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FROM CRACK INITIATION TO INSTABILITY AT HIGH TEMPERATURE: A TWO-STAGE MECHANISM FOR FIRE-INDUCED SPALLING IN CONCRETE

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Abstract: Concrete's vulnerability to fire-induced spalling poses a critical challenge in structural applications, especially under extreme conditions. This phenomenon is highly material-dependent, with an elevated risk for modern concrete mixes, such as High-Performance Concrete (HPC), due to their dense microstructure. Understanding and mitigating this risk is crucial for enhancing structural safety in fire scenarios.

This study investigates the two-stage mechanism underlying spalling: crack initiation and crack instability, both driven by thermal and hygral interactions and strongly influenced by the fracture behaviour of concrete. In the first stage, spalling begins when driving forces—such as pore pressure and thermal stress—surpass the tensile strength of concrete. Biot's coefficient, the shape and dimension of the structure are critical in determining this threshold. The second stage involves rapid crack propagation, driven by thermal energy conversion through vaporisation. This vaporisation occurs adjacent to the cracked region, pressurising the crack and accelerating it for instability.

To explore these mechanisms, innovative testing methods were employed, including a frameless direct-tension test setup to evaluate fracture behaviour and a small-scale spalling test to analyse instability thresholds. The results reveal the complex interplay of pore pressure, thermal stresses, and moisture content in spalling dynamics.

1 INTRODUCTION

Concrete as the most used structural material is known to exhibit good behaviour in fire due to its thermal properties [1]. However, the fact that concrete is prone to the spalling phenomenon when exposed to fire poses a significant obstacle to its widespread utilization. Explosive spalling is defined as the projection of concrete flakes and the reduction of the structural element cross-section [2]. This complex phenomenon is influenced by thermal, mechanical, and hygral factors which is more probable in new-generation concrete mixes like HPC, UHPC [3]. Existing literature identifies pore pressure [4,5]and thermal stress [6–8] as primary driving mechanisms. However, their individual explanations are not fully descriptive of the interplay of these factors and the lack of a clear quantitative assessment make it challenging to identify the dominant mechanisms and parameters governing explosive spalling in concrete. Elastic energy which is linked to thermal stress cannot justify the explosive nature of the process [9]. On the other hand, accumulated thermal energy has a higher order of magnitude which makes it a proper alternative to thermal stress [10]. The water in the pores has a key role in the conversion of available thermal energy to mechanical work by vaporization.

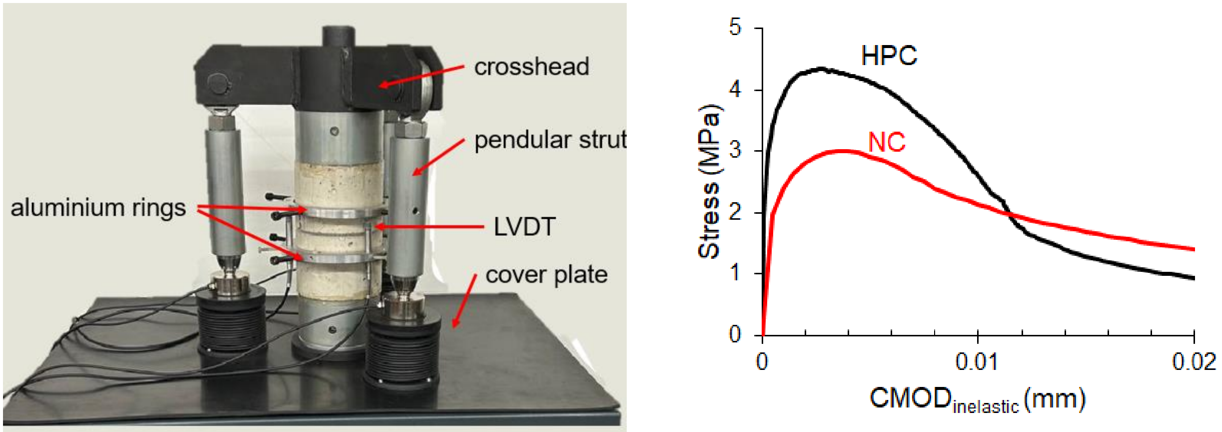

Figure 1: (left) 3ACTION test setup [11], (right) example of fracture behaviour of different concrete grades [2].

The study proposes a two-stage mechanism to unravel the intricacy of spalling.

- **First stage - incipient crack formation:** Crack initiation in concrete involves factors such as restrained or loaded sections experiencing thermal expansion [12], mesoscale heterogeneity [13,14], element shape and reinforcing bars [7] and pore pressure [15].
- **Second stage - crack instability:** This stage involves rapid crack propagation and particle projection. The driving energy source is the thermal energy accumulated in heated concrete, converted into mechanical work through flash vaporization of water from a thin concrete layer facing the opening crack [16,17].

2 FRACTURE BEHAVIOUR OF CONCRETE

The fracture behaviour of concrete is a key factor in the spalling process, as it governs the material's ability to resist cracking and damage during both stages of spalling. This is particularly relevant when comparing the spalling tendencies of high-performance concrete (HPC) and normal concrete (NC), as their fracture properties differ significantly. HPC, due to its dense microstructure, exhibits distinct spalling characteristics compared to NC, often leading to more severe damage under similar conditions.

Among the techniques used to study fracture behaviour, the direct-tension test is considered the simplest and most direct method. However, the strain-softening nature of concrete poses significant challenges in these tests, especially in maintaining both axial and flexural stability. Issues such as frame deformability and uneven load distribution exacerbate these challenges, making precise testing essential for understanding the nuanced behaviour of concrete under high-stress conditions.

To address these challenges, a frameless test rig was developed to enable controlled direct tension tests on notched concrete samples (see Figure 1-left) [11]. This design eliminates the need for a traditional loading frame by distributing the load across three parallel actuators and incorporating a removable crosshead for straightforward sample installation.

This rig provides critical insights into the tensile strength of concrete, particularly when comparing High-Performance Concrete (HPC) to Normal Concrete (NC). For example, as shown in Figure 1-right, differences between two concrete mixes with different spalling sensitivities are highlighted. From the perspective of the two-stage spalling mechanism, these differences relate to both crack initiation—primarily influenced by tensile strength—and the post-peak response. Notably, the varying slopes of the descending branches in the test results suggest differences in cohesion, which plays a pivotal role in resisting crack instability during the second stage of spalling.

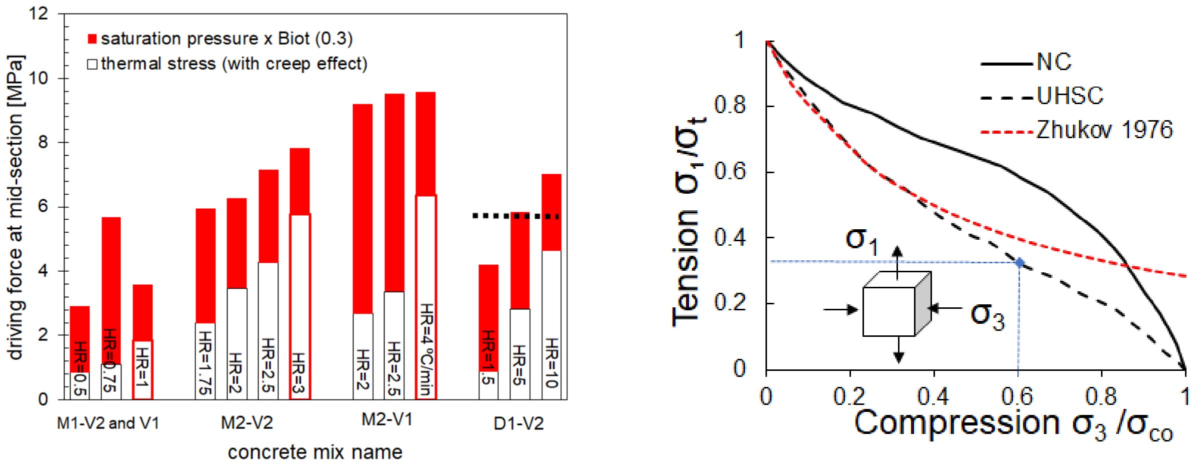

Figure 2. Combination of effective pore pressure and thermal stress (considering creep effect) in cylinder samples with different heating rates for different concrete mixes [18], (right) failure criteria for concrete slabs exposed to bi-axial compression and tension.

2 FIRST STAGE (CRACK INITIATION)

In the first stage of spalling, the critical question arises: how does concrete's tensile strength fail under elevated temperatures? Felicetti et al. demonstrated that pore pressure alone is insufficient to initiate cracking [19,20]. Instead, pore pressure contributes to a fraction of the tensile strength loss, influenced by the connectivity of pores and micro-damages, expressed as Biot's coefficient. This coefficient is approximately 0.6-1.0 for normal concrete (NC) and as low as 0.2-0.3 for high-performance concrete (HPC), indicating significant differences in their behaviour.

By combining the effects of pore pressure and thermal stress, a cumulative driving force is generated, capable of surpassing concrete's strength [18]. In convex-shaped samples, this combination is particularly effective, as temperature gradients induce tensile stresses. These stresses, moderated by transient creep effects, can be additively combined with the effective pore pressure to lead to tensile failure.

Yarmohammadian et al. investigated these interactions in Ultra-High-Performance Concrete (UHPC) mixes under spalling conditions. Their experiments revealed that each concrete mix exhibited a specific threshold, determined by its tensile resistance, at which spalling was triggered (Figure 2-left).

In the more realistic case of flat exposed faces (e.g. walls, tunnel linings), the biaxial compressive thermal stress exceeds the effective hydrostatic tensile stress produced by pore pressure, leading to a mixed multiaxial stress condition. In Figure 2-right, Kupfer and Zhukov's failure criteria highlight the pronounced mutual interaction of compressive and tensile stress [21]. As an example, by having 60% of biaxial compressive stress (which can be assumed in case of fire in a tunnel [22]), the tensile failure occurs just by around 1/3 of the uniaxial tensile strength. Future research should investigate the interaction of biaxial compression and hydrostatic pore pressure more deeply. This would involve applying heating sealed samples while imposing radial confinement using brushes.

3 SECOND STAGE (CRACK INSTABILITY)

In the second stage of spalling, the critical question arises: how does an incipient crack switch to an unstable state? Post-fire assessments of concrete structures have frequently revealed stable delamination cracks in the cover, emphasising that instability is not a guaranteed outcome [23]. However, when a crack becomes unstable, it can lead to significant cross-sectional loss and expose reinforcing bars to extreme temperatures—an outcome with severe structural implications. This underscores the importance of thoroughly understanding the second stage of spalling.

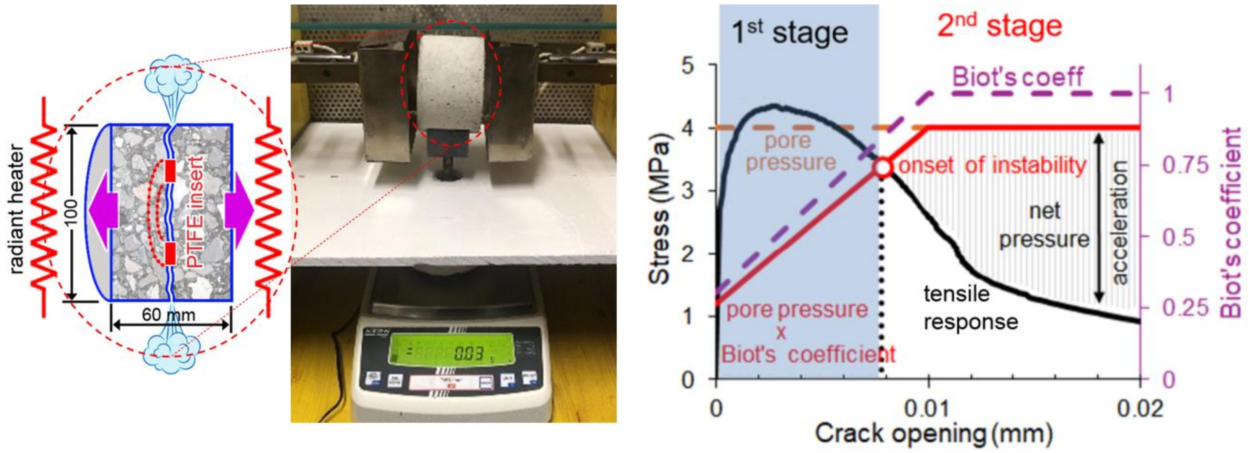

Figure 3. (left) Crack instability test setup including a polymer insert for crack initiation [17], (right) two stages of spalling versus fracture behaviour of concrete [2]

To investigate this phenomenon, a small-scale spalling test was developed, focusing on key parameters influencing crack instability [2,17]. This test allows for the observation of mass loss and rapid crack propagation during the onset of instability on concrete disks of 10 cm diameter and 6 cm thickness (see Figure 3, left). Crack initiation in the test sample is achieved through a polymeric insert (PTFE) that exhibits greater thermal expansion compared to the surrounding concrete. The geometry and dimensions of both the concrete disk and the polymer insert were meticulously optimised using finite element modelling (FEM) in ABAQUS. Following this, the polymer thickness was precisely calibrated to ensure that the mid-section temperature at the time of cracking lies within the typical spalling temperature range.

Crack instability is triggered when the internal pressure within the crack surpasses the remaining resistance of the cross-section. In this study, the measured relative acceleration of the specimen halves allowed assessing the net pressure developed in the opening crack. Notably, the maximum inferred acceleration during instability closely matched the saturated pressure at the fracturing temperature, underscoring the critical role of moisture in the instability stage.

To validate the relevance of this experimental setup to real-world spalling phenomena, the spalling risk assessment conducted using the screening setup was cross-verified with intermediate-scale tests on identical concrete mixes. This validation confirms the reliability of the setup in replicating key aspects of spalling dynamics [17]. This highlights the potential of the new test to reduce the need for intermediate-scale tests, updating the process of screening mixes, and ultimately cutting costs.

The main key findings are:

- Mass losses correlate with crack instability, attributed to water vaporization.
- Acceleration of separating parts corresponds to substantial pressurization within the crack, with calculated net pressure approaching the saturation limit. In this stage, due to the growing interconnection of pores crossed by the crack, the Biot's number raises up to unity.
- Crack initiation timing is crucial, due to the concurrent need of sufficient thermal energy and water. Hot concrete retaining significant moisture boosts spalling severity.
- Polypropylene fibre proves effective in mitigating spalling by lowering the pore saturation before the onset of cracks. The benefit may be impaired in stiff and brittle concrete.

4 CONCLUSION

A two-stage spalling mechanism is herein proposed to clarify the tricky phenomenon of explosive spalling in concrete exposed to fire. In the first stage, crack initiation occurs when the combined effects of pore pressure, thermal stress, and mesoscale heterogeneity exceed the material's tensile strength. This stage highlights the importance of fracture behaviour, with HPC showing higher spalling sensitivity due to its dense microstructure and lower Biot's coefficient. The second stage involves crack instability, where thermal energy is converted into mechanical work through vaporization, causing rapid crack propagation and splinter ejection. The findings confirm that moisture and its associated vapour pressure play a pivotal role in this process.

Advanced testing methodologies were developed to explore these stages. The frameless direct-tension rig provided insights into tensile behaviour, highlighting the different post-peak responses depending on the concrete grade. The small-scale spalling test validated the role of thermal energy and vapor pressure in instability, replicating real-world spalling dynamics and releasing from the need of large-scale tests for the preliminary screening of concrete mixes.

Practical mitigation strategies, such as the incorporation of polypropylene fibres, were found effective in reducing spalling risk by accelerating moisture loss. These insights contribute to improved understanding, design, and optimisation of fire-resistant concrete, advancing both safety and cost efficiency in construction practices.

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