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A multi-level factor interaction framework of fire-induced spalling of cementitious material based on a systematic review

Guan Quan [a,b], Runyi Zhang [a,b], Ian Burgess [c], Jun Ye [d,*], Shilang Xu [a,b]

[a] Institute of Advanced Engineering Structures, Zhejiang University, Hangzhou 310058, China
[b] Intelligent Industrial Construction Laboratory, Innovation Center of Yangtze River Delta Zhejiang University, Jiashan, Zhejiang 314102, China
[c] School of Mechanical, Aerospace and Civil Engineering, University of Sheffield, Sheffield S1 3JD, UK
[d] School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK

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ABSTRACT

Fire-induced concrete spalling under high temperatures is a complex phenomenon that affects the safety of reinforced concrete structures in fire. However, there have been few attempts to comprehensively review or systematically analyze the results of existing studies, which cover different types of concrete and different influencing factors. Hence there is no consistent understanding of the mechanism of fire-induced concrete spalling that can be applied across the range of types of concrete. This study provides a critical review of the fire-induced concrete spalling mechanism, covering ordinary concrete (OC), fibre-reinforced concrete (FRC), ultra-high performance concrete (UHPC), ultra-high toughness cementitious materials (UHTCC) and engineered cementitious composite (ECC). The reviewed research results are summarized in the context of a multi-level factor interaction framework (MFIF), in which the influencing factors and parameters of fire-induced concrete spalling are de-coupled and ranked into two levels on the basis of causality. The first-level factors include water/cement ratio (W/C), fibres, moisture content, aggregate, geometric characteristics, heating conditions and mechanical conditions. These factors can be directly manipulated in the design of concrete material. The second-level parameters include material high-temperature strength, pore pressure, thermal stress and mechanical stress. These parameters are directly influenced by the factors in the first level and, if linked with the classic theories of fire-induced concrete spalling to form a spalling criterion that considers the whole range of influencing factors. This review aims to help understanding the nature of fire-induced concrete spalling in a systematic fashion, with the aims of assisting in the design of spalling-inhibiting concrete materials and providing guidance on fire-induced concrete spalling criteria for numerical simulations.

1. Introduction

1.1. Background

Concrete, as one of the main building materials in the field of civil engineering, has always been characterized as having excellent fire resistance properties. However, fire-induced concrete spalling, a phenomenon in which fragments or layers of concrete separate from the surface of a concrete structural element [1,2], often occurs. This has often been observed to take place explosively, with detached fragments being thrown at high velocity from the member surface. Fire-induced concrete spalling poses a potential challenge to the load-bearing capacity and operational safety of concrete or composite structures in fire.

Concrete can undergo several types of fire-induced spalling, which can be classified [3] according to the circumstances in which they occur, as: explosive spalling, surface spalling, corner spalling and aggregate spalling. These are illustrated in Fig. 1.

Explosive spalling is a violent event that occurs to a whole concrete element under high-temperature conditions, as shown in Fig. 1. (a) [4]. This is mostly encountered in highly compacted concrete structures. In comparison, surface spalling is less explosive and shows lamellar peeling, as shown in Fig. 1. (b) [5]. Corner spalling, shown in Fig. 1. (c) [6], usually occurs in areas where the heated surface of a concrete member is concentrated, especially tending to occur where heat flows concentrate in the corners of the heated members. Aggregate spalling, as shown in Fig. 1. (d) [7], occurs due to a mismatch in thermal properties, particularly in coefficients of thermal expansion, between the concrete

* Corresponding author.
E-mail address: j.ye2@leeds.ac.uk (J. Ye).

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Nomenclature

Abbreviations

3DPC	3D-printed concrete
AI	Artificial intelligence
ANN	Artificial neural network
CF	Carbon fibre
CNF	Carbon nanofibre
CNT	Carbon nanotube
CR	Crumb rubber
DL	Deep learning
ECC	Engineered cementitious composite
FRC	Fibre-reinforced concrete
GF	Glass fibre
HSC	High-strength concrete
MFIF	Multi-level factor interaction framework
NMR	Nuclear magnetic resonance
OC	Ordinary concrete
PE	Polyethylene
PPF	Polypropylene fibre
PVA	Polyvinyl alcohol
SEM	Scanning electron microscope
SF	Steel fibre
UHPC	Ultra-high performance concrete
UHTCC	Ultra-high toughness cementitious material
X-ray CT	X-ray computer tomography

matrix and the aggregate. Although aggregate spalling is usually not explosive, it poses a threat to the load-bearing capacity and durability of structural members. Fire-induced concrete spalling is usually observed in the temperature range 200–550℃ [8,9], but the exact critical temperature varies depending on the constituents of the concrete material and environmental influences. When concrete spalls, it is usually accompanied by a cracking or even explosion-like popping sound [10–14]. When it is not possible to directly observe the concrete spalling phenomenon at high temperatures, this sound can be an important basis for determining whether fire-induced concrete spalling has occurred [14].

From the viewpoint of load-bearing capacity, fire-induced concrete spalling can cause the steel reinforcement inside a structural member to be exposed to high temperatures, which accelerates the softening and yielding of the steel. Fire-induced concrete spalling can also reduce the effective cross-sectional area of a member, decreasing its load-bearing capacity, and may even lead to premature failure. In addition, from the point of view of safety in operation, the explosive spalling may cause damage to equipment or injury to personnel inside a structure. Fire-induced concrete spalling is commonly observed in constructions under fire scenarios. In a fire that occurred in 1916 in Far Rockaway, United States [15], investigations revealed extensive fire-induced concrete spalling within the building. Similarly, during a fire incident in the Channel Tunnel in 1996 [16], there were reports of significant fire-induced spalling of the concrete lining.

In other contexts, fire-induced concrete spalling should also be fully considered in the design of special structures such as RC structures in nuclear power plants, pressure vessels, and kilns in high-temperature environments. These constructions place higher demands on the integrity and safety of the structures under extreme conditions. With the advancement of construction material technology, high-performance concretes are becoming popular material options for modern civil engineering, due to their excellent mechanical properties and durability. High-performance concrete includes ultra-high performance concrete (UHPC), ultra-high toughness cementitious material (UHTCC) engineered cementitious composite (ECC). UHPC is made of a cementitious matrix mixed with steel or other synthetic fibre, which provides extremely high compressive strength at ambient temperature. UHTCC and ECC [17] are types of cementitious composite reinforced with specially selected short random fibres, usually of polymer materials. These materials exhibit remarkable tensile strain capacity (exceeding 3%). They develop sequential micro-cracks with widths controlled below 100 micrometres during strain hardening. This mechanism collectively contributes [18] to the material's superior ductility and

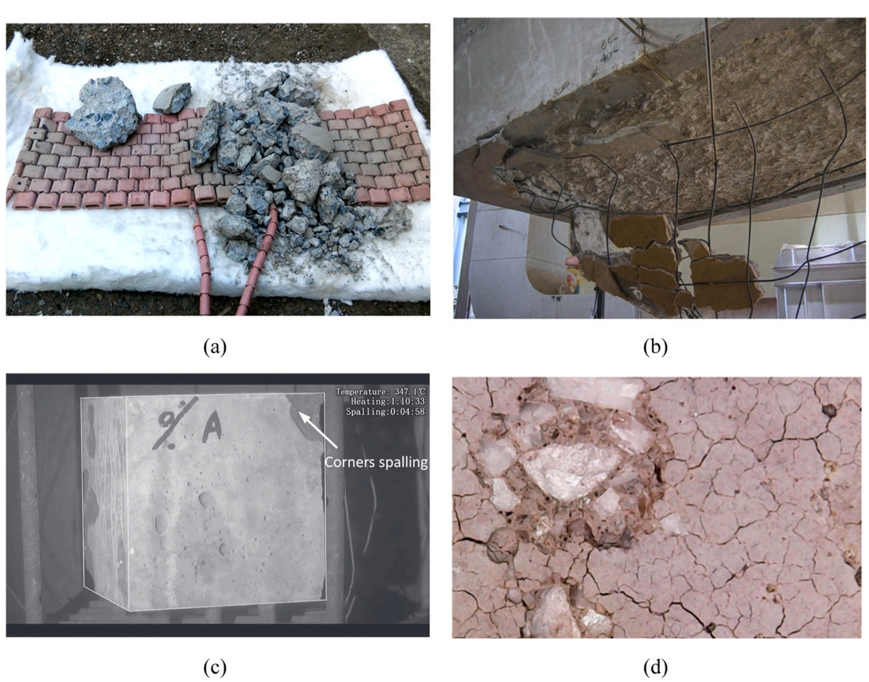

Fig. 1. Types of spalling: (a) Explosive [4]; (b) Surface [5]; (c) Corner [6]; (d) Aggregate [7].

fracture toughness in terms of its macroscopic properties. Figs. 2 and 3 show the differences in components and mechanical properties of ordinary concrete (OC), fibre-reinforced concrete (FRC), UHPC, UHTCC, and ECC.

It has been observed [26–28] that UHPC shows higher fire-induced concrete spalling sensitivity and more severe spalling phenomena than OC under fire conditions, due to its high density, while UHTCC [22,29] and ECC [21,30,31] show better resistance to fire-induced concrete spalling. The spalling phenomenon varies with different types of concrete, and hence the development of prevention measures is an important research topic in the field of structural fire engineering.

The study of fire-induced concrete spalling at elevated temperatures can be traced back to Barret's [32] early report in 1854. As research developed, the academic community mainly explained the fire-induced concrete spalling phenomenon from two perspectives: (i) the vaporization pressure of pore water inside the concrete at elevated temperatures [33], and (ii) internal stresses induced by thermal gradients [34]. Nevertheless, research on the mechanism of fire-induced concrete spalling is still immature, because:

- Firstly, there are a variety of microscopic and macroscopic influencing factors and parameters, for example water-cement ratio (W/C), fibres, moisture content, aggregate, heating and loading conditions, material strength and pore pressure. Existing research has usually carried out a coupled analysis of several factors/parameters which can influence one other; for example, W/C can influence both material strength and pore pressure. There is a need to decouple and rank these factors and parameters when investigating the mechanisms of fire-induced concrete spalling.
- Secondly, there are many types of concrete, and the research on fire-induced concrete spalling is normally confined to a particular type. There is a lack of analysis attempting to summarize the numerous research results into a unified framework that applies to the spalling analysis of the majority of types of cementitious composite material, which is possibly because that the development of the unified framework needs a summary of mass data of different types of concrete, while researchers investigating the fire-induced concrete spalling phenomenon normally always focus on specific types of concrete that they are particularly interested in. Therefore, the effective way of developing a unified framework is to carry out a systematic review rather than embedding it in daily research work.

1.2. Contributions

To attempt to fill the research gap mentioned above, a systematic review has been carried out to analyze the mechanism of fire-induced concrete spalling that covers a variety of popular concrete types. This paper reviews the relevant literature involving OC, FRC, UHPC and ECC/UHTCC. The review summarizes the numerous research findings into a unified framework that applies to these concrete types. In the framework, the influencing factors and parameters of fire-induced concrete spalling are decoupled and ranked into two levels based on their causality. The first-level factors include W/C, fibres, moisture content, aggregate, geometric characteristics, heating conditions and mechanical conditions. These factors can be directly manipulated in the design of concrete material. Their influencing mechanisms are reviewed and analyzed. The second-level parameters include material high-temperature strength, pore pressure, thermal stress and mechanical stress. These parameters are directly influenced by the first level factors, and could be linked using the classic theories of fire-induced concrete spalling mechanisms to form a spalling criterion that considers all the influencing factors. The review of fire-induced concrete spalling mechanisms and the development of a systematic framework aim to provide logic and fundamental knowledge to help understand the nature of fire-induced concrete spalling, to guide the design of spalling-inhibiting concrete materials, and to provide guidance on fire-induced concrete spalling criteria for numerical simulation.

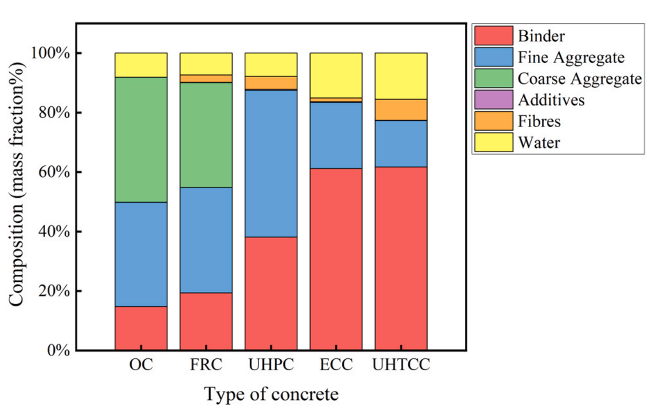

Fig. 2. Comparison of cementitious composite material components for (OC [13], FRC [19], UHPC [20], ECC [21]. UHTCC [22]).

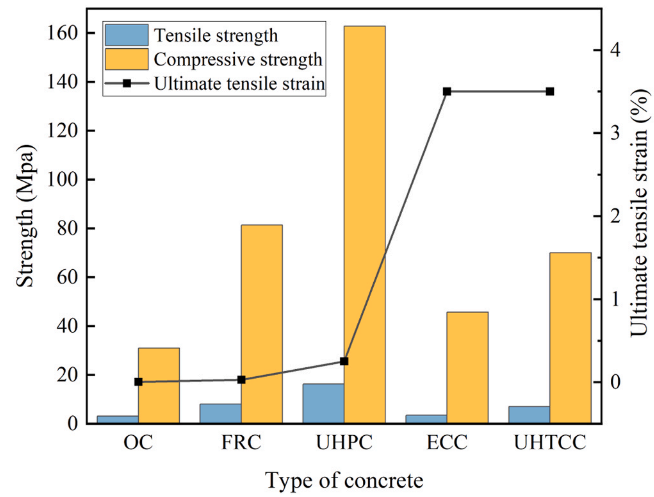

Fig. 3. Comparison of the mechanical properties of different types of concrete (Strength: OC [13], FRC [19], UHPC [20]. ECC [21]. UHTCC [22], Ultimate tensile strain: OC [23], FRC [24], UHPC [25]. ECC [24]. UHTCC [24]).

1.3. Organization

The full text of the review is organized as follows: Section 2 outlines the research methodology adopted in this paper and provides an overview of the relevant literature. Section 3 reviews the history of research in the field of fire-induced concrete spalling. Section 4 proposes a three-level theoretical framework to determine the occurrence of fire-induced concrete spalling. Section 5 summarizes the influencing factors that can be directly manipulated by the design of concrete materials in the first level of the framework. Section 6 summarizes the relationship between the influencing factors in the first level and the spalling criteria parameters in the second level. Section 7 summarizes the utilization of the second-level parameters to determine fire-induced concrete spalling. Section 8 and 9 discuss future work based on this paper, as well as conclusions.

2. Research methodology

2.1. Search strategy

The literature collection strategy of this paper utilises a combination of both direct and indirect search methods and sets up two rounds (initial and in-depth) of literature screening. In the 'Identification of studies via databases and registers' step, there were three steps, namely 'Identification', 'Screening' and 'Eligibility'. In the 'Identification' step, the inclusion criterion was searching core keywords and conducting the Boolean operator "(concrete OR cementitious composite) AND spall*" through Web of Science. A total of 5958 related articles were retrieved and included in the review databases. In the Screening step, the articles were ranked by citation number from high to low. The inclusion criteria were articles with citations of more than 20, the research context was concrete materials or structures/elements containing concrete, and the content related to the performance of concrete under or after high-temperature conditions. The exclusion criteria were the exclusion of review literature and non-peer-reviewed conference papers. A total of 472 articles were retrieved and included in the Screening. In the 'Identification of studies via other methods' step, a 'Citation searching' step was adopted, supplementing relevant literature that might have been omitted through the Screening step , which included literature published in the last 5 years but with a citation of less than 20 to avoid bias toward older studies. 70 articles were added to the review databases in this step. Together with the 'Eligibility' step, which was literally manual selection of 109 literature from the 'Screening' step, a total of 179 high-quality references were ultimately included as the basis of this review. This selection aimed to ensure that each major review topic, such as a key influencing factor, parameter, or discussion point, was supported by at least five relevant references. The process is summarised in Fig. 4.

By carefully selecting and analyzing the literature, it was expected to gain a comprehensive understanding of the fire-induced concrete spalling, and to explore in depth its various influencing factors and parameters.

2.2. Summary of selected articles

After the above screening, 179 papers were finally selected, including 163 journal papers, 8 books, 2 standards, 3 conference papers and 3 other types of articles. The distribution of journal papers is shown in Fig. 5. The top five journals with the most reviewed papers are *Construction and Building Materials*, *Cement and Concrete Research*, *Cement and Concrete Composites*, *Materials and Structures* and *Journal of Building Engineering*.

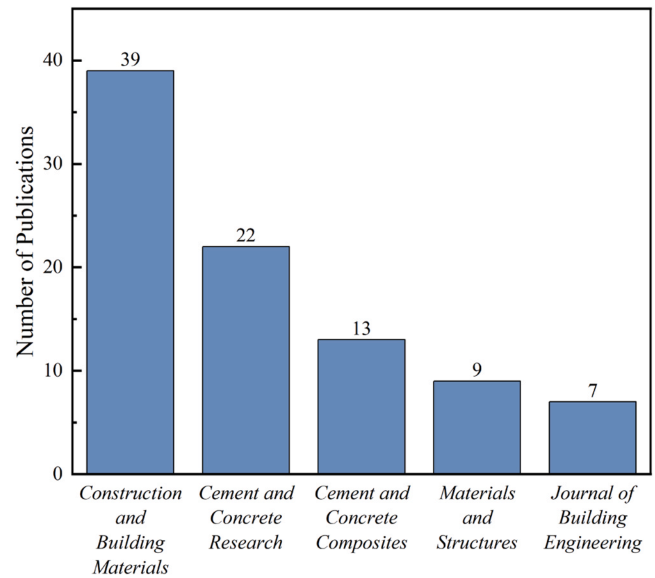

Fig. 5. Distribution of papers by journal.

In addition, the selected articles were chronologically grouped within roughly five-year periods, as shown in Fig. 6. 31.8% of the total number of articles were published between 2020 and 2026; 21.8% between 2015 and 2019; 18.4% between 2010 and 2014 and approximately 27.9% before 2010. This chronological distribution was intended to ensure that the literature is comprehensive and up-to-date over time; a historical overview of the development of research in the fire-induced concrete spalling area follows in Section 3.

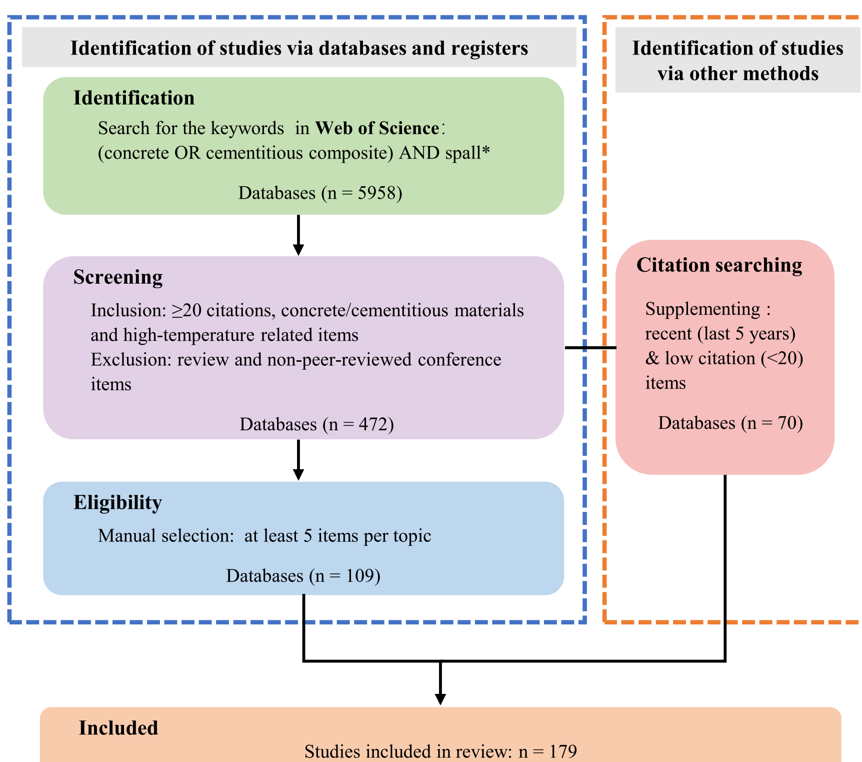

Fig. 4. Literature screening flowchart for fire-induced concrete spalling review.

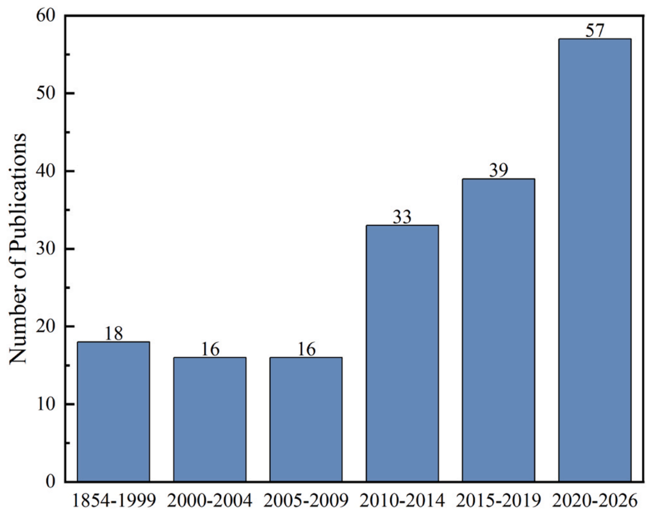

Fig. 6. Chronological distribution of selected literature.

3. Historical background

The development of investigations on fire-induced concrete spalling can be divided into four distinct periods: "Recognition", "Early Research", "Enhanced Attention" and "Artificial intelligence (AI) Methods". The development of research is illustrated in Fig. 7.

The initial "Recognition" phase lies between the 1850s and the 1960s. Barret [32] first reported the splintering and yielding of flint-aggregate concrete at elevated temperatures. Woolson [35] first documented the oozing of liquid water from the unexposed surface of concrete during fire experiments. Hasenjäger [36] categorized the factors and parameters contributing to fire-induced concrete spalling into four main categories: heating rate, concrete strength, aggregate properties, and vapour pressure. During this period, the main issues of the research concentrated on initial observation, categorization, and influencing factors and parameters of the fire-induced concrete spalling phenomenon. The main research method was experimental observation.

During the second period, "Early Research", between the 1960s and the 1990s, early theoretical studies on the mechanism of fire-induced concrete spalling gradually unfolded. Two major theories on fire-induced concrete spalling gradually established mainstream positions in the academic community. A schematic diagram of the two fire-induced concrete spalling mechanisms is shown in Fig. 8 [37]. The first theory focuses on the pore pressure within the concrete. Harmathy [33] first introduced the concept of "moisture clog" in 1965. Under fire conditions, water vapour released from the concrete permeates to the interior under pressure, as well as toward the concrete surface, and in the cooler environment at high pressure, this water vapour re-condenses to the liquid phase. The continuation of this process leads to the formation of a thick saturated zone within the concrete, the so-called "moisture clog" phenomenon, which restricts further inward movement of water vapour and increases the vapour pressure in the gas phase. This high vapour pressure results in fire-induced concrete spalling once the tensile strength of the surface concrete is reached. The second theory focuses on thermal stresses parallel to the heated surface attributed to differential restrained expansion resulting from the thermal gradient within the concrete. In 1966, Saito [38] proposed the theory that fire-induced concrete spalling occurred when this thermal stress becomes greater than the compressive strength of concrete. Dougill [39] further developed Saito's theory and found that fire-induced concrete spalling would not occur when the material thermal stress reached its compressive strength but the material with heavy axial and flexural restraint would. Therefore, in Dougill's point of view, it was more appropriate to consider fire-induced concrete spalling as a form of compressive instability, by considering the nonlinear elastic properties of material strain softening. By 1997 Bazant [34] analyzed the growth of pore pressure using the finite element method, and pointed out that pore pressure only acts as trigger for fire-induced concrete spalling. The actual fire-induced concrete spalling mechanism should be explained by combining thermal stress energy and fracture mechanics. This phase of the study further explored the triggering mechanisms of the fire-induced concrete spalling phenomena observed in the previous phase, and re-focused the perspective to microscopic phenomena inside the concrete. This period provided an important theoretical and ideological basis for the subsequent studies.

Between the 1980s and 2010s, with the development of a variety of new concrete materials, including FRC, UHPC, and ECC/UHTCC, some types of concrete were more susceptible to fire-induced concrete spalling at elevated temperatures than traditional concrete, while others incorporating specific fibres demonstrated better resistance to fire-induced concrete spalling than traditional concrete. The fire-induced concrete spalling properties of these groups of materials, including the former group's vulnerability and the latter group's tendency to inhibition, at high temperatures attracted enhanced attention. Based on the second stage of theoretical development, some new mechanical hypotheses were proposed to explain the fire-induced concrete spalling characteristics of these new types of concrete.

Research on fire-induced concrete spalling entered the third period, "Enhanced Attention", in the 1980s. For concretes which were more vulnerable to spalling than OC, Hertz [28,40] conducted heating experiments on high-strength silica fume concrete cylinders, and found that high-compactness concrete was more prone to fire-induced concrete spalling than traditional concrete; this was attributed to its low permeability limiting the gradual release of internal vapour. It therefore became particularly important to study the internal pore pressure for high-compactness concrete. Kalifa et al. [41] developed an experimental setup to measure the pore pressure of HPC and OC during the heating process. Their experimental results revealed that HPC with low permeability and high density generated higher internal pore pressures at elevated temperatures. Thus, HPC was more likely to spall due to greater pore pressure than OC. The development of this experimental

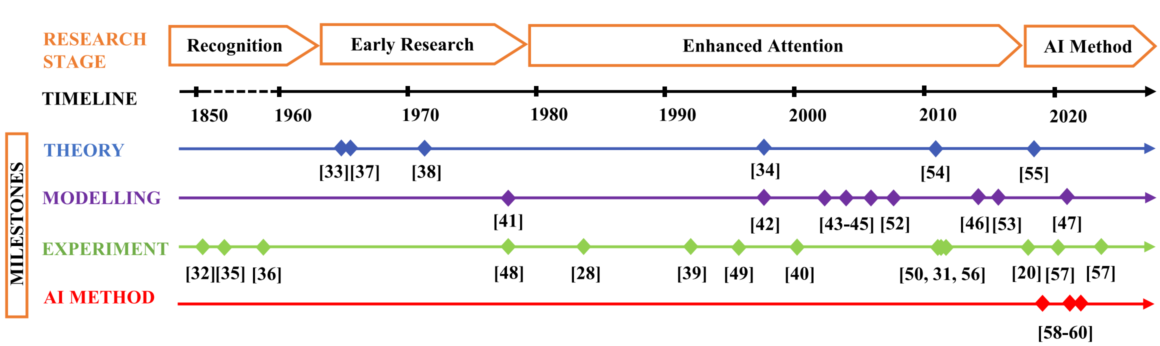

Fig. 7. Historical evolution of the investigation of fire-induced concrete spalling.

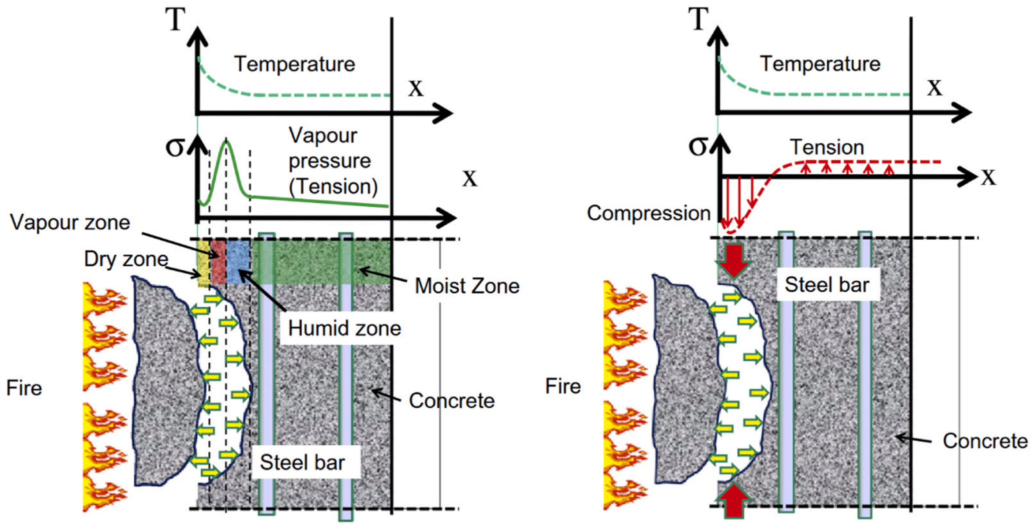

Fig. 8. Schematic diagram of the two fire-induced concrete spalling mechanisms [37].

methodology was important for subsequent pore pressure measurements. In addition to experimental methods, there was also an increase in research on finite element simulation methods to model the onset of fire-induced concrete spalling. Bazant et al. [42] and Khoylou [43] modelled the fire-induced concrete spalling phenomenon from the perspective of moisture migration. Gawin et al. [44–46] developed a mathematical model of concrete as a polyphase porous medium under heating conditions from the perspective of pore pressure, and further considered the combined effect of pore pressure with thermal stress to assess the risk of fire-induced concrete spalling. Zhao et al. [47] simulated the HPC matrix and aggregate at a mesoscopic scale, and determined that thermal stress was the major factor in initiating fire-induced concrete spalling, while the pore pressure played only a triggering role. While the above material-level simulations focused on the interaction of intrinsic properties of the cross-section in a single material, Kodur et al. [37] extended the simulation from the material and section level to the component level. In addition to the effect of pore pressure, this simulation specifically considered the effect of structural mechanical stresses and thermal stresses, showing a non-uniform fire-induced concrete spalling extent along the length of a beam.

With respect to FRC, Hertz's heating test [28] on cylinder specimens of high-strength silica fume concrete found that, although the addition of steel fibres (SF) could not prevent fire-induced concrete spalling, they could raise the temperature at which fire-induced concrete spalling occurs. Hannant [48] first suggested in his work that polypropylene fibres (PPF) could be used as an inhibitor of fire-induced concrete spalling, and the effectiveness of PPF in inhibiting fire-induced concrete spalling was further confirmed by the study of Ali et al. [49]. Subsequently, the inhibition of fire-induced concrete spalling by PPF became a popular research topic, and the effects of other fibre types (for example, polyvinyl alcohol (PVA) and jute fibres [31,50,51]) on the fire-induced concrete spalling phenomenon were also extensively studied. Finite element simulation methods were also developed to consider the effect of fibres in FRC. Witek et al. [52] considered the effect of PPF on the concrete model by translating the effect of PPF into an additional parameter to adjust the permeability and porosity of concrete. Mazzucco et al. [53] established the effects of PPF length and temperature on porosity, and further considered the damage parameter of the occurrence of micro-cracks in the void channels after melting of the PPF.

During this period, new theories emerged to provide a comprehensive explanation of the fire-induced concrete spalling phenomenon. One such theory was the thermal cracking theory, which was proposed by Fu et al. [54]. This theory postulated that fire-induced concrete spalling occurs when the pore pressure increases faster than the rate of cracking, as the accumulated pressure exceeds the stress dissipation capacity through controlled cracking. Since fire-induced concrete spalling is initiated by cracking, and since differences in the type (tensile or shear) and spatial distribution (clustered or dispersed) of cracks inherently exist, these variations subsequently propagate into uncertainties in the actual spalling area and size. Liu et al. [55] introduced three types of fire-induced concrete spalling mechanism: thermo-hygral, caused by moisture clogging and pore pressure buildup; thermo-mechanical, caused by applied stress and restraint-induced thermal stress; and thermo-chemical, caused by decomposition of hydrated products and calcite and rehydration of calcium oxide. These correspond to different temperature stages: 220°C - 320°C, 430°C - 660°C and above 700.

Research in this third period significantly expanded in depth and breadth. On the experimental side, researchers developed new experimental devices and methods to measure and understand the pore pressure and vapour release behaviour within concrete. On the numerical simulation side, by developing polyphase porous medium-based concrete models, researchers were able to evaluate the combined effects of pore pressure and thermal stresses, as well as consider the influence of fibres, which were modelled by changing the concrete properties. On the theoretical side, new theories were proposed to further explain issues not covered by the previous mainstream hypotheses, such as the uncertainty of the spalling region and special spalling phenomena in the cooling phase. Numerous research results on different types of concrete highlighted the complexity of concrete spalling at high temperatures, revealing it to be a multi-factorial (for example, heating rate, water-to-cement ratio, size, fibre, aggregate, and moisture content) coupled phenomenon.

From the 2010s to the present, in addition to the continuation of previous research advances and further exploring the multi-factorial coupling effect [20,56,57], emerging intelligent techniques, such as machine learning and deep learning (DL), have been introduced to the study of fire-induced concrete spalling phenomena. As a result, the research has now entered the fourth phase, the "AI Method". Seitllari et al. [58] compared and combined different algorithms: artificial neural network (ANN), adaptive neuro-fuzzy inference system and genetic algorithm, together with traditional statistical analysis using multilinear regression, to develop procedures for predicting fire-induced concrete spalling. The data were selected from the results of notable experimental works, on OC columns as well as high-strength and high-performance concrete columns. The effectiveness of using AI to predict fire-induced concrete spalling was demonstrated. Liu et al. [59] considered the effect of PPF, compared and predicted the effective usage of PPF using ANN and Extreme Gradient Boosting models for UHPC. The data were selected from the results of previous experimental works. The conclusions showed that for UHPC with 6% moisture content, 3.5 kg/m^3 PP fibres are required. The threshold PP fibre dosage to prevent fire-induced concrete spalling in UHPC depends on the silica fume replacement level and moisture content, and the threshold dosage may vary with PP fibre diameter and aspect ratio. Naser et al. [60] utilized Random Forest, extreme gradient boosted trees, and DL to provide a quantifiable and explicable prediction of the fire-induced concrete spalling of reinforced concrete columns. The data were also derived from existing experimental results covering various types of concrete columns, including OC, high-strength concrete (HSC) and UHPC. The machine learning analysis highlighted that concrete cover thickness, compressive strength, and column geometric size are crucial to fire-induced concrete spalling. It also indicated that concrete cover, applied load magnitude, and restraint conditions significantly affect column fire resistance. Traditionally, factors affecting fire resistance and spalling (including the geometric properties of the concrete element, load magnitude, reinforcement configuration, and strength of the concrete) are usually estimated by methods such as empirical formulas. This is not the case with AI predictions which, by analyzing large amounts of experimental data, can reveal the complex non-linear relationships between these factors and can provide transparent explanations, leading to a better understanding of the coupling between factors and how they affect the results. These intelligent techniques can be used as new methods for further research and prediction of fire-induced concrete spalling phenomena.

4. Multi-level factor interaction framework

The fire-induced concrete spalling phenomenon is a complex physical-chemical process that may be explained and evaluated at multi-scale levels [1]. For example, the behaviour of internal water at high temperatures, at the micro level, involves the evaporation of water from within the concrete and the decomposition of chemically bound water [33]. At the macroscopic level, this is reflected in a reduction in mechanical strength due to chemical decomposition [27,61–64]. In reviewing the factors and parameters that influence fire-induced concrete spalling, it is necessary to classify the factors and parameters into different levels. This is because, although fundamental studies on the effects of individual factors have been well-established in previous research, the factors and parameters considered are random, and may have an influence on one another, which makes the analysis of the fire-induced concrete spalling problem non-orthogonal.

This work proposes a three-level classification framework, designated as a Multi-level Factor Interaction Framework (MFIF) with 3 levels, illustrated in Fig. 9. The proposed framework consists of:

- Level 1: Basic factors influenced by the intervention of humans or manipulation of external conditions.
- Level 2: Second-order mechanistic parameters determined by factors in Level 1 and directly affect the occurrence of fire-induced concrete spalling in Level 3.
- Level 3: The criterion for the determination of spalling occurrence.

The rationale behind the MFIF is based on the assumption that the occurrence of fire-induced concrete spalling phenomenon is determined by an ultimate limit state of concrete, which could be represented by the comparison between stress and strength of concrete. While the stress and strength of concrete are related to the external loading and heating conditions and the nature of the concrete material, such as water-cement ratio, fibre dosage, moisture content, etc. The causal relationships between levels of the MFIF are: Level 1 lists the nature of concrete material and applied loading and heating conditions of the concrete structure, Level 2 lists the stress and strength of the concrete structure, which is

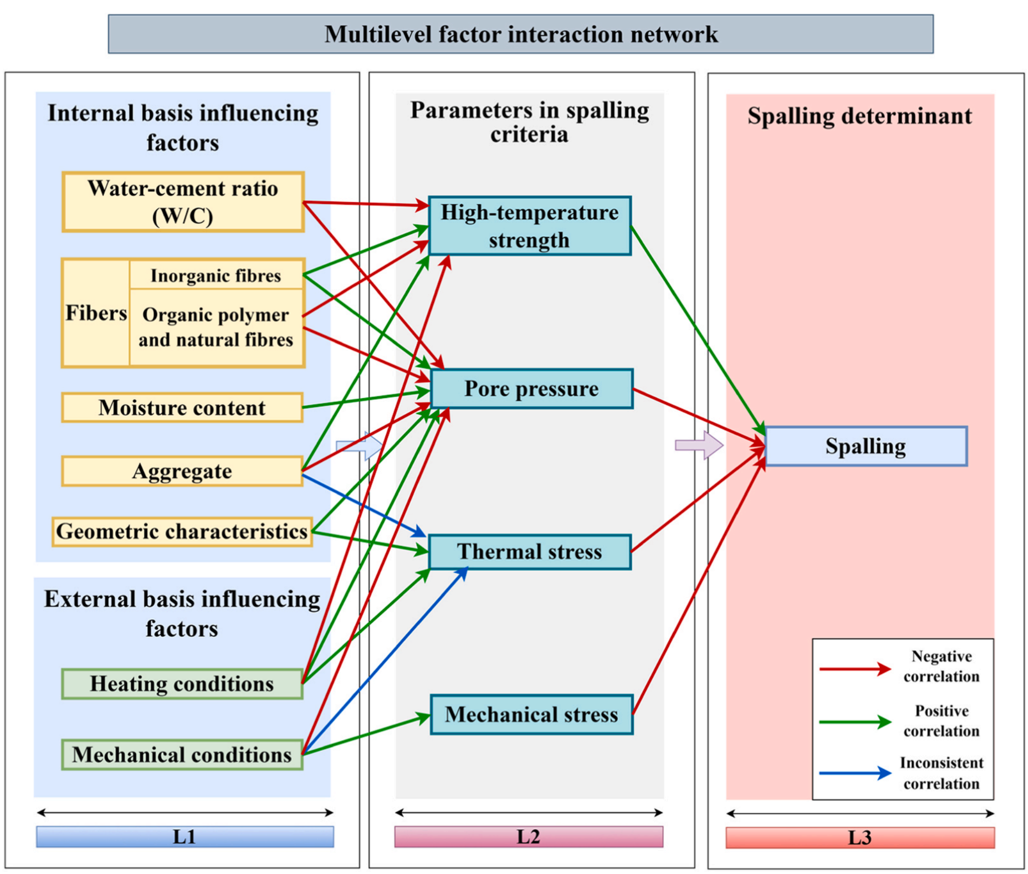

Fig. 9. Multi-level factor interaction framework.

influenced or could be calculated or measured by factors in Level 1, and they directly affect the concurrence of fire-induced concrete spalling in Level 3. Factors and parameters belonging to the same level do not have an influence on each other, and the occurrence of fire-induced concrete spalling in Level 3 is only influenced by factors in Level 2, without further considering the factors listed in Level 1. In MFIF, directional arrows with "red" "green" or "blue" colours are used to demonstrate the causal relationship between adjacent levels, with "red" arrow indicating negative influence "green" arrow indicating positive influence and "blue" indicating inconsistent influence.

The framework provides a clear approach to judge the occurrence of fire-induced concrete spalling, given the material and its external loading and heating conditions, in which the fire-induced concrete spalling criteria can be qualitatively represented by the comparison between stress and strength of concrete in Level 2. Further, stress and strength of concrete in Level 2 are influenced by the internal and external factors in Level 1. The construction of such a framework helps to integrate the various influencing factors of the two classical theories of pore pressure and thermal stress into a unified framework.

In engineering practice, L1 parameters are primarily used to guide the design and optimisation of concrete materials resistant to spalling, as this level encompasses fundamental factors that can be directly controlled. Consequently, L1 can be used to guide mix design, material selection and preventive measures in fire safety design. By contrast, L2 parameters are primarily used to provide a mechanistic basis for establishing spalling criteria in numerical simulations. Parameters such as high-temperature strength, pore pressure, thermal stress and mechanical stress can be incorporated into finite element analysis or other computational models to determine whether a component meets the conditions for spalling during the heating and cooling processes. In other words, the MFIF establishes a bridge between qualitative material design and quantitative simulation assessment in its application.

The next sections will systematically investigate how external/internal factors influence fire-induced concrete spalling behaviour, as well as the cross-level causality in the proposed multi-level network.

5. Level 1 factors

Level 1 constitutes the base layer and represents factors that can be directly manipulated by the design of a concrete material. These basic factors are characterized by their ability to be explicitly controlled or measured. They can be categorized into internal and external factors. This level consists of eight main influencing factors, classified according to their origin as either internal (W/C, moisture content, fibre, aggregate and geometric characteristics), or external (heating conditions and mechanical conditions).

Internal factors are primarily related to the composition of the material, and have an impact on the intrinsic properties of Level 2, which can either positively or negatively affect the cementitious material's susceptibility to fire-induced concrete spalling. External factors, on the other hand, are the driving forces behind the fire-induced concrete spalling phenomenon and influence the tendency of the material to spall. The roles of internal and external factors in Level 1 are now discussed.

In this review, the classification of "spalling" (including surface spalling, severe spalling and explosive spalling etc.), "no spalling" and "crack" is based primarily on textual descriptions and published images in the original references. "Spalling" refers to visible loss of material, "no spalling" refers to the absence of such loss, whilst "crack" refers to the formation of cracks without associated material loss.

5.1. Water-cement ratio (W/C)

W/C refers to the ratio by weight of water and cement content in the concrete mix. It is a determinant of the concrete strength, durability and a series of other physical and mechanical properties. When the W/C is low, the distance between the cement particles is small, the colloid produced by the hydration of cement can easily fill the gaps between the particles, and the water void volume left behind after evaporation is low, the strength and compactness of the concrete is high, and its permeability is low. These characteristics are advantageous at room temperature, however, at high temperatures they make it difficult for water vapour to escape, leading to a higher pore pressure than those of OC under the same heating, and the moisture clog is created more easily. Therefore, a low W/C increases the vulnerability of concrete to spalling.

Table 1 summarizes the effect of W/C on the fire-induced spalling phenomenon of OC and FRC of small specimens (typically 100 mm × 200 mm × 200 mm blocks, Ø 100 mm × 200 mm cylinders or rectangular pillar-shaped specimens). It can be seen that the probability of fire-induced concrete spalling decreases with the increase of W/C. For OC, and no spalling occurred when the W/C ratio was equal to or above 0.55 [26,65,66]. Fire-induced concrete spalling occurred when the W/C ratio was equal to or below 0.45 [13,26,65–67]. One exception is that in [13] when the W/C ratio was 0.33, and no spalling occurred. This is possibly because the heating rate of 0.83℃/min was relatively slow, which reduced the temperature gradient and vapour pressure inside the specimen. For FRC, no spalling occurred when the W/C ratio was equal to or above 0.42 [68,69]. Fire-induced concrete spalling occurred when the W/C ratio was equal to 0.33 [68]. OC tended to spall more easily than FRC.

5.2. Fibres

Fibre incorporation is an important means of inhibiting the occurrence of fire-induced concrete spalling. Commonly incorporated fibres include inorganic fibres such as steel (SF), glass (GF) and carbon (CF); the latter include normal CF, carbon nanofibres (CNF) and carbon nanotubes (CNT). Organic polymer fibres include PPF, PVA and polyethylene (PE) fibres, as well as natural fibres such as jute and sisal. Although it has been generally accepted that fibre incorporation enhances the spalling resistance of concrete, there are still several possible explanations as to how fibres mitigate fire-induced concrete spalling under high-temperature conditions. The beneficial effects of the incorporated fibres at high temperatures may broadly be classified into two categories: (i) strength enhancement; and (ii) permeability enhancement. In this section, the behaviour of different fibre types at elevated temperatures will be systematically analyzed to elucidate the physicochemical nature of fibres, and their contribution to the spalling behaviour, as well as their effect on the concrete matrix.

5.2.1. Effect of inorganic fibres

The effect of inorganic fibres is mainly the strength enhancement of concrete. Inorganic fibres are physico-chemically stable at high temperatures, and they can maintain their bridging effect in concrete, thus increasing the spalling threshold of the concrete material. However, this kind of passive action cannot completely inhibit the occurrence of fire-induced concrete spalling. Table 2 lists the results of single and hybrid fibre additions in FRC and UHPC in the literature. In this table, small specimens refer to those of the sizes 100 mm × 100 mm × 100 mm cubes, Ø 150 mm × 300 mm cylinders, 40 mm × 40 mm × 160 mm prisms, and 100 mm × 100 mm × 300 mm prisms, etc.

The summary result of Table 2 is listed in Fig. 10. It is worth noting that when the moisture content in some literature was not measured, it was assumed to be 4% on the boundary line of spalling and non-spalling. When the moisture content was in a range, the average value was used. It can be summarised from the collected literature that UHPC normally has less W/C ratio than FRC. When the inorganic fibres are added to both FRC and UHPC, all the small specimens tend to crack or spall regardless of the W/C and moisture content. This indicates that inorganic fibres have a limited inhibitive effect on FRC and UHPC spalling. The only exception is in [77], in which the W/C ratio was 0.46; no spalling was observed in the specimens. This was because of the combined effect of

Table 1
Effect of W/C on fire-induced concrete spalling phenomenon.

Ref.	W/C	Moisture condition	Concrete type/ fibre	Geometric feature	Heating method	Behaviour
[26]	0.57	Submergence	OC	small specimens	5℃/min linear heating to 600℃	no spalling
	0.23					explosive spalling
[65]	0.55	2.35%	OC	small specimens	ISO 834 fire curve	no spalling
	0.42	2.91%				spalling
	0.32	3.12%				spalling
[66]	0.57	7.3%	OC	small specimens	5℃/min linear heating to 100℃, 200℃, 300℃, 450℃, and 600℃	no spalling
	0.33	6.1%				full spalling at 600℃
		6.3%				full spalling at 600℃
	0.22	5.0%				full spalling at 450℃
[67]	0.45	NA	OC	small specimens	5℃/min linear heating to 100℃, 300℃, 600℃, and 900℃	minor spalling over 600℃
	0.3					severe spalling over 300℃
	0.2					severe spalling at 300℃
[13]	0.55	NA	OC	small specimens	ISO-834 fire curve; 0.83℃/min linear heating	no spalling
	0.33					surface spalling/no spalling
	0.18					spalling
	0.125					explosive spalling
[68]	0.42	NA	FRC; PPF	small specimens	ISO 834 fire curve	no spalling
	0.33					surface spalling
[69]	0.5	NA	FRC; PPF	small specimens	2℃/min linear heating to 1000℃	no spalling

Table 2
Effect of inorganic fibre on fire-induced concrete spalling phenomenon.

Ref.	W/C	Concrete type/ fibre	Moisture condition	Geometric feature	Heating method	Behaviour
[62, 70–74]	0.18–0.55	FRC; SF	3% - 5.8%	small specimen	1–10℃/min linear heating to 800℃ or immediate heating to 1000℃ or ISO 834 fire curve	spalling
[63,75]	0.32–0.66	FRC; SF	NA	small specimen	2.9℃/min-5℃/min linear heating up 600℃	crack
[76]	0.35	FRC; SF	NA	small specimens	8℃/min linear heating up to 600℃	minor crack
[77]	0.46	FRC; SF	NA	small specimens	2.5℃/min linear heating up to 600℃	no spalling
[78,79]	0.3–0.4	FRC; GF	NA	small specimen	5℃/min linear heating up to 800℃ or KSF 2257 fire curve	spalling
[62,78, 80]	0.3–0.6	FRC; CF	3.5% - 5.8%	small specimens	10℃/min linear heating up to 800℃ or KS F 2257 fire curve, flame at 1000℃	spalling
[81]	0.3	FRC; CNF	submergence	small specimens	free heating to 800℃	minor cracks
[82]	0.42	FRC; CNT	NA	small specimens	4.5℃/min linear heating up to 600℃	spalling
[14,83, 84]	0.15–0.27	UHPC; SF	NA	small specimens	2.5℃/min-7.5℃/min linear heating up to 800℃ or ISO 834 fire curve	spalling
[9]	0.19	UHPC; GF	submergence	small specimens	heating up to 800℃	spalling at 400℃
[85]	0.14	UHPC; 3% SF, or GF or hybrid	NA	small specimens	4℃/min linear heating up to 800℃	crack at 600 ℃
[86]	0.21	UHPC; CNT	NA	small specimens	2℃/min linear heating up to 600℃	spalling

preheating specimens to 105℃ or 120℃ for 24 h or 48 h and a low heating rate of 2.5℃/min. In this context, lowering the heating rate helps reduce the fire-induced concrete spalling phenomenon.

5.2.2. *Effect of organic polymer*

Organic polymers show a stronger potential for spalling inhibition than inorganic fibres. While the latter depend on the crack bridging effect to retard crack extension, organic polymers rely on the enhancement of permeability, the mechanism of which can be simply described as: (i) formation of connected lumen channels by molten fibres; (ii) formation of micro-crack networks by thermal expansion of fibres compressing the surrounding matrix; and (iii) creation of interfacial spaces by the decomposition and shrinkage of fibres.

Popular organic polymer fibres include PPF, PVA and PE. In addition, crumb rubber (CR) can be included in this scope as an organic doping. The effect of organic polymer on the fire-induced concrete spalling phenomenon collected from the literature is listed in Table 3 and shown in Fig. 11.

It can be seen from Table 3 that small FRC specimens, FRC columns [87–89] and FRC slabs [90] with organic fibres do not normally spall, showing effective mitigation of organic fibres to FRC. The exceptions include [73,91,92] with CR alone or in combination with SF and PVA/PE fibres [73], where spalling occurs in some [73,92] and significant cracking in others [73,91,92].

The addition of PVA [93] or PE fibre [94,95] is ineffective in inhibiting spalling of UHPC. Fire-induced concrete spalling inhibition of UHPC can only be achieved by combining PVA/PE fibre with sufficient quantities of other fibres (e.g. PVA and SF [93,96], PE and PPF [94]). Sufficient quantities of PPF [95,97–100] (1.32% by volume or 2 kg/m^3) and a hybrid of PPF and SF [14,96,100] also demonstrate good fire-induced concrete spalling resistance of UHPC. However, excessive PPF (18.2 kg/m^3) can actually cause UHPC to spall [101] due to the gaseous by-products from molten PPF under high temperatures. Adding special low-density PE fibre [95] is another effective method, because low-density PE fibres have higher numbers of fibres per unit mass, if the dosing is specified by mass, than ultra-high molecular weight PE fibre.

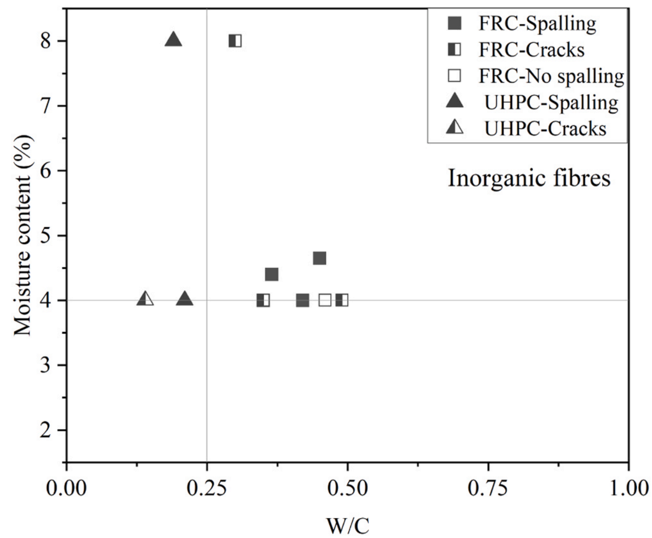

Fig. 10. The spalling tendency of concrete with inorganic fibres.

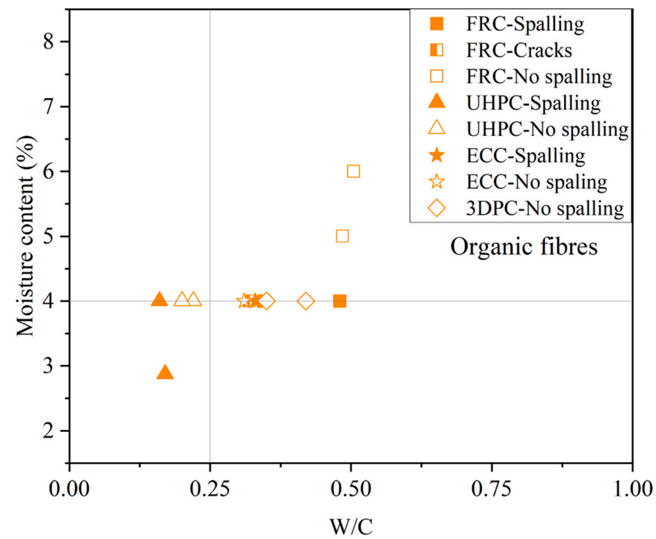

Fig. 11. The spalling tendency of concrete with organic fibres.

Table 3
Effect of organic polymer on fire-induced concrete spalling phenomenon.

Concrete type and fibre	Reference	W/C	Moisture condition	Geometric feature	Heating method	Spalling behaviour
FRC; PPF (optimized to 1 kg/m^3 or over 0.1% by volume)	[87,90, 110–112]	0.3–0.67	3% - 7%	small specimens, slabs, columns	ISO 834 fire curve, CNS 12514–1 Standard heating curve, 10℃/min linear heating or free heating to 700℃	no spalling
FRC; PPF and SF	[89,111, 113]	0.3–0.67	5% - 7.5% or NA	small specimens, columns	ISO 834 fire curve, 5℃/min and 10℃/min linear heating to 600℃	no spalling
FRC; PVA fibre (0.75–2.25% by volume)	[88]	0.48	NA	small specimens, columns	heated up to 600℃	minor spalling
FRC; PVA fibre (over 0.1% by volume)	[87,111]	0.34–0.67	5%-7% or NA	small specimens, columns	ISO 834 fire curve	no spalling
FRC; PVA and SF	[111]	0.59–0.67	5% - 7%	small specimens	ISO 834 fire curve	no spalling
FRC; CR	[73,92]	0.3–0.39	NA	small specimens	ISO 834 fire curve, 1℃/min linear heated up to 800℃	spalling
FRC; CR (1–8% by volume)	[91,92]	0.25–0.39	NA	small specimens	EN-UNE 1363–1 and ISO 834 fire curve	cracks
FRC; CR and SF	[73]	0.3	NA	small specimens	1℃/min linear heated up to 800℃	spalling
FRC; CR and SF and PVA fibre/ PE fibre						cracks
UHPC; PPF (0.99% by volume or below, 1 kg/m^3)	[98,99]	0.2–0.24	NA	small specimens	ISO 834 fire curve, 0.5–8℃/min linear heating up to 1000℃	spalling
UHPC; PPF (18.2 kg/m^3)	[101]	0.16	NA	small specimens	4–5℃/ min linear heated up to 1000℃	spalling
UHPC; PPF (1.32% by volume or 2 kg/m^3)	[95,97–100]	0.2–0.24	NA	small specimens	ISO 834 fire curve, 0.5–8℃/min linear heating up to 1000℃	no spalling
UHPC; PPF (0.3% by volume or 633 or higher L/D) and SF	[14,96,100]	0.22–0.27	NA	small specimens	ISO 834 fire curve, 2℃/min linear heated up to 600℃	no spalling
UHPC; PVA fibre	[93]	0.17	2.0%-3.75%	small specimens	5℃/min linear heated to 700℃	spalling
UHPC; PVA fibre and SF	[93,96]	0.17–0.18	2.0–3.75% or NA	small specimens	5℃/min linear heated to 1050℃	no spalling
UHPC; normal/ultra-high molecular weight PE fibre	[94,95]	0.2	NA	small specimens	1℃/min linear heating up to 800℃, ISO 834 fire curve	spalling
UHPC; low-density PE fibre	[95]	0.2	NA	small specimens	ISO 834 fire curve	no spalling
UHPC; PE fibre and PPF (0.1% by volume)	[94]	0.2	NA	small specimens	1℃/min linear heating to 800℃, ISO 834 fire curve	spalling
UHPC; PE fibre and PPF (0.3%, 0.5% by volume)						no spalling
ECC; PVA fibre	[21,31,102]	0.2–0.42	NA	small specimens	15–20℃/min linear heated up to 800℃	no spalling
ECC; PVA fibre and SF	[12,103, 104]	0.25–0.62	0.9% or NA	small specimens	ISO 834 fire curve, 10℃/min linear heated to 900℃	no spalling
ECC; PVA fibre and 0.5% CF	[102]	0.2	NA	small specimens	20℃/min linear heating to 200℃, 400℃, 600℃, and 800℃	minor spalling
ECC; PVA fibre and 1% CF						surface spalling
ECC; PE fibres	[105,106]	0.23–0.43	NA	small specimens	10℃/min linear heated to 600℃, or heated up to 400℃ in 7 min	spalling
ECC; PE fibres and SF/PPF (0.3%, 0.5% by volume)	[105,106]	0.23–0.43	NA	small specimens	10℃/min linear heated up to 600℃, or heated up to 400℃ in 7 min	no spalling
3DPC; PE fibre	[107]	0.35 0.42	NA	small specimens	heated up to 800℃	no spalling

They also have a higher coefficient of thermal expansion than ultra-high molecular weight PE fibre, which together manifests a good spalling inhibition effect.

In terms of ECC, PVA fibre alone [21,31,102] or in combination with SF [12,103,104] shows good fire-induced spalling inhibition. When PVA was partially replaced by CF [102], fire-induced spalling occurred, reflecting the requirement for a minimum amount of PVA fibre. However, PE alone [105,106] is not effective in inhibiting spalling. It must be combined with sufficient PPF/SF [105,106] to inhibit spalling. For PE fibre-reinforced 3D-printed concrete (3DPC), no spalling occurred [107]. This is partly because the 3DPC interlayers help internal gases to escape and reduce the pore pressure, mitigating the tendency to spall.

A comparison of the functional characteristics of different fibres reveals that a hybrid of inorganic and organic fibres is highly effective in harnessing the synergistic effects of both. Hybrid fibre of SF and organic polymer show distinct but complementary mechanisms that could reduce spalling and maintain superior residual strength of cementitious materials [108,109].

It can be seen from Fig. 11 that UHPC has a higher tendency to spalling than FRC, with no obvious tendency related to W/C, and moisture content of approximately 4% tend to be the threshold of concrete spalling with organic fibre. ECC is less prone, and FRC is the least prone. This is mainly because the low W/C of UHPC induces high compactness. This inhibits the release of vapour from inside the material and increases the pore pressure.

The effectiveness of fire-induced concrete spalling inhibition by organic polymers appears to lie in their different melting points [87,90, 91,107,110–112,114] and coefficients of thermal expansion [94–98, 100,103]. It is traditionally believed that PE fibre, PPF, CR and PVA fibre have melting/softening points at temperatures of approximately 145℃, 165℃, 170℃ and 230℃, which are an order of magnitude lower than for inorganic fibres such as SF [94,101,110,114]. The organic PE, PPF and PVA fibres and CR decompose and disappear at temperatures of approximately 500℃ [106], 240℃ [115], 300℃ [116] and 300℃ [117]. After the fibres have decomposed, the void channels left behind act as vapour escape routes, thus relieving the pore pressure inside the concrete. In addition, according to recent Scanning Electron Microscope (SEM) and other means of research [94,95,97,98,100], the coefficients of thermal expansion of PE fibre (100×10^{-6}/℃ [118]), CR (77×10^{-6}/℃ [119]), PPF (210×10^{-6}/℃) and PVA fibre (100×10^{-6}/℃) are 10, 7.7, 21 and 10 times higher than that of the concrete matrix (10×10^{-6}/℃) [96], which induces the thermal expansion mismatch between the fibres and concrete matrix. The restraint to the expansion of the fibres by the surrounding concrete causes radial micro-cracks around the fibre cross-section. These cracks are connected and become an effective network to allow the escape of internal vapour. The thermal expansion coefficient of PPF is 21 times that of the concrete matrix, and its melting temperature is 165℃, which enables PPF to expand sufficiently at 150℃ to effectively create microcracks (see Fig. 12), and its decomposition temperature is 240℃, after which void channels are formed as vapour escape routes. Other fibre types have disadvantages compared to PPF. The thermal expansion coefficients of CR and PVA are respectively about 37% and 48% of that of PPE. PVA decomposes at a slightly higher temperature than PPF, and PE decomposes at the much higher temperature of 500℃, leaving only minor void channels for vapour escape. Together these findings explain the reasons that PPF is the most effective spalling inhibitor. PVA is slightly less effective on spalling inhibition than PPF but more effective than PE fibres or CR.

5.2.3. Natural fibres

The natural fibres commonly studied include sisal, flax, and jute fibres, which, due to their natural biological properties, shrink and carbonate at elevated temperatures. This creates interfacial gaps between the fibres and the matrix to dissipate the pore pressure. In addition, microscopic observations have also revealed [120] that the structure of these natural fibres themselves resembles a lumen (see Fig. 13), and this hollow structure can also be a pathway for internal pore pressure evacuation. However, natural fibres do not expand in concrete under high temperatures, and thus they do not form micro-cracks in the concrete. The spalling inhibition effect of natural fibres lies between those of organic polymers and inorganic fibres.

Table 4 summarises the research on natural fibres as described above. It can be seen that normally, small FRC specimens and FRC columns [122] with hybrid fibres with sisal [122] and jute fibre [51, 123] exhibit minor spalling or cracking. This is mainly due to the low

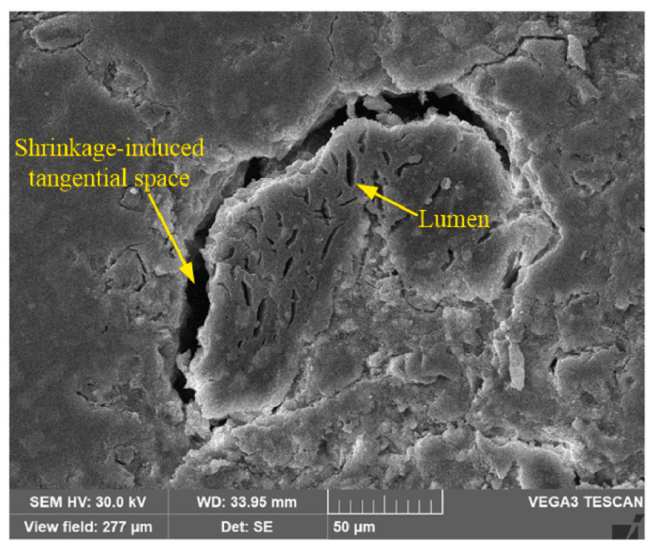

Fig. 13. Tangential space induced by sisal fibre shrinkage [121].

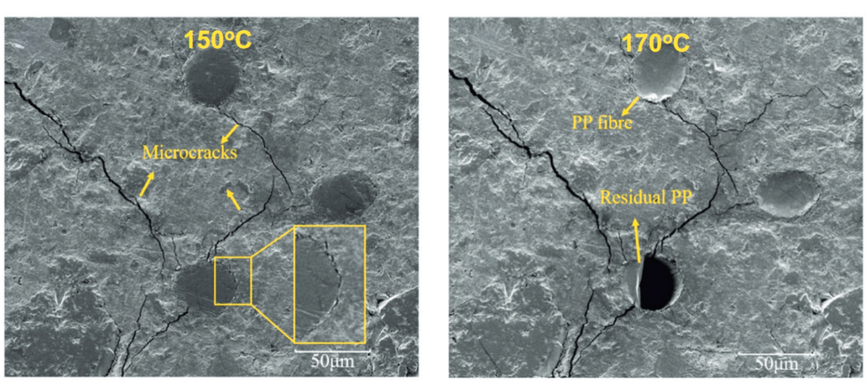

Fig. 12. Micro-cracks around the PPF [97].

Table 4
Effect of natural fibres on fire-induced concrete spalling phenomenon.

Concrete type and fibre	Reference	W/C	Moisture condition	Geometric feature	Heating method	Spalling behaviour
FRC; sisal fibre with micro-SF and PPF	[122]	0.37	moisture cured	columns	2°C/min linear heated to 800°C	cracks
FRC; jute fibre	[51,123]	0.2–0.3	3.5–5.5% or NA	small specimens	RABT 30 curve, ISO 834 fire curve, heated up to 1200 °C in 5 min, 1.7°C/min linear heated to 400 °C	minor spalling or cracks
UHPC; sisal fibre UHPC; sisal fibre and SF	[121]	0.21	NA	small specimens	10°C/min linear heated to 800°C	no spalling no spalling
UHPC; flax fibres and SF UHPC; flax fibres and SF	[125]	0.2	NA	small specimens	ISO 834 fire curve	spalling or cracks no spalling
UHPC; jute fibre (10 kg/m^3)	[51]	0.2	NA	small specimens	ISO 834 fire curve	no spalling
UHPC; jute fibre and SF	[124, 126]	0.14–0.23	2.2–2.6% or NA	small specimens	ISO 834 fire curve, heated up to 500°C in 30 min	spalling
UHPC; PPF or/and PVA fibre and jute fibre and SF	[124]	0.23	NA	small specimens	heated to 500°C in 30 min	no spalling
UHPC; jute fibres and SF	[127]	0.2	NA	small specimens	3°C/min linear heated to 600°C	cracks

dosage of fibres, making it difficult to achieve sufficient spalling inhibition. The spalling inhibition of the hybrid fibres [122] was found to be more effective than that of jute alone [51,123]. For UHPC, sufficient quantities of sisal [121]/ jute [51] or flax fibres only, and a hybrid of PPF/PVA fibre [124] with SF [121,125] still demonstrate good spalling resistance. However, when the fibre dosage is insufficient, spalling [124–126] or cracking [125,127] still occurs. To achieve adequate spalling resistance, there is a high quantitative requirement for natural fibres, as the study of [51] indicated that a 10 kg/m^3 admixture is required to produce the full inhibition effect. However, too high a fibre admixture makes the concrete work less well, and may even reduce the normal mechanical properties of the material [122]. A good approach is again to use multiple fibres working in concert. The composite effect of natural fibres with other fibres was investigated in [121,122,124,125,127,128], in which the combination of natural fibres with inorganic fibres and organic polymers produced an ideal balance of spalling inhibition and mechanical properties. The mechanisms of action of the different fibre types are shown in Fig. 14.

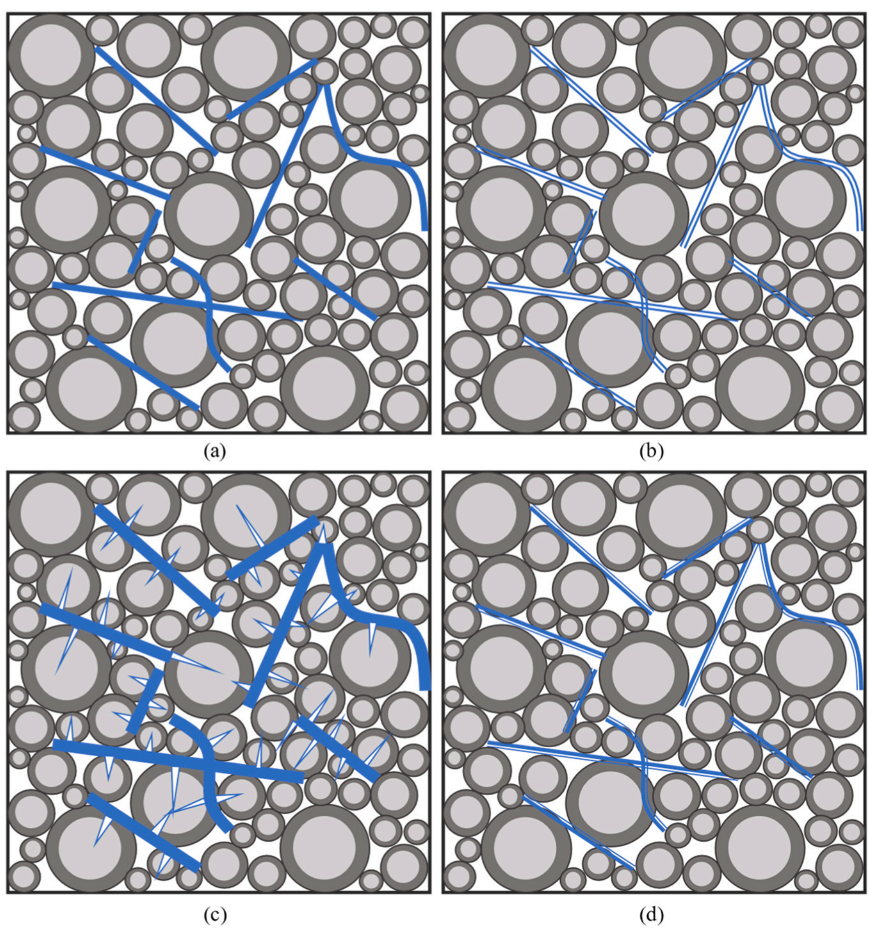

Fig. 14. The mechanisms of action of the different fibre types: (a) inorganic fibres: bridging effect, (b) organic polymer fibres: melting, (c) organic polymer fibres: expansion and cracking, and (d) natural fibres: shrinking.

5.3. Moisture content

Water in concrete can be divided into free water and chemically bound water. Free water is the water in concrete that has not reacted within the cement; it exists in the pores of the concrete. At temperatures between 105 ℃ and 160 ℃, free water undergoes a phase change into water vapour. Chemically bound water exists as the hydration product of the chemical reaction between water and cement. The hydration products dehydrate at temperatures between 160 ℃ to 180 ℃, and the chemically bound water is then converted to water vapour [26].

The moisture content of concrete is usually measured by weighing [129,130], and can be calculated using Eq. (1), in which m denotes the mass of the specimen at the start of the test, in kg; m_0 denotes the mass of the specimen after drying to constant weight at 105°C ± 2°C, in kg; and w denotes the percentage of free water mass relative to the dry mass of concrete. The water content of concrete in general engineering is equal to or lower than 10% [131]. Mixing, curing conditions and storage conditions all affect the moisture content of concrete [26,56,131].

$$w = \frac{m - m_0}{m_0} \tag{1}$$

When studying the effect of moisture content on fire-induced concrete spalling, two main aspects need to be considered. The first is its effect on the fire-induced concrete spalling phenomenon, and the second is the mechanism of water phase change and transport within the concrete at high temperatures. Experimental studies have recorded that for OC and UHPC, dry specimens with very low moisture content (below or equal to 1.8%) did not spall [13,26,56,132,133], while all specimens with higher moisture content spalled [13,26,56,132–134], and that the degree of spalling increased with increasing moisture content [133, 135]. For FRC and ECC/UHPC, as fibre acts as an inhibition factor, the likelihood of spalling of these concretes is determined by the balance of moisture content, fibre type and addition ratio.

Studies [12,13,26,100,129,136–138] have investigated how moisture changes phase and migrates through concrete. One of these studies [26] suggested that chemically bonded water would have a stronger effect on the pore pressures than free water. However, from the current review it is concluded [13,26,56,132,133] that specimens with very low moisture content (below or equal to 1.8%) do not spall. Based on this finding, it is assumed that free water also has a significant effect on fire-induced concrete spalling, and the eventual fire-induced concrete spalling is a product of the accumulation of vapour pressure due to both free and chemically bonded water. The phenomena observed in [12] show a correlation between the release of water vapour, the temperature change, the pore pressure change and the popping sound of the explosions, strongly suggesting that water vapour in the concrete triggers the fire-induced concrete spalling. Choe et al. [13] and Li et al. [100], on the other hand, suggested that the mechanism of fire-induced concrete spalling is not limited to the internal pore pressure, but when closed pores are broken the pore pressure decreases, leading to a decrease in the boiling temperature of the liquid, which induces vaporization of more superheated liquid water, once again generating a high vapour pressure. With regard to the migration of water inside the concrete, X-ray Computer Tomography (X-ray CT) and Nuclear Magnetic Resonance (NMR) have been used [129,136–138] to capture the internal water migration, and experimentally captured the "moisture clog" proposed by Harmathy [139]. It has also been shown that fibres, represented by PPF, allow faster and deeper moisture migration [138], whereas concrete without PPF exhibits strong moisture accumulation [136]. This further supports the conclusions of Section 5.2 about the improved gas permeability due to the presence of fibres.

It is clear that the moisture content of concrete is a key factor affecting fire-induced concrete spalling, and the generation of water vapour at high temperatures is the main source of internal pore pressure. To inhibit fire-induced concrete spalling, it is therefore necessary to control the moisture content. The Eurocode BS EN 1992–1–2:2004 [140] specifies an upper limit k, which is the water content as a percentage by weight, above which it is necessary to take into account the effects of possible fire-induced spalling in the structural design The generic range specified in Eurocode [140] is $2.5\% \le k \le 3\%$, although the value used in different jurisdictions may be nationally determined.

5.4. Aggregate

Aggregate is an important constituent of concrete materials and is classified as either coarse or fine according to particle size. Coarse aggregate plays the role of a structural skeleton in the concrete, while fine aggregate plays a role of filling the voids.

Aggregates do not participate in the main chemical reaction during the heating process, which is thermal decomposition of the cement matrix, but they are still subject to thermal expansion at high temperatures. If this expansion is different from the thermal deformation of the matrix, cracking can be produced within the concrete, which has an impact on fire-induced concrete spalling. In addition, the thermal properties of the aggregate significantly affect the heat transfer properties of the concrete, which influences the temperature patterns through the depth and therefore the thermal stresses generated by thermal gradients in heating. Therefore, there is a need to investigate the effect of aggregate type and size on the spalling of concrete at elevated temperatures.

Among the concretes reviewed in this paper, OC, FRC and some types of UHPC contain both fine and coarse aggregates, whereas ECC/UHTCC and other types of UHPC contain fine aggregate only. Yang et al. [141] investigated the effect of the presence or absence of coarse aggregate; overall, the specimens without coarse aggregate spalled more severely.

Coarse aggregates can be classified into commonly used aggregates, lightweight aggregates and heavyweight aggregates. Commonly used aggregates include siliceous (gravel) and calcareous (limestone) aggregates. Lightweight aggregates include clay-based and shale-based aggregates [142,143], and heavyweight aggregates include barite and magnetite aggregates [7,144]. There are differences in the coefficients of thermal expansion of different types of coarse aggregate. For concrete with coarse aggregates, the vulnerable surfaces lie at the interfaces between the concrete matrix and the aggregate. At high temperatures the differences in the coefficients of thermal expansion of the concrete matrix and the coarse aggregate particles result in a mismatch of the thermal deformation, which can produce cracks at the interfaces [145]. The action of such cracks also has a dual effect: on the one hand, they may increase the permeability of the concrete, reducing the pore pressures [146], while on the other hand, they may also act as weak zones, leading to the occurrence of aggregate spalling [7,147]. Therefore, there are no consistent rules relating to the thermal expansion of coarse aggregate to fire-induced concrete spalling.

Some aggregates, such as flint [148], barite [7], may also be inherently thermally unstable at elevated temperatures, and such aggregates can themselves decompose and crack at elevated temperatures, which can lead to aggregate spalling [149].

In terms of the size of aggregates, the tendency to spall generally decreases with the dimension of the coarse aggregate [137,146,150]. The results of [137] showed that larger aggregates (8 mm) produce a more generalized cracking network than smaller aggregates (4 mm), which accelerates the drying process. The experimental results of [146] showed that the depth of spalling decreased when the particle size of coarse aggregate increased from 7 mm to 20 mm.

Fine aggregates have been less studied, but work [151] which has been done also shows that large particle size (5 mm) fine aggregates expand at elevated temperatures to produce micro-cracks due to thermal incompatibility, which enhances the permeability of the concrete material. The use of steel slag as fine aggregate has been shown [20] to reduce thermal incompatibility and to enhance thermochemical stability, thus delaying the onset of fire-induced concrete spalling compared to quartz sand. The use of crushed waste glass improve the spalling resistance by improved thermal stability and insulation [152].

5.5. Geometric characteristics

Geometric characteristics are also important features of concrete members in practical applications. They affect the heat transfer and so the stress distribution of members when heated at surfaces. Different sizes and shapes of members also produce different vapour evacuation paths, which can alter the susceptibility of the members to fire-induced concrete spalling. Furthermore, in the case of large-scale structures, high-temperature conditions also give rise to issues concerning the interaction between cementitious materials and reinforcing steel; in such circumstances, the interface between the steel and the concrete (such as the surface protective cover) of the members (columns [153], beams [154–156] and slabs [5]) becomes a particularly vulnerable area prone to spalling.

Most reported studies on columns [146], beams [157] and plates [146,157] have found that larger structural members of OC, FRC and UHPC show more obvious fire-induced concrete spalling phenomena than smaller structural members, while studies on small-size specimens (cubes [56,158], cylinders [57,146,158] and prisms [56]) mainly indicate that the size of the specimen has negligible effect on spalling. This may be because the size differences of small specimens are too small to fully reveal any size effect. Experiments on fire-induced concrete spalling of realistically sized engineering structures are still lacking because of the limitations of laboratory conditions, cost, and safety issues. More experimental comparisons on small-size specimens and large-scale structural members using identical concrete types are needed to fully investigate the size effect on various concrete types.

5.6. Heating conditions

Factors characterizing heating generally include a target temperature and a rate of heating. The critical temperature at which spalling occurs and the effect of different rates of heating on the susceptibility to fire-induced concrete spalling are always investigated. There are generally two perspectives for evaluating the specific temperatures, including the environment temperature inside the furnace and the internal temperature distribution of the concrete itself, which are both functions of time. The temperature inside a furnace can generally be obtained from the pre-set heating curve, or thermocouples can be used to measure the furnace atmosphere temperatures. The internal temperature distribution of concrete is normally measured by pre-embedded thermocouples. As for the study of the influence of heating rate, the difference can generally be demonstrated by setting a series of different linear rates of heating [4,20,159,160], the ISO 834 standard fire curve, and the hydrocarbon fire curve [161].

During the first 20 min, the hydrocarbon fire curve has the fastest heating rate of more than 50°C/min up to 1068°C; the ISO 834 fire curve also has relatively fast heating rates of approximately 38°C/min up to 781°C and 20°C/min between temperatures of 200°C and 600°C, respectively. The generally used linear heating rates of 1°C/min, 5°C/min and 10°C/min are clearly lower than those of the standard curves. The main effect of different fire curves on fire-induced concrete spalling lies in different heating rates.

The furnace temperatures at which spalling of different concretes in response to different fire curves have occurred within the reviewed literature are summarized in Table 5 and illustrated in Fig. 15. From this figure it can be seen that, overall, the spalling of OC, FRC and UHPC has been seen between 250 °C and 850°C.

- For OC, spalling with linear heating rates between 1°C/min and 5°C/min has been identified at fire temperatures in the range from 300°C [57,162,163] to 600°C [4]. Under heating by the ISO 834 standard and hydrocarbon fire curves, the critical spalling has been identified in the range from 550°C to 800°C of furnace temperature [13,161,162].

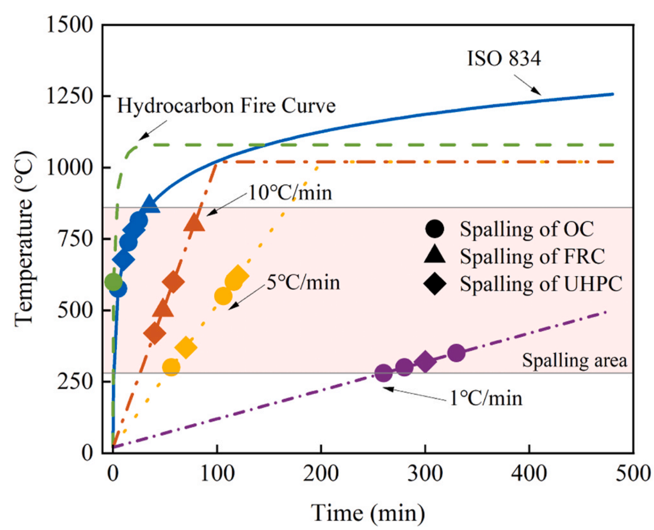

Fig. 15. Spalling furnace temperatures of different concretes on different fire curves.

Table 5
Effect of heating characteristics on fire-induced concrete spalling.

Concrete type and fibre	Reference	W/C	Moisture condition	Geometric feature	Heating method	Spalling behaviour
OC	[13,57,163]	0.125–0.62	3.7–4.16%	small specimens	1°C/min linear heating to 600°C	spalling at 280°C, 300°C and 355°C
OC	[67,113]	0.2–0.45	6–7.5%	small specimens	5°C/min linear heating to 900°C	spalling at 300°C, 550°C and 600°C
OC	[13,161, 162]	0.125–0.55	3.5–6%	columns and small specimens	ISO 834 fire curve	spalling at 550°C, 750°C and 800°C
OC	[161]	NA	3.5–6%	slabs	hydrocarbon fire curve	spalling at 600°C
FRC; SF, CF, PPF	[19,62]	0.33–0.42	3.2–5.2%	slabs and small specimens	10°C/min linear heating to 800°C	spalling at 500°C and 800°C
FRC; PPF, SF	[19,72,164]	0.38–0.54	3.2–5.2%	small specimens	ISO 834 fire curve	spalling at 850°C
UHPC; PPF, SF	[20,159]	0.195–0.21	NA	small specimens	1–5°C/min linear heating to 1000°C	spalling at 323°C, 357°C and 600°C
UHPC; PPF, SF	[20,159]	0.195–0.21	NA	small specimens	8–15°C/min linear heating to 1000°C	spalling at 422°C and 600°C
UHPC; PPF, SF, jute fibre, PE fibre	[94,126, 165]	0.14–0.2	NA	small specimens	ISO 834 fire curve	spalling about 543°C-757°C, 645°C and 700°C

- For FRC, the critical fire temperatures for spalling have ranged between 500℃ to 800℃ with a heating rate of 10℃/min [19], and 250℃ [164] and 800℃ [164] under the ISO 834 fire curve.
- For UHPC, the critical fire temperatures for spalling with linear heating rates between 1℃/min and 10℃/min have ranged between 323℃ and 422℃ [20]. Under ISO 834 standard and hydrocarbon fire heating, spalling has been identified in the range 650℃ to 757℃ [94,126,165].

Moreover, spalling tends to occur at higher fire temperatures with higher heating rates. This does not conflict with common sense in that, when the fire is severe, concrete structures tend to spall earlier, as the higher temperature is reached within a much shorter time. It is worth noting that that some OC does not spall, and no FRC has been found to spall, with a slow heating rate such as 1℃/min [13] or 5℃/min [26,66]. Therefore, it is inaccurate to say that a slow heating rate reduces the spalling temperatures of OC and FRC, as a slow heating rate may completely inhibit their spalling.

The influence of heating rate involves a balance of mechanisms in the concrete. Rapid heating produces cracks within the concrete and these cracks contribute to the release of internal pore pressures, which can mitigate the potential for fire-induced concrete spalling [19,160,164]. On the other hand, rapid heating can produce high pore pressure for concrete with identical moisture content. This phenomenon can be considered in conjunction with the thermal cracking theory of Fu et al. [54], that there are multiple competing relationships between crack development, the development of internal pore pressure and mechanical strength. When the development of permeability due to cracking is greater than the development of pore pressure, the pore pressure is relieved, which presents a favourable outcome, but when the loss of strength caused by crack development is too large, it then increases the likelihood of spalling.

Spalling during the cooling phase after heating has also been found [166–168], and the mechanism of occurrence of this spalling break through the framework of traditional theoretical hypotheses. While the main thermal effect is reduction of the temperature gradients in the concrete, producing a generally more even temperature field, the previously heated surface cools and the local temperature gradient near this surface now reverses, causing the thermal strains to reverse [166,167], causing a new mismatch of the thermal stresses [168]. In addition, considering the reduction of strength at high temperatures, the vulnerable regions of concrete even struggle to resist the material's self-weight [167].

5.7. Mechanical conditions

Loading and constraints characterize the external mechanical conditions for structural members. Those in this review are mainly derived from tests on actual members, which are also subject to the limitations of the experimental conditions.

In the traditional "thermal stress" hypothesis, fire-induced concrete spalling is caused by compressive yielding due to compressive stresses arising from the constrained thermal deformation of the surface layer [38,169]. Thus, the possibility of fire-induced concrete spalling increases with any increase of compressive stress, either in the heating [8,65,170–172] or cooling phases [166]. However, when the material is subjected to tensile stress the concrete cracks, which helps to release pore pressures and counteracts the compressive stress [8,147,173], which inhibits fire-induced concrete spalling. As a result, columns [89,172,174,175], which are predominantly subjected to compression in normal service, are more prone to spalling than beams [167,172] or slabs [8,170,172]. When the compressed zone of material is mechanically subjected to tensile straining, thus countering the compressive "thermal stress", the resistance to the spalling tendency is increased [8,89,147]. For eccentrically loaded columns, the zone of higher compression in a cross-section is more prone to spalling than the zone of lower compression or net tension [89]. In beam elements, the main spalling is concentrated in the compression zone [167,175]; however, it must be remembered that the highest local compressive stress may be due to the superposition of tensile mechanical stress and compressive thermal stress due to restrained thermal expansion. This increases the possibility of fire-induced concrete spalling [176,177]. Overall, the effect of mechanical stress on fire-induced spalling is similar across the different concretes [177].

6. Correlation between Level 1 and Level 2

In the MFIF, L2 in Fig. 9 constitutes the "force" and "resistance" parameters that can directly be used to form fire-induced concrete spalling criteria ("force" exceeding "resistance") for structural design. The "force" parameters in this level consist of pore pressure, thermal stress and mechanical stress. "Resistance" consists of the high-temperature strength of the material. L1 describes the internal and external factors that influence the spalling behaviour of the material in question; these can be used qualitatively to judge the occurrence of spalling. L2 parameters can be used to form quantitative predictive equations for spalling. This section links the factors in L1 and the parameters in L2. Table 6 summarizes the outcomes of Section 5 on the influence of factors of L1 on the parameters of L2.

This table shows:

- Strength: Elevated-temperature W/C and heating conditions reduce the compressive strength, whereas inorganic fibres and aggregate incorporation enhance the strength. Organic polymers and natural fibres both lead to a slight weakening of the strength, and there is no direct correlation between moisture content, geometric characteristics or mechanical conditions and strength.
- Pore pressure: Among these, decreased W/C significantly increases the pore pressure. Inorganic fibres enhance the maximum value of pore pressure through their bridging effect, while organic fibres and natural fibres show a more significant pressure-reducing effect. Moisture content, geometric characteristics and heating conditions can all positively enhance the pore pressure, and aggregate can weaken it. Microcracks in the material produced by mechanical loading, especially by tension, help to reduce pore pressure.
- Thermal stress: Geometric characteristics and heating conditions can positively increase thermal stress. Aggregate type affects thermal stress via thermal expansion mismatch, and the tendency depends on the coefficients of thermal expansion and thermal instability of varied aggregates. In terms of mechanical conditions, constraints and compression typically cause thermal stresses to increase, whilst

Table 6
Correlation between L1 and L2.

		High-temperature strength	Pore pressure	Thermal stress	Mechanical stress
W/C		-	-	/	/
Fibres	Inorganic fibres	+	+	/	/
	Organic polymer and natural fibres	-	-	/	/
Moisture content		/	+	/	/
Aggregate		+	-	+ /-	/
Geometric characteristics		/	+	+	/
Heating conditions		-	+	+	/
Mechanical conditions		/	-	+ /-	+

Note: + represents a positive correlation; - negative correlation; + /- inconsistency in the direction of action (both positive and negative correlations may occur); / no correlation.

tensile stresses may have a certain offsetting effect. The rest of the L1 factors have no direct correlation to thermal stress.

- Mechanical stress:Only the mechanical conditions generate mechanical stress in concrete. The other L1 factors have no direct correlation to mechanical stress.

7. Utilization of Level 2 parameters in Level 3

In the MFIF, L3 is the result of the "spalling or no spalling" decision in Fig. 9, based on L2 criteria. Based on the classic "pore pressure" and "thermal stress" theories, this paper proposes a general formula to judge the occurrence of fire-induced concrete spalling based on the combination of the two theories, expressed as concrete spalling occurs when the combined effect of thermal stress, pore pressure and mechanical stress exceeds the representative high-temperature strength of concrete. The general formula is expressed as Eq. (2):

$$D = f(S) - f(P, T, M) \tag{2}$$

In Eq. 2, S represents high-temperature strength, P represents pore pressure effect, T represents thermal stress effect, M represents mechanical stress effect, and D is the spalling judgment value.

The classic "pore pressure" hypothesis compares concrete tensile strength with pore pressure, and the classic "thermal stress" hypothesis compares concrete compressive strength with thermal stress. The innovative aspect of Eq. 2 is that, in addition to comparing high-temperature strength with pore pressure and thermal stress, the mechanical stress is also considered to evaluate the influence of the structural mechanical condition on fire-induced concrete spalling. Fire-induced concrete spalling is predicted when the spalling judgment value D is less than or equal to zero.

In Eq. (2), $f(S)$ represents the resistance of concrete to fire-induced spalling. This resistance gradually degrades with increasing temperature and can be regarded as relatively independent from the driving-force term $f(P, T, M)$. By contrast, $f(P, T, M)$ represents the internal effects developed in concrete under elevated temperature and mechanical loading and should be understood as a highly coupled stress state. This highly coupled stress state involves the superposition of thermal stress and mechanical stress, temperature-dependent and stress-dependent evolution of gas permeability [142], migration of the moisture-saturated zone with the temperature field [33,43,138], the build-up and release of pore pressure during heating and cooling [42, 160], and the development of bonding degradation and stress redistribution [178,179]. Therefore, pore pressure, thermal stress, and mechanical stress are not treated as isolated effects, but as interacting components within the overall thermo-hydro-mechanical process governing fire-induced spalling.

This general formula can be used in finite element simulations to predict concrete spalling in structural analysis.

8. Conclusions and discussions

Fire-induced concrete spalling has a significant influence on the safety of reinforced concrete structures under fire conditions. Numerous studies exist on the spalling phenomenon for various types of concrete. However, there has been no comprehensive review to systematically analyse the results of existing studies, which are based on different concrete materials and influencing factors, to form a consistent understanding of the spalling mechanism applicable to the majority of concrete types. The conclusions of this systematic review can be summarised as:

- An increase in water-cement ratio (W/C) reduces the tendency of concrete spalling. For OC, the W/C ratio of 0.45 plays as a threshold of spalling; for FRC, the W/C ratio of 0.33 plays as a threshold of spalling. For UHCP, ECC or UHTCC, differences in spalling behaviour arise due to variations in mix design.
- The addition of fibre generally affects inhibiting spalling. Inorganic fibres normally perform better in terms of spalling inhibition than inorganic fibres. Natural fibres can achieve adequate spalling resistance when a high quantitative of 10 kg/m^3 admixture is added, and a good approach to balance spalling resistance and mechanical property is a combination of natural fibres with inorganic fibres and organic polymers.
- An increase in the size of the coarse aggregates decreases the tendency for concrete spalling. Concrete without coarse aggregates exhibits more severe spalling than concrete with coarse aggregates.
- Spalling tends to occur at high temperatures with higher heating rates, but normally after a much shorter heating time compared to that at lower heating rates. However, there are situations in which a low heating rate may also completely inhibit spalling. This is because rapid heating produces cracking within the concrete, and this contributes to the release of internal pore pressures, while a low heating rate may induce vapour escape without producing high pore pressures or high loss of mechanical strength.

After a comprehensive review of the research on the spalling mechanism, this paper summarizes the numerous research results into a unified framework that applies to spalling analysis of the reviewed types of concrete. This framework aims to systematically help further understanding of the nature of concrete spalling, L1 factors mainly guide the design of spalling-resistant concrete in engineering practice, while L2 parameters mainly provide the basis for establishing spalling criteria in numerical simulation.

Based on this review, further work is recommended to promote the research on concrete spalling as follows:

- The spalling inhibition mechanisms of fibres are clear. However, there is a lack of research to quantify the contributions of fibre melting, expansion, and shrinking to inhibiting concrete spalling. Further study is recommended on microscopic observation of fibres and their surrounding matrix states during heating. Statistical methods should be combined to quantify fibre and crack distribution. Permeability tests after heating could be used to investigate vapour escape routes.
- Despite some high-temperature experiments on concrete structural components, the majority of work on concrete spalling has been concentrated on small-sized specimens. Large overall dimensions can more easily prevent vapour from escaping compared with smaller dimensions. Mechanical conditions, which are not reflected in small-size specimens, also play an important role in concrete spalling. More experiments on full-scale structural components at high temperatures are needed to examine the spalling behaviour at a realistic scale.
- Due to the limitations of cost and laboratory conditions, useful approaches to numerical simulation of concrete spalling of real-size components are needed. This would be most useful if implemented in commonly used commercial finite element modelling software so that the approach could be used by all researchers. The framework proposed in this review could be a basis on which to guide the simulation. Based on L2 of the framework, the high-temperature strength and pore pressure could be manually input into the commercial FEM software, and the thermal stress and mechanical stress can be automatically calculated by the FEA software. A spalling criterion can be input as a subroutine to relate these factors in L2 to decide the spalling and concrete, and the deletion of the elements in the FEA. The simulation could involve the whole heating process, including the cooling phase.
- A key future research need is to clarify the pore-pressure behaviour of different cementitious materials under elevated temperatures. While OC and UHPC have been more extensively studied, ECC/

UHTCC and other novel cementitious composites still lack systematic investigation. Future work should focus on quantifying the magnitude, evolution, and dissipation of pore pressure in these materials, identifying both shared and material-specific characteristics, and coupling these findings with thermal-stress analysis to support the establishment of a unified theoretical framework for fire-induced spalling.

- The prediction of the occurrence of concrete spalling by AI methods could be promising. Datasets can be developed, and prediction models can be developed by machine learning methods, in which the ingredients of concrete, heating conditions and structural type of concrete structures are input, the position of the occurrence of fire-induced spalling and the correlating fire resistance can be output.

CRediT authorship contribution statement

Guan Quan: Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Runyi Zhang:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Ian Burgess:** Writing – review & editing, Investigation, Conceptualization. **Jun Ye:** Writing – review & editing, Supervision, Conceptualization. **Shilang Xu:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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