FIRE CONCRETE 2025

Katarzyna Mróz and Izabela Hager
Editors

Book of Abstracts

8th International RILEM Workshop on Concrete Behaviour due to Fire Exposure

Kraków, 18-19 September 2025

Organized by:

Cracow University of Technology
80th Anniversary

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8th International RILEM Workshop on Concrete Behaviour due to Fire Exposure

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PREFACE

We are pleased to welcome you to the 8th International RILEM Workshop on Concrete Behaviour due to Fire Exposure (IWCF 2025), held in Kraków, Poland, on 18–19 September 2025. This year's edition is organized by Politechnika Krakowska im. Tadeusza Kościuszki, celebrating its 80th Anniversary, and proudly held under the honorary patronage of Prof. dr hab. inż. Andrzej Szarata, Rector of the Cracow University of Technology.

Since 2009 the International Workshop on Concrete Spalling due to Fire Exposure (IWCS) offered a platform to get in touch with other researchers, share the latest research achievements and newly gained data of real fire scenarios and discuss the current developments in the field of fire-induced concrete spalling. The successful workshops took place in Leipzig (2009, 2015), Delft (2011), Paris (2013), Borås (2017), Sheffield (2019) and Berlin (2022).

Now, we are honoured to host the event in the historic and academic city of Kraków and provide wider scope of topic during workshop under changed name and scope: Workshop on Concrete Behaviour due to Fire Exposure.

This year's workshop is held in conjunction with RILEM TC 306-CFR: "Concrete during Fire – Reassessment of the Framework", continuing the mission of advancing fire safety knowledge through collaborative research. The 2025 program comprises 8 thematic sessions, over 40 presentations, and a keynote lecture by Dr. Pierre Pimienta, highlighting experimental approaches to understanding concrete under fire. Topics range from the mechanisms of fire-induced spalling, through assessment, modeling, and mitigation techniques, to sustainable materials, structural fire performance, and post-fire evaluation of concrete structures. These sessions reflect the interdisciplinary nature and practical urgency of fire safety research in the built environment.

We express our sincere gratitude to all speakers, authors, reviewers, session chairs, and participants. Your contributions are key to the continued success of this Workshop. We also thank the organizing team and supporters who made this event possible.

We hope IWCF 2025 will be an inspiring and fruitful forum for exchanging knowledge, sparking new collaborations, and the shaping of the future of fire-resilient concrete structures.

Katarzyna Mróz and Izabela Hager
Cracow University of Technology, 2025

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UNDERSTANDING CONCRETE UNDER FIRE: EXPERIMENTAL APPROACHES FROM MATERIAL BEHAVIOUR TO FULL-SCALE APPLICATIONS

Pierre Pimienta[1]

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Abstract

Understanding the behaviour of concrete under fire is essential for ensuring the safety of structures and their users, particularly in high-risk environments such as tunnels, car parks and strategic infrastructure. Among the various phenomena associated with fire exposure, spalling remains a major concern due to its sudden onset, multi-scale complexity, and the uncertainties it introduces regarding the load-bearing capacity of concrete structures at elevated temperatures.

This presentation draws on a series of studies conducted over the past 30 years, predominantly through experimental research in collaboration with numerous academic and industrial partners in France and abroad. Many of these collaborations were carried out in close cooperation with members of successive RILEM technical committees dedicated to the fire behaviour of concrete.

Three main experimental scales have been employed: small-scale, intermediate-scale, and full-scale testing. These investigations aim to characterize the properties of concrete at high temperatures and to deepen our understanding of the physical mechanisms underlying its thermo-mechanical and thermo-hygro-mechanical behaviour, as well as the spalling phenomenon. The studies also explore the influence of specific parameters, such as the incorporation of polypropylene fibres, or the type of binder or aggregates. Moreover, they aim to assess the performance of concretes under realistic fire scenarios. Finally, small-scale characterization tests provide essential input data for numerical modelling, while intermediate- and full-scale experiments are crucial for improving and validating these models under realistic conditions.

The presentation will include results on ordinary concrete, high-performance concrete (HPC), ultra-high-performance fibre-reinforced concrete (UHPFRC), and self-compacting concrete (SCC). Low-carbon concretes will also be addressed, as this emerging field is gaining increasing attention due to the growing demand for sustainable construction materials, raising new questions about fire performance and spalling resistance.

The presentation will further highlight the importance of translating research into practical applications, with the goal of evaluating the suitability of different concretes

through reliable and reproducible testing programmes and protocols. In this context, two major initiatives led by expert working groups in France will be presented. The first focused on defining technical specifications for underground structures by identifying the types of experimental investigations required to assess spalling risk in tunnel concretes. The second, which will be detailed during this workshop, aimed to develop assessment methods and experimental protocols for evaluating concretes incorporating innovative, low-carbon binders not yet covered by existing standards. These initiatives, along with other experimental studies, have also contributed to the development of state-of-the-art reports and recommendations within RILEM technical committees,

This presentation aims to showcase key findings from recent experimental research. It also seeks to identify a number of still poorly understood issues that remain open and deserve further exploration in order to advance our knowledge of the fire performance of concrete structures, and of spalling in particular.

Finally, it is hoped that these cooperative projects may serve as examples and sources of inspiration for future collaborations, especially for the next generation of researchers and engineers.

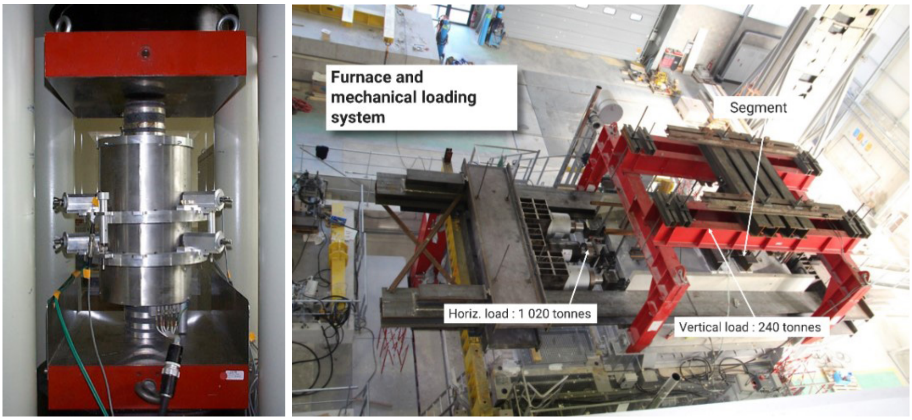

Figure 1. Setups for investigating concrete under fire: from material characterisation to full-scale tunnel test performed at CSTB

S1:

Fire-Induced Concrete Spalling:

Mechanisms and Evaluation

FIRE RISK ASSESSMENT IN STANDARDS USING RILEM TC 256-SPF SCREENING TESTS

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Abstract

The revised EN 1992-1-2 adopts a risk-based design philosophy with stricter requirements for critical structural elements, such as slender webs of beams. According to the concept of levels of approximation, the higher the consequence of potential structural failure, the more rigorous the assessment of explosive spalling must be, ranging from conservative design choices (e.g. increased cross-sections) to representative experimental testing. In many engineering contexts, particularly during preliminary design or the evaluation of existing structures, material screening tests can provide essential insights. These include (i) optimization of mix design or (ii) small-scale, minimally invasive tests to support decision-making.

A recent research project funded by the Swiss Federal Roads Authority investigated a screening test method based on RILEM TC 256-SPF recommendations to evaluate the spalling propensity of concrete – an essential factor in fire performance. The proposed procedure is designed to be practical, scalable, and robust, enabling engineers to make informed, safety-conscious decisions. The test uses specimens of at least 0.5 × 0.5 m^2 and 0.3 m thickness (0.2 m for restrained configurations), mounted in a steel frame with edge insulation to simulate restraint. The sample is wheeled in front of a preheated furnace, exposing only the cast surface. Temperatures are recorded at multiple depths via thermocouples, and spalling is detected acoustically. After testing, spalling depth and volume are assessed visually and by the sand-patch method, as shown in Fig. 1

To test the sensibility of the RILEM high-performance concrete down to low compressive strength concretes have been prepared. For one cement strength grade the binder types have been changed to more limestone powder addition ending up with a SCC concrete and to more reactive additions by keeping all other constituents' constant. For each mix two samples have been prepared and tested. The results of the screening test are shown in Fig. 2.

The two consecutive series show similar spalling results. Further in-depth analyses are shown in [Greve-Dierfeld and Bischof et. al. 2025].

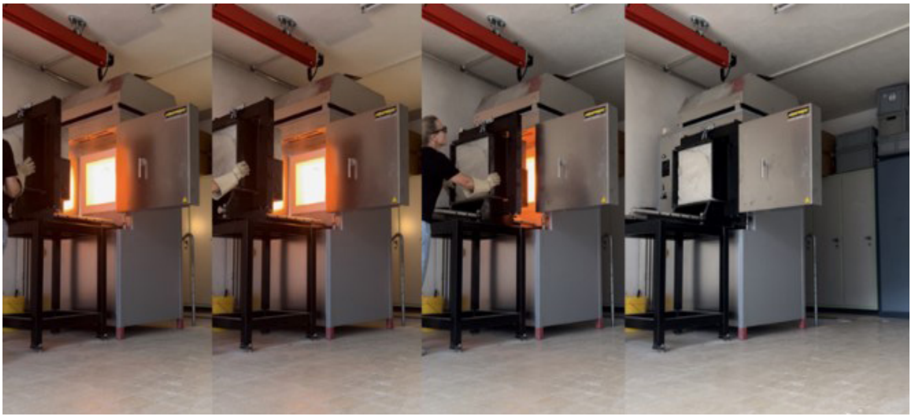

Figure 1. Test setup following RILEM TC 256-SPF screening test

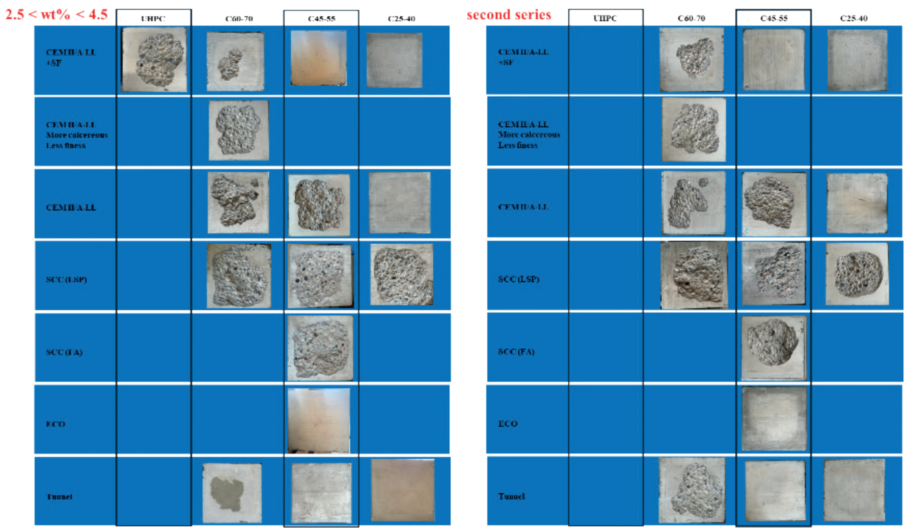

Figure 2. Visual results

Acknowledgments

We would like to thank the ASTRA (Swiss road authorization) for funding this research project.

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[2] Greve-Dierfeld Sv, Bischof P, Sörensen L, Bamonte P et al. (2025) Improved concrete performance during fire. ASTRA research Project final Report.

THE ROLE OF RESTRAINT AND LOAD IN FIRE-INDUCED SPALLING OF CONCRETE: OBSERVATIONS FROM EXPERIMENTAL TESTING

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Abstract

The following abstract includes a compilation of spalling observations from fire testing of concrete at RISE in Sweden to be discussed during the workshop in Krakow.

An illustrative example of the effect of restraint is presented in Figure 1. A corner formed by two small concrete slabs—one containing polypropylene (PP) fibres—was directly exposed to a flame for 10 minutes. During this initial heating, no spalling was observed. After allowing the specimens to cool for approximately 30 minutes, the slab without PP fibres was reheated at the centre using the same flame. This time, severe spalling occurred. This clearly demonstrates that restraint from surrounding areas plays a significant role in the spalling phenomenon, as no spalling was observed during the initial exposure of the unrestrained corner.

Moreover, the spalling behaviour observed in small, unloaded specimens during fire exposure does not accurately reflect the behaviour of large, loaded slabs. This size effect was clearly demonstrated in a test involving eight loaded slabs (measuring 1800 × 1200 × 200 mm^3) and nine corresponding cubes made from the same concrete mixes. While three of the large slabs experienced spalling, none of the cubes did, as illustrated in Figure 2.

A test program on self-compacting concrete included both small and large specimens. A more detailed analysis of the results was conducted on the smaller slabs (600 × 500 × 200 mm^3), which were equipped with an internal post-tensioning

Figure 1. left: First heating of the corners of the specimens, no spalling recorded, right: Second heating of the centre of the specimen without a PP fiber addition, violent spalling occurred [1]

system [1]. The objective of the analysis was to perform multiple least squares fit using all available material- and test method-dependent parameters, to best predict the measured average spalling depth.

The central question was whether it is even feasible to develop such a predictive model, or if an unknown randomization effect exists that fundamentally limits this possibility. Naturally, some of the parameters are interdependent, which complicates the interpretation of the results. The conclusions from the study were that spalling behavior depends on many factors, but it is possible to predict the spalling depth inside a data set with a fairly high accuracy. And most important for the discussion in this paper the application of a compressive load influenced the results substantially giving more severe fire spalling.

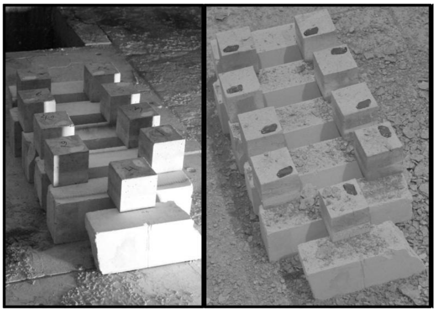

Figure 2. Photographs taken before and after a fire test conducted in a horizontal furnace [2]

References

[1] Jansson R. "Fire Spalling of Concrete - Theoretical and Experimental Studies" PhD Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2013.
[2] Jansson R. and Boström L.(2012) "Determination of fire spalling of concrete – relevance of different test methods" Proceedings from the 7th International Conference on Structures in Fire, M. Fontana, A. Frangi, M. Knobloch (Eds.), Zurich, Switzerland, June 6-8, 2012.

CONCRETE SPALLING REFRAMED: A NEW THEORY BUILT ON KNOWN MECHANISMS

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Abstract

Despite extensive experimental research, numerous theoretical models, and advanced simulations, the mechanism behind concrete spalling under high-temperature exposure remains poorly understood. It is widely recognized that both pore pressure and thermal stresses contribute to the phenomenon. However, measured pore pressures are often too low to explain the observed cracking, and thermal stresses are largely mitigated by thermal creep. As such, classical theories typically attribute spalling to a combination of these effects.

Alternative models introduce additional physical mechanisms. Notably, the BLEVE (Boiling Liquid Expanding Vapor Explosion) theory and the fully saturated pore pressure theory offer distinct perspectives. More recently, Yarmohammadian and Felicetti [1] proposed a two-stage mechanism in which an initial crack forms due to thermal stresses and vapor pressure, followed by a rapid pressure drop that induces flash vaporization and the violent ejection of concrete fragments—an effect analogous to the BLEVE phenomenon.

This paper proposes a new theory that builds on the two-stage concept but is based entirely on the thermodynamic behavior of water. It integrates elements of both the fully saturated pore pressure model and the BLEVE mechanism. During heating, as liquid water and vapor coexist within concrete pores, pressure follows the vapor saturation curve. However, when thermal expansion causes the liquid phase to completely fill the pore volume, a strong pressure buildup occurs, as shown in Fig. 1 for different initial saturations. This liquid pressure quickly exceeds the tensile strength of the concrete and initiates cracking—a mechanism already described in [2]. The resulting pressure release then causes immediate boiling and flash vaporization, producing a surge in vapor pressure that violently ejects concrete fragments.

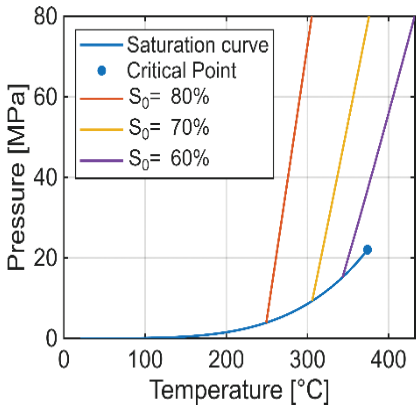

Figure 1. Pressure

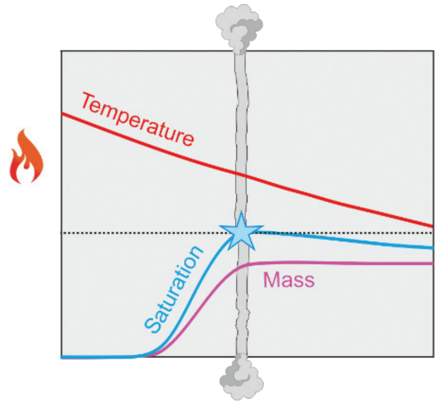

Figure 2. Concept

Figure 2 illustrates the concept for one-sided heating. A region of high saturation forms just behind the drying front, where sufficient liquid mass expands due to elevated temperatures. As the pores become fully saturated, the liquid pressure rises rapidly with temperature and cracks the concrete. This releases the pressure of the superheated liquid and produces flash vaporization.

To validate this theory, several representative heating scenarios are simulated using a simplified model developed by Weber [3], including one-sided heating of slabs, two-sided heating of thin webs, and slow heating of cylindrical specimens. The simulations show how moisture content, porosity, permeability, and heating rate influence the evolution of liquid content during heating. A key insight lies in the temperature and the temperature-dependent saturation at the drying front—both closely governed by moisture. High moisture content slows the progression of the drying front, keeping it in the hot zone near the surface. Additionally, high moisture levels can lead to full saturation at elevated temperatures, triggering hydraulic fracturing in the concrete skeleton. High temperature and high saturation are also the critical conditions for flash vaporization, as confirmed experimentally in [1]. The fact that the same conditions apply to both crack initiation and explosive spalling makes the proposed theory particularly compelling.

References

[1] Yarmohammadian & Felicetti, SiF 2024, Coimbra, Portugal.
[2] Khoylou, PhD Thesis 1997, Imperial College of Science, London.
[3] Weber, 7th International Workshop on Concrete Spalling due to Fire Exposure, Berlin, 2023.

S2:

Fire-Induced Concrete Spalling:

Assessment and Mitigation

HIGH-TEMPERATURE MICROSTRUCTURAL EVALUATION OF FIBRED CONCRETE USING X-RAY TOMOGRAPHY AND DIGITAL IMAGE ANALYSIS

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[1] *Université de Pau et des Pays de l'Adour, E2S UPPA, SIAME, Pau, France*

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Abstract

The performance of concrete when exposed to elevated temperatures, such as during a fire, is governed by complex thermo-hydric interactions, often resulting in internal damage such as micro-cracking, increased porosity, and explosive spalling in extreme cases. This study explores the influence of aggregate types and the presence of polypropylene (PP) fibers on the microstructural evolution of concrete exposed to high temperatures, using X-ray computed tomography (CT) as a non-destructive diagnostic tool. Four concrete formulations were tested, incorporating either calcareous or mortar-based aggregates, with and without PP fibers. Samples were subjected to controlled heating at 80°C, 150°C, 200°C, 300°C, and 450°C. CT scans were conducted after each heating stage to capture internal transformations. Advanced image analysis techniques were applied, including manual alignment, image registration, and subtraction, to isolate and visualize the effects of temperature on the concrete microstructure. Post-processing steps such as segmentation and intensity mapping enabled quantification of pore connectivity, crack propagation, and fiber-induced vapor pathways. Findings reveal a strong correlation between aggregate type and thermal mismatch-induced cracking. Mortar aggregates exhibited reduced micro-cracking due to better thermal compatibility with the cement matrix, while PP fibers formed vapor channels that alleviated internal pressure build-up due to its melting around 170°C.The result of permeability measurements on these four concrete formulations further supported these findings, offering a comprehensive understanding of thermo-hydrodynamic behaviour under fire-like conditions. This study demonstrates the efficiency of advanced tomographic imaging methods in evaluating thermally induced damage in concrete and paves the way for more resilient fire-safe structural designs.

Keywords: X-ray tomography, Image subtraction, segmentation, thermal mismatch, polypropylene fibers, mortar aggregate, micro-cracking

Table 1. Heating protocol

Samples	C1-0	C1-18/32(0.5)	C1MA	C1MA-18/32(0.5)
Heating/cooling temperature	80°C, 150°C, 200°C, 300°C and 450°C			
Heating/cooling rate	2°/minute			
Dwelling	3 hours			

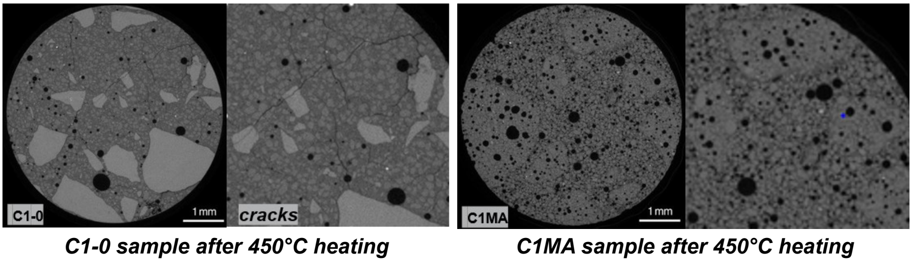

Figure 1. X-ray Tomography Images after heating to 450°C

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ON FRACTURE BEHAVIOUR OF MODERATELY HEATED HIGH-PERFORMANCE CONCRETE

Ramin Yarmohammadian[1], **Roberto Felicetti**[2]

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[2] *DICA . Politecnico di Milano, Italy*

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Abstract

This study investigates the tensile behaviour of High Performance Concrete (HPC) with and without polypropylene (PP) fibres under direct tension and compares it with the conventional splitting tensile test. A novel, fully controlled direct tension setup was employed on notched cylindrical specimens, enabling precise control and measurement of Crack Mouth Opening Displacement (CMOD). Samples were tested both at ambient conditions and after exposure to 250°C (heating rate: 20°C/h, 2-hour dwell). Heat exposure induced 4.7% and 5.2% mass loss in plain and fibre-reinforced mixes, respectively.

Contrary to expectations, the residual tensile strength increased in both mixes, possibly due to microstructural changes such as reduced saturation and improved Interfacial Transition Zone between cement and aggregate. Fibre-reinforced samples exhibited slightly reduced stiffness and strength but benefited from enhanced post-peak deformability and brittleness reduction. Compared to direct tension, splitting tests consistently overestimated tensile strength and exhibited higher variability, reflecting their limited capability to characterise fracture processes. The results substantiate the effectiveness of the proposed direct tension test in capturing the true tensile and fracture behaviour of brittle cementitious composites. The impact of the results on the inherent susceptibility to explosive spalling will also be discussed in the concluding remarks.

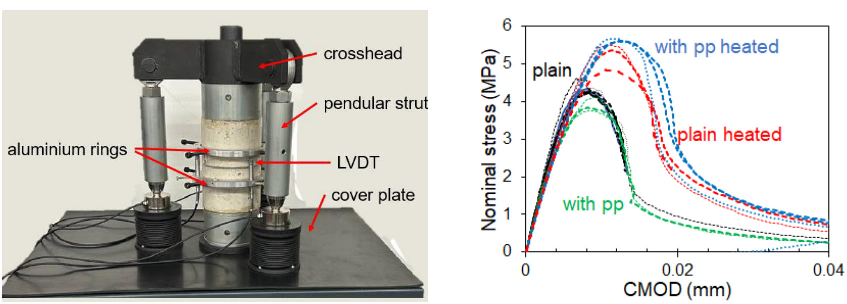

Figure 1. Direct-tensile test setup and obtained results

Acknowledgments

This work was conducted as part of the PhD project "Severe Spalling in Concrete Exposed to Fire," supported by the Professional Syndicate of the French Cement Industry (SFIC).

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FIRE SPALLING BEHAVIOR OF ULTRA-HIGH--PERFORMANCE FIBER-REINFORCED CONCRETE WITH STEEL FIBER AND JUTE FIBER

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Abstract

In this study, we confirmed the fire spalling limitation effect of ultra-high-performance concrete reinforced with natural fibers. It conducts heating tests of small cylindrical and ring-restrained specimens with jute fiber contents ranging from 0 to 0.5 vol%. A control specimen of UHPC is added with steel fiber at 1.0 vol. The results of simple fire spalling tests in which small cylindrical specimens were heated at a constant 850 °C for 30 min indicated that using 0.5 vol% of jute fibers shortened the fire spalling duration and decreased the mass loss rate (Fig.1,2). The results of the ring-restrained heating tests confirmed that the incorporation of more than 0.4 vol% of jute fibers suppressed the fire spalling compared to the specimens with no jute fibers (Fig.3).

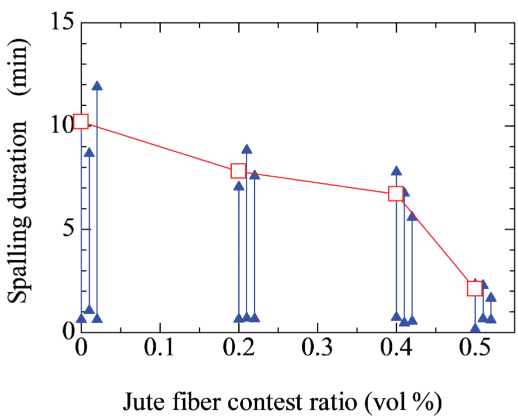

Figure 1. Spalling duration of the small cylinder heating test

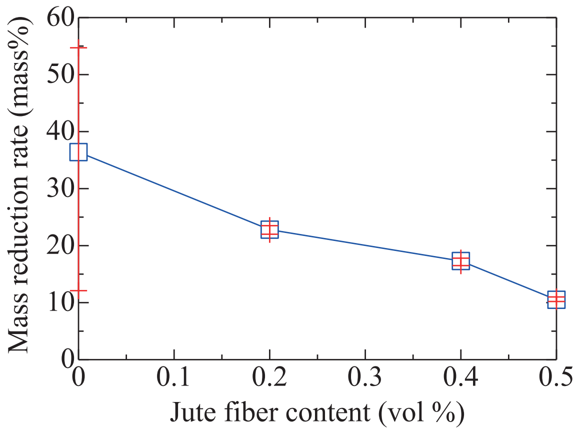

Figure 2. Mass loss of the small cylinder heating test

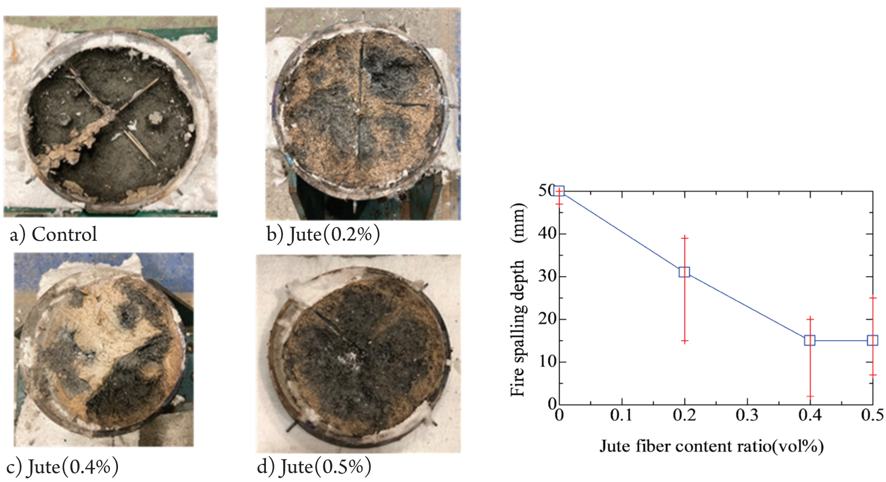

Figure 3. Results of spalling damage and depth of ring-restrained specimen heating test

Acknowledgments

This study was supported financially by the Japan Society for the Promotion of Science (Scientific Research C: No.23K03984) and Japan Concrete Institute. The authors would like to express their gratitude to these organizations for their financial support.

THE BENEFITS OF INCORPORATING BIO- -SOURCED FIBRES FOR THE FIRE SPALLING BEHAVIOUR OF CONCRETE

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[2] *ECOMINERO, France*
[3] *CAPREMIB, France*
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Corresponding author: f.robert@cerib.com

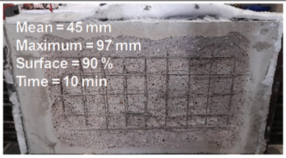
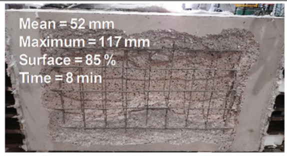
Abstract

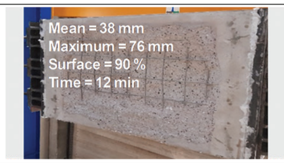
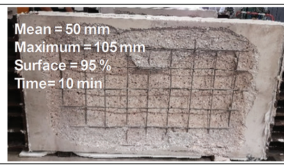
While the addition of polypropylene fibres in concrete to improve the fire spalling has been intensively studied and is now widely recognised, the addition of bio-sourced fibres still needs to be assessed, especially in the framework of the RILEM and Eurocode 2-1-2 recommendations, which consider representative geometry and stress levels. Depending on the results, bio-sourced fibres may replace polypropylene fibres.

Jute fibres are the most widely studied biobased fibres in the literature. Several studies carried out on small samples in Japan have shown that the addition of jute fibres improves concrete's resistance to spalling at high temperatures ([1], [2], [3], [4]). In these tests, their performance even proved to be more effective than that of polypropylene (PP) fibers. The present study is based on a research project on recycled concrete aggregates, which identified specific mixes prone to spalling (35 to 40 MPa at the day of the fire test), as well as a high strength concrete with natural aggregates (85 MPa at the day of the fire test). Three biobased fibres were then selected for testing, from different sources. Cellulosic fibres are industrial fibres. Biosourced fibres A come from kenaf and are produced on an industrial scale. Biosourced fibres B come from hemp and were produced for this experimental campaign. The specimen geometry was 1,7 m × 1 m × 0,3 m, tested under load levels of 2 or 8 MPa with varying fibres dosages.

This experimental campaign highlights the potential of biosourced fibres with defined geometries to improve the fire behaviour of concrete, yielding positive results.

<table>
<tr><th>FIBRES CONTENT (kg/m³)</th><th>STRESS LEVEL 2 MPa</th><th>STRESS LEVEL 8 MPa</th></tr>
<tr><td>No fibres

Water content [0 – 2,5 cm] = 4,2 %
Water content [2,5 – 5 cm] = 6,0 %
$f_{c,test}$ = 33 MPa</td><td>
</td><td>
</td></tr>
<tr><td>1,2 cellulosic fibres

Water content [0 – 2,5 cm] = 4,3 %
Water content [2,5 – 5 cm] = 5,8 %
$f_{c,test}$ = 37 MPa</td><td>
</td><td>
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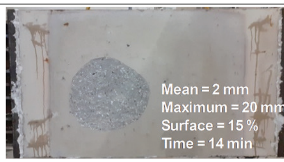
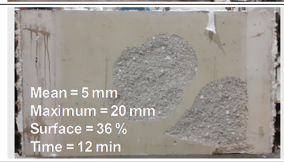
Water content [0 – 2,5 cm] = 4,6 %
Water content [2,5 – 5 cm] = 6,7 %
$f_{c,test}$ = 34 MPa</td><td>
</td><td>
</td></tr>
<tr><td>1,8 bio fibres A

Water content [0 – 2,5 cm] = 4,3 %
Water content [2,5 – 5 cm] = 6,3 %
$f_{c,test}$ = 39 MPa</td><td></td><td></td></tr>
</table>

Figure 1. Spalling results depending on fibres type and dosage

Acknowledgments

The authors are grateful to FIB and ECOMINERO for the financial support.

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REDUCING EXPLOSIVE SPALLING IN HIGH-STRENGTH CONCRETE: EXPERIMENTAL RESULTS FROM FIRE TESTS

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Abstract

This paper presents the results of screening tests on concretes regarding their susceptibility to spalling under high temperatures due to fire exposure. Thermal load was applied according to the standard fire curve ISO-834 [1]. The tests were carried out on slab specimens (785 mm × 785 mm × 150 mm) heated from one side, following the procedure described in [2], and on column specimens (500 mm × 500 mm × 700 mm) heated from four sides (Fig. 1). Elements were produced using two reference recipes of high-performance self-compacting concrete (SCC, HPC). A simplified concrete mixture composition is shown in Table 1. For the elements produced using both concrete mixes, high-temperature tests were conducted. The following parameters were varied: the amount of polypropylene fibers, the content and type of steel fibers, the internal reinforcement layout, and the presence of compressive force acting on the element. In total, 19 concrete mixes were tested, including 19 slab specimens (A1–A9, A11–A14, A21, B51–B53, B61) and 12 column specimens.

The mechanical properties of concrete deteriorate with increasing temperature, as presented in earlier studies [4-5]. In structural concrete elements with high fire resistance requirements (e.g., 240 minutes), the reinforcement is usually placed at a depth of 55–75 mm, effectively protecting it from temperature effects and limiting strength reduction. Nevertheless, even accurate knowledge of mechanical properties cannot fully guarantee safety if spalling exposes the reinforcement.

In slab specimens (A11–A21 and B51–B53, B61), biaxial compressive stresses were applied, and deformation was restricted using cross reinforcement of Ø16 mm bars spaced at approximately 230 mm intervals. The reinforcement was positioned at an axial depth of 75 mm from the bottom of the slab, like the typical depth of primary reinforcement in column elements exposed to fire for 240 minutes. Column specimens (Fig. 1) were similarly constructed with primary reinforcement at identical depths and stirrups of Ø8 mm bars at 250 mm intervals. These tests improved the understanding

of concrete spalling behavior in structural elements with reinforcement layouts like real structures, aiding their assessment under fire conditions.

Table 1. Concrete mixes

Component	Unit	Concrete mix	
		A	B
CEM I 52,5R and limestone filler	kg/m^3	500	570
Water	dm/m^3	500	570
Water-powder ratio, w/p	-	0,31	0,28
Aggregates: quartz sand 0-2 mm	kg/m^3	1757	1686

Figure 1. Column specimen with insulaton covers

Acknowledgments

This project was co-financed by the European Union under the FENG.01.01-IP.01-A063/23-00 program entitled "Development, through R&D activities, of an innovative prefabricated industrial hall construction system based on proprietary material, structural, and IT solutions by PEKABEX BET S.A., along with the creation of an environmentally friendly, automated production technology". The research was conducted in cooperation with Cracow University of Technology and the Building Research Institute.

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FIRE TESTING OF VARIOUS MEASURES TO PREVENT SPALLING OF CFRP-REINFORCED CONCRETE

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Abstract

In a joint research project, an interdisciplinary team of researchers and practitioners design a new prefabricated, prestressed floor system for common building constructions. To achieve a lightweight floor element, concrete with a high compressive strength is combined with high tensile strength carbon textile reinforcement. The corrosion resistant carbon textile reinforcement consists of carbon fibres embedded in a polymer matrix. The use of Carbon Fibre Reinforced Polymer (CFRP) allows a reduction of the required concrete cover and enables the design of thin-walled and highly efficient cross-sections in a variety of shapes.

However, the use of concrete with high compressive strength increases the risk of explosive spalling of concrete under fire exposure. Experimental studies conducted at BAM have shown that carbon textile reinforcement creates a discontinuity in concrete resulting in a delamination of the concrete cover. Concrete spalling also depends on the type of CFRP-reinforcement. The comparison of the specimens with different CFRP-reinforcement shows an earlier event of spalling in the case of epoxy-based CFRP.

In the 8th International RILEM Workshop on Concrete Behaviour due to Fire Exposure, fire tests on CFRP-reinforced concrete elements without and with various protection measures to prevent spalling will be presented and discussed. The protection measures include the application of an intumescent coating to the fire exposed surface as well as the use of a modified concrete mixture containing polypropylene fibres (PP-fibres). The concrete mixtures used have a maximum grain size of 2 mm and correspond to concrete grade C50/60. The specimens include variants with and without carbon textile reinforcement. Two types of textile reinforcements are investigated, i.e., acrylate-based and epoxy-based resin. The specimens have circular and square forms. The lateral surfaces of the circular specimens are enclosed by a steel ring to restrain the thermal expansion of the concrete during the fire test. In contrast, at the square specimen's free thermal expansion is allowed. The fire tests are carried out with fire exposure in accordance

with the ISO-834 fire curve and without mechanical load. During the fire test, thermocouples are used to measure the temperature within the specimen and on the unexposed surface.

The fire test results show that the intumescent coating effectively prevents the concrete spalling in both unreinforced specimens and those with acrylate-based CFRP-reinforcement. However, the intumescent coating was not able to prevent the concrete spalling at the specimens with epoxy-based CFRP-reinforcement, despite the time of the spalling was delayed compared to uncoated specimens. The specimens containing PP-fibres show no spalling, which applies to both types of carbon textile reinforcement used as well as the unreinforced variant.

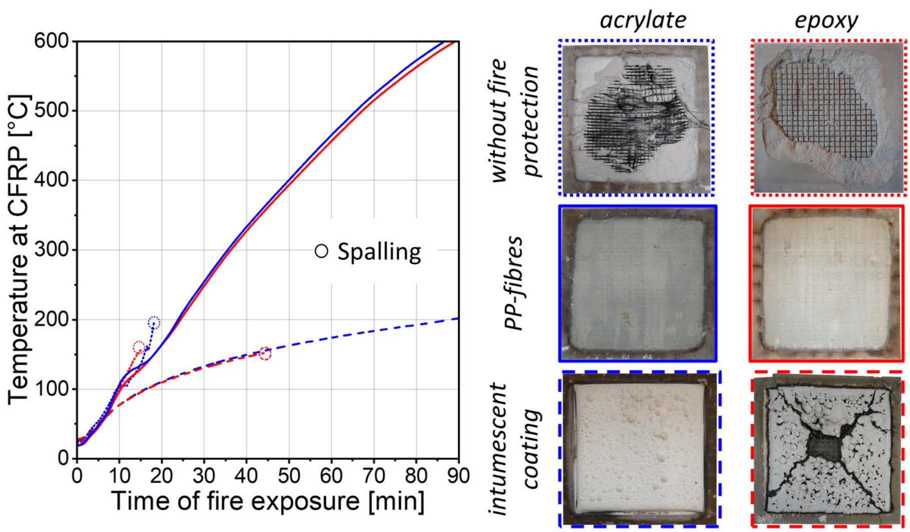

Figure 1. Left: Temperatures at the CFRP-reinforcement measured at square shaped specimens; Right: Fire exposed surface of the specimens after the fire test

S3:

Fire-Induced Concrete Spalling:

Experiments and Modelling

LIBRARY OF EXPERIMENTS ON FIRE-INDUCED CONCRETE SPALLING

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Abstract

This presentation focuses on the spalling behaviour of concrete structures under fire and the creation and development of the *„Fire-Induced Concrete Spalling Library"*, initiated by the RILEM Technical Committee (TC) 306-CFR: *Concrete during Fire – Reassessment of the Framework* (2022–2026). This committee was established in response to the growing demand for a unified and comprehensive understanding of the complex phenomena that occur in concrete during fire exposure, particularly explosive spalling, which remains one of the most critical and unpredictable issues in fire safety engineering of concrete structures.

The primary objective of *Task C*: *"Fire spalling library"* of the TC 306-CFR is to develop an open-access, quality-controlled experimental database that consolidates existing knowledge from the literature and industrial fire tests. This database will specifically target studies that investigated spalling as a central phenomenon, as well as those where spalling was observed as a side effect, even if not explicitly studied. By including both categories, the library aims to provide a more holistic picture of how and why spalling occurs, contributing to a reassessment of existing predictive frameworks and engineering models.

This effort is inherently interdisciplinary and international in scope. The committee includes experts from academia, research institutions, and industry worldwide, fostering collaboration and knowledge exchange across sectors. The database will include not only experimental results, but also detailed metadata on test configurations, material properties, boundary conditions, and thermal loading, enabling better comparison, modelling, and validation efforts.

Additionally, TC 306-CFR aims to improve the general framework for understanding concrete behaviour in fire by identifying critical gaps in existing data, suggesting standards for future testing, and promoting the development of new modelling approaches. By leveraging its members' collective access to key publications, unpublished datasets, and experimental expertise, the committee is uniquely positioned to lead this initiative.

Ultimately, the *Fire-Induced Concrete Spalling Library* is envisioned as a foundational tool that will support future research, enhance fire safety engineering practices, and facilitate the development of performance-based design methods for concrete structures under fire conditions.

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SAMPLE SIZE EFFECTS ON FIRE-INDUCED CONCRETE SPALLING

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Abstract

Concrete spalling under fire exposure presents a serious threat to structural integrity and life safety. Although fire-induced spalling has been studied since the 19th century, the phenomenon remains poorly understood due to inconsistent experimental results and varying test configurations. A particularly under-explored variable is sample size, specifically the influence of thickness and span. This study addresses this gap by conducting a parametric investigation using a validated finite element (FE) model developed in ABAQUS [1]. The model incorporates temperature-dependent material properties and applies the Concrete Damage Plasticity (CDP) model to simulate the coupled thermo-mechanical behaviour of concrete under fire. The heating follows the standard ISO 834 fire curve, and different boundary conditions, restraint and loading, are applied to reflect realistic scenarios. As shown in Fig. 1, four configurations, extracted from [2], were modelled: (A)Unrestrained and unloaded, (B) Partially restrained using a circumferential steel ring, (C) Eccentrically loaded near the hot face, (D) Eccentrically loaded near the cold face. Each configuration was investigated numerically under varying thickness and span to assess their influence on stress state, displacement, and spalling potential.

KEY FINDINGS

- In unrestrained slabs (A), increasing thickness leads to higher compressive and tensile stresses with steep stress gradients, correlating with spalling.
- In partially restrained slabs (B), the steel ring limits expansion and overrides the effect of thickness.
- For eccentrically loaded slabs (C and D), span has minimal effect on stress but influences surface displacement and failure abruptness.
- Rear-loaded samples (D) exhibit higher tensile stress deeper in the sample, and larger displacements, but the overall stress distribution remains similar.

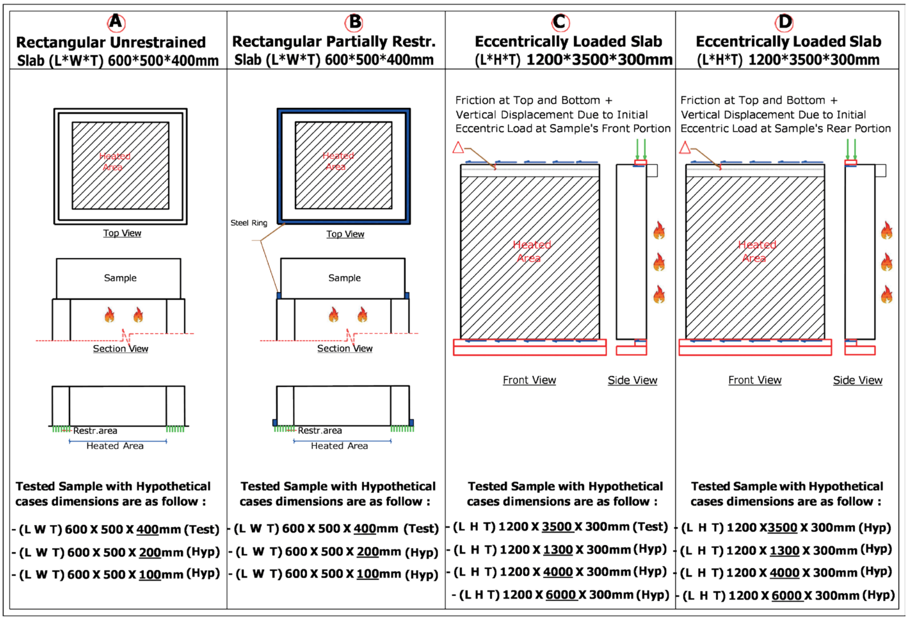

Figure 1. Different sample sizes with various boundary conditions

CONCLUSION and RECOMMENDATIONS

- Thickness has a stronger effect on spalling than span.
- Thick slabs build high stress and spall explosively; thin ones bend and fail more gradually.
- Restraint reduces stress gradients and improves spalling resistance.
- Span has little effect on stress but longer spans deform more and fail less abruptly.
- Eccentric loading affects initial bending: Front-eccentric slabs bend away from the fire at first, then toward it as heating progresses, rear-eccentric slabs bend toward the fire from the start, with heating amplifying the deformation, hence fail more smoothly, emphasizing test set up effects on spalling.
- Accurate fire tests must reflect real thickness, loading, and restraint; span is less critical.

Acknowledgments

Many thanks to Newcastle College for their support in attending this workshop.

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PREDICTION OF PORE PRESSURE IN HEATED CONCRETE: STOCHASTIC ANALYSIS AND DRIVING PARAMETERS

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Abstract

Understanding concrete behavior at high temperatures is crucial due to spalling, which can lead to structural collapse, economic losses, and potential loss of life. While spalling mechanisms are not fully understood, pore pressure buildup within concrete is believed to play a key role [1]. Predicting pore pressure during heating is challenging due to the complex, nonlinear coupling of thermal and hygral processes, significant material variability, and the demanding nature of property characterization. For similar concrete mixes and thermal conditions, measured pore pressures range from under 1 MPa [2] to 4 MPa [3], likely due to this variability.

To identify key material parameters and guide experimental efforts, this study presents a stochastic analysis using a one-dimensional stochastic finite element model based on a coupled thermo-hygral multiphysics framework. A sensitivity analysis is performed on critical thermal and hygral parameters, varied using their coefficients of variation while others are held constant, to quantify their impact on pore pressure predictions.

Results show intrinsic permeability and its law coefficients have the greatest influence. Dehydration-related parameters are also significant, while thermal properties and those governing porosity and liquid saturation have less impact. Depending on the parameter set, predicted pore pressures varied by nearly a factor of three, underlining the uncertainty driven by material variability (see Figure 1).

This study confirms existing assumptions in the literature regarding the critical role of permeability in modelling concrete at high temperatures, while also highlighting the significance of dehydration processes. In doing so, it provides guidance on where to direct material characterization efforts. Further, the findings reinforce the need for enhanced experimental characterization and more rigorous uncertainty quantification of material properties.

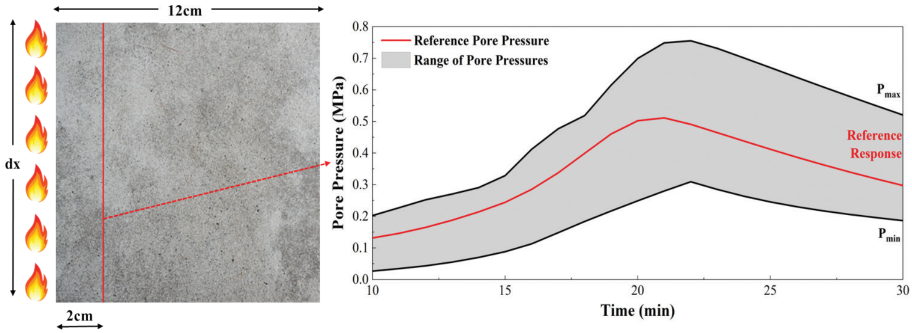

Figure 1. View of the simulated geometry (left) and FE prediction of the pore pressure y evolution with time at 20 mm from the heated boundary of the specimen (right)

Acknowledgments

The authors would like to thank EPSRC, Sellafield Ltd., Nuclear Restoration Services and ANR Project (Grant no: ANR-23-CE51-0001-01) for providing financial support.

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COMBINING QUANTITATIVE IMAGING AND NUMERICAL MODELING: AN INSIGHT INTO CONCRETE AT HIGH TEMPERATURE

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Abstract

The evaluation of cementitious materials under high temperatures currently suffers from the absence of a consistent approach integrating both experimental investigations and computational modeling. Existing numerical tools often exhibit limited predictive accuracy, particularly when phenomena like spalling arise. Furthermore, standard testing procedures present inherent limitations in their ability to fully represent the material's behavior under such extreme conditions.

To address these shortcomings, the proposed approach focuses on developing a comprehensive numerical tool – a digital twin – informed and validated by ad hoc experiments (see fig.1) [1,2]. A comprehensive experimental campaign, designed to generate a consistent material dataset, will be combined with advanced imaging techniques, such as neutron and X-ray tomography, to provide insight into material behavior and the underlying physics. Quantitative imaging will serve as a cornerstone for the validation of numerical models. This integrated strategy represents a novel approach in the current landscape of research concerning the behavior of concrete at high temperatures.

Acknowledgments

The authors acknowledge the support of the French Agence. Nationale de la Recherche (ANR) (project MULTI-FIRE ANR-23-. CE51-0001-01)

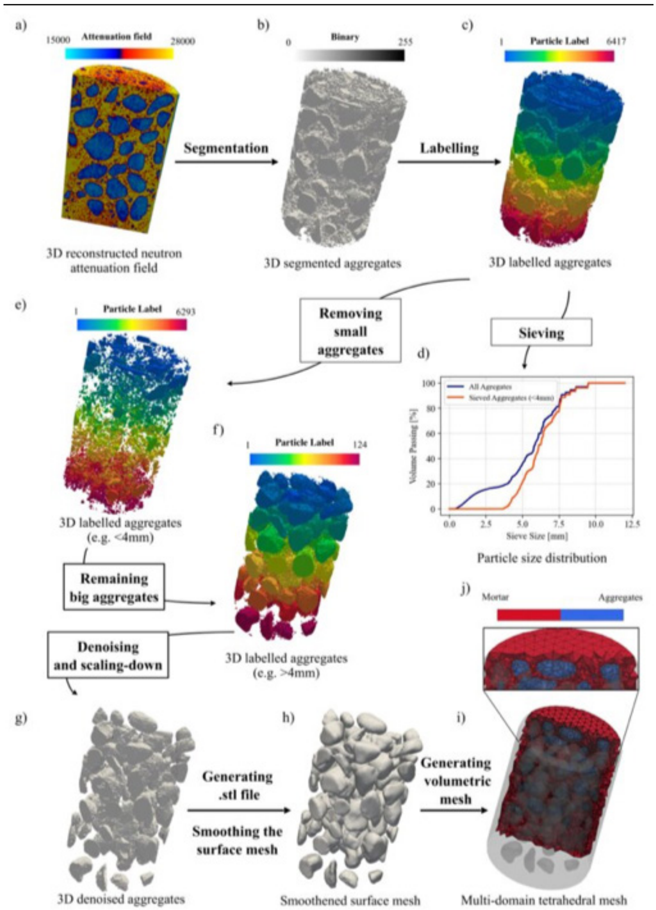

Figure 1. Pyhon pipeline: *https://github.com/ANR-MultiFIRE/TomoToFE*

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IMPLICATIONS OF USING STRESS-STRAIN RELATIONSHIP WITH IMPLICIT TRANSIENT STRAIN FOR CONCRETE AT ELEVATED TEMPERATURE

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Abstract

The uniaxial compressive stress-strain relationship for concrete at elevated temperature in EN 1992-1-2 [1], implicitly considers the transient strain components. This stress-strain relationship is widely used in numerical models for simulating a wide range of concrete types at elevated temperatures. The numerical models vary from beam elements using only uniaxial stress-strain relationships to 3D solid elements using yield surfaces under 3D state of stress. In literature two main limitations of stress-strain relationship with implicit transient strain are frequently mentioned; 1) the implicit component of transient strain is insufficient [2,3] and 2) recovery of otherwise irrecoverable transient strains during unloading or during cooling phase [4].

The implicit stress-strain curve with a plasticity-based material model, implies that the plastic strain (which by its definition is irrecoverable) implicitly consists of the irrecoverable transient state strain and the plastic strain due to mechanical stresses. Therefore, the above-mentioned limitations would mean the same i.e., EN 1992-1-2 implicit model underestimates the irrecoverable transient stain component. Hence, logic dictates that to increase the implicit transient strain component the plastic strain components should be increased. With this aim the paper presents a numerical investigation at material and member level using the stress strain relationships given by Eq. (1) and (2).

Eq. (1) takes the form of EN 1992-1-2 stress strain relationship when “n” equals 3 and Eq. (2) is the stress-strain equation from EN 1992-1-1 [5] for concrete at ambient condition. Both Eq. (1) and (2) increases the plastic strain component by increasing the Youngs modulus. Furthermore, Eq. (2) also offers the possibility to account for the Youngs modulus degradation as observed in experiments. It should be noted that the EN 1992-1-2 stress-strain relationship leads to a different degradation of Youngs modulus with temperature as compared to experiments.

$$\sigma(T)=\frac{n\cdot\varepsilon\cdot f_{c,T}}{\varepsilon_{c1,T}\cdot\left((n-1)+\left(\frac{\varepsilon}{\varepsilon_{c1,T}}\right)\right)} \quad where,\ n=2 \tag{1}$$

$$\sigma(T)=f_{c,T}\cdot\frac{k_T\eta-\eta^2}{1+(k_T-2)\eta} \quad where,\ \eta=\frac{\varepsilon}{\varepsilon_{c1,T}} \quad k_T = Plasticity\ index \tag{2}$$

The predicted response of concrete cylinder(s) with different load levels and reinforced concrete column(s) using the stress-strain relationships given by EN 1992-1-2, Eq. (1) and Eq. (2) are compared in this paper. The 3D finite element simulations using solid elements are performed using general purpose finite element software Ansys.

The study shows that a stress-strain relationships which represents realistically the Young's modulus of concrete at elevated temperature and, also have higher irrecoverable strain component (plastic strain) were of little help in simulating the response of concrete at material scale and member scale as observed in experiments. Thus, emphasising on the need for looking at the limitations of implicit stress-strain curve from a different perspective.

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RESIDUAL MECHANICAL BEHAVIOUR OF A REFERENCE MORTAR EXPOSED TO HIGH TEMPERATURE FOR THCM MODELLING UNDER FIRE

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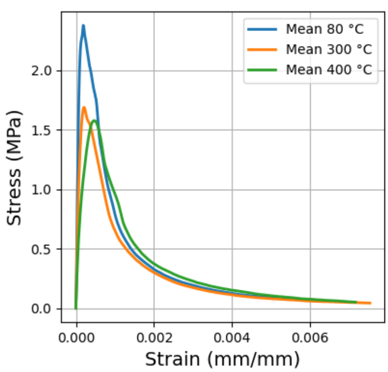
Abstract

Materials and Methods A standardised mortar (EN 196-1) was preparing using CEM II 32.5 cement, standard sand, and a water-to-cement ratio of 0.5. After 28 days of water curing, specimens were heated at 1°C/min to 120, 300, 400 or 600°C and naturally cooled before testing, avoiding spalling and thermal gradients.

Three sample geometries were tested: Cylindrical specimens (Ø 4.5 cm×10 cm) for uniaxial compression (compressive strength, Young's modulus, Poisson's ratio); Prismatic beams (4×4×16cm) for flexural strength; Dog bone-shaped specimens for direct tension tests, enabling full stress–strain curve analysis from elastic to failure regimes.

Experimental Results In this abstract, a particular focus is placed on the direct tensile tests, for which post-elastic behaviour, due to damage, is known to be difficult to measure in quasi-brittle materials. Figure 1 presents the stress/strain curves obtained at various temperatures, illustrating the progressive deterioration of tensile capacity. Tensile strength decreased from 3.39 MPa (80°C) to 1.59 MPa (400°C) indicating severe microstructural degradation. **Young's modulus**, measured from the linear portion of the stress–strain curves in both tension and compression, shows an almost linear decrease with temperature from 21 GPa to 1.5GPa at 600°C. This stiffness loss is attributed primarily to dehydration and the evolution of the pore structure. These results are not particularly innovative for the pre-peak part. In contrast, our study on the reference mortar produced fairly repeatable results and with little variability.



Moreover, the tensile results are complemented by compression tests (included the transverse strain and post-peak behaviour) and bending tests, giving a complete dataset for advanced simulations at high temperature.

Mazars Damage Model Calibration The **Mazars isotropic damage model** [1] is widely used to simulate concrete damage. It links nominal stress σ as a function of the effective stress $\tilde{\sigma}$ and a scalar damage variable D:

$$\boldsymbol{\sigma} = (1 - \mathrm{D})\ \tilde{\boldsymbol{\sigma}} \tag{1}$$

Damage evolves with equivalent strain ε as:

$$\mathrm{D} = 1 - (\varepsilon_0 / \varepsilon) \exp\left[-\beta (\varepsilon - \varepsilon_0)\right] \qquad \text{for } \varepsilon \geq \varepsilon_0 \tag{2}$$

Here, **ε_0 is the damage onset threshold strain**, **β** controls damage growth. The model is implemented in Cast3m to simulate 3D tensile tests. An optimisation procedure is used to calibrate **the parameters at each temperature, providing a consistent set of parameters for multiphysics THCM simulations.**

Conclusion and Outlook This study provides a consistent set of residual mechanical data for mortar exposed to high temperatures, using three complementary testing configurations. The data are suited for calibrating damage-based constitutive models, and for improving input databases for THCM simulations in structural fire engineering. Ongoing work integrates porosity and permeability measurements to complete the multiphysics coupling. The dataset contributes to efforts within **RILEM TC CFR**, supporting the harmonisation of thermal degradation models for concrete materials.

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S4:

Fire-Induced Concrete Spalling

in Environmentally Optimized Concrete

FIRE PERFORMANCE OF SWISS BUILDINGS INCORPORATE CONCRETE WITH RECYCLED AGGREGATES

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Abstract

This research project investigates the propensity to explosive spalling in concrete containing recycled aggregates when exposed to fire. Although such concretes have been used in Switzerland for over two decades, the used concretes lack systematic studies concerning their fire behaviour. The project was initiated in response to the revised EN 1992-1-2 standard, which requires fire spalling testing for concretes with more than 20% recycled aggregate content, in response to recent research results (e.g. [1], [2]). This requirement could impose significant cost and technical burdens on producers.

This study assesses how core moisture content (WA24), compressive strength, and substitution rate of recycled aggregates influence explosive spalling. Common Swiss practice served to design concrete mixes, incorporating (i) varying proportions of recycled concrete and recycled mixed aggregates and (ii) targeting different WA24 levels and compressive strength ranges. Material screening fire tests followed RILEM recommendations. Accompanying measurements included core moisture, gas permeability, porosity, surface moisture, and strength at the time of testing.

Almost all RC concretes were prone to explosive spalling, with only those exhibiting low strength (below ~25 MPa) showing no damage (see Table 1). An increased WA24 and both the likelihood and severity of spalling showed a strong correlation. For concretes with WA24 values around 4–6%, even moderate strengths in the range of 28...33 MPa led to significant spalling. However, all tested specimens exhibited high surface moisture levels of 4.0 … 4.8% (measured with Tramex).

Accordingly, the next project phase will address the key challenge identified: ambient drying alone may be insufficient to achieve representative internal moisture distributions. Instead, the focus will be on replicating the moisture conditions typically found in buildings during service. The corresponding investigation on existing structures will rely on surface moisture measurements calibrated against internal moisture profiles from extracted cylinders. The goal is to define realistic reference conditions reflecting moisture variations depending on building locations and ages, enabling fire testing scenarios representative of real-world exposure.

Table 1. Summay of tested mixes; note: RCA = Recycled Concrete Aggregate, RCM = Recycled Mixed Aggregate, start = initiation of spalling, depth = spalling depth, *u* = moisture content

Mix	**RC rate**	**fc,cube [MPa]**	**Start [min]**	**Depth [mm]**	**u [%]**
C25/30	0% RCA	40.4	0; 0	0	4.7
C30/37	0% RCA	49.4	0; 0	0	4.7
RC-C2	24% RCA	38.5	0; 0	0	4.2
RC-C2	24% RCA	43.6	6; 3	26	4.0
RC-C4	50% RCA	32.3	0; 4	0	4.8
RC-C4	50% RCA	42.8	2; 10	39	4.5
RC-C6	100% RCA	34.0	2; 28	61	4.8
RC-C6	100% RCA	33.8	5; 14	65	4.7
RC-M2	24% RCM	38.7	3; 4	14	4.7
RC-M4	77% RCM	21.9	0; 0	0; 0	4.3

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INVESTIGATIONS INTO THE EXPLOSIVE SPALLING OF ENVIRONMENTALLY OPTIMISED CONCRETES IN THE EVENT OF FIRE

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Abstract

The behaviour of environmentally optimised concretes in the event of fire is currently being investigated in a joint research project. The Karlsruhe Institute of Technology (KIT) is examining the thermo-mechanical and thermo-physical properties of these concretes, while the German Cement Association (VDZ) is carrying out tests on fire-induced spalling.

One key approach to reducing CO_2 emissions from cement production is to use cements with a lower clinker content. The new EN 197-5:2021 standard [1] introduces the cement type CEM VI. CEM VI cements have a clinker content of between 35% and 49%, with the remaining constituents consisting of between 31% and 59% blast furnace slag and between 6% and 20% limestone.

It was shown in [2] those concretes produced with blast furnace cements (CEM III/A), i.e. cements containing 35–64% blast furnace slag, exhibited increased susceptibility to explosive spalling in fire tests. On the other hand, concretes made from Portland limestone cements (CEM II/A-LL) exhibited a low tendency to spall due to their pore size distribution and a pronounced interfacial transition zone (ITZ) between the cement paste and the aggregates. Therefore, it could be expected that the additional use of limestone as a main constituent of CEM VI (S-L) or CEM VI (S-LL) cements will reduce the spalling susceptibility of concretes with cements containing blast furnace slag. The present research project investigates the potential of using the new, clinker-efficient cement types for concrete elements that are vulnerable to spalling.

The use of recycled aggregates plays an important role in increasing the resource efficiency of concrete and conserving primary natural raw material sources. The number of scientific studies on the spalling of concrete with recycled aggregates is limited. For this reason, rather conservative rules have been included in Annex C, ‚Recycled Aggregate Concrete Structures', of the revised prEN 1992-1-2:2021 standard.The current research project therefore systematically investigates the susceptibility of concretes with different proportions of recycled aggregates (with different porosities) and different storage regimes.

Recycled aggregates consist of natural aggregates, as well as the cement paste or mortar that adheres to them from the ‚old' concrete. Due to the presence of this cement paste, recycled aggregates tend to be more porous and absorb more water than natural aggregates. High concrete moisture content can significantly contribute to spalling in the event of a fire. Therefore, depending on how the recycled aggregates are stored prior to concrete production, concretes containing recycled aggregates could be more prone to spalling than those containing natural aggregates, depending on the concrete's composition.On the other hand, the difference in thermal expansion between the aggregate and the cement paste is expected to be smaller for recycled aggregates than for natural aggregates. This could reduce the susceptibility to spalling.

First research results will be presented during the workshop in Kraków.

Acknowledgments

The project is supported within the programme for promoting the Industrial Collective Research (IGF) of the German Federal Ministry of Economic Affairs and Energy based on a resolution of the German Parliament.

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ANALYSIS OF THERMOHYDRAULIC SPALLING IN BLENDED CEMENT CONCRETE

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Abstract
The cement industry is responsible for high CO2 emissions, which occur during the production of Portland cement clinker. To reduce these emissions, blended cements become more and more popular. Therefore, it is expected that these cements find frequent application in infrastructure and housing construction in the future. The increased use leads to a higher probability of concrete buildings with blended cements being exposed to extreme conditions such as fire. Concrete under fire can experience heavy damage in the form of explosive spalling which is caused by thermohydraulic and thermomechanical mechanisms leading to the lowering of the cross section. Furthermore, the reinforcement may be subjected directly to the fire, which can lead to a rapid decline in its load-bearing capacity.

The current state of the art showed that the cement type used can show great impact on the fire induced spalling behavior. However, large proportion of the reported spalling results took place under unsuitable testing conditions with insufficient evaluation. The smaller fraction of more profound spalling experiments showed inconsistences and contradictions, whereby no clear relation between cement type and spalling susceptibility could be drawn [1]. Against this background in depth spalling experiments following the recommendations of RILEM TC 256-SPF [2] of concrete with four different types of cement including Portland cement (CEM I), limestone cement (CEM II/A-LL), slag cement (CEM III/A) and Portland pozzolana cement (CEM II/B-Q) were carried out. Summarizing, CEM I concrete showed the lowest amount of spalling, followed by CEM II/A-LL and CEM III/A concrete and lastly CEM II/B-Q concrete [3]. To understand the appearing differences in spalling susceptibility, the influence of the thermally induced moisture transport was studied by 1H-NMR relaxometry. From a thermohydraulic point of view, it was shown that initial differences of permeability and moisture content are responsible for the variations in spalling susceptibility. Furthermore, the appearance of the moisture clog was confirmed in every sample [4]. To further analyze the contribution of the thermohydraulic mechanism, the phase composition of the cement paste was analyzed before and after high temperature exposure regarding the dehydration behavior. Less C-S-H and portlandite were observed in CEM III/A

and CEM II/B-Q pastes. However, the C-S-H seemingly showed increased thermal stability. In addition, lower amounts of AFt and AFm phases were found in blended cement pastes corresponding to lower amounts of degradation and water released at lower temperatures.

In conclusion, the increased spalling proneness in blended concretes is caused by higher initial moisture contents paired with lower initial permeabilities and less amounts of early dehydrating phases. It was also shown that the addition of PP-fibers remains a successful avoidance strategy regardless of the cement type used, by increasing permeability and thus the release of water vapor.

Acknowledgments

We gratefully acknowledge the support of the German Research Foundation (DFG) and extend our gratitude for their financial support throughout the project (Project Nr. 491928256).

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EXPERIMENTAL INVESTIGATIONS ABOUT THE FIRE PERFORMANCE OF CONCRETE WITH HIGH RECYCLED AGGREGATE CONTENT

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Abstract

Over the past decade—particularly in recent years—construction costs have risen significantly, largely due to the growing scarcity of natural resources. Simultaneously, the annual generation of millions of tons of mineral-based construction waste underscores the need to recycle aggregates for concrete, a practice that both alleviates natural-resource depletion and advances environmental-change mitigation.

According to DIN EN 12620 [1], which governs the use of aggregates in concrete, two types of recycled aggregates—Type 1 and Type 2—are defined in DIN 4226-101 [2] based on their composition and quality. The primary distinction between the two types lies in the proportion of their constituent materials. Type 1 contains approximately 90% Rcu and only about 10% Rb, whereas Type 2 includes around 70% Rcu and a significantly higher proportion of Rb, approximately 30%. In this classification, Rcu refers to constituents derived from concrete, mortar, concrete-based products, and natural stone, while Rb denotes materials originating from clay masonry units, such as solid clay bricks and clinker bricks.

According to the DAfStb [3] guidelines for reinforced concrete, the proportion of recycled aggregates—based on the total aggregate volume—is limited to 45% for Type 1 and 35% for Type 2. The research project presented here examines how the fire performance of concrete is influenced when these recommended limits are exceeded. To investigate this, concrete specimens were produced using recycled aggregates at substitution levels of 45%, 70%, and 100% for Type 1, and 35%, 70%, and 100% for Type 2.

To achieve this aim, a three-phase experimental program was developed. In the first phase, the thermal properties of the materials were investigated, including the determination of specific heat capacity, thermal conductivity, and mass loss. The second phase focused on analyzing the stress–strain behavior at elevated temperatures, as well as the material's thermal expansion. The third phase was dedicated to examining the spalling behavior. To comprehensively investigate the

factors affecting the behavior of this type of concrete at elevated temperatures, overlapping experimental techniques were employed. For example, samples used for mass loss assessment were tested using both thermogravimetric analysis (TGA) and cone calorimetry.

The experimental results suggest that while the proportion of recycled aggregate in concrete offers useful key insights for predicting its high-temperature performance, it must be supplemented with additional influential factors such as casting conditions, pore structure, and other material characteristics. This is particularly relevant for predicting spalling behavior, where ambient temperature conditions also play a significant role. Nonetheless, the data collected offer a valuable foundation for the development of predictive models that describe the behavior of concrete with high recycled aggregate content under fire exposure.

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S5:

Sustainable Materials at High Temperature

FOAMED GEOPOLYMER COATINGS AS SUSTAINABLE THERMAL PROTECTION FOR CONCRETE ELEMENTS

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Abstract

For structural safety, solutions to reduce the risk of spalling are continually being sought. Two well-known methods are the addition of polypropylene fibers and the use of thermal barriers. Research on geopolymers has shown that these materials demonstrate high resistance to elevated temperatures due to their aluminosilicate polymer network structure. The presence of dispersed nanopores in geopolymer concrete allows water vapor to migrate and evaporate without damaging the aluminosilicate network. Given these favorable high-temperature properties, our study investigates the potential of geopolymer-based mortar coatings to protect concrete by reducing temperature rise within its cross-section and minimizing spalling during fire exposure. As cement-free composites derived from industrial by-products, geopolymers also contribute to sustainable construction, making them a promising material for the future.

High-strength concrete specimens for fire testing were produced using CEM I 42.5R cement, basalt aggregate, and a water-to-cement ratio of 0.30, a mixture known to be susceptible to thermal spalling. The protective layer was prepared from geopolymer mortar based on fly ash from "Połaniec" power plant, ground granulated blast furnace slag, and quartz sand, activated with an alkaline solution (Geosil 34417) and water. Two variants were tested: non-foamed and foamed (with aluminum powder as the foaming agent). Both variants contained 2 kg/m^3 of polypropylene fibers to reduce shrinkage and improve fire stability.

Laboratory tests included density, flexural, compressive, and splitting tensile strength measurements before and after exposure to 350 °C and 900 °C. Fire performance and spalling tests were conducted in the DRAGON furnace under ISO 834-1 standard fire conditions for 60 minutes, according to the Recommendation of RILEM TC 256-SPF for materials screening tests [1]. Temperature distribution, depth of spalling, and adhesion (Pull-off method) of geopolymer coatings before and after fire exposure were evaluated.

Results showed that conventional high-strength concrete lost over 80% of its strength at 900 °C, while geopolymer mortars retained 50–70% of their mechanical performance, with the non-foamed variant even exhibiting a slight strength increase after heating to 350 °C. Unprotected concrete exhibited spalling up to 8.8 mm deep, whereas both geopolymer coatings completely eliminated spalling. The foamed geopolymer variant maintained excellent adhesion and reduced internal concrete temperature to approximately 110 °C, compared to over 900 °C for unprotected concrete.

The study confirms the potential of geopolymer coatings, particularly foamed formulations, as effective thermal barriers for concrete structures, significantly mitigating spalling and temperature rise during fire, and contributing to sustainable construction using cement-free, industrial waste-based binders.

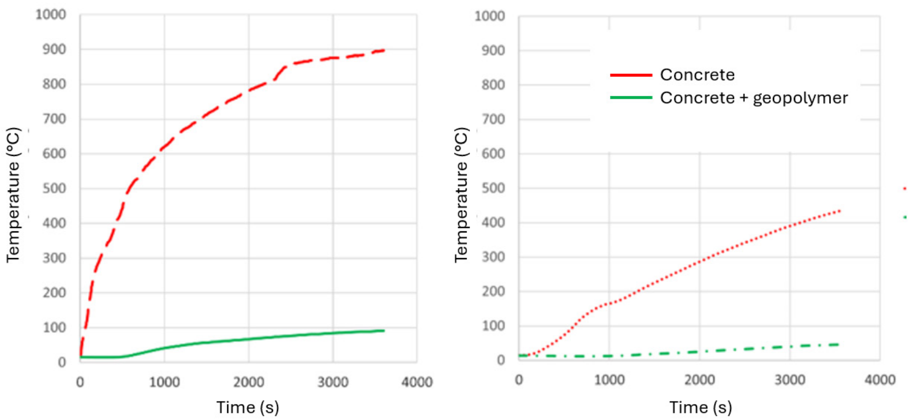

Figure 1. Left: temperature development on the surface of concrete with and without the geopolymer layer; right: temperature development at a depth of 3 cm in concrete with and without the geopolyer layer

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HIGH-TEMPERATURE BEHAVIOUR OF CONCRETE WITH LOW-EMISSION BINDERS: CURRENT KNOWLEDGE AND RESEARCH GAPS

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Abstract

In the face of growing demands for reducing greenhouse gas emissions, increasing attention is being paid to alternative, low-emission binders used in concrete production. Geopolymers and systems incorporating mineral additives such as fly ash are among the most promising [1].

The behavior of concrete under the influence of high temperatures – both in fire situations and long-term thermal exposure – is crucial from the point of view of structural safety. Previous studies on concretes with low-emission binders indicate significant diversification of their thermal and mechanical properties depending on chemical composition, type of mineral additives and microstructure [2]. Some of these materials show greater resistance to degradation at high temperatures than concrete made of traditional Portland cement, but the lack of standardized test methods and long-term data makes it difficult to clearly assess their effectiveness [1][3].

Despite significant potential to reduce CO_2 emissions, the behavior of these materials under conditions of elevated temperature and fire is not yet sufficiently understood, which makes their use in structures requiring high fire resistance difficult (e.g. tunnels, industrial facilities, high-rise buildings).

Despite these positive results, the behavior of low-emission concretes at high temperatures remains ambiguous and strongly depends on the mix composition, precursor properties, curing method and service conditions. There are still significant research gaps, including in the field of microstructural degradation mechanisms (dehydration, thermal cracking, pore pressure), lack of standardized fire testing methods and insufficient knowledge about long-term durability after fire [1][2].

The presentation will present the current state of knowledge regarding the high-temperature behavior of concretes with low-emission binders, including literature research results, identification of key degradation mechanisms, and suggestions for future research directions. Particular emphasis will be placed on knowledge gaps related to durability, thermal shock resistance, interactions with chemical admixtures, and the possibilities of standardizing research for this type of materials.

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CONSTRUCTION DECARBONIZATION VIA LOW EMBODIED CARBON CONCRETE AND OPTIMIZED SECTIONS: IMPACTS ON STRUCTURAL FIRE DESIGN AND RECOMMENDATIONS

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Abstract

As said by the French writer Antoine de Saint-Exupéry „With regard to the future, our task is not only to predict it, but to enable it", Citadelle, 1948. Decarbonization has become today a global imperative and a priority for the construction industry. With the increasingly successful reduction of operational energy and thus carbon emissions, the industry's current challenge is now to reduce the carbon intensity of the structures themselves and to accelerate the transition to net-zero emission construction. Concrete is the most widely used construction material in the world and its impact on the environment is part of embodied carbon emissions. The constituent in concrete responsible for most CO2 emissions is cement. The cement industry is a major emitter of CO2, responsible for approximately 6% to 8% of global greenhouse gases emissions. With rare exceptions, concrete is now omnipresent in individual and collective buildings we live and work in, and in transport infrastructures like roads and bridges that connect us. The predominance of the concrete material in our daily lives and the actual crucial concerns related to sustainable development obliges us to reduce the emissions related to its production. The easiest way for construction to begin its journey to net-zero is to use low-carbon concrete or to use less concrete by adopting optimized designs practices allowing concrete savings, and architects and structural engineers have also a key role to play. Researchers from the University of Bath, Cambridge and Dundee involved in the ACORN project acronym of Automating Concrete Construction, has also developed a segmented vaulted thin-shell concrete floor that uses 75% less material than a traditional flat slab floor and 60% less CO2 emissions [1]. The floor derived from principles of shallow arching action known as compressive membrane action, to initiate internal load transfer dominated by compression with minimal tensile stress rather than bending normal stresses, and this could allow significant material savings over bending structures. A 4.5m×4.5m

prototype was built in the NRFIS Laboratory of Cambridge University's Civil Engineering Department. Engineers from Massachusetts Institute of Technology also developed a segmental concrete columns-beams frame for buildings made of assembling thin elements, called PixelFrame [2]. Like the ACORN floor slab, the Pixelframe allows the concrete building elements to be disassembled and reused, driving circularity, and lowering the environmental impact. The system allows for a 77% reduction in embodied carbon in comparison to typical cast on-site reinforced concrete frame construction. It is however important to emphasize that levels of material savings obtained by focusing only on mechanical resistance could be revised downwards when taking also into account fire, acoustic and dynamic performances whose requirements are standardized and must be respected. Fire performance requirements must be thoroughly assessed before implementation in real building projects. This present study focuses on fire performance and aims to examine what impacts the thinning of structures and the use of low-carbon concrete could have on Eurocode fire design requirements, specifically concrete spalling, thermal insulation and residual resistance. To this end, an experimental campaign was performed on representative shells exposed to an ISO 834 standard fire during 2 hours, and completed with thermo-mechanical finite element modeling. Different parameters are studied and their possible impact on the results: shell thickness, ordinary and low carbon concrete, addition of steel and polypropylene fibers in the recipe, and addition of insulating material. The authors' goal at large is to share learnings and recommendations that will help engineering accelerate progress towards net zero.

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THERMAL DEGRADATION AND MICROSTRUCTURAL EVOLUTION OF LC3 MORTARS WITH VARYING CLINKER CONTENT

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Abstract

Limestone Calcined Clay Cement (LC^3) is a low-carbon binder capable of reducing CO2 emissions by up to 40% compared to traditional Portland cement. This study examines various LC^3 formulations exposed to high-temperature conditions to inform discussions on potential adaptations of fire design standards for these new low-carbon binders.

1. Methodology

Four mortars (M-100, M-60, M-50, M-40) were prepared with a 2:1 calcined clay to limestone ratio, supplemented with hemihydrated calcium sulfate (see Table 1). Each formulation underwent thermal cycling at 150°C, 300°C, 450°C, 600°C, and 800°C, followed by cooling, with a 2-hour isothermal hold at each temperature level. The mortars' properties were assessed through several tests: compressive strength according to NF EN 196-1, ultrasonic pulse velocity, porosity, thermal expansion, and microstructural analyses using Thermogravimetric Analysis (TGA), X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM).

Table 1. Binder Mix compositions

Wt%	Clinker	Gypsum	Calcined Clay	Limestone	Hemihydrate α
M-100	97.5	2.5	-	-	-
M-60	60	1.6	24.9	12.5	1.1
M-50	50	1.3	31.1	15.6	2
M-40	40	1	37.4	18.7	2.9

2. Results & Discussion

- At 150°C, LC^3 mortars exhibit a mechanical strength loss of approximately 15% to 20%, whereas CEM I mortar maintains stable strength.
- LC^3 mortars display lower ultrasonic pulse velocities, correlating with their increased porosity.

- Beyond 450°C, LC^3 mortars retain better mechanical performance compared to CEM I, which experiences a sharp decline.
- TGA, XRD, and SEM analyses reveal a progressive dehydration of hydration products, with notable transformations including ettringite, C-(A)-S-H gels, and carboaluminates.

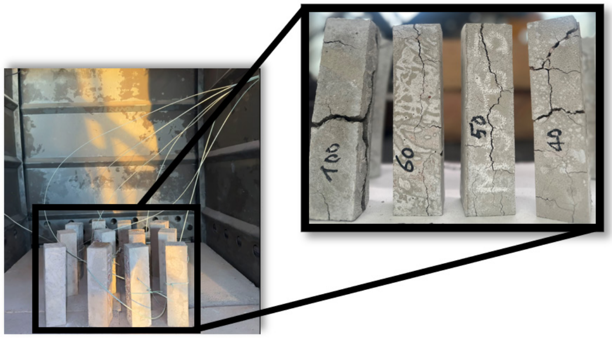

Figure 1. Samples before and after heating to 800°C

3. Conclusion

This study assessed the impact of clinker content variation on high-temperature performance of LC^3 mortars. While LC^3 presents an environmentally promising alternative, a mechanical strength loss was observed starting at 150°C, which must be considered in the design of structures exposed to fire.

Acknowledgments

This research was made possible through the support of CY Cergy Paris University and L2MGC, as well as the valuable technical assistance of their teams.

FIRE PERFORMANCE ASSESSMENT OF CONCRETES MADE WITH NON-STANDARDIZED BINDERS – A FRENCH NATIONAL FRAMEWORK

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Abstract

In France, in response to the urgent need to reduce the carbon footprint of construction materials, a large multidisciplinary working group was established under the auspices of the French standardization Committee dedicated to Concrete material. This group has brought together more than fifty stakeholders from across the concrete value chain, including material producers, contractors, technical experts, and public authorities. One of the key deliverables of this collaborative effort is the Fascicule de Documentation FD P 18-484 [1], a technical booklet that provides a comprehensive overview of the experimental needs for assessing concretes formulated with new and non-standardized low-carbon cements and additions. It covers a wide range of properties, including chemical characterization, mechanical and durability performance, shrinkage, creep, bond with reinforcement, and fire behaviour.

The FD P 18-484 booklet introduces a classification system for new cements and additions, organized into five categories: 1a, 1b, 2a, 2b, and 3. This classification reflects how closely the characteristics of these binders resemble those of standardized binders. The experimental programs defined in the booklet are adapted to each category, following a progressive approach: the further a binder deviates from current standards, the more extensive the required testing.

The FD P 18-484 also provides specific recommendations for evaluating the fire performance of concretes made with new low-carbon binders. Three main aspects are addressed: thermal properties at high temperature, mechanical properties at high temperature, and spalling behaviour. Regarding thermal properties, only category 3 is subject to experimental characterization of diffusivity, performed via inverse calibration based on test data. For mechanical performance, the required tests include compressive strength at elevated temperature, free thermal strain, and transient thermal strain. These tests are conducted using a comparative approach, in which the performance of concretes made with new binders is benchmarked for various types of aggregates against reference concretes produced with standardized binders, or compared to reference values specified in the Eurocode 2 part 1-2.

For the evaluation of spalling behaviour, the testing scale depends on the binder category. For categories 1 and 2, intermediate-scale tests are recommended, in which the spalling behaviour of concretes with new binders is compared to that of concretes made with conventional binders for different kinds of aggregates (figure 1). For category 3 binders, which significantly deviate from traditional formulations, full-scale fire tests, preceded by intermediate-scale tests, are required to assess their performance under realistic fire exposure conditions.

All these tests are conducted in accordance with recommendations from RILEM, ensuring internationally recognized methodologies.

The presentation of the French testing protocol will be complemented by a discussion of the underlying technical arguments that supported the development of these recommendations. It will also include examples of results obtained during the first evaluations of new cements, illustrating how the proposed approach is being applied in practice.

Figure 1: example of spalling comparison after ISO 834-1 fire: reference cement concrete (left) vs. low-carbon cement-based concrete (right)

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S6:

Structural Performance in Fire: Testing and Modelling

FIRE RESISTANCE OF WALL ELEMENTS MADE OF WOOD-CHIP LIGHTWEIGHT CONCRETE

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Abstract

Due to their incorporation of bio-based materials, wood-chip lightweight concretes can offer a promising low-carbon alternative to conventional concretes, particularly in applications where high mechanical performance is not the primary requirement. Their reduced environmental footprint makes them attractive for sustainable construction, but their behavior under fire exposure remains insufficiently documented. This article may potentially represent one of the initial public communications of results in this domain [1].

This paper presents results from fire resistance tests conducted on two types of wood-chip based concretes with densities of 800 kg/m³ (F800) and 1000 kg/m³ (F1000). Structural wall elements made of these concretes, with thicknesses of 24 cm and 30 cm, were tested under both concentric and eccentric axial loads during standard fire exposure ISO 834-1.

Temperatures were measured at various depths within the specimens to assess thermal gradients and insulation performance. These temperature evolutions are compared with the reference temperature profiles of conventional concrete provided in the Eurocode 2 to evaluate their fire insulation capacity. The comparison between concentric and eccentric loading conditions also reveals the influence of load eccentricity on structural fire behavior. Some tests resulted in fire resistance performances exceeding REI 120.

Out-of-plane and vertical displacements were recorded throughout the fire tests to evaluate the structural response. The F800 elements showed outward deformations (away from the furnace), while the F1000 elements exhibited only minor displacements. In contrast, conventional concrete elements typically deform towards the fire-exposed face primarily due to temperature gradients and differential thermal expansion.

Moreover, in some tests, the F800 concrete exhibited post-fire secondary smouldering within the specimen, with self-sustained combustion observed after furnace shutdown. This phenomenon was never observed in F1000 concrete, indicating a higher fire safety margin for denser wood-based concretes.

To better understand and model the behavior of the walls, we also determined the material mechanical properties of F800 (compressive strength and modulus of elasticity), at room temperature and at 90°C, with three different moisture contents (from dry to after immersion in water).

These findings highlight distinct thermo-mechanical behaviors under fire exposure and support the safe use of wood-chip lightweight concretes in construction, provided that they are employed under appropriate design and application conditions. The results are overall very encouraging and demonstrate that, when properly accounted for, wood-chip lightweight concretes can perform reliably and safely in fire scenarios.

Finally, the comparison between the behavior of wood-based and conventional concrete elements can also contribute to a deeper understanding of fire-induced phenomena in traditional concretes.

Figure 1. Surface of F800 and F1000 wood-chip based concretes

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APPLICATION OF THE SUBSTRUCTURE METHOD TO ASSESS THE FIRE RESISTANCE OF THERMALLY RESTRAINED COLUMNS

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Abstract

Usually, the fire resistance of load-bearing structural elements is determined by single members testing. A mechanical load is applied to the member in a force-controlled manner and is maintained constant throughout the fire test. After applying the mechanical load, the thermal exposure starts according to the ISO 834 fire curve. In this conventional test method, no interaction between the tested member and the entire building structure is considered. In buildings, the surrounding structure can restrain the thermal expansion of a member in case of fire. This may have both positive and negative effects on the fire resistance of this structural element.

Several years ago, the Institute for Sustainability and Innovation in Structural Engineering (ISISE) at the University of Coimbra in Portugal and the Bundesanstalt für Materialforschung und -prüfung (BAM) in Germany carried out fire tests on circular and square steel-reinforced concrete columns with restrained thermal expansion [1,2]. BAM´s column test furnace allows the specimen to be subjected to thermal exposure and mechanical loading simultaneously. In addition, this device has a substructure test module, which can also provide restrained test conditions. In an ongoing research project at BAM and Technische Universität Braunschweig, the effect of restrained test conditions on the behaviour of steel-reinforced columns under fire exposure is further investigated [3].

The comprehensive test programme of the project includes 14 steel-reinforced concrete columns. Several parameters are varied, i.e., the stiffness representing the surrounding structure of the column, the load level, the eccentricity of the applied load, and the fire exposure to be used. The selection of parameters is based on a real building case study. Furthermore, material tests are carried out to characterise the mechanical properties of the concrete at elevated temperatures, to be included in a numerical simulation.

This will give a first insight to the experimental results and compare the structural behaviour of columns tested with free and restrained thermal expansion. Identical fire tests (geometry, materials, initial test load and fire exposure) under different restraining conditions have been carried out on high-performance steel-reinforced concrete columns. The results show that the restrained test conditions have a significant influence on the behaviour of structural elements under fire exposure. Due to the thermal expansion and the restrained test conditions the axial force increases and results in an earlier failure of the column. In addition, the column with free thermal expansion showed a much higher expansion.

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EXPERIMENTAL INVESTIGATION ON THE BURNOUT RESISTANCE OF A REINFORCED CONCRETE COLUMN SUBJECTED TO A NATURAL COMPARTMENT FIRE

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Abstract

The load-bearing capacity of concrete structural elements continues decreasing during the cooling phase of a fire and beyond, as demonstrated by real-world failures and numerical studies [1]. In a previous study [2], furnace tests were conducted on reinforced concrete columns with a section of 300x300 mm^2, using standard ISO 834 heating curves and controlled cooling phases. These tests demonstrated that concrete columns could fail during the cooling phase, highlighting the importance of considering the entire fire duration, including the cooling phase, in structural design.

This study presents the results of a new experimental investigation on the behavior of a reinforced concrete column subjected to a natural compartment fire. The objective is to compare the structural response of the column under natural fire conditions with those tested under standard furnace fires, including ISO and Duration of Heating Phase (DHP) tests. The column was subjected to constant axial loading during the fire test. The natural compartment fire was characterized by a fire load of 780 MJ/m^2 and an opening factor of 0.065 m$^{0.5}$ (Figure 1). Thermocouples were placed at different positions and heights within the column section, and gas-phase temperature measurements were conducted using plate thermometers (Figure 2).

The column was designed to have a fire resistance rating of 60 minutes. Fig. 2 shows that the compartment temperature development was close to the ISO curve during most of the test for 52 minutes and decreased thereafter. The load was maintained for 8 hours, then decreased to 50 kN for 2 days as the specimen was left unattended during the weekend. The column survived the natural fire test until all measured temperatures were decreasing, including the heart of the section. Explosive spalling has been observed on several faces.

The residual capacity of the column was measured, providing insights into the long-term structural integrity post-fire. The data collected from this natural fire test will be used to validate and calibrate numerical models for predicting the behavior of concrete under realistic fire scenarios.

Figure 1. Natural fire test of the concrete column

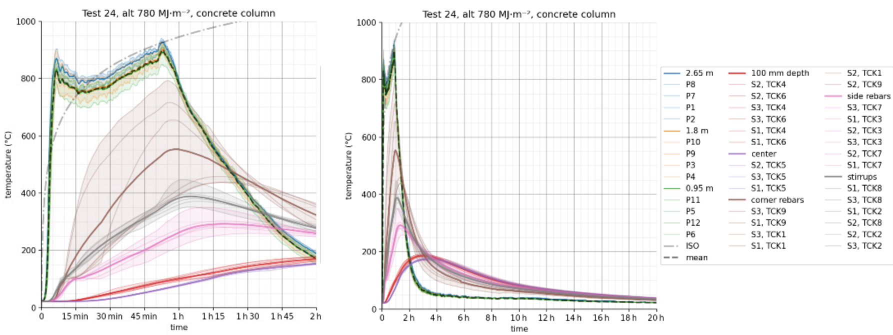

Figure 2. Temperature measurements

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ANALYSIS OF THE STRUCTURE AND SELECTED PROPERTIES OF AUTOCLAVED AERATED CONCRETE IN THE CONTEXT OF FIRE RESISTANCE TESTING

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Abstract

Wall systems made of autoclaved aerated concrete (AAC) are widely used as structural elements in residential buildings and industrial facilities, due to their favorable thermal and mechanical properties. In the context of structures exposed to a high risk of fire, determining the fire resistance of these materials is crucial. The aim of the conducted research was to examine the thermal behavior of AAC under fully developed fire conditions and to analyze the physical and chemical changes occurring in the material at extreme temperatures corresponding to a fully developed fire. As part of the experimental studies, full-scale fire tests were carried out on wall panels measuring 3 m × 3 m, made of AAC of specified classes, according to the standard heating curve. The samples were subjected to a 360-minute fire resistance test, during which surface temperatures exposed to heat and the unexposed side were monitored. Additionally, phase changes and microstructural modifications of the material were analyzed using thermal analysis methods, as well as XRD and SEM techniques. The experimental results showed that reinforced autoclaved aerated concrete maintains structural integrity and exhibits high resistance to fire. Based on the results obtained, an analysis was conducted of the panels' ability to predict temperature distribution during a fire and their impact on the fire safety of building structures. The findings confirm the validity of implementing wall systems made from AAC in high-risk fire environments. The developed methodology can also be applied to evaluate other variants of AAC with different densities, enabling the optimization of the design process regarding fire resistance.

A load-bearing wall made of Ytong Panel SWE Ultra+ aerated concrete with a thickness of 240 mm, heated at a temperature of 1300 °C, was tested. The wall was divided into 3 zones, from which 3 samples were taken at different distances (layers) from the surface: up to 3 cm, 3-6 cm, 6-9 cm (Fig. 1). The samples taken were subjected to XRD phase composition analysis. Example diffractograms are shown in Fig. 2.

In the reference concrete sample not exposed to high temperature (marked in

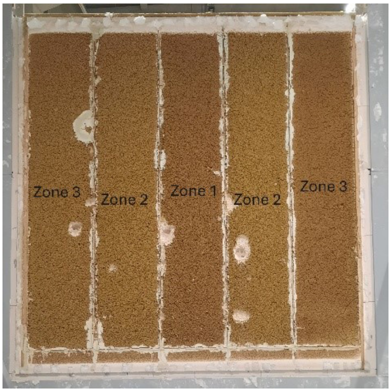

Figure 1. View of the sample from the heated side

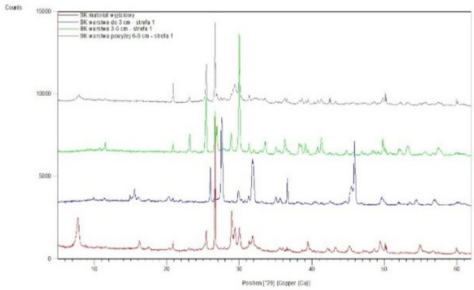

Figure 2. Example of diffraction patterns of samples taken from zone 1

red in Figure 2), the main mineral phases are identified: tobermorite, calcite, quartz and anhydrite.

After heating the sample, in layers from 0 to 3 cm of all tested zones, complete disappearance of tobermorite, calcite and anhydrite phases is observed, with simultaneous appearance of pseudowollastonite. In layers from 3 to 6 cm, wollastonite and anhydrite phases are identified, which in this zone did not decompose completely, in contrast to the layer 0–3 cm, where anhydrite disappears. On the other hand, in layers 6–9 cm, the presence of tobermorite is again detected, although in smaller amounts than in the reference concrete, as well as anhydrite, quartz and calcite, which also did not decompose completely, which indicates a smaller effect of temperature in this zone. High temperature causes dehydration and loss of the tobermorite phase, which results in the formation of pseudowollastonite or wollastonite. This phase transformation is a key thermal reaction leading to changes in the volume of the material, which results in the formation of cracks and fissures in the wall structure. Regardless of the zone of the tested samples, the greatest changes occur in the surface layer of concrete, i.e. 0–3 cm, where the intensity of high temperature is the greatest. In the 3–6 cm layer, the changes are less advanced, while in the 6–9 cm layer we observe minor changes.

ASSESSING EUROCODE MATERIAL LAWS FOR POST-TENSIONED CONCRETE BEAMS IN FIRE THROUGH FINITE ELEMENT MODELLING

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Abstract

In this work, we present a finite element model specifically developed to simulate the behavior of post-tensioned concrete beams exposed to fire. The model currently excludes explosive spalling and focuses on capturing the fundamental thermo-mechanical response of the structure. A distinguishing feature of the approach is the separate treatment of the prestressing tendons and the reinforced concrete beam, which are coupled through a dedicated contact law. This separation enables independent monitoring of each component's performance and failure, offering deeper insight into their interaction under fire conditions. The model is based on a beam-type formulation with linearized kinematics and demonstrates high numerical efficiency. It runs quickly, yields accurate results, and remains easy to interpret—making it suitable for both research and practical applications. The central aim of the ongoing research is to assess the applicability of the temperature-dependent material laws for concrete prescribed in Eurocode 2 when modeling post-tensioned members under fire exposure. Particular emphasis is placed on the role of individual strain components, such as creep and transient strains, which are typically included implicitly in Eurocode-based constitutive models. By considering these components explicitly, the study seeks to provide new insights into their influence on structural response and to contribute to the broader discussion on the validity and completeness of the current stress–strain formulation for concrete at elevated temperatures as defined in Eurocode 2. Figure 1 presents a comparison between the computed and measured evolution of the vertical displacement at the midspan of simply supported slab T5, tested by Ellobody and Bailey [1]. Four approaches to modeling the material behavior are considered: an implicit treatment of creep and transient strains (A), as proposed in [2], and three explicit formulations following the methodology described in [3]. Approach B explicitly considers creep strains, C considers transient strains, and D considers both. The results are compared with the finite element analysis (FEA) by Bailey and Ellobody [4]. The results indicate that different modeling approaches can yield varying outcomes in some cases.

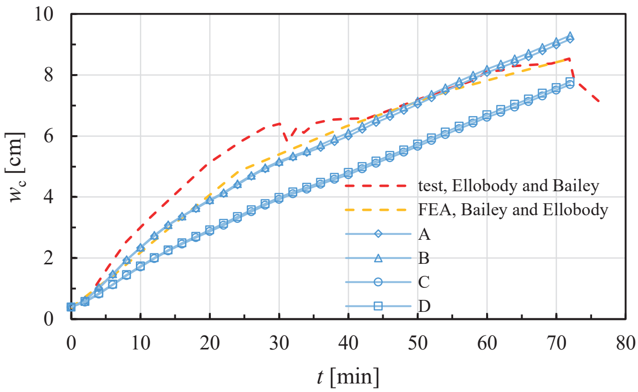

Figure 1. Comparison of computed and measured midspan vertical displacement w_c for slab T5 during fire exposure

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TOWARD A HYBRID COUPLED SIMULATION APPROACH USING THE PHASE-FIELD METHOD FOR PREDICTING THE BEHAVIOR OF CONCRETE STRUCTURE UNDER REAL FIRE

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Abstract

The structural integrity of buildings exposed to fire are significantly reduced due to high thermal loads, since concrete shows a non-linear behavior, particularly when subjected to non-isothermal conditions such as fire. The resulting degradation leads to substantial challenges, particularly for rescue workers, who must ensure occupant evacuation despite the high risks of progressive collapse. Determining safe escape routes under such hazardous conditions is a complex task, demanding specialized expertise. Alternatively, computational simulations employing a methodology may identify viable escape routes. Recently, the phase-field method has been proposed to simulate fire-induced concrete degradation. This approach facilitates a straightforward numerical setting to simulate complicated phenomena at the component level, e.g., the initiation and development of cracks. The reduction in the load bearing capacity of a substructural component results in a redistribution of the internal forces and the corresponding deformations at the structural scale. Furthermore, simulations of the structural scale necessitate damage simulations of each component and a computational framework, which can deal with scale transition during fire-structure interactions [1]. However, simulating these phenomena for fire-structure interaction is numerically very challenging. The objective of this contribution is to present a computational framework for fire-structure simulations of concrete damage due to fire and its effects on the burning building. In this simulation framework, the temperature distributions and the evolution of the fire exposed components are taken from the simulation results of the real fire scenario using the Fire Dynamics Simulator. It is a computational fluid dynamics code relying on the large-eddy simulation. Unlike the frequently used ISO fire curve, which specifies a uniformly distributed temperature field on the fire

exposed surface, real fire scenarios show a more complex temperature distribution with localized hot spots caused by the numerous physical effects that play a decisive role. To take this issue into account, a 3D model is used in this work. Furthermore, the substructural scale model treats concrete components locally exposed to the fire, whereas the structural scale model simulates load-bearing capacity on the building scale. Thus, in the proposed computational setup, the substructural scale model uses a FEniCS-based solver for the concrete material. Herein, the concrete damage is computed using a unified phase-field method. The structural scale model uses Abaqus and the subroutine UMAT for mechanical simulations and to initiate the coupling. These solvers exchange information on the damage and the resulting changes in geometry across scales through the coupling library preCICE. The proposed model is illustrated by an example case that forecasts the fire-induced damage of the concrete substructure and its effects at the building scale.

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S7:

Concrete Properties at High Temperature

RELATIONSHIP BETWEEN DEHYDRATION AND SHRINKAGE RATE OF HARDENED CEMENT PASTE UNDER HIGH TEMPERATURE CONDITIONS

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Abstract
Concrete is a composite material in which hardened cement paste (HCP) acts as a matrix and aggregates act as inclusions1). When concrete subjected high-temperature, elastic modulus and compressive strength is deteriorated due to differences in the thermomechanical properties of the matrix and inclusion. The purpose of this study was to clarify deformation behavior of HCP at high temperature environments to better understand the thermomechanical properties of concrete.

In this study, HCP specimens were prepared and their thermal shrinkage behavior under high-temperature conditions were measured. The water binder ratio of the cement paste was set at three levels: W/B=50%, W/B=30%, and W/B=18%. when a level of W/B=18%, Silica fume was added 10 mass% to the cement. The specimens were pre-dried to remove free water. Pre-drying was performed by placing the specimens in a drying oven at 40°C for 24 hours. After pre-drying, the specimens were stored in a desiccator with relative humidity of 0% containing silica gel until TMA measurement. Furthermore, to clarify the relationship between shrinkage rate under high temperature conditions and dehydration of HCP, samples were heated to each target temperature using TMA, and powdered samples were prepared. The amount of water dehydrated at each temperature was measured by thermogravimetric analysis (TG) of the powder samples.

Figure 1(a) shows the Relationship between furnace temperatures and shrinkage rate of cement paste Positive values indicate expansion behavior, while negative values indicate Shrinkage behavior. Figure 1(b) shows Differential thermogravimetric (DTG) values of cement paste before exposure to high temperatures.

The deformation behavior of HCP in high temperature environments due to dehydration was revealed. HCP with W/B18% and W/B30% turned from expansion behavior to shrinkage behavior near 100°C.Then, there are four phases in the shrinkage rate of HCP under high-temperature conditions: phase 1, in which the

expansion behavior transitions to shrinkage behavior; phase 2, in which shrinkage occurs at a constant rate; phase 3, in which the shrinkage rate increases; and phase 4, in which the shrinkage rate slows down. Last, the shrinkage behavior of HCP in Phase 3 was related to the dehydration of interlayer C-S-H, and rapid shrinkage occurred due to the dehydration of interlayer water.

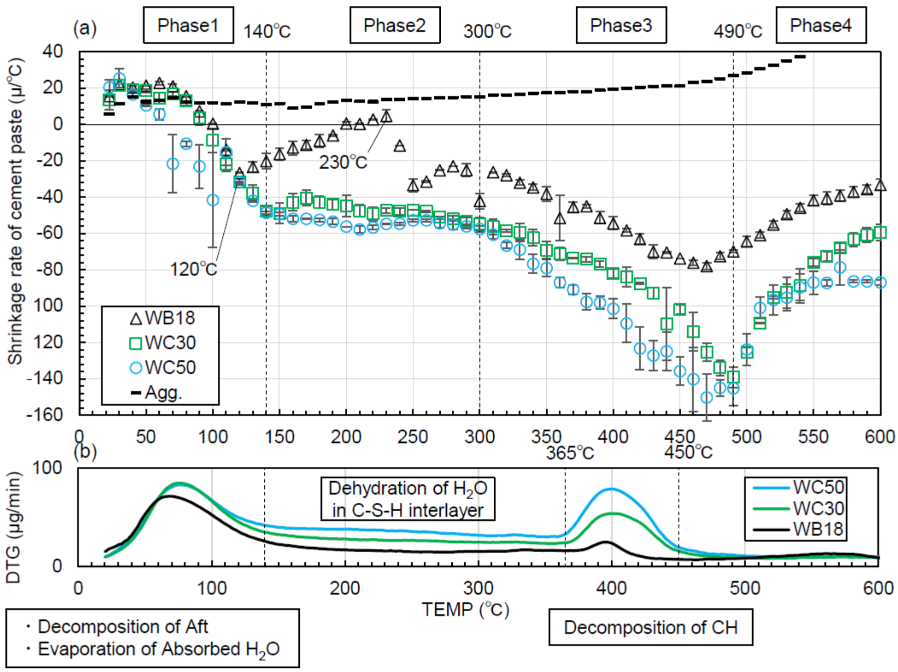

Figure 1. (a) Relationship between furnace temperatures and shrinkage rate of cement paste. Positive values indicate expansion behavior, while negative values indicate Shrinkage behavior; (b) DTG curve of cement paste before exposure to high temperatures

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STRENGTH RECOVERY OF HIGH--PERFORMANCE CONCRETE MATERIAL AND COLUMN AFTER FIRE EXPOSURE

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Abstract

High-performance concrete (HPC) exhibits excellent strength, durability, and workability, but its properties deteriorate significantly under high temperatures, making post-fire repair challenging. Water and water–CO_2 cyclic recuring offer promising recovery potential, though their mechanisms remain unclear [1]. This study explores the recovery of thermally damaged HPC materials and columns, elucidating the microstructural mechanisms of strength restoration.

Materials and methodology HPC was prepared using Portland cement, silica fume (SF), superplasticizer, ISO sand, quartz sand, and PP fibers. The mix designs included 0SF, 0.1SF, and 0.2SF (W/B = 0.18; SF = 0%, 10%, 20%) and 0.1SF-HW (W/B = 0.36; SF = 10%). Cube specimens (50 mm) were heated to 600 or 900 °C at 1 °C/min and held for 1 hour. Columns ($200 \times 200 \times 600$ mm^3) were exposed to the ISO-834 standard fire for 1 hour. After heating, water and water–CO_2 cyclic curing were applied. Mechanical recovery was evaluated by compressive strength and load capacity, while microstructural and phase changes were characterized by MIP and XRD.

Results Figure 1 shows the compressive strength, phase composition, and pore structure of HPC after recuring. Cyclic recuring achieves higher strength recovery than water recuring. The 0.1SF and 0.1SF-HW mixes perform best among the different SF contents and W/B ratios. In water recuring, rehydration products (AFt, CH, and C–S–H) fill pores and restore strength, while in cyclic recuring, additional carbonation products (calcite and vaterite) densify the surface and further enhance mechanical performance.

Figure 2(a) shows the load–displacement curves of 0.1SF and 0.1SF-HW columns. In cyclic recuring, rehydration and carbonation products filled cracks, restoring strength and stiffness. However, columns recovered less than cubes due to higher temperature gradients, which caused macro-cracks. 0.1SF column with higher thermal conductivity suffered more severe damage and weaker recovery.

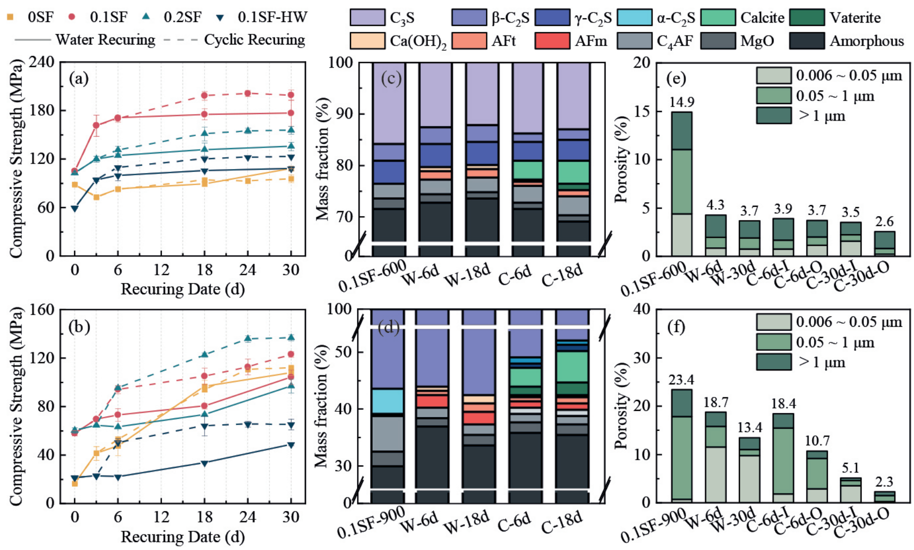

Figure 1. Compressive strength, phase composition, and pore structure of HPC after recuring following thermal damage at (a, c, e) 600°C and (b, d, f) 900 °C

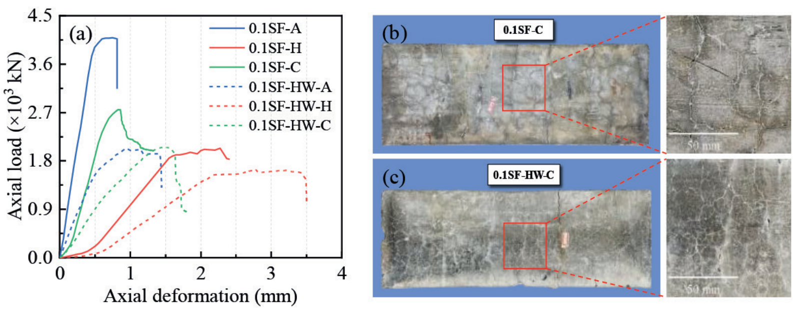

Figure 2. (a) Load-displacement curves of columns and the visual inspection of (b) 0.1SF column ,(c) 0.1SF-HW column after cyclic recuring.

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EFFECT OF SPECIMEN SIZE AND SHAPE ON RESIDUAL COMPRESSIVE STRENGTH OF CONCRETE AFTER FIRE EXPOSURE

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Abstract

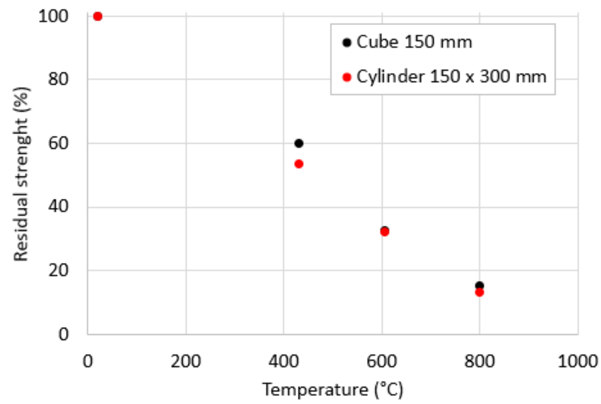
This study examines how specimen geometry affects the residual mechanical properties of ordinary concrete after heating. Two specimen shapes were evaluated: cylindrical (100×200 mm and 150×300 mm) and cubic (100 mm and 150 mm) to determine geometry-related differences.

Specimens were placed in a 150-liter furnace. Their mid-height was at the same level above the furnace floor, with at least 6 cm distance between the furnace floor and the bottom of each specimen. Specimens were heated at 2 °C/min to 430 °C, 605 °C, and 800 °C.

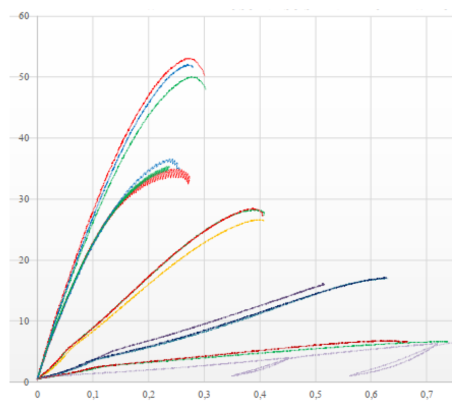
We assessed degradation using destructive methods (compressive strength and, for cylinders, stress–strain response) alongside non-destructive techniques (ultrasonic pulse velocity and Schmidt hammer). Results were compared to reference samples at ambient temperature (20 °C). The obtained results revealed a significant decrease in concrete strength with increasing temperature, confirming the material's high susceptibility to thermal degradation. Ultrasonic testing reflected the deterioration of concrete, whereas the Schmidt hammer measurements did not show substantial differences. Additionally, colour changes in the samples (a reddish hue) and the occurrence of cracks - especially after heating to 600 °C and 800 °C — were observed.

The strain was captured using a pair of extensometers, and, simultaneously, a DIC system. A good agreement between the two systems was achieved. Evaluation of the stress-strain field using a DIC, allowed to study the thermally-induced cracking. Interestingly, DIC shows strain localisation in the areas of thermally-induced cracks.

The research revealed some differences in relative residual compressive strength of cylindrical and cubical specimens (Fig. 1a), susceptibility of the stress-strain response to the initial load used for the axiality check [1] (Fig. 1b), and apparent strain localization in the area of thermally-induced cracks.



a)



b)

Figure 1. (a) Residual strength (in %) for 150 mm cubes and 150 x 300 mm cylinders,
(b) stress-strain relationships for 28-day, 90-day speciemens and specimens after elevated temperatures

Acknowledgments

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EXPERIMENTAL ASSESSMENT OF POLYPROPYLENE FIBER EFFECTIVENESS IN SELF-COMPACTING CONCRETE FIRE RESISTANCE: A SYSTEMATIC INVESTIGATION

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Abstract

This study explores the influence of polypropylene fibers on the residual mechanical properties of Self-Compacting Concrete (SCC) when exposed to elevated temperatures through a comprehensive experimental campaign. The investigation encompasses 156 cubic specimens (15×15×15 cm), equally distributed between SCC with polypropylene fibers (1 kg/m^3 dosage, 6.12 mm length) and plain SCC without fibers, subjected to thermal exposure up to 800°C. The experimental approach follows RILEM TC 200-HTC recommendations [1], maintaining 90-minute exposure at target temperatures for REI 90 compatibility. The thermal protocol involves gradual heating with 30-minute exposure periods at different temperatures (150°C through 800°C). Heating begins at 150°C for 45 minutes, followed by 100°C increments. Specimens are cooled using water spray. Preliminary results from 80 tested specimens gave insights into fiber effectiveness. Plain SCC specimens demonstrate significant vulnerability at high temperatures, with explosive failures occurring around 500°C due to internal vapor pressure. Four plain SCC specimens exploded during the tests: three within the furnace and one during cooling after 10 seconds of water exposure. Fiber-reinforced specimens exhibit better thermal resistance, withstanding temperatures up to 800°C with only superficial micro-cracking. The polypropylene fibers, melting at ~145°C, create micro-drainage pathways that release internal vapor pressure, preventing explosive failure. Experimental results show strength degradation for fiber-reinforced SCC from 76.63 MPa at ambient temperature to 21.81 MPa at 800°C. The complete experimental program will generate comprehensive stress-strain relationships across the full temperature range, providing fundamental data for developing optimized fire-resistant concrete formulations and advancing performance-based design methodologies for resilient structural applications.

Table 1. Experimental results at selected temperatures

Temp. [°C]	**Plain R**ck [**MPa**]	**Fiber R**ck [**MPa**]
20	86.39	76.63
250	72.41	67.35
450	61.08	56.02
650	-	26.02
800	-	21.81

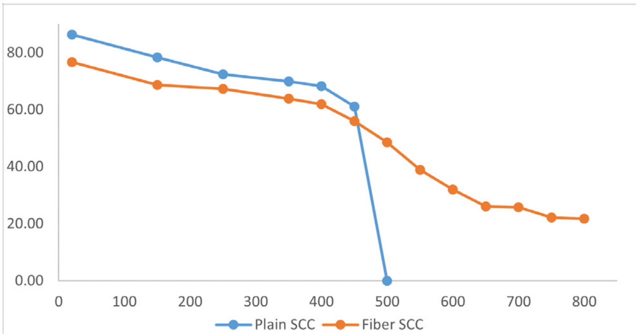

Figure 1. Compressive strength vs. temperature for plain and fiber-reinforced SCC

Acknowledgments

The financial support provided through the AI-PROMPT - CHANGES project is gratefully acknowledged.

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S8:

Post-Fire Assessment and Protection of Concrete Structures

THE POST-FIRE INVESTIGATION OF A REINFORCED CONCRETE STRUCTURE: A GARAGE CASE STUDY

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Abstract
An indoor fire may cause a high temperature peak and severe damage. A fire in a garage caused a relevant damage and spalling of reinforced concrete beams and insole. The insole exhibits a strength drop to 30%. The concrete beams show a decrease of 17%. The fire zones show a higher strength reduction for the 10 cm surface concrete as for the concrete in depth, up to 23%. The tensile strength of rebars shows a decrease to 13%. The rebars were affected from the intense indoor fire.

Introduction In reinforced concrete structures, the fire duration and peak temperature affect damage [1]. The heating / cooling rate controls the concrete deterioration [2-3]. The rebars loose mechanical strength from 300 °C [4]. With a high temperature peak and fire duration, concrete spalling and deformation of the rebars lead to structural deterioration [5].

Experimental procedure Concrete cored specimens (ø 50 mm - 150 mm length) and steel rebars were prepared. Concrete compressive strength [6] and rebar tensile strength [7] were measured.

Results and discussion Fire in a garage highly damaged the reinforced concrete beams and the insole with a spalling down to 2-3 cm in depth. The elements were covered with fire insulating materials (Fig. 1).

Figure 1. Concrete spalling of beams (left) and insole (right) at the fire zone

The strength drop for the insole reaches 30%. The beams exhibit a strength reduction from 13% to 17%. The strength redution from the surface (label A) and the zones in depth (label B) varies from 3-6% to 12-23%. The surface strength is always lower as in the depth (Table 1 left).

Table 1. Concrete compressive strength (left) and steel tensile tests (right)

Client labelling	Sample nr. IMC	Dimensions height	Dimensions diameter	Apparent density	Compressive strength load	Compressive strength tension
		mm	mm	kg/m³	kN	N/mm²
Insole fire zone	1A	50.2	52.1	2149	69.1	32.4
	1B	49.4	52.1	2155	89.3	41.9
Beam fire zone	2A	50.0	52.2	2121	81.2	37.9
	2B	50.8	52.2	2171	91.8	42.9
Beam fire zone	3A	49.2	52.2	2194	79.5	37.2
	3B	50.2	52.2	2169	85.5	40.0
Beam fire unaffected zone	4A	49.6	52.1	2185	96.0	45.0
	4B	49.9	52.1	2247	102.1	47.9
Insole fire unaffected zone	5A	49.9	52.2	2294	111.8	52.2
	5B	49.9	52.2	2201	115.8	54.1

Sample nr.		Dimensions		Yiedl strength $R_{p0.2}$ / R_e	Ultimate tensile strength R_m	Elongation at max-force R_m	
IMC	Client	Diameter nom. [mm]	Section nom. [mm²]	Tension [N/mm²]	Tension [N/mm²]	A [%]	A_{gt} [%]
1	Insole fire	10	78.5	536.7	623.2	26.5	9.47
5	Insole no fire	10	78.5	642.3	715.7	18.8	6.47
2	Beam fire	12	113.1	583.3	677.3	28.6	13.4
4	Beam no fire	10	78.5	540.7	608.6	18.7	6.79

The fire affected rebars of the insole exhibit a lowering of the ultimate tensile strength (UTS) of 12.8%. The beams show a different rebar (stirrups) diameter and the increase in UTS cannot be directly compared. However, an increase in elongation for the fire-affected steels (Table 1 right), is likely due to a slight coarsening of the microstructral features.

Conclusions The fire caused spalling and a compressive strength drop from 17% to 30 % on structural elements. The strength decrease from the concrete surface to depth, reaches 23%. The rebar tensile strength decreases to 13%, indicating a relevant influence of fire to damage down to 5-10 cm.

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POST-FIRE STRUCTURAL ASSESSMENT OF AN INDUSTRIAL FACILITY IN RAJKOT, INDIA: A CASE STUDY

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Abstract

This study presents a comprehensive post-fire structural assessment of a multi-building industrial facility in Rajkot, India, following a large-scale fire event that caused complex thermomechanical degradation in reinforced concrete (RC) and composite structural systems. The buildings featured a hybrid combination of RC, hollow steel tubular, and concrete-filled steel tubular elements, with varying degrees of exposure to high temperatures and fire suppression conditions.

The investigation aimed to evaluate the residual performance of affected structural members and develop a rational basis for repair and rehabilitation. The assessment methodology employed a multi-modal diagnostic framework comprising detailed visual inspections, distress mapping, non-destructive testing, laboratory-based strength evaluations, and thermal history assessments. Ultrasonic Pulse Velocity and Rebound Hammer testing were utilized to characterize the mechanical integrity of concrete, while core strength data served to calibrate and extend these assessments to broader regions. Thermal exposure and fire-induced chemical transformations were evaluated through two key techniques: (i) Depth of Neutralization (DoN), conducted via phenolphthalein-based pH profiling to detect loss of alkalinity in concrete; and (ii) Thermogravimetric Analysis (TGA), which provided insight into the decomposition of hydration products and offered indirect quantification of historical temperature exposure [1]. The combined use of these tools enabled a layered understanding of both surface-level and internal thermal degradation.

The findings underscore that fire-induced damage is not solely a function of thermal exposure or fire duration but results from a complex interplay of structural detailing, material characteristics, construction quality, fire dynamics, and suppression methods.

One of the key insights from the study is the inadequacy of standalone indicators, such as DoN; in reliably capturing the extent of thermal degradation, particularly in cases where firefighting efforts introduced significant rehydration of decomposed compounds. This phenomenon can result in chemically restored alkalinity at

the surface while concealing deeper damage, thus requiring corroboration with techniques like TGA for accurate interpretation.

The assessment further revealed that post-fire deterioration can continue to evolve over time, particularly in members with compromised microstructures or exposed reinforcement. Observations of progressive spalling emphasized the need for staged and temporally distributed evaluations, rather than a one-time post--incident inspection.

Moreover, the absence of passive fire protection on steel components was identified as a critical vulnerability, with early-stage failure modes such as local buckling and loss of continuity observed in several members.

The behavior of self-compacting concrete (SCC) under thermal loading also emerged as a particular concern. Although advantageous under normal conditions due to its high workability and dense matrix, SCC exhibited severe spalling when subjected to rapid cooling during fire suppression, an effect attributable to internal pore pressure buildup [2]. This finding suggests that fire performance characteristics of advanced concrete mixes must be carefully considered during design, especially for structures with high fire risk potential.

Overall, the study underscores the need for an integrated, multi-scale diagnostic approach, combining mechanical, chemical, and thermal evaluations, for reliable post-fire assessment of RC and composite structures. It highlights the limitations of visual cues and standard thresholds, offering a robust framework applicable to critical infrastructure requiring prompt yet technically sound rehabilitation decisions.

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APPLICATION OF THE SCLEROMETRIC METHOD TO CONCRETE DAMAGE ASSESSMENT IN POSTFIRE STRUCTURES

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Abstract

Assessing the condition of concrete in post-fire structures differs significantly from evaluating concrete quality under normal conditions. This is primarily because concrete exposed to fire temperature is no longer uniform. The investigation purpose is then to identify the areas where the concrete has been significantly damaged, and to determine the thickness of the near-surface layer where the mechanical properties of concrete have deteriorated so significantly that it no longer fulfils its function and should be considered destroyed. However, the boundary between fire-damaged concrete and concrete that can be regarded as intact is not sharp and can only be assumed.

The sclerometric method [1, 2], in which the relationship between the concrete compressive strength and its surface hardness is used, can be suitable for a relatively simple and quick assessment of concrete quality in structures exposed to fire. However, the testing must take into account the fact that such concrete is non-uniform.

Tests were carried out on concrete members heated in a planned way for 60, 120, 180, and 240 minutes. The members were made of ordinary concretes differing in compressive strength (corresponding to C30/37 and C40/50 classes) and in the aggregate used (siliceous and basalt).

After the members cooled freely, sclerometric measurements were taken directly on the heated surfaces and surfaces corresponding to the location of the 500°C and 350°C isotherms in the member cross-section. These surfaces were obtained after gently chiseling the top layers of concrete.

Relative rebound number ($RT/R0$), defined as the ratio of the average result obtained on the tested surface to the average value on the concrete surface in the same structure at a location that was not exposed to fire temperature, was adopted as a parameter for the concrete damage evaluation in post-fire structures. Based on the test results analysis, the following recommendations were proposed:

Before taking sclerometric measurements in a post-fire structure, grinding of the concrete surface, which is recommended under normal conditions, can be omitted. This simplifies and reduces the time of testing, which is often carried out under unfavorable conditions.

If a relative rebound number (RT/R0) of not less than 0.8 is obtained on the tested surface, the concrete can be considered not significantly damaged.

Concrete, on the surface of which RT/R0 < 0.6, from a practical point of view, should be regarded as destroyed and qualifying for replacement.

If a RT/R0 value in the range of 0.6-0.8 is obtained, the decision on whether or not to replace the damaged concrete should depend on the loading and function of the tested member.

The sclerometric test can also be used to estimate the thickness of the near-surface layer of deteriorated concrete to be removed. Removal of concrete layers of small thicknesses of about 1-2 cm should continue until RT/R0 ≥ 0.8.

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AI-BASED ANALYSIS OF CONCRETE STRUCTURES IN CASE OF FIRE

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Abstract

Artificial Intelligence (AI) is today a tool of great applicability in different areas. It can also be used to predict the behavior of concrete structures in a fire situation. Evaluations were previously done manually, consuming a lot of time and could even lead to unsafe situations. AI can now combine experimental data, computer models and intelligent algorithms, to quickly and safely predict the behavior of structures in the event of a fire. AI can, for example, predict the internal temperature of concrete over time, the loss of mechanical strength of concrete, the opening and propagation of cracks, the risk of collapse or structural failure, the location of damage such as spalling, time remaining to collapse during real fires, etc.

AI models need reliable experimental laboratory data, results from computer simulations using, for example, finite element software, results from sensors embedded in structures that can measure temperatures, deformations, displacements, the use of thermal or visual images taken by drone, among others. On the other hand, Machine Learning models, associated with Random Forest models, XGBoost, Artificial Neural Networks (ANNs), can predict the reduction of the mechanical properties of concrete with temperature, while Deep Learning models, associated with Convolutional Neural Networks, analyze thermal or visual images to detect cracks and damage, and RNN/LSTM models deal with sequential data (time) to predict collapse or behavior throughout the fire.

The use of AI thus has great advantages in predicting the damage of concrete structures in the event of a fire without destructive testing, supporting the decision on maintenance, reinforcement or post-fire demolition. This article will summarize all these techniques currently available to the designer of concrete structures in a fire situation

MATERIAL SOLUTIONS FOR PASSIVE FIRE PROTECTION OF TUNNEL LININGS

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Abstract

Road tunnels are very sensitive areas in terms of fire safety. Their complex access, enclosed configuration, heavy traffic, and the presence of high combustible loads make them high-risk environments. For this reason, tunnels are equipped with both active and passive fire protection systems. Active protection is designed to control the fire at an early stage. However, hydrocarbon fires can reach temperatures above 1300 °C, which requires the use of passive systems to prevent the destruction of structural materials such as reinforced concrete.

Passive fire protection aims to slow down the temperature increase in reinforced concrete and thus reduce the risk of spalling. This phenomenon is caused and worsened by the presence of water in the concrete, which turns into vapor under heat, creating internal pressure. To limit this effect, concrete is often reinforced with polypropylene (PP) fibers. When the temperature reaches about 170 °C, the fibers melt, creating microchannels that allow water vapor to escape and reduce internal pressure.

To further improve passive protection performance, geopolymers are being developed. These materials are more environmentally friendly, do not suffer from spalling, and can keep their mechanical properties up to 1200 °C. Geopolymers are alkaline-activated binders that contain no Portland cement and offer an innovative alternative. In a foamed version, they provide low thermal conductivity, high fire resistance, good dimensional stability, and a lower carbon footprint.

These materials can be applied as sprayed mortars or as prefabricated fire-resistant panels. Their performance must be validated through standardized fire tests (EN 1363-1, ENV 13381-3) or according to the HCM fire curve, as recommended by CETU and the RILEM TC 256-SPF committee, which insists on realistic testing conditions (humidity, load, geometry).

Fiber-reinforced concretes and geopolymers are therefore effective and sustainable solutions for ensuring fire safety in modern tunnels. Choosing the right solution depends on a balance between material performance, practical application, and regulatory compliance.

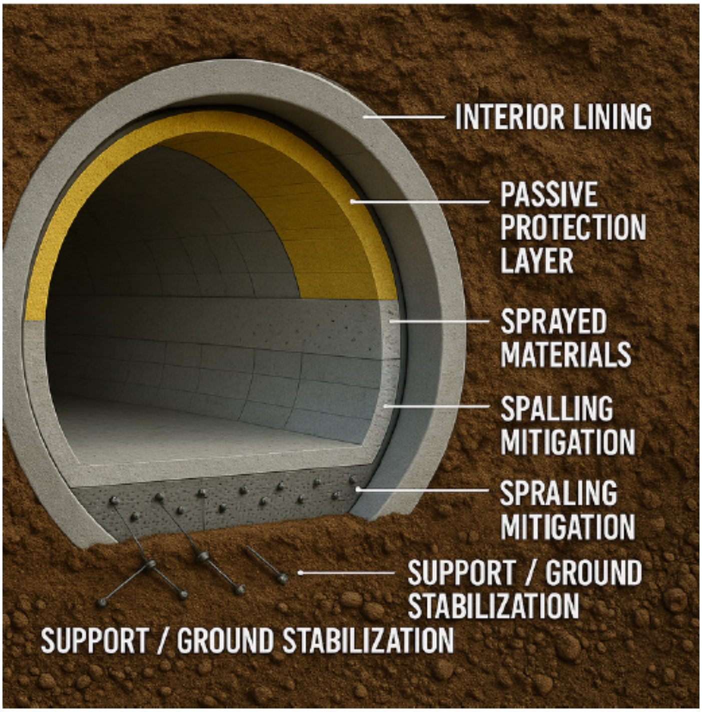

Figure 1. Passive fire protections, Image generated using ChatGPT (OpenAI), July 2025

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The 8th International RILEM Workshop on Concrete Behaviour due to Fire Exposure focuses on a broad understanding of how concrete responds to fire, with particular attention to fire induced spalling. Key themes include also the mechanisms and strategies for its mitigation, as well as the influence of modern materials such as fibre-reinforced and recycled aggregate concretes.

The workshop also highlights advances in experimental testing, numerical modeling, and structural performance under fire. Post-fire assessment techniques and case studies further demonstrate the practical importance of this research.

The IWCF 2025 is aimed to be an inspiring and fruitful forum for exchanging knowledge, sparking new collaborations, and the shaping of the future of fire-resilient concrete structures.

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