : -
7	ACI216.1-7 : Standard method for determining fire resistance of concrete and masonry construction assemblies [128]	<u>General</u> : Minimum thickness and concrete cover requirement were mentioned for concrete walls, floors and roofs for the purpose of barrier fire resistance. Also, calculations regarding determining the fire resistance of concrete members after applying finishes of gypsum wallboard or plaster to one or two side of the member are presented. <u>Spalling</u> : Only in the section talking about minimum cover for prestressed concrete beams this sentence referring to spalling phenomenon is mentioned: " Adequate provisions against spalling shall be provided by U-shaped or hooped stirrups spaced not to exceed the depth of the member, and having a cover of 1in."
8	Indian standard: Fire safety of buildings (general): Details of construction-Code of practice: IS 1642:1989 [129]	<u>General</u> : Referring to the required fire resistance, minimum concrete cover for different concrete member are presented. <u>Spalling</u> : -

3 PROPERTIES OF CONCRETE MATERIALS AT ELEVATED TEMPERATURES

3.1 Mechanical properties of concrete

Referring to many experimental studies, deterioration of mechanical properties of concrete is one of the unsuitable behaviours of this material while heating. The deterioration could be due to physiochemical changes in either aggregate or cement paste or the thermal gradient between aggregate and cement paste [20]. To investigate the fire performance of concrete, reviewing the mechanical properties at high temperatures is essential.

3.1.1 Compressive strength

Compressive strength of concrete facing fire depends on many factors including the concrete components, moisture content, loading levers, cooling methods, rate of heating, and the number of thermal cycles. In general, results show that compressive strength of concrete decreases at elevated temperatures [30], [130]–[134]. As can be seen in Figure 4 the trend of changing the compressive strength is nearly similar for concretes with different strengths. Below 100°C, compressive strength decreases due to increasing the energy and movement of free water inside concrete. The water movement causes triaxle stresses, weakening Van der Waals forces among the molecules and consequently moving apart the layers

of concrete, softening of concrete paste and attenuation of surface forces because of removal of absorbed water [20]. Between 100-300°C, both free water and absorbed water inside concrete start evaporating. Some believe that the water reduction in addition to dehydration of binder and stiffening of the cement gel are attributed to the increase in Van der Waals forces between gel particles and improve the compressive strength at this stage [7], [26]. Referring to higher density of HSC and lower rate of moisture escape, the improvement in compressive strength happens later (after 300°C) in HSC. From 300-600°C, dehydration and decrease in bond between aggregate and paste take place, causing disintegration of the concrete. Reduction of bond strength is mainly owing to thermal transient between paste and aggregates. At this stage concrete paste tends to shrink while aggregates tend to expand. Above 600°C, phenomenon such as calcination of limestone and decomposition of Ca(OH)₂ and C-S-H gels could be the cause of a quicker decrease of compressive strength [135]. In general, NSC losses less compressive strength than HSC when exposed to a temperature of 100°C, which could be due to easier movement of water in NSC with less permeability than HSC [133], [135].

3.1.2 Modulus of elasticity

The modulus of elasticity of concrete at room temperature ranges between 5×10^3 to 35×10^3 MPa and depends on factors including w/c ratio, age of the concrete, method of conditioning and type of aggregates [65]. In general, this parameter decreases

with increasing temperature (Figure 5). Experimental results indicate that changes of modulus of elasticity for NSC and HSC have the same trend, but the slope of stress-strain curve for HSC is more than NSC [136]. At temperatures up to 400°C, due to the water removal, concrete becomes compressible. So the modulus of elasticity reduces. In the temperature range of 400°C to 600°C, reduction of modulus of elasticity is due to dehydration that happens inside concrete member and therefore the bond between

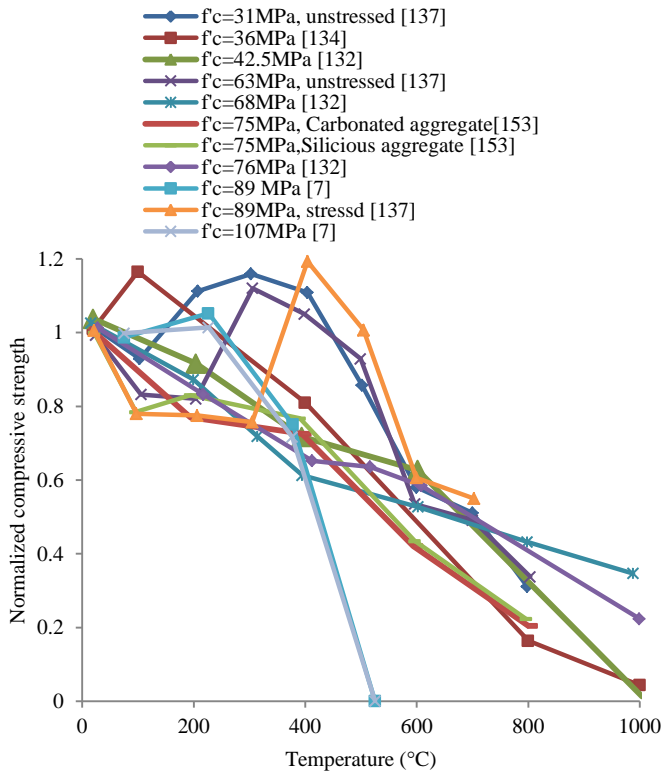


Figure 4: Concrete compressive strength at elevated temperatures

aggregates and cement paste mitigates. Above 600°C, specifically between 600-700°C absorption of heat for calcination or other transaction procedures in aggregates prevents any specific change in modulus of elasticity.

The reduction of modulus of elasticity is also less in concrete heated under load than the one with no load. The loading can limit the reduction of modulus of elasticity by compacting concrete and preventing the cracks to develop [20], [133].

Studies conducted by Tian [137], investigated the effect of heating time on modulus of elasticity of NSC. Results show that this property reduces with increasing heating time, due to the increase of deformation and decrease of bearing capacity and durability of concrete.

3.1.3 Tensile strength

Tensile strength of concrete is much lower than compressive strength. This characteristic becomes more important during a fire, when tensional micro

cracks happen in the concrete and their propagation could cause spalling. Hence, understanding the tensile strength of concrete is crucial in predicting the fire performance of concrete.

Results of some experimental studies [62], [138] confirm that tensile strength of concrete decline with increasing temperature (Figure 6). The tensile strength relationship with temperature is claimed to be similar for HSC and NSC. It is also shown that

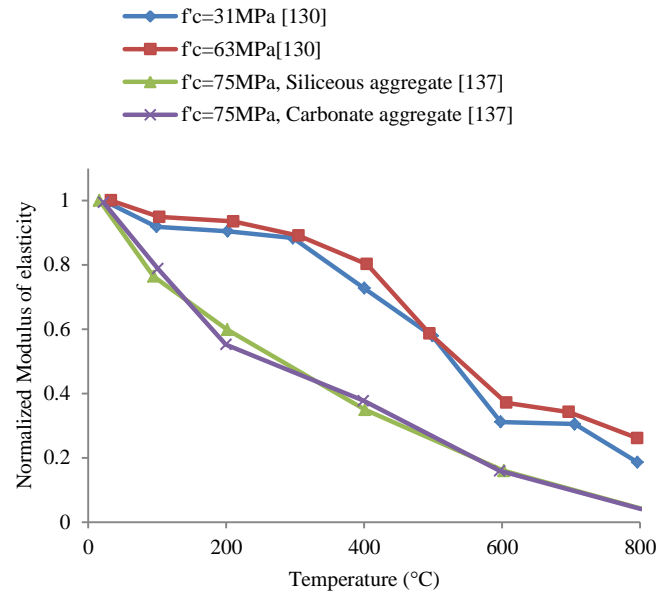


Figure 5: Modulus of elasticity of concrete at elevated temperatures

tensile splitting strength of concrete is more sensitive to high temperatures than compressive strength [26].

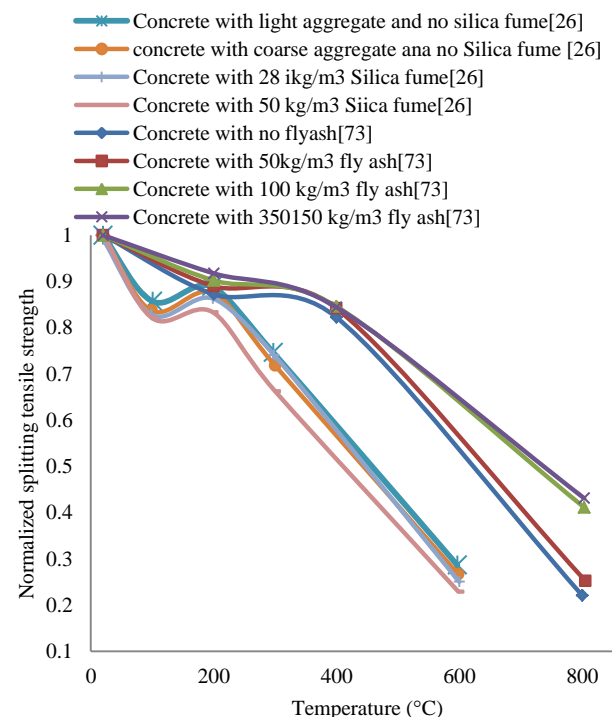


Figure 6: Tensile strength of concrete at elevated temperature

3.1.4 Flexural strength

Flexural strength of concrete is another measure of the tensile strength of concrete showing the resistance to bending failure. As can be seen in figure 7, flexural strength of concrete, similar to other mechanical properties, deteriorates at elevated temperature due to dehydration and degradation of Van der Waals forces. Comparing the behavior of NSC and HSC shows that decrease in flexural strength of NSC is more than HPC while heating up to 400°C. Above 600°C, decrease in flexural strength of both type of concrete increases [139]–[141].

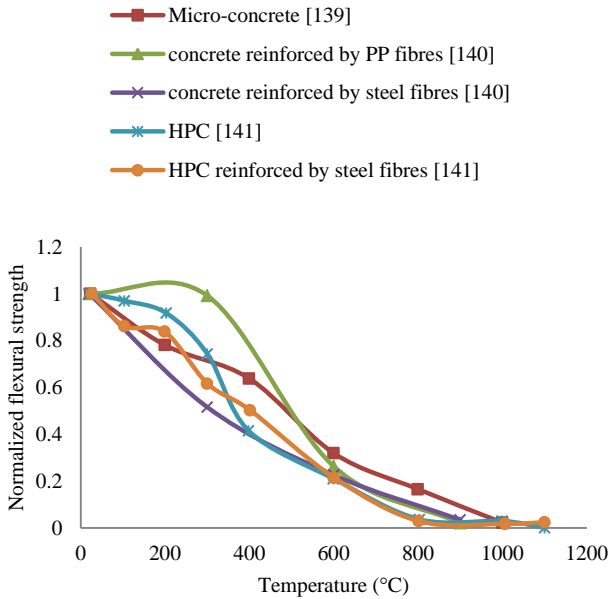


Figure 7: Flexural strength of concrete at elevated temperatures

3.1.5 Poisson's ratio

Poisson's ratio of concrete represents the ratio of lateral to axial deformation under uniaxial loading and varies between 0.11 to 0.32; but is generally considered in the range of 0.15 to 0.2. at room temperature. Figure 8 indicates that Poisson's ratio of both NSC and HSC decreases with increasing temperature due to loss of evaporable water in the matrix (Figure 8) [141]–[144].

Studies conducted by Tian [137], investigated the effect of heating time on modulus of elasticity of NSC. Results show that this property reduces with increasing heating time, due to the increase of deformation and decrease of bearing capacity and durability of concrete.

3.2 Thermal properties of concrete

During heating, cracks happen in concrete due to either thermal gradient or dehydration of concrete paste [145]. To manage the thermal cracks, a deep understanding of the thermal behaviour of concrete is needed. Thermal properties of concrete that can

affect the temperature rise and temperature distribution in concrete during heating are discussed in this section.

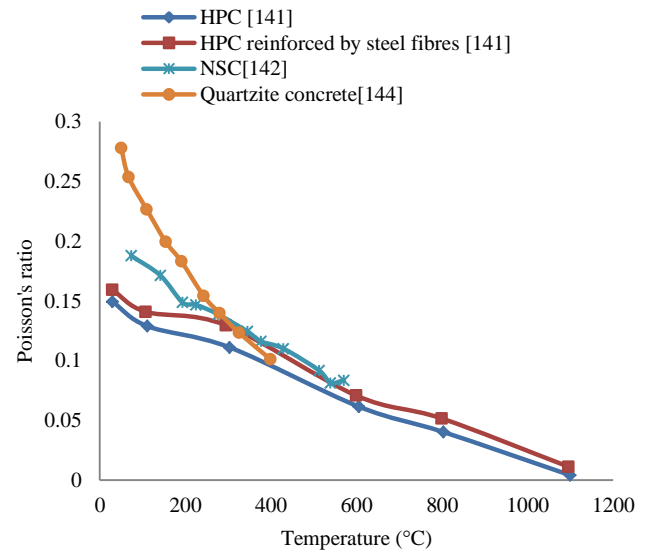


Figure 8: Poisson's ratio of concrete at elevated temperatures

3.2.1 Thermal conductivity

Thermal conductivity is a material property which shows the ability of conducting heat and is defined by the ratio of heat flow rate to temperature gradient. It is the property that affects the temperature gradient in different parts of concrete exposed to heat [64]. Concrete with low thermal conductivity has great thermal insulation; hence, concrete with high thermal conductivity would be useful in reducing thermal gradient among different parts of a concrete, which could reduce the thermal gradient and spalling risk.

As the Figure 9 shows, over 100°C free water evaporates, so the empty pores reduce the speed of conduction due to the fact that air existed in the concrete pores has less thermal conductivity than water [64].

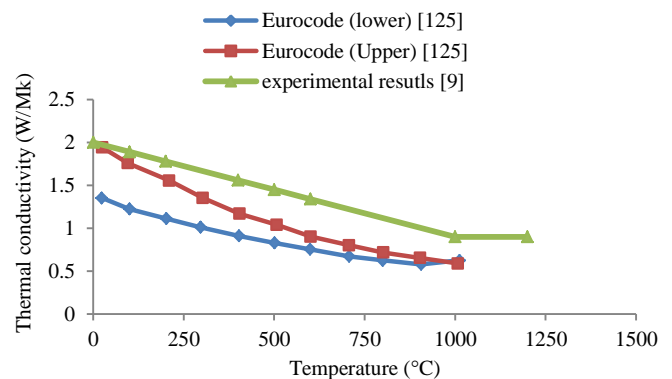


Figure 9: Thermal conductivity of concrete as a function of temperature

In addition to moisture content, the exact amount of thermal conductivity is affected by the accuracy and measuring methods of the instruments [145]. Experimental tests show that concrete with higher density has more thermal conductivity [146]. Higher crystallinity causes higher thermal conductivity and its rate of decrease with temperature [28]. That is why thermal conductivity of concrete with siliceous aggregate, which has higher crystallinity, is higher than carbonate concrete in the temperature range of 200-800°C.

3.2.2 Specific heat

Specific heat is known as the amount of required heat per unit mass to change the temperature of a material by one degree and is given by:

$$C_p = (\partial H / \partial T)(p, \xi) + (\partial H / \partial \xi)(p, T) d\xi / dT \quad (5)$$

Where H is enthalpy, T is temperature, p is pressure and ξ is the degree of conversion of reactants; if heating is accompanied by chemical reactions or phase transitions inside the concrete. Specific heat of NSC at normal temperature ranges between 0.5-1.13 kJ kg⁻¹ K⁻¹[9].

Temperature stability of a structure increases using concrete materials with high specific heat. At high temperatures, this characteristic is affected by moisture content, aggregate type and density of concrete [65]. Dehydration of Tobermorite gel and calcium hydroxide is the main reactions happen at elevated temperatures. Absorption of heat in this reaction increases the specific heat of concrete at different temperatures. The noticeable peak at 500°C in Figure 10 is related to dehydration of calcium hydroxide.

Adding materials such as steel fibres or super absorbent polymers in to concrete mix, able to absorb heat at elevated temperature could be beneficial in increasing specific heat, reducing internal energy and hence preventing the concrete from increasing temperature. So it can reduce the spalling risk[66].

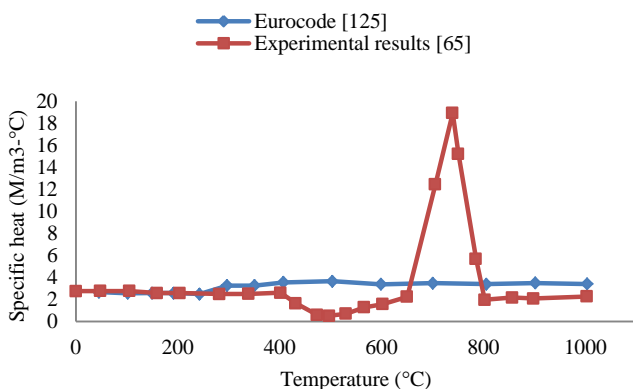


Figure10: Specific heat of NSC as a function of temperature

3.2.3 Thermal expansion

Coefficient of thermal expansion, α , is the thermal strain per degree Centigrade. Thermal expansion of concretes with lower proportion of aggregates increases as the thermal expansion of cement paste is higher than usual aggregates. Age of concrete has some influence on the thermal expansion of concrete. Experimental results show that the value of α has minor decrease in aged concrete [9].

One of the main factors affecting the thermal expansion of concrete is the temperature. Figure 11 shows that the relationship between the thermal strain of concrete and temperature is linear until about 500°C. At elevated temperatures transformations in the aggregates, failure of the bond between aggregates and cement paste and shrinkage due to dehydration of concrete cause nonlinear or even negative expansion. Increasing temperature leads to an increase in thermal stress inside concrete members. This stress and the resultant thermal gradient could cause either thermal expansion or deterioration of the bonds between aggregates and cement paste.

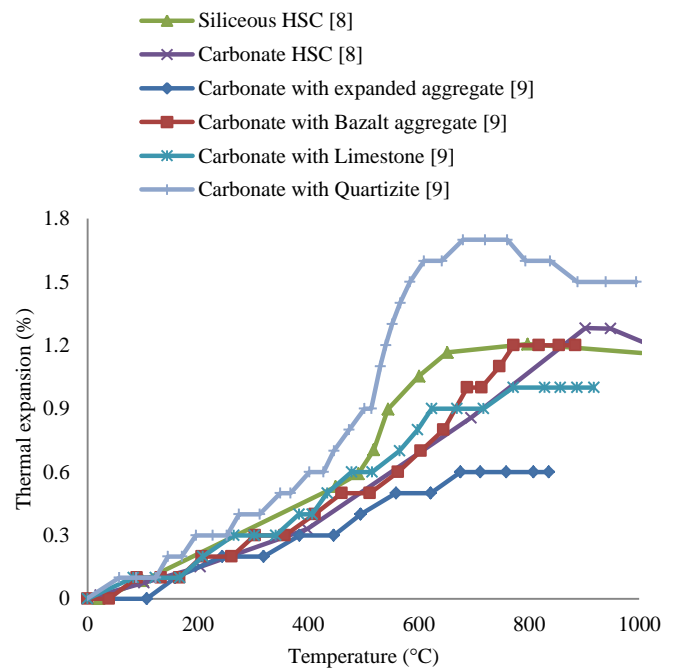


Figure 11: Thermal expansion of concrete with a variety of aggregates at different temperatures

4 FACTORS GOVERNING FIRE SPALLING OF CONCRETE

The magnitude of spalling is governed by many dependent factors including the material, environmental and geometrical parameters. Many numerical and experimental studies have been implemented to investigate the effecting parameters on this phenome-

non; among which some of the leading factors are discussed in this section.

4.1 Porosity and pore pressure

Pore pressure is due to liquid mass transfer through the pores. Referring to Hertz, dense concrete is more susceptible to spalling than traditional one due to its lower porosity [8]. Referring to many experimental and numerical studies conducted to assess the spalling risk of concrete exposed to fire, one of the main reasons affecting the fire spalling behaviour of concrete is the vapour pressure generated in the pores of a concrete with low gas permeability [16], [58]. By increasing the temperature, water in the pores evaporates and then solves in free water until the pores become fully saturated. At this stage, pores cannot contain water and vapour at the same time, which causes the pressure inside them to increase considerably. When the pressure becomes more than the tensile strength of concrete, spalling happens (Figure 10). Low permeability of concrete impedes internal pressure to escape from concrete and could be the reason that HSC materials are more susceptible to spalling than NSC [8].

On the other hand, some of the investigations show that increasing porosity does not necessarily reduce spalling; By increasing the porosity the amount of free water inside concrete and hence the amount of vapour and consequently the pore pressure will be increased [16]. This is with the assumption that the pores are full of free water. In those pores full of air, again increasing the porosity leads to increase of the amount of internal air that reduces the thermal conductivity of concrete. Reduction of thermal conductivity leads to an increase in the thermal gradient and thermal stress inside concrete and could increase the magnitude of spalling.

Due to the different views, considering the pore pressure and porosity as the main causing factor of this phenomenon has become a controversial issue [2], [3], [147].

4.2 Moisture content

The amount of moisture inside concrete is one of the influencing factors affecting fire spalling risk. Some believe that dry NSC with low moisture will not spall [8].

When a concrete member exposes to fire, water inside the concrete pores evaporates. The pressure gradient in the concrete causes the mass transfer [148]. A part of the vapour leaves concrete from the heated surface and the other part moves toward a concrete section with less pressure and temperature. By reaching a cold section, the vapour condenses and changes into water. Continuing the heating pro-

cess generates a layer of saturated water near the heated surface. This layer acts as an impermeable wall and impedes the vapour pass through. If the porosity of the cold section is not enough to let the internal vapour get out of the concrete, the pressure inside the concrete increases and a pressure peak is located at the saturated layer. Sudden release of the energy of the pressure could cause spalling. The lower the permeability of the material, the sooner (and the closer to the heated surface) this moisture clog is generated and the higher the pressure and the pressure gradient [9], [149].

On the other hand, HSC with lower w/c is more prone to explosive spalling and it has been reported that even the crystal water can be sufficient for causing an explosive spalling in HSC. This leads to the conclusion that it is really difficult to make an assessment only on the basis of an initial moisture content regarding the possible likelihood of explosive spalling [150].

4.3 Thermal gradient and heating rate

The temperature gradients induce gradients of thermal dilation, which in turn generate tensile stresses perpendicular to the heated face. Local strain incompatibilities between the cement paste and the aggregates also exists; While the aggregates dilate with increasing temperature until they are chemically degraded [9], [42], the cement paste shrinks as soon as it loses water (by drying and dehydration) [42]. Due to non-uniform temperature distribution in concrete structure during heating, the differences between the thermal expansion of concrete paste and aggregates induce some stresses. Some investigators claim that the main driving force causing spalling in concrete members exposed to fire is the sudden release of energy stored from thermal stresses. Thermal gradient in concrete member exposed to fire causes failure in bonds between aggregates and cement paste and could be sufficient to cause spalling. Therefore the main cause of explosive spalling in HSC could be the thermal gradient-induced thermal stress and not the vapour pressure or even the generation of moisture clog [24].

Type of fire is another governing factor that has considerable effects on the magnitude of spalling. Many experimental studies show that rapid or asymmetrical heating gives rise to both temperature and moisture gradient, which leads to higher build-up of pore pressure and tensile stress and then larger spalling [8], [39], [53], [58], [131]. Increasing the spalling depth of HSC exposed to hydrocarbon fire with higher rate of temperature comparing with NSC testifies this effect [74].

On the other hand, there is a doubt that fast heating causes more cracks on the concrete surface.

These cracks can act as gateways for the vapour and liquid, thereby decreasing the internal pressure and spalling of the concrete [3], [53].

Referring to different views on the effect of heating rate on spalling, the influence of this factor needs more investigations.

4.4 Concrete mixture

It was claimed that expansion and rapid change of volume of aggregates such as Quartz and Limestone filler could increase the probability of spalling in concrete exposed to fire [79]. Filler makes the concrete denser, thereby not enough space for the internal pressure to release from the concrete and could cause spalling.

On the other hand, type of aggregate as a governing factor on fire spalling is rejected by a few researchers [3], [8]; They believed that aggregate expansion such as what happens in Quartz causes micro cracks in the concrete and leads in small deterioration but not spalling. Also, mismatching between the expansion of aggregates and the concrete generates cracks that could act as gateways for both vapour and free water and reduce the magnitude of spalling.

In spite of controversial views on the effect of concrete mixture on the magnitude of spalling, it is believed that choosing appropriate aggregate could have positive impact on the concrete fire performance. As an example, utilizing aggregates with high thermal stability and low thermal expansion improves their compatibility with the cement paste and enhances concrete integrity. Aggregates with angular surfaces have better bond with the paste. Also, using reactive silica improves the chemical bond with the paste [130]. Carbonate aggregates absorb heat to dispel CO₂ and magnesium carbonate decomposes at elevated temperatures. These reactions are endothermic that absorb heat and reduce the increasing speed of temperature inside concrete; Hence the fire endurance of concretes with these types of aggregates will be improved [78], [151].

4.5 Concrete member geometry

Spalling probability in concrete members with acute angles is larger than circular ones with lower thermal stress concentration. It seems that damage on concrete surface with a reinforcing bar will be more serious due to low thermal strength of steel used as reinforcement. Since maximum cover of reinforcement is needed for spalling prevention which adds weight and cost, finding optimum cover for reinforcements to improve the general behaviour of concrete members while exposing to fire is required.

Khoury [4] revealed that peak pore pressure usually happens near the surface of the concrete, especially in HPC. Consequently thinner ones experience more severe spalling in fire; Results of Hertz's experiments also show that development of rapid heat and consequently increasing temperature and moisture gradient in thin cross-sections is easier. So the chance of spalling will be increased in thinner members [8].

On the other hand, since reaching thermal equilibrium is easier and faster in small specimens, concrete panels with larger surface area and/or larger thickness are more prone to fire spalling [39].

Finding the exact effect of size and shape of the concrete members is another unknown area related to fire spalling that needs more investigations.

4.6 Loading level and boundary conditions

Mechanical stress induced in a concrete face exposed to fire especially in fixed ends of concrete slab or beam is another influencing factor on the magnitude of fire spalling [8]. Some experimental results show that fire spalling in members with higher compressive stress happens more easily and/or more severely [77]. Accordingly, pre-stressed concrete with restricted tensile cracking, may suffer more from this phenomenon. In concretes with no pre-stress forces, compressive stress will be reduced by generating tensile cracks near the surface; So the internal stress of the concrete member, which could increase the magnitude of spalling will be reduced [61]. Considering the effect of initial cracks generated in members with low mechanical loading on reducing the internal vapour pressure and the magnitude of spalling, also emphasises that vapour pressure could be one of the leading reasons of spalling in concrete members.

4.7 Age of concrete

The experimental study conducted by Boström & Jansson [152] shows that in spite of initial expectations of decreasing spalling in aged concrete, even after years of producing concrete, the spalling still happens. Also, it was shown that age of concrete in large concrete specimens and concrete with low permeability doesn't have considerable effect. Since these types of concrete can hardly achieve the humidity equilibrium with environment after a while. Hence no strong evidences has been found to claim that the probability of spalling will be decreased by increasing the age of the concrete [15]. Therefore, defining an exact age in which concrete won't spall is to some extent impossible [150].

5 PREVENTION STRATEGIES FOR FIRE SPALLING OF CONCRETE

To mitigate or prevent fire spalling in concrete members, a few suggestions are presented by researchers based on factors influencing this phenomenon. This section discusses some of these suggestions and their negative and positive effects on spalling.

5.1 Addition of textile fibres and fabrics

Different type of fibres has been used as supporting materials in concrete paste to enhance the final properties. Some of which found to be effective in improving spalling performance of concrete material are discussed in this section.

5.1.1 Polypropylene fibres

Many experimental studies claim that using Polypropylene fibres (PP) decrease and in some circumstances prevent the fire spalling of the concrete members [19], [39], [59]. Microscopic study on the behaviour of PP fibres in concrete shows that by exposing concrete to fire, these fibres start to expand, melt, and then shrink at around 170°C [67]. The void spaces occur in the concrete referring to melting of PP fibres can be considered as weak points inside concrete. Increasing the heat causes cracks at the edges of the voids. These cracks act as micro gateways around fibres, from which moisture and water vapour can pass through by the aid of either capillary forces or the pressure difference. By reducing the vapour pressure built-up in the concrete moving free water from critical zone, the local stress and then the magnitude of spalling could be reduced [3], [61].

One of the concerns of adding fibres to concrete is reduction of the workability especially in self-compacting concretes [69]. To improve the workability of concrete reinforced by PP fibres, results of a study show that adding Super Absorbent Polymers (SAP) to self-compacting concrete could be beneficial in reducing the amount of free water in the pores and consequently reduces the gas pressure after exposing to fire. It seems that by using optimum amount of SAPs, the optimum dosage of PP fibres needed in concrete can be reduced and a better workability in concrete can be achieved [67].

Other concern of adding of PP fibres is production of some additional void spaces in concrete during a fire, which may decrease the durability of the member at first steps of exposing to fire. These voids may be converted in to micro cracks and may become places for stress concentration inside the concrete at temperatures up to 175°C [26].

Referring to Eurocode, adding more than 2 kg/m³ of monofilament PP fibres in the concrete mix is suggested to prevent spalling; while in Australian standard a dosage of 1.2 kg/m³ of PP fibres with 6 mm length are recommended. Experimental tests suggest different dosage of this fibre (0.9-3 kg/m³).

In general, fibres with smaller cross-section and longer length have more positive impacts on mitigating the fire spalling [153]; but referring to the effectiveness of fibre specification on spalling behaviour of concrete, further research to achieve a better understanding of the exact microstructural mechanism of added fibres and their behaviour in concretes during a fire is needed. Also, the optimum dosage, dimension and number of fibres in unit volume of concrete that could improve the fire spalling behaviour of concrete members needs to be clarified for both HSC and ultra-high strength concrete (UHSC) [130], [153].

5.1.2 Steel fibres

Some experimental results show that adding steel fibres improves the mechanical behaviour of concrete such as flexural fatigue strength and ductility of HSC [33], [78], and they are beneficial in reducing spalling. Few other results indicated that these fibres were only beneficial for increasing the temperature tolerated by reinforcement bars and were not successful in hindering the fire spalling of the concrete [8], [10].

5.1.3 Hybrid fibres

Some experimental studies [30], [31], [34], [56] investigated the effect of adding hybrid fibres to HSC on residual mechanical strength at elevated temperature. Results show that combination of PP fibres and Carbon and/or Steel fibres could improve the mechanical properties of the HSC and alleviate the pore pressure inside concrete [154]. This could be due to melting of PP fibres and generation of micro channels that lead to reduce the inside vapour pressure. Addition of Carbon and Steel fibres were also beneficial in generating bridges over internal cracks and improving the stability of the concrete at high temperatures.

Addition of Nylon and PP fibres were also suggested to mitigate the spalling [32], [33]. Since Nylon fibres have smaller diameters, they can distribute evenly in the concrete paste and can improve the workability and make joints between small pores and help PP fibres reducing the internal pressure.

5.1.4 Textile fabrics

In a research conducted by Ehlig [155] textile fabric made of carbon fibres were used as concrete reinforcement. The fabric was responsible for load distribution and increasing tensile strength of concrete

exposed to fire. It should be noted that the problem of reduction in workability of concrete is more severe in concretes reinforced by fabrics.

5.2 Reducing water content

To improve the fire spalling performance, pre-drying the concrete at 80° is suggested [61], [156]. Eurocode also suggests decreasing the amount of free water in concrete to less than 3% by weight to reduce the amount of vapour inside concrete at high temperatures.

To improve the concrete behaviour in terms of moisture clog, efforts need to be made on finding out the optimum amount of moisture, the moisture distribution in different types of concrete and the effect of saturated water inside concrete members on fire performance of concrete [61].

5.3 Utilizing thermal barrier

It is believed that thermal barrier and blocking the heat transfer to the concrete structure are the most effective but expensive way to improve the fire spalling behaviour of HSC [4], [31].

6 CONCLUDING REMARKS

Reviewing the recent achievements on concrete fire spalling, shows that the exact origin of the phenomenon and the physics involved is not yet understood.

Referring to the probable factors influencing the fire spalling of concrete, it seems that this phenomenon occurs under a combination of governing factors including vapour pressure and thermal gradient, which are considered as the main factors causing spalling and the rest are influencing factors that have effect on the magnitude of spalling and not necessarily the main reason of this phenomenon. Even by accepting this idea, researchers have not yet completely agreed on the relative contribution of the influencing factors on the concrete fire spalling phenomenon. The research gap that has been reported is due to the erratic and random nature of spalling phenomenon. Other functions include non-homogenous structure of concrete material, large number of factors that influence spalling and their interdependency.

Referring to the importance of this phenomenon and necessity of its avoidance, it is important to achieve a better understanding of the real mechanisms responsible for fire spalling of concrete and then develop a realistic predictive model and present practical eliminating methods. These methods should be a feasible alternative way to expensive tests, through which concrete behaviour can be pre-

dicted and simulated under realistic conditions and with real concrete member geometry.

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