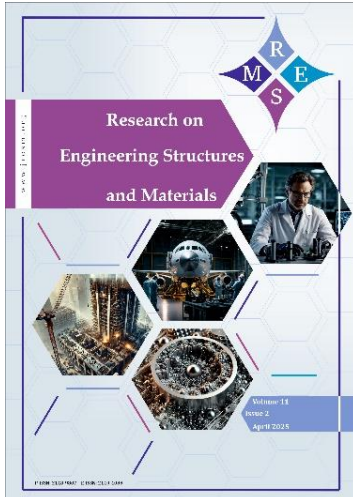




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Thermo-mechanical response of fire-exposed concrete protected by intumescent coating: An equivalent-layer numerical study of coating thickness effects

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Abstract

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The thermal degradation of concrete is a result of the coupled heat penetration, temperature-dependent degradation of materials and thermally induced deformation. This paper presents an experimentally validated three-dimensional finite element study of normal strength concrete cylinders coated with different thicknesses of intumescent coatings. The temperature-displacement ABAQUS model with Concrete Damage Plasticity (CDP) and temperature-dependent material properties was validated with the experimental data of unprotected and 2 mm-coated concrete cylinders, which were exposed to 500 °C for 5400 s. The intumescent coating was represented by an equivalent-layer approach with temperature dependent thermal conductivity; its physical volumetric expansion was not explicitly modelled. A parametric study was then performed on uncoated and 1, 2 and 4mm coated cylinders at 100, 300, 500 and 700 °C. The coating thickness was found to significantly affect transient heat penetration and the subsequent mechanical response. The 4-mm coating retained 84.89% of the compressive strength at 700 °C versus 36.75% for the uncoated concrete, reducing the strength loss from 63.25% to 15.11%. Thicker coatings also reduced the heat penetration into the core, thermal induced tensile damage and displacement, proving that coating thickness is a crucial parameter to control the thermal protection and residual concrete performance.

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1. Introduction

Concrete is one of the most popular construction materials in the world due to its availability, economic efficiency, durability and capacity to withstand high compressive loads [1-3]. Its versatility, ease of casting, compatibility with reinforcement and relatively low maintenance requirements have made it a fundamental material in modern infrastructure systems [4, 5]. However, concrete, despite its good performance under normal conditions, can deteriorate significantly under extreme environmental conditions, in particular at elevated temperatures resulting from fire exposure [6, 7]. Exposure to high temperatures induces complex physical, chemical and mechanical changes in concrete. Evaporation of free and physically bound water can lead to internal pore pressure and microcracking starting at around 100°C. With increasing temperature, the concrete matrix gradually deteriorates because of the deterioration of cement hydrates and differential thermal expansion between aggregate and cement paste. This leads to an ever more pronounced decrease in compressive strength, tensile strength and elastic modulus, especially in the temperature range of approximately 300-600°C [8]. Reaching temperatures of 800°C can cause severe cracking, loss of cohesion and surface spalling, accelerating the

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deterioration and failure of structures [9]. Experimental and numerical studies have shown that temperature-dependent degradation significantly influences the structural response of concrete subjected to fire conditions [10, 11]. Numerical modelling has become an important tool for the investigation of the thermal and mechanical response of concrete at elevated temperatures. The finite element method through advanced software such as ABAQUS enables especially to simulate the temperature distribution, material degradation and structural response to thermal loading [12, 13]. The Concrete Damage Plasticity (CDP) model is one of the most used among the available constitutive models to describe the nonlinear behavior of concrete, including tensile cracking, compressive crushing, stiffness degradation and damage evolution [14, 15]. Response of concrete under elevated temperature has been simulated using coupled thermo-mechanical finite element analyses in previous studies [16-18]. However, the interplay of heat transfer, temperature-dependent material degradation and thermally induced mechanical response is still highly complex and attracts a lot of research attention. As a result, many passive fire protection systems have been developed to improve the fire resistance of concrete structures. Among these systems, intumescent coatings have attracted significant attention due to their ability to swell at high temperatures and form a thermal insulating protective layer [18, 19]. This extra layer effectively reduces heat transfer to the concrete substrate and retards the temperature increase in the member thus mitigating thermally induced deterioration [20]. The effectiveness of fire-protection coatings to preserve the post-fire performance of concrete has also been successfully validated through recent experimental studies. Li et al. observed a significant improvement in the residual compressive and splitting tensile strength of fireproof coated concrete exposed to temperatures of up to 800°C due to less heat penetration into the concrete [21]. Li et al. in a later study showed that fireproof coatings significantly improved the durability of concrete after fire by reducing water absorption and improving carbonation resistance after exposure to high temperatures [22]. More recently, Fu et al. provided a comprehensive review on the recent advances in intumescent coating technology and pointed out that coating formulation, thermal insulation efficiency and heat-transfer mitigation are still the most important factors deciding the fire-protection performance [23]. However, the authors also pointed out the need for additional studies on the coupled thermal and mechanical behavior of protected concrete members at high temperatures. In addition, Chun et al. showed that the residual mechanical performance of fire damaged concrete is mainly dependent on the degree of thermal exposure and the consequent degradation of the cementitious matrix [24]. Moreover, the comprehensive review performed by Ghiji et al. [24] showed that, although the promising thermal insulation properties of passive fire-protection systems, systematic studies on the coupled thermo-mechanical behavior of protected concrete are relatively scarce [18].

In finite element analyses, the complex expansion and progressive charring of intumescent coatings can be modelled explicitly by the evolving coating geometry and temperature dependent material behavior, or more simply using an equivalent-layer approach. In the latter approach, the thermal protection of the thermally transformed coating is represented by effective temperature-dependent thermal properties while the coating geometry is maintained. The method reduces the complexity and computational requirements of the numerical model and allows the practical evaluation of the heat transfer through the protected system. However, it does not explicitly reproduce the evolving char thickness, volumetric expansion, cracking, shrinkage nor possible local debonding of the coating during heating. Predictions obtained with an equivalent-layer representation should then be interpreted mainly in terms of the effective thermal protection transferred to the concrete rather than a direct simulation of the physical intumescence process. However, although these contributions are important, the current research has mainly focused on the thermal insulation performance or residual mechanical properties separately. Very few studies have considered the transient temperature evolution, thermally induced displacement, tensile damage evolution and residual compressive strength in a unified experimentally validated thermo-mechanical framework, particularly for thin intumescent coating systems. Therefore, the novelty of the present study is the development and experimental validation of a sequentially coupled thermo-mechanical finite element model able to quantitatively evaluate the effect of the intumescent thin coating thickness of 0, 1, 2 and 4 mm on the total thermal and mechanical behavior of normal strength concrete at elevated temperatures ranging from 100 to 700°C. The present work provides a more comprehensive evaluation of coating effectiveness than those

reported in previous investigations, by combining the thermal behavior, deformation, damage evolution and residual compressive performance in one framework.

2. Methodology and Numerical Modeling

First, a detailed sequentially coupled thermo-mechanical finite element (FE) model was developed in ABAQUS to simulate the transient thermal and post-fire mechanical behavior of concrete cylinders protected with intumescent coatings. A targeted experimental program was undertaken on five concrete cylinders to calibrate and verify the predictive accuracy of the Concrete Damage Plasticity (CDP) model. Three specimens were tested in uniaxial compression at room temperature to determine the baseline mechanical properties and calibrate the CDP parameters. The remaining two specimens (uncoated and coated) were subjected to controlled thermal exposure for numerical validation of temperature fields and residual strength. The numerical model was then cooled to ambient temperature and subjected to displacement-controlled compression to simulate the post-fire testing procedure following thermal loading. Mesh convergence study was performed to ensure the accuracy of the spatial discretization. Finally, the FE model validated by the experiments was used to perform a comprehensive parametric study on the combined effects of temperature of exposure and thickness of the intumescent coating. The overall research flowchart is summarized in Figure 1.

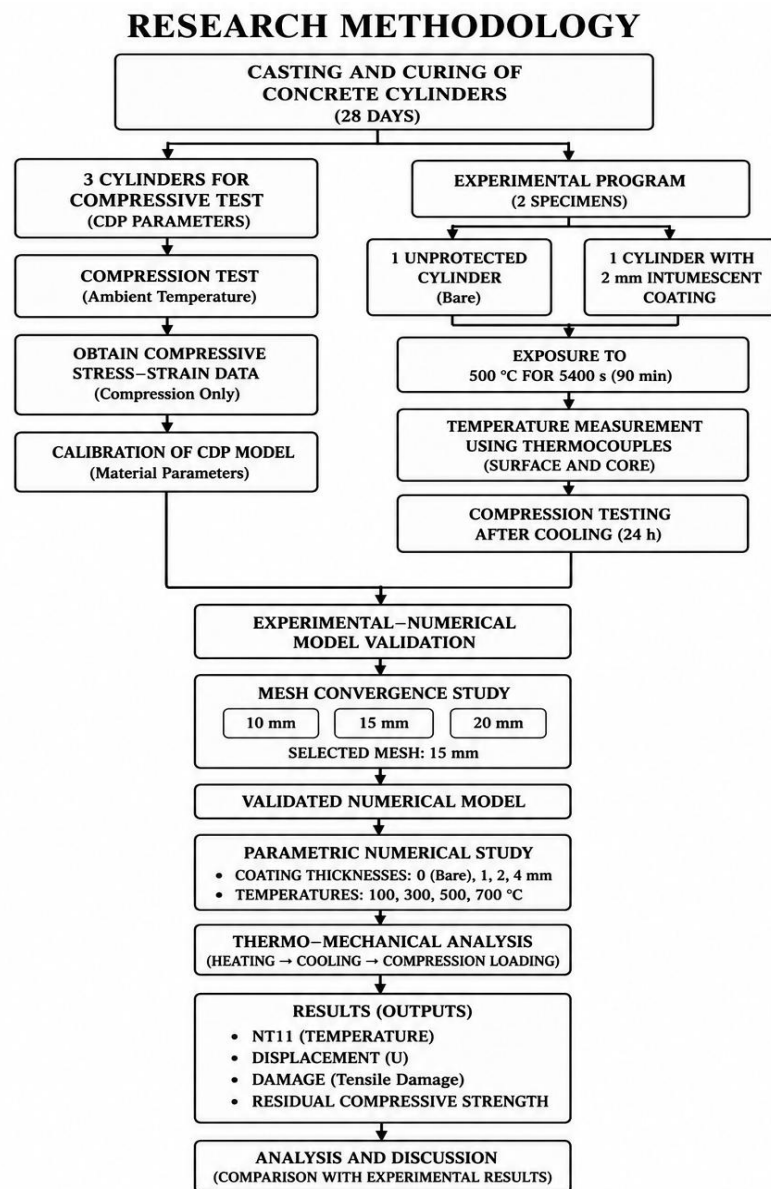


Fig. 1. Flowchart of research methodology

2.1 Finite Element Model Formulation

2.1.1 Material Model

The Concrete Damaged Plasticity (CDP) model implemented in Abaqus was used to model the concrete mechanical behavior. This constitutive model was chosen because it is able to describe the nonlinear behavior of concrete in tension (cracking) and compressive (crushing) regimes, taking into account the progressive loss of elastic stiffness due to damage. The theoretical basis of the model is based on the plastic-damage formulation proposed by Lubliner et al.[26] and its subsequent development for concrete structures by Lee and Fenves [27]. The implementation used in Abaqus provides separate tensile and compressive damage variables and allows to define stiffness degradation and recovery during load reversal [28, 29]. The corresponding damage variables, (d_t) and (d_c), vary between zero and unity, where zero indicates an undamaged material state and increasing values indicate progressive stiffness and strength degradation. The model also considers a partial recovery of stiffness during unloading and load reversal, which makes the nonlinear response of concrete more realistic. The required stress–inelastic strain relationship for the compressive response was obtained from the experimentally determined compressive stress–strain curve. The elastic strain component was subtracted from the total strain to get the inelastic strain [30]:

$$\varepsilon_c^{\sim in} = \varepsilon_c - \varepsilon_c^{el} \quad (1)$$

where:

$$\varepsilon_c^{el} = \sigma_c / E_0 \quad (2)$$

In this case $\varepsilon_c^{\sim in}$ is the inelastic compressive strain, ε_c is the total compressive strain, σ_c is the compressive stress, and E_0 is the initial elastic modulus of concrete.

The compressive damage variable was introduced only on the post-peak softening branch where the degradation of stiffness is observed after the peak compressive stress. Earlier it was assumed that the material before its softening was intact ($d_c=0$). The compressive damage variable for the post-peak response was calculated as:

$$d_c = \begin{cases} 0, & \varepsilon_c \leq \varepsilon_{c,peak} \\ 1 - \frac{\sigma_c}{f'_c}, & \varepsilon_c > \varepsilon_{c,peak} \end{cases} \quad (3)$$

where (d_c) is the compressive damage variable, (σ_c) is the post-peak compressive stress, and (f'_c) is the peak compressive stress. Thus, at the beginning of the post-peak softening, (d_c) is zero and increases gradually as the compressive stress decreases.

The cracking strain was also used to characterize the tensile response, which was calculated by subtracting the elastic strain from the total tensile strain:

$$\varepsilon_t^{\sim ck} = \varepsilon_t - \varepsilon_t^{el} \quad (4)$$

with:

$$\varepsilon_t^{el} = \sigma_t / E_0 \quad (5)$$

The tensile damage variable was also induced by the occurrence of tensile softening. The material was regarded as undamaged ($d_t=0$) prior to the peak tensile stress. The post-peak softening response was defined by the tensile damage variable as

$$d_t = \begin{cases} 0, & \varepsilon_t \leq \varepsilon_{t,peak} \\ 1 - \frac{\sigma_t}{f_t}, & \varepsilon_t > \varepsilon_{t,peak} \end{cases} \quad (6)$$

(σ_t) is the post peak tensile stress, (f_t) is the peak tensile stress and (d_t) is the tensile damage variable. Accordingly, is zero at the start of tensile softening and approaches unity with increasing loss in tensile load carrying capacity.

The concrete stress–strain behavior under compression and tension and the related damage variables were implemented in Abaqus from the experimental results and the inelastic and cracking strains calculated by Equations (1) – (6). The obtained constitutive relations were used to define the compressive and tensile behavior of concrete in the CDP framework. The main parameters used for the Concrete Damaged Plasticity model are listed in Table 1. The flow potential eccentricity, the ratio of biaxial to uniaxial compressive strength and the ratio of second stress invariant have been chosen according to the default values given in Abaqus formulation. The dilation angle and viscosity parameter were selected based on the values commonly used for normal strength concrete in the nonlinear finite element analyses. The same parameters were used in the numerical simulations to provide a unified constitutive representation of the concrete response.

Table 1. Parameters adopted for the concrete damaged plasticity model

Parameter	Value
Dilation angle, ψ	37°
Flow potential eccentricity, ϵ	0.10
f_{b0}/f_{c0}	1.16
K	0.667
Viscosity parameter, (μ)	0.0005

The CDP flow-potential and yield-surface parameters, such as dilation angle, eccentricity, f_{b0}/f_{c0} and K_c , were kept unchanged during the thermal analyses. The adopted values ($\psi = 37^\circ$, $\epsilon = 0.10$, $f_{b0}/f_{c0} = 1.16$, and $K_c = 0.667$) are in accordance with those commonly adopted in previous ABAQUS concrete simulations [31, 32]. In particular previous CDP studies have used a dilation angle of 37° together with $\epsilon = 0.10$, $f_{b0}/f_{c0} = 1.16$, and $K_c \approx 0.67$. The values of 0.10, 1.16 and 0.667 for eccentricity, f_{b0}/f_{c0} and K_c respectively are commonly used standard CDP parameters [32]. The main parts of the present model for describing the effects of elevated temperature on the concrete response were the temperature dependent mechanical properties and the constitutive stress–strain relationships. In an effort to simplify the modelling in line with established numerical practice, the CDP flow-potential and yield-surface parameters were therefore kept as temperature-independent parameters. The overall adequacy of the constitutive representation was assessed by comparing the numerical predictions with the experimental thermal and residual strength results.

The CDP yield and flow parameters were kept constant during the thermal analyses, while the temperature dependency of the concrete mechanical response was represented by the temperature-dependent stress–strain relationships and damage evolution. The importance of the temperature-dependent calibration of damage-plasticity formulations for concrete at elevated temperatures has been evidenced by experimental studies [33]. In the present study, constant CDP flow parameters were chosen to reduce the number of constitutive parameters that vary independently and to keep the formulation consistent during the parametric analysis. This assumption may affect the predicted deformation and damage response at extreme temperatures. The present study did not include a dedicated sensitivity analysis of the temperature-dependent CDP flow parameters, therefore, the mechanical predictions at the highest exposure temperatures must be interpreted with this modelling limitation in mind. The sensitivity of the predicted response to the temperature dependence of CDP parameters should be investigated in future work.

The numerical model was defined to account for the changes occurring during thermal exposure since the concrete specimens were exposed to elevated temperatures, the thermo-mechanical properties of concrete were defined in the numerical model. The thermal behavior of concrete is determined by its thermal conductivity, specific heat capacity, density and coefficient of thermal expansion, while the mechanical behavior is greatly affected by the degradation of elastic stiffness

with temperature. So, the thermal and mechanical relevant properties were taken into consideration to define the thermo-mechanical behavior of the concrete specimen. The mechanical properties of concrete and thermal expansion were temperature-dependent as specified in EN 1992-1-2 and literature. In the numerical model used here a modelling simplification was to assign constant representative values of 1.80 W/m·K for the thermal conductivity and 900 J/kg·K for the specific heat [34]. and the detailed review and experimental data presented by Kodur (2014) [3]. These references indicate that concrete undergoes significant changes in thermal and mechanical behavior with an increase in temperature. In particular, the elastic modulus decreases considerably with increasing temperature, while the thermal expansion increases generally. The thermal conductivity, specific heat capacity and density may also vary with temperature due to moisture loss and temperature-induced changes within the cementitious matrix. In the present study, the temperature dependence was mainly attributed to variations in Young's modulus and coefficient of thermal expansion, whereas thermal conductivity, specific heat capacity, density and Poisson's ratio were kept constant in the simulations. The adopted values were chosen to represent normal weight, normal strength concrete with a nominal compressive strength of about 30 MPa and to be consistent with the concrete used in the experimental program. Table 2 presents the thermo-mechanical properties of concrete used. The temperature-dependent Young's modulus was used to represent the gradual deterioration of concrete stiffness under heating, and the temperature-dependent coefficient of thermal expansion was used to represent the generation of thermal strains. Other properties were constant as defined in the numerical model. These properties were then used to simulate the transient thermal response and the subsequent thermo-mechanical behavior of the concrete specimen.

Table 2. Temperature-dependent thermal properties of concrete

Temperature (°C)	Thermal conductivity, (k) (W/m·K)	Specific heat, (cp) (J/kg·K)	Density, (ρ) (kg/m ³)	Thermal expansion coefficient, (α) (1/K)	Young's modulus, (E) (MPa)	Poisson's ratio, (ν)
20	1.80	900	2400	1.00×10^{-5}	29,791	0.18
100	1.80	900	2400	1.00×10^{-5}	28,200	0.18
200	1.80	900	2400	1.05×10^{-5}	25,200	0.18
300	1.80	900	2400	1.10×10^{-5}	20,700	0.18
400	1.80	900	2400	1.15×10^{-5}	16,300	0.18
500	1.80	900	2400	1.20×10^{-5}	11,900	0.18
600	1.80	900	2400	1.25×10^{-5}	7,600	0.18
700	1.80	900	2400	1.30×10^{-5}	3,700	0.18
800	1.80	900	2400	1.35×10^{-5}	1,500	0.18

The modelling simplification is the assumption of constant thermal conductivity and specific heat over the investigated temperature range. Although these properties are known to be temperature dependent, for the purpose of keeping a consistent definition of thermal properties within the present parametric study, representative constant values have been used. The validity of this simplification was checked by comparison with the experimental temperature-time response at 500°C for 5400 s. The good agreement between the experiments and the numerical results supports the use of the model for a comparative evaluation of the coating configurations investigated in the present study. This validation should not be interpreted as a general predictive accuracy for all temperatures or fire situations. The use of constant thermal properties can affect the absolute prediction of temperatures outside the validated condition. Therefore, future studies should fully include temperature dependent thermal conductivity and specific heat, as well as moisture effects, especially when extending the model to larger temperature ranges or structural-scale fire scenarios.

The intumescent coating was considered as a homogeneous protective material surrounding the concrete specimen. The coating layer was treated as a thermal insulation layer, whose main function was to slow down the rate of heat transfer from the external heating environment to the concrete surface and thereby delay the propagation of heat towards the specimen core. Thermal

and mechanical properties were assigned to the coating to enable its representation in the coupled thermo-mechanical finite element analysis. The thermal conductivity of intumescent coating was considered as a temperature dependent property and is presented in Table 3. The thermal conductivity adopted decreased remarkably with the increase of temperature, which was the effective reduction in heat-transfer capability of the thermal transformation of intumescent protective material. In the present model the behavior was modelled using an equivalent-layer approach; the coating geometry was kept the same and the physical volumetric expansion of the coating was not explicitly simulated. The specific heat capacity and density of the coating in the adopted mm–N–s–°C unit system were 1.47×10^9 and 1.19×10^{-9} , respectively. The elastic response of the coating was characterized by a Young's modulus of 2000 MPa and a Poisson's ratio of 0.30. The modelled coating should therefore be regarded as an equivalent thermal-protection layer, which represents the effective insulating response of the thermally transformed coating, and not as an explicit simulation of the physical intumescence process. Differences between the numerical and physical responses might be attributed to phenomena such as changing char thickness, volumetric expansion, cracking, shrinkage and local debonding, which were not explicitly modelled. The experimental database available does not allow to isolate the individual contribution of these mechanisms and a reliable independent numerical error margin for the omitted expansion process could not be estimated. Instead, the accuracy of the adopted equivalent-layer representation was directly validated using the available experimental temperature–time response.

Table 3. Thermo-mechanical properties of the intumescent coating

Temperature (°C)	Thermal conductivity, (k)	Specific heat, (cp) N.mm/(tone·°C)	Density, (ρ) tone/mm ³	Young's modulus, (E) (MPa)	Poisson's ratio, (ν)
20	0.149294	1.47×10^9	1.19×10^{-9}	2000	0.30
100	0.125649	1.47×10^9	1.19×10^{-9}	2000	0.30
300	0.066537	1.47×10^9	1.19×10^{-9}	2000	0.30
400	0.007425	1.47×10^9	1.19×10^{-9}	2000	0.30
500	0.007277	1.47×10^9	1.19×10^{-9}	2000	0.30

Note: All coating properties were characterized in the consistent mm–N–s–°C unit system used in ABAQUS model. So, the consistent mass unit is the tone. So, the coating density of 1.19×10^{-9} is equal to 1190 kg/m^3 , and the specific heat of $1.47 \times 10^9 \text{ N}\cdot\text{mm}/(\text{tonne}\cdot^\circ\text{C})$ is equal to $1470 \text{ J}/(\text{kg}\cdot^\circ\text{C})$. These values therefore correspond to the usual physical properties of the coating in the consistent unit system adopted in the numerical analysis.

2.1.2 Geometry, Mesh, Boundary Conditions, Thermal Loading, and Analysis Procedure

The numerical model consisted of a concrete cylinder of 150 mm diameter and 300 mm height. For the coated configuration, the 2 mm thick intumescent coating was geometrically modelled as three separate components, a hollow cylindrical shell enclosing the concrete cylinder and two solid circular end caps covering the upper and lower surfaces of the concrete specimen. This arrangement permitted the maintenance of a constant coating enclosure about the concrete cylinder including the lateral and end surfaces. Figure 2 presents the separate components of the concrete cylinder and the intumescent coating. Note that in the experimental program the intumescent coating was applied only on the external cylindrical surface, while the numerical model considered coating also on the upper and lower end surfaces. The numerical end caps were introduced as a geometric idealization to provide a continuous protective enclosure and a constant representation of the thermal boundary. Thus, the numerical coating configuration does not exactly reproduce the experimental coating geometry at the ends of the specimen, and this difference is acknowledged as a limitation in the interpretation of the experimental-numerical comparison.

The overall specimen configuration was comprised of the concrete cylinder and coating components concentrically placed. The computational domain was discretized with three-dimensional 8-node coupled temperature-displacement brick elements (C3D8T). To assess the impact of mesh refinement on the predicted thermal response, a mesh-sensitivity study was conducted using global element sizes of 10, 15, and 20 mm.

The temperature-time histories for the temperature histories are given in Figure 3. During the heating phase, a good consistency was found between the three discretization levels, which suggests that the predicted core-temperature response was not significantly affected by further mesh refinement in the range investigated.

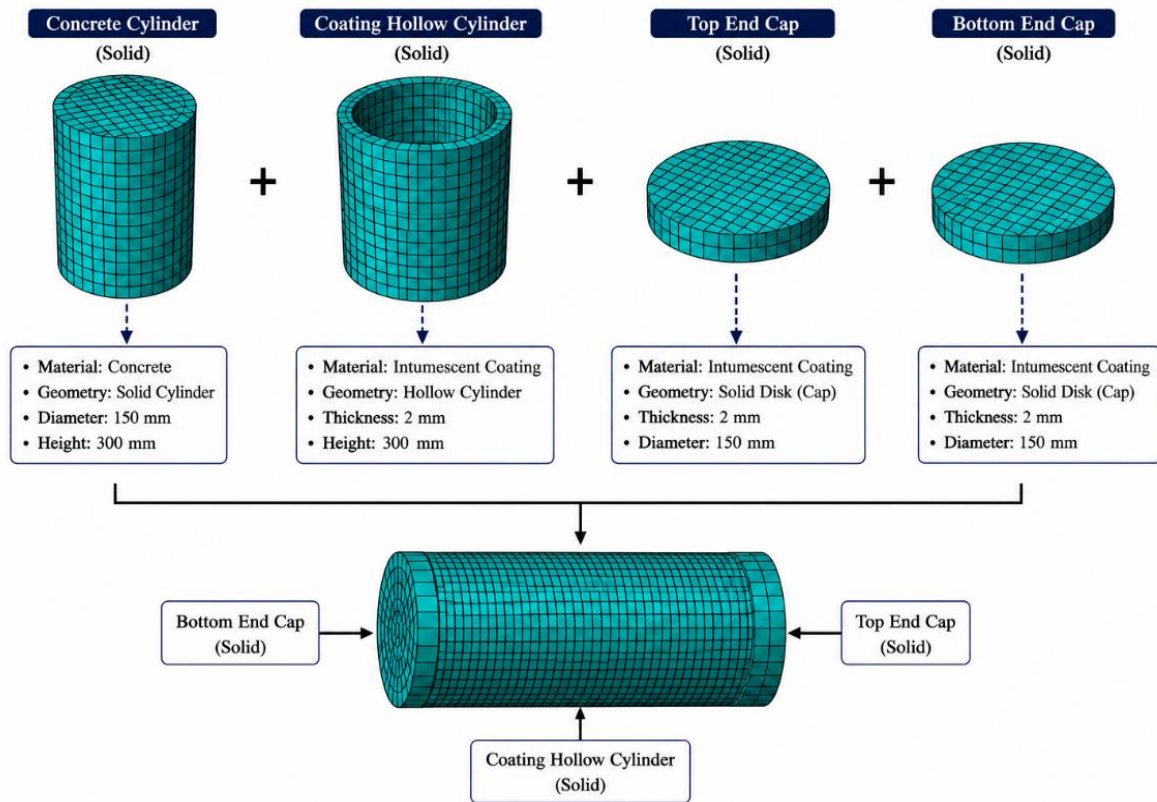


Fig. 2. Geometry and mesh configuration of the concrete cylinder and intumescent coating system

Hence, a global mesh size of 15 mm was chosen as a good compromise between numerical accuracy and computational cost. The concrete cylinder was modelled by 1,920 solid elements and 2,373 nodes with the discretization used. The 2-mm coating was discretized separately, with two elements provided through its thickness, since the coating thickness was much smaller than the global concrete mesh size. The hollow cylindrical coating had 1282 elements and 2016 nodes, and the top and bottom end caps each had 246 elements and 420 nodes. So, the whole 2 mm coating system was composed of 1774 elements and 2856 nodes. This local through-thickness refinement was used in an effort to obtain an adequate discretization of the thin protective layer while keeping the 15-mm global mesh over the larger dimensions of the specimen. The mesh-sensitivity assessment was focused on the core-temperature response as the heat penetration through the specimen governs the subsequent thermo-mechanical response. Table 4 summarizes mesh discretization details.

The bottom surface of the concrete cylinder was constrained against rigid body motion for the thermo-mechanical analyses. The axial displacement was prescribed to the upper loading surface in the subsequent compression stage. The uncoated and coated specimens were subjected to the same prescribed furnace temperature-time history during thermal exposure, from an initial ambient temperature of 20°C up to the target exposure temperature. The prescribed temperature was representative of the environment surrounding the furnace and was not imposed directly as the temperature of concrete or coating surface. The heat transfer from the furnace environment to the specimen was simulated by film convection and surface radiation. These thermal interactions were applied on the outer surface of the intumescent coating for the coated specimen and on the external concrete surface for the uncoated specimen. The heat was then transferred through the intumescent coating to the underlying concrete. Thus, the different surface temperature histories

obtained for the uncoated and coated specimens are a consequence of the thermal response of the respective configurations and not of the different imposed thermal boundary conditions. Both configurations were intentionally exposed to the same furnace temperature-time history and duration of exposure to simulate a common external heating environment and to facilitate a direct evaluation of the thermal protection offered by the intumescent coating.

Table 4. Mesh discretization details for concrete cylinder and 2 mm coating system

Component	Mesh specification	Elements	Nodes
Concrete cylinder	15-mm global mesh	1,920	2,373
Hollow cylindrical coating	2 elements through 2-mm thickness	1,282	2,016
Top coating end cap	2 elements through 2-mm thickness	246	420
Bottom coating end cap	2 elements through 2-mm thickness	246	420
Complete coating system	—	1,774	2,856

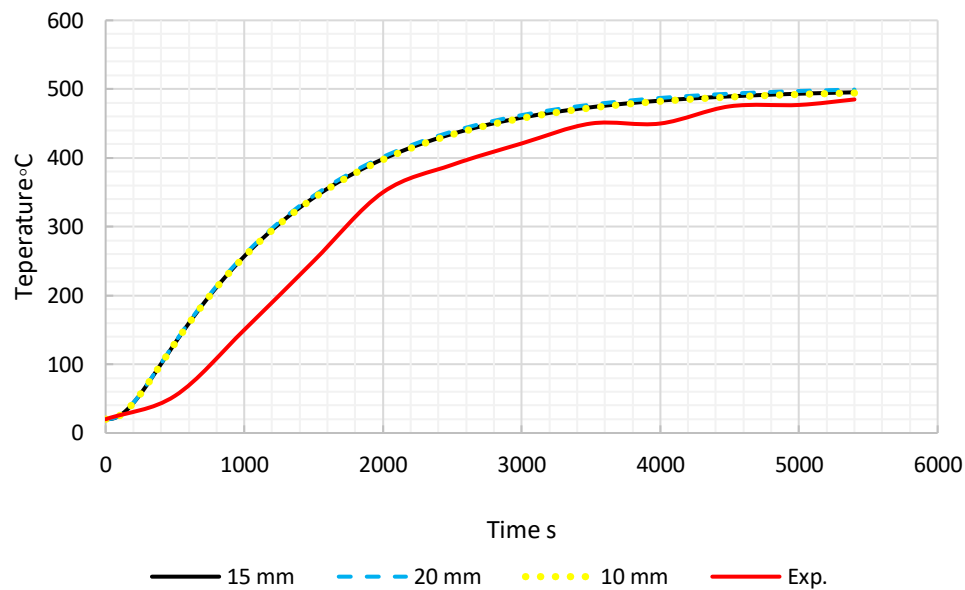


Fig. 3. Effect of mesh size on the predicted core temperature history of the coated concrete cylinder during exposure to 500°C

To reproduce the experimental heating, cooling and post-fire compression procedures, the numerical simulations were performed by a series of analysis steps. A heat transfer analysis was first performed to simulate the thermal exposure at 500°C for 5400 s (90 min) and to obtain the transient temperature distribution in the uncoated and coated concrete cylinders. For thermal validation, the predicted surface and core temperatures were compared with the experimental thermocouple data. Then, a coupled temperature-displacement sequential analysis was performed by using the validated thermal conditions and temperature-dependent material properties to simulate the thermo-mechanical response during heating including thermal expansion, stress, displacement and damage evolution. Then the specimens were numerically cooled from high temperature to 20 °C after the heating stage to simulate the experimental cooling procedure, where the specimens were cooled down in ambient air for 24 h prior to the compression testing. The thermal contraction and the mechanical and damage states associated with it were maintained at the end of the cooling stage and used as initial condition for the following residual strength simulation. Finally, a Static General compression with displacement controlled axial loading was performed to simulate the post-fire compression test. The numerical residual compressive strength was regarded as the maximum compressive stress obtained from the numerical stress-strain response using the resulting reaction force and axial displacement. The numerical results were then compared to the corresponding experimental measurements for uncoated and 2 mm intumescent coated specimens.

3. Experimental Validation Program

The experimental program was performed in order to define the mechanical behavior of normal strength concrete and to provide experimental data for the calibration and validation of the numerical model. Five concrete cylindrical specimens were cast with a diameter of 150 mm and a height of 300 mm (Figure 4b and c). The concrete was designed to achieve a nominal compressive strength of about 30 MPa after 28 days of curing. The concrete mix was made with ordinary Portland cement, clean and well graded natural river sand as fine aggregate, crushed gravel as coarse aggregate and potable water (Figure 4a). The fine aggregate had a maximum size of 4.75 mm, a specific gravity of 2.65 and a fineness modulus between 2.6 and 2.9. The coarse aggregate had a nominal maximum size of 10 mm and a specific gravity of 2.70. The physical and chemical properties of the Ordinary Portland cement used for the study are shown in Tables 5 and 6. The specimens were cured for 28 days under normal laboratory conditions after casting. After the curing period the five specimens were divided according to the intended experimental purpose. Three specimens were used to characterize the mechanical behavior of the concrete at the ambient temperature while the other two specimens were used for the thermal exposure and the experimental validation program.

Table 5. Physical properties of ordinary Portland cement (OPC)

Property	Value
Cement Type	Ordinary Portland Cement (OPC)
Standard	ASTM C150 Type I
Specific Gravity	3.15
Fineness (Blaine)	340 m ² /kg
Initial Setting Time	120 min
Final Setting Time	210 min

Table 6. Chemical properties of ordinary Portland cement (OPC)

Chemical Compound	Content (%)
CaO	63.5
SiO ₂	21.2
Al ₂ O ₃	5.41
Fe ₂ O ₃	3.30
MgO	2.13
SO ₃	2.71
Na ₂ O + K ₂ O	0.82
LOI	1.53

Three concrete cylinders (150 mm x 300 mm) were tested in uniaxial compression after 28 days of water curing as shown in Figure 4f according to ASTM C39/C39 [25]. The stress–strain relationship and the compressive strength of the concrete were obtained by continuously recording the applied load and the corresponding deformation during the tests. The average compressive strength of the three specimens was around 30 MPa, which confirms the concrete produced was in the target normal-strength grade. The experimental stress-strain response and compressive strength were then used to characterize the mechanical behavior of concrete and to define the material parameters required for the Concrete Damage Plasticity (CDP) model implemented in the software ABAQUS.

The remaining two concrete cylinders were used to investigate the thermal response and residual mechanical behavior of concrete after elevated temperature exposure. One specimen was left uncoated and used as a reference specimen, while the second specimen was coated with an intumescent coating of 2 mm thickness applied uniformly on the external cylindrical surface (Figure 4d). The intumescent coating used in this study had a density of 1.34 g/cm³ and a high-volume solids content of approximately 96%, which contributes to minimizing shrinkage during curing. The coating also exhibited a relatively high viscosity of approximately 35,000 cP, allowing

effective application on vertical surfaces with limited sagging. In addition, its volatile organic compound (VOC) content was less than 50 g/L, indicating its suitability for practical applications. The concrete surface was cleaned prior to application of the coating to remove dust, loose particles and other contaminants that could negatively influence adhesion. Surface defects (cracks and voids) were repaired to create a relatively uniform substrate. Then, an epoxy-based primer was added to improve the bond between the intumescent coating and the concrete substrate, and to reduce surface porosity. The primer was dried in ambient laboratory conditions before the application of the protective coating. Then, the intumescent coating was uniformly sprayed on the external cylindrical surface of the selected specimen to provide a nominal thickness of 2 mm. After application, the coated specimen was left to undergo the required drying and curing period under room temperature conditions to ensure sufficient adhesion and development of coating properties before thermal exposure. The uncoated and coated specimens were then exposed to a temperature of 500°C for 5400 s (90 min) under the same heating conditions (Figure 4e). This experimental setup enabled a direct comparison between the uncoated concrete (reference condition) and the concrete coated by the 2 mm intumescent coating, so that the effect of the protective layer on the heat penetration and residual mechanical behavior of the concrete could be evaluated.

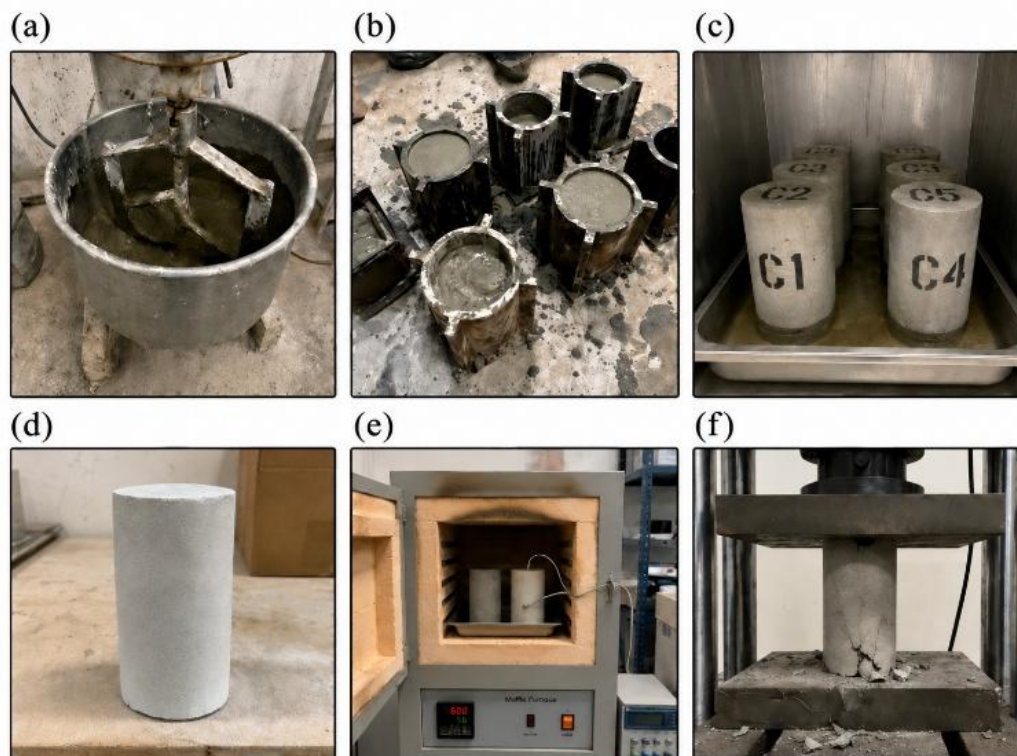


Fig. 4. (a) Concrete mixture preparation, (b) Casting of cylindrical specimens, (c) Curing of specimens, (d) Application of intumescent coating (2 mm), (e) Thermal exposure in furnace, (f) Compression testing after cooling

The temperature development in the concrete specimens during the thermal exposure was recorded by thermocouples positioned at two representative locations, i.e., in the near-surface region of the concrete and at the core of the specimen (Figure 4e). The exact depth of the near-surface thermocouple embedment was not documented during the specimen preparation, so this measurement is referred to as the near-surface temperature instead of an estimated distance from the exposed surface for the duration of this study. A core thermocouple was used to monitor the heat penetration in the interior of the concrete sample. The temperature profiles were continuously measured during the heating period for the uncoated and 2 mm-coated specimens. The measured temperature-time histories provided direct experimental information on the rate of heat penetration into the concrete and the thermal protection provided by the intumescent coating. These experimental temperature histories were then compared with the corresponding temperature predictions from the ABAQUS finite element model. The specimens were allowed to cool down to room temperature after the completion of the 90-min thermal exposure and the

residual mechanical tests were performed. Both the uncoated and 2 mm-coated specimens were then tested for axial compression. Residual compression test was conducted to assess the effect of thermal exposure on the remaining mechanical capacity of the concrete and to compare the performance of the coated and uncoated specimens. The measured mechanical response after exposure was then compared with the corresponding numerical predictions from the coupled thermo-mechanical ABAQUS analysis. The measured experimental and predicted numerical responses were compared to evaluate the reliability of the developed finite element model.

3.1 Model Validation Results and Comparison

The compressive stress-strain responses of three concrete cylinders tested at ambient temperature are shown in Figure 5. The three specimens exhibited similar stress-strain behavior with peak compressive stresses of about 30 MPa. The corresponding peak strains were in the range of 0.0015–0.0016. The stress of all the specimens decreased gradually with the increase of strain after the peak stress. The three stress-strain curves agree excellently and indicate a consistent experimental response. The stress-strain data obtained from the tests were used for the calibration of the Concrete Damage Plasticity (CDP) model in the numerical analysis.

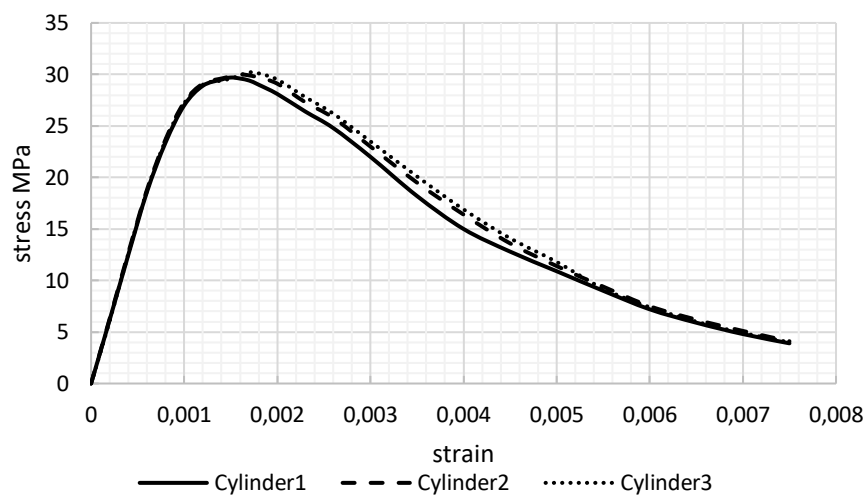


Fig. 5. Experimental compressive stress-strain curves of the three concrete cylinders at ambient temperature

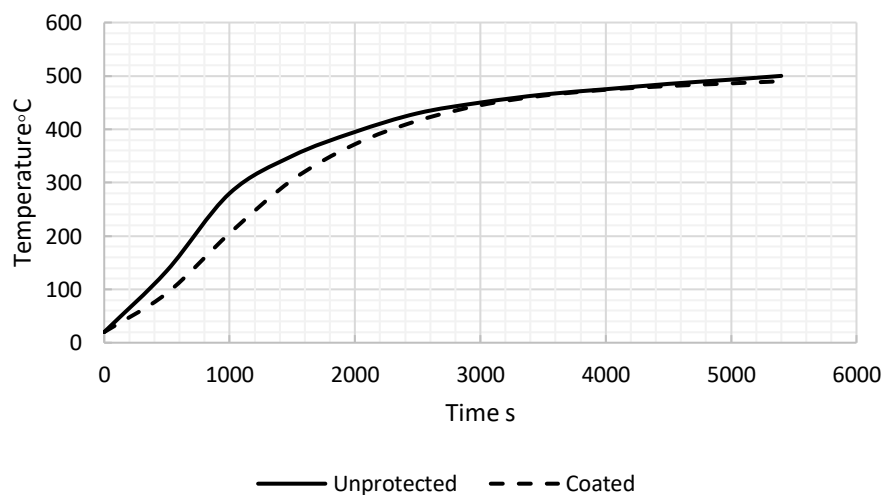


Fig. 6. Experimental surface temperature histories of the uncoated and 2 mm intumescent-coated concrete specimens during exposure to 500°C

The experimental temperature-time histories of the uncoated and 2-mm intumescent-coated concrete specimens are shown in Figures 6 and 7. Temperatures close to the exposed surface are shown in Figure 6. At 1500 s, the surface temperatures of the uncoated and coated specimens were

about 350 and 305°C, respectively, a difference of about 45°C (12.9%). The respective temperatures at 2000 s were ~395 °C and ~372 °C with a difference of ~23 °C (5.8%). The surface temperatures at 3000 s were about 450°C and 445°C, respectively. The end-of-exposure surface temperatures of the uncoated specimen and the coated specimen were about 500°C and 490°C, respectively, at the end of the 5400 s exposure period, indicating a difference of about 10°C (2.0%). In particular, small local fluctuations in the experimental temperature histories were observed during the latter part of the heating period.

Figure 7 shows the temperature histories at the geometric center of the concrete cylinders. At 1500 s, the core temperatures of the uncoated and coated samples were about 338 °C and 246 °C respectively, yielding a difference of about 92 °C (27.2%). The corresponding temperatures were approximately 393°C and 325°C at approximately 2100 s, with a difference of approximately 68°C (17.3%). The core temperatures after approximately 3000 s were approximately 430°C and 421°C, respectively, so the difference was approximately 9°C (2.1%). After the 5400 s exposure, the core temperatures of the uncoated and coated specimens were around 500°C and 485°C, respectively. The temperature difference at the end of the 5400 s exposure was 15 °C, corresponding to a reduction of 3.0%.

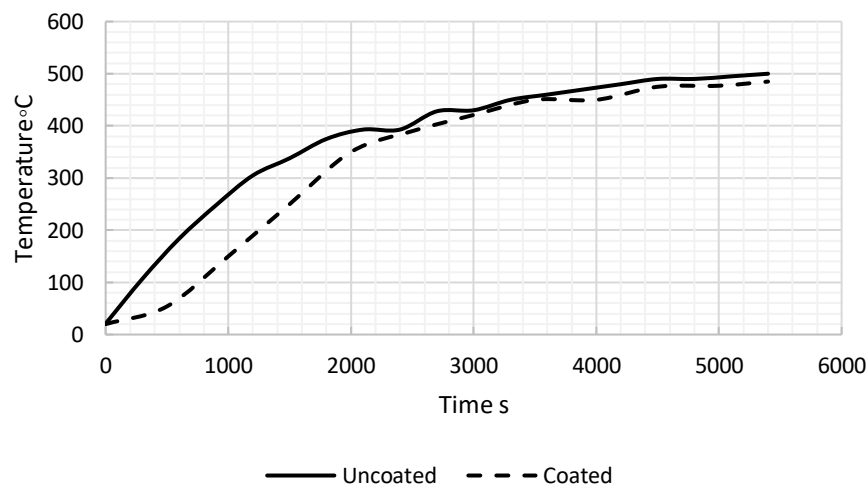


Fig. 7. Experimental core temperature histories of the uncoated and 2 mm intumescent-coated concrete specimens during exposure to 500°C

Table 7. Quantitative comparison of experimental temperatures between uncoated and coated specimens

Time (s)	Uncoated Surface (°C)	Coated Surface (°C)	Surface Reduction (°C)	Surface Reduction (%)	Uncoated Core (°C)	Coated Core (°C)	Core Reduction (°C)	Core Reduction (%)
1000	280	205	75	26.8	184	148	36	19.6
1500	350	305	45	12.9	338	246	92	27.2
2000	395	372	23	5.8	393	325	68	17.3
3000	450	445	5	1.1	430	421	9	2.1
4000	475	474	1	0.2	463	463	0	0.0
5000	493	486	7	1.4	495	478	17	3.4
5400	500	490	10	2.0	500	485	15	3

Table 7. Summary of main experimental temperature differences between uncoated and coated specimens. The maximum temperature difference was 92 °C (27.2%) at the concrete core at 1500 s. After the 5400 s exposure, the temperature difference between the uncoated and coated specimens was about 10 °C in the near-surface region and 15 °C (3.0%) in the core. The gradual decrease of the core-temperature difference with increasing exposure time can be explained by the transient nature of the heat transfer through the protective layer. In the early and middle stages of heating, the coating slowed the heat transfer into the concrete, resulting in a relatively large

temperature difference between the coated and uncoated specimens. With longer exposure the heat builds up in the coated system and continues to diffuse into the concrete core, reducing the temperature difference. Therefore, the decrease of 92 °C at 1500 s to 15 °C at 5400 s indicates that the 2 mm coating just postpones the heat penetration rather than totally prevents it during long thermal exposure times.

Figure 8 shows the compressive stress–strain behaviors of the concrete specimens before and after thermal exposure, and Table 8 presents the corresponding retained compressive strengths. The unheated concrete specimen withstood a peak compressive stress of about 29.83 MPa. The uncoated specimen exposed to 500°C for 90 min (5400 s) and then natural cooling to room temperature for 24 h had a maximum compressive stress of about 22.0 MPa, which was equivalent to the retained compressive strength of about 73.8%, and the strength loss of about 26.2%. The coated specimen attained a maximum compressive stress of about 25.85 MPa corresponding to a retained compressive strength of 86.7 % of the initial strength. Thus, the residual compressive strength of the coated specimen was about 17.5% higher than the uncoated specimen. The relative reduction of the compressive-strength loss was about 49% when compared to the uncoated specimen.

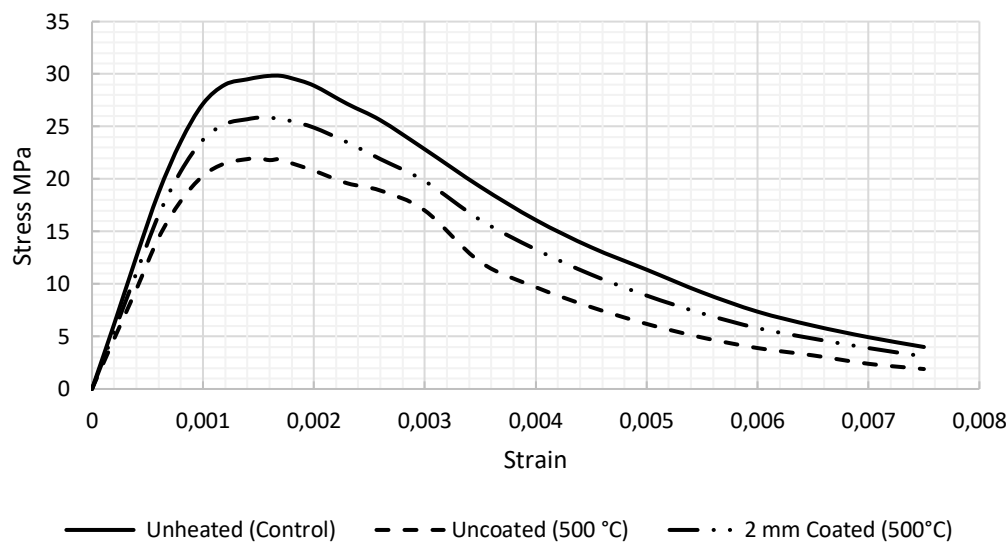


Fig. 8. Compressive stress–strain responses of concrete before and after thermal exposure at 500°C

Table 8. Summary of peak compressive stress, peak strain, and retained compressive strength

Condition	Peak compressive stress (MPa)	Peak strain	Retained strength
Before heating	29.83	0.0015–0.0016	100%
Uncoated after heating	22.00	≈ 0.0015	73.8%
Coated after heating	25.85	≈ 0.0015	86.7%

The differences in the post-peak response of the stress–strain curves are also observed between the unheated, thermally exposed uncoated and thermally exposed coated specimens. The reduction in the descending branch was greater for the uncoated specimen than for the unheated specimen. The coated specimen exhibited a stress-strain response intermediate between that of the unheated and the thermally exposed uncoated specimens. The intumescent coating was manually removed from the coated specimen after cooling, and the compressive response thereafter represented the residual response of the concrete specimen before the residual compression tests.

The thermal response of the uncoated concrete cylinder was validated by comparing the numerically predicted temperature history at the cylinder core with the corresponding experimental measure (see Figure 9). The numerical and experimental responses were in good

agreement over the 5400 s exposure time. The numerical core temperature increased from 20°C at the start of the analysis to 484°C at the end of the exposure, whereas the experimental temperature increased from 21°C to 500°C. The last numerical prediction was thus 96.8% of the experimental temperature with an absolute difference of 16 °C (3.2%). The average absolute temperature difference between numerical and experimental results was about 7.7 °C, which corresponds to the average relative deviation of about 2.2%. The maximum absolute difference was about 17°C at 2400 s. Notwithstanding this difference at the intermediate stage, the numerical temperature-time response followed the general trend of the experimental response for the whole heating period. The quantitative comparison provided an RMSE of 9.32 °C and a R^2 value of 0.9953 indicating a close agreement between the numerical and experimental core-temperature histories.

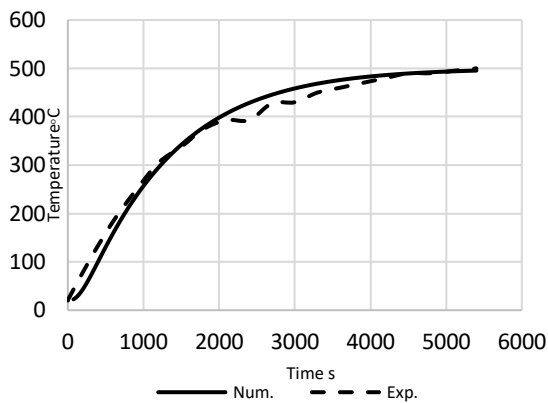


Fig. 9. Thermal validation of the uncoated concrete cylinder

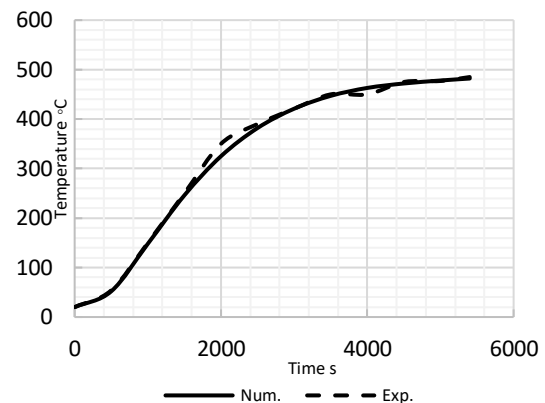


Fig. 10. Thermal validation of the 2-mm intumescent-coated concrete cylinder

The corresponding experimental measurements are also compared with the numerical thermal response of the 2-mm intumescent-coated concrete cylinder, as shown in Fig. 10. The predicted core temperature during the 5400 s exposure period increased from 20°C to 482°C and the experimental temperature increased from 20°C to 485°C. So, the difference between numerical and experimental temperatures at the end of the exposure period was 3°C (0.62%). The maximum difference was 25°C (7.14%) at 2000 s where the numerical temperature was 325°C and the experimental temperature was 350°C. At 3000 s, numerical and experimental temperatures were 421°C. The difference at the last exposure time was only 3°C. Overall the numerical and experimental temperature histories were similar during the heating period. The maximum difference was observed during the middle heating stage. The corresponding RMSE and R^2 were 8.71 °C and 0.9971, respectively, which further confirmed the good agreement between the numerical and experimental temperature histories.

4. Parametric Study

4.1 Effect of Exposure Temperature on the Thermal Response of the Uncoated Concrete Cylinder

The temperature-time response of the uncoated concrete cylinder exposed externally to 100, 300, 500, and 700 °C is shown in Figure 11. The internal thermal response shows a distinct and systematic increase with increasing exposure temperature. In all cases, the temperature increases slowly from the initial temperature of 20 °C, but the magnitude and rate of heating increases significantly with the imposed exposure temperature. The slowest thermal response is observed for the 100 °C exposure, with the core temperature rising steadily and reaching about 99 °C at the end of the 5400 s exposure period. The 300 °C case results in a final core temperature of about 297 °C, whereas a 500 °C exposure results in a much higher final core temperature of about 495 °C. The 700 °C exposure causes the most severe thermal response with the core temperature reaching a maximum of approximately 693 °C at the end of the 5400 s analysis. The differences between the four curves are most obvious at the initial heating stage. The steepest temperature increase is observed for the 700 °C case, followed by the 500, 300 and 100 °C cases, respectively. This shows that the rise of the external exposure temperature leads to an increase of the thermal driving force

between the heated boundary and the interior of the concrete and, thus, to an acceleration of the heat transfer into the specimen. For example, the 500 °C curve reaches ~100 °C after ~410 s and ~300 °C after ~1325 s, while the 300 °C exposure reaches ~200 °C after ~2300 s. The response at 700 °C is even faster, reaching over 300 °C in about 850 s and 500 °C in about 1800 s. The differences indicate that the temperature of the imposed exposure controls the rate at which thermal energy penetrates through the concrete and the final thermal state of the cylinder. Regardless of the different heating rates, all four curves show a nonlinear, asymptotic response with a relatively fast temperature increase in the initial heating phase, followed by a gradual decrease in the heating rate. This behavior is consistent with transient heat conduction in concrete, where the temperature gradient is initially high but gradually decreases as the internal temperature approaches the imposed thermal environment.

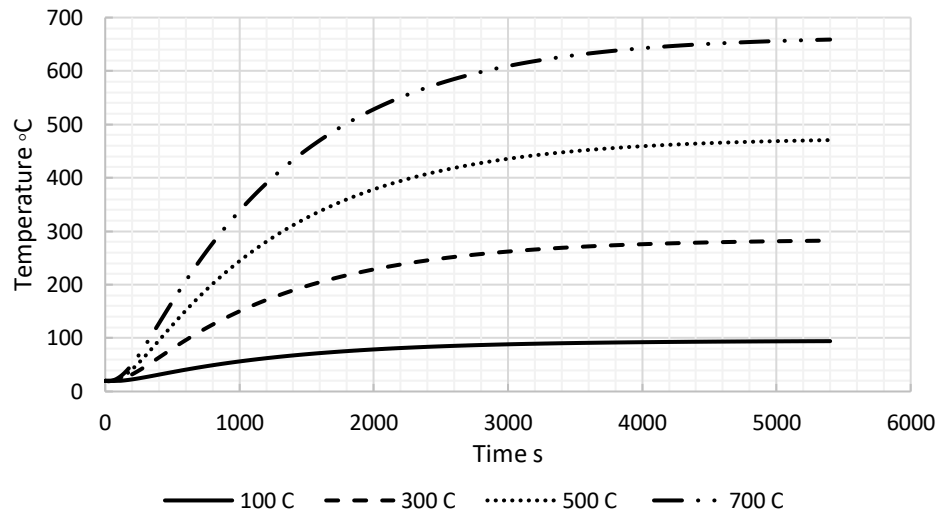


Fig. 11. Effect of exposure temperature on the thermo-mechanical response of uncoated concrete cylinder at core

The reduction of the slope of each curve indicates the gradual reduction of the thermal driving force and the increasing thermal equilibration within the cylinder. The results also showed that the uncoated concrete cylinder is very sensitive to the severity of thermal exposure. The final internal temperature, compared to the initial 100 °C case, increases by a factor of ~7 with increasing exposure temperature from 100 to 700 °C. This temperature dependent response is critical from a thermo-mechanical point of view since the higher thermal fields associated with severe exposure are expected to produce larger thermal expansion and thermal gradients and consequently more significant thermally induced stresses and deformation. Furthermore, the temperature-dependent degradation of mechanical properties of concrete, such as the loss of elastic stiffness and strength at elevated temperatures, is likely to increase the mechanical effects of thermal exposure. Therefore, the results presented in Figure 11 represent a reference case in order to evaluate the capability of the intumescent protective coating to reduce the heat penetration and the resulting thermo-mechanical response, being the uncoated cylinder the reference case.

4.2 Effect of Intumescent Coating Thickness

The effect of intumescent coating thickness on the thermal response of the concrete cylinder was examined by applying coating thickness of 1, 2 and 4 mm under exposure temperature of 100, 300, 500 and 700°C. The results show that the temperature development in the concrete core was controlled by the effect of the external exposure temperature and the thickness of the protective coating. Higher final core temperatures were generally achieved with higher exposure temperatures, but the effectiveness of thermal protection was strongly dependent on coating thickness. For the 1-mm coating, the final core temperatures after 5400 s were 88.04 °C, 276.76 °C, 471.89 °C, and 665.85 °C for exposure temperatures of 100 °C, 300 °C, 500 °C, and 700 °C, respectively. The ultimate core temperatures were reduced to 70.00, 264.12, 455.61 and 640.32°C when the coating thickness was increased to 2 mm. The reductions compared to the 1-mm coating

were 20.5%, 4.6%, 3.5%, and 3.8%, respectively. The 2-mm coating provided a measurable improvement in thermal protection, although the reduction in core temperature became relatively limited at the higher exposure temperatures. The 4-mm coating gave extra protection against heat. The final core temperatures at the end of the 5400 s exposure period were approximately 71.5, 275, 460 and 648 °C for exposure temperatures of 100, 300, 500 and 700 °C, respectively. These values exhibit a physically consistent increase in core temperature with increasing exposure temperature.

Table 9. Final concrete core temperatures at 5400 s and reductions relative to the uncoated condition

Exposure temperature (°C)	Uncoated core temp. (°C)	1 mm core temp. (°C)	Reduction (%)	2 mm core temp. (°C)	Reduction (%)	4 mm core temp. (°C)	Reduction (%)
100	99.21	95.11	4.1	74.70	24.7	71.50	27.9
300	297.29	285.00	4.1	281.50	5.3	275.00	7.5
500	495.38	475.00	4.1	482.00	2.7	460.00	7.1
700	693.47	664.00	4.2	686.00	1.1	648.00	6.6

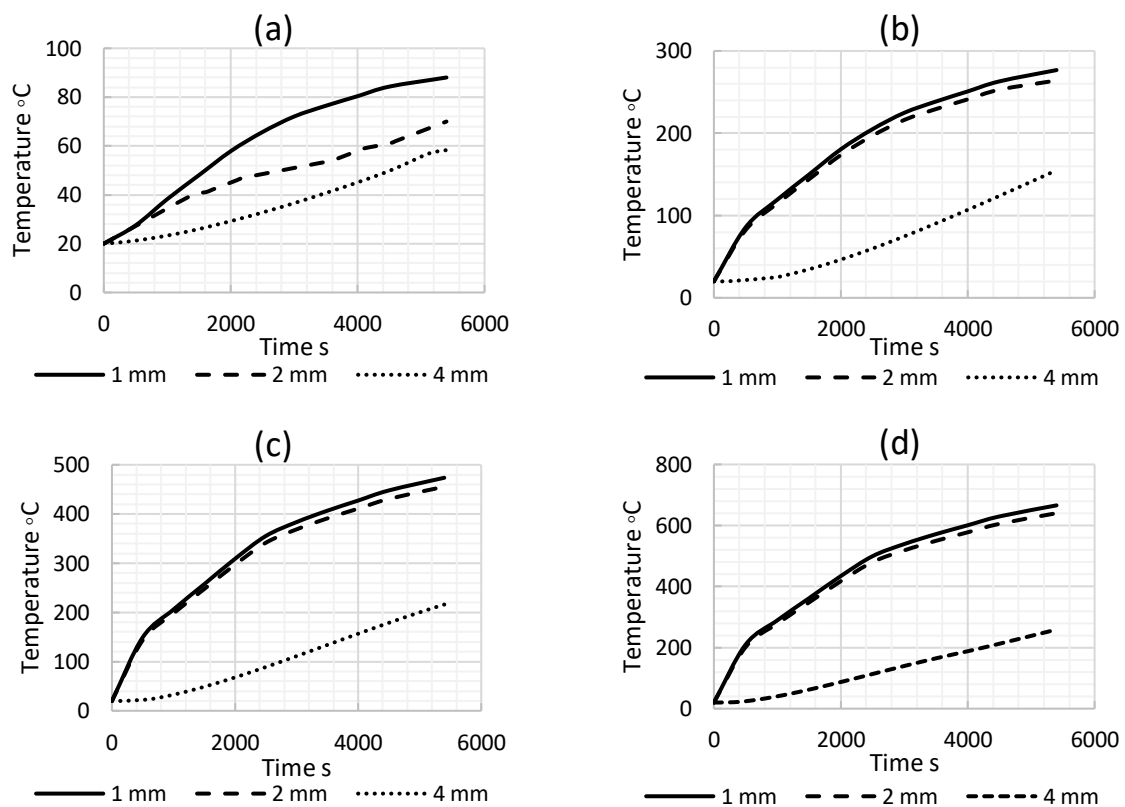


Fig. 12. Effect of intumescent coating thickness (a) Exposure temperature = 100°C, (b) Exposure temperature = 300°C, (c) Exposure temperature = 500°C, and (d) Exposure temperature = 700°C

The final core temperature decreased by about 18.8%, 0.6%, 2.5% and 2.7% at 100, 300, 500 and 700 °C respectively, when the coating thickness was increased to 4 mm compared to the 1-mm coating. The corresponding decreases were approximately 4.3%, 2.3%, 4.6% and 5.5% relative to the 2 mm coating. The results thus indicate that an increased coating thickness provides additional thermal protection, but the level of improvement is dependent on the exposure temperature and is not proportional to the increase of coating thickness. The results confirm that the overall thermal performance of the intumescent coating is governed by the interaction between exposure temperature and the thickness of the protective layer. The 4-mm coating provided the best thermal

protection, particularly important at high thermal exposure. The ability to reduce the final concrete core temperature is about 61.1% compared to the 1-mm coating at 700°C, which shows the improved ability to delay the penetration of heat and to reduce the thermal severity experienced by concrete.

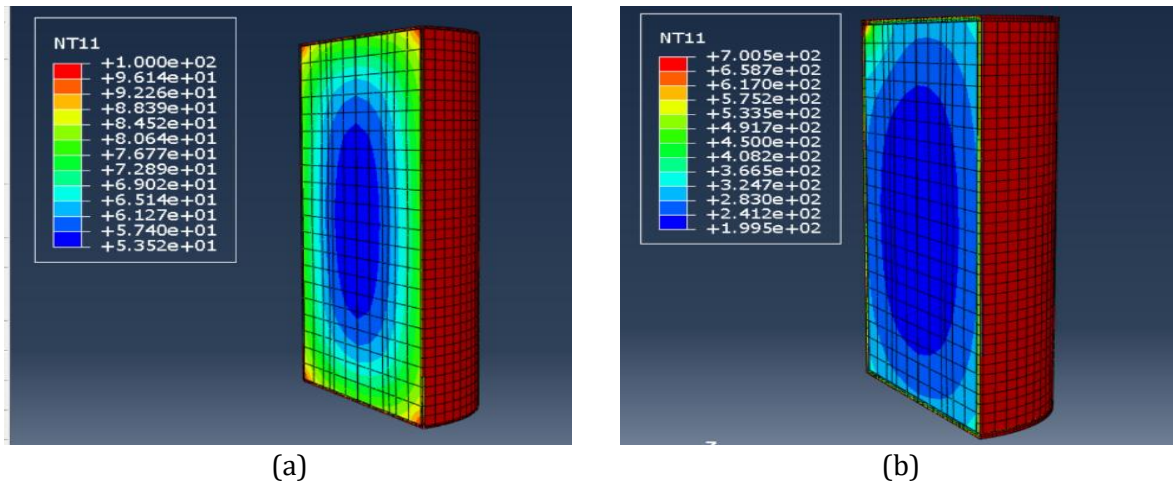


Fig. 13. Comparison of temperature contours under the least severe thermal condition (a: 1-mm intumescent coating exposed to 100°C) and the most severe thermal condition (b: 4-mm intumescent coating exposed to 700°C), illustrating the combined influence of exposure temperature and coating thickness on heat penetration

Therefore, the 4 mm intumescent coating was identified as the most effective thermal barrier and the most promising thickness to reduce the thermal degradation of the concrete cylinder under elevated temperature conditions. For a direct quantitative comparison of the investigated coating thicknesses, the final concrete core temperatures at 5400 s and the corresponding percentage reductions relative to the uncoated condition are summarized in Table 9. Figure 12 summarizes the effect of intumescent coating thickness. The lowest final core temperature was obtained with 4 mm coating at all investigated exposure temperatures as shown in Table 9. However, the extent of the thermal benefit was affected by the exposure temperature, confirming that the effect of the coating thickness was not strictly proportional in all the explored thermal conditions.

The temperature contours shown in the Figure 13 provide a visual representation of the combined effects of the exposure temperature and intumescent coating thickness on the heat penetration into the concrete cylinder. The comparison of 1-mm vs 4-mm coatings indicates the significant enhancement of thermal protection with the increase of coating thickness. The thinner coating allows for much greater heat penetration to the concrete core in severe exposure conditions, while the thicker 4 mm coating maintains a substantially cooler internal region. The contour distribution also confirms the presence of a steep temperature gradient passing through the coated system indicating that the intumescent layer effectively delays heat propagation. These visual observations are consistent with the temperature-time results and further support the superior thermal protection of the thicker coating.

4.3 Effect of Intumescent Coating on Mechanical Response

4.3.1 Displacement Response

The thermo-mechanical displacement behavior of the coated concrete cylinder was studied by means of the displacement histories obtained at the exposed surface and at the cylinder core for the three investigated intumescent coating thicknesses. For all coating configurations, displacement values were extracted from two identical reference locations within the concrete cylinder: a node at the geometric center of the concrete cylinder (core location) and a node at the center of the upper concrete surface (surface location). Therefore, the surface displacement was acquired from the concrete surface, not the outer surface of the intumescent coating. The displacement histories showed a general overall trend for all analyzed cases: an initial transient contraction and a gradual transition to positive displacement as the thermally induced expansion

took over. The first negative displacement is not an indication of actual shrinkage of concrete on heating. Rather it is a transient thermo-mechanical response associated with the rapid and non-uniform development of temperature field at the onset of thermal exposure. The exposed surface is heated and tends to expand faster than the relatively cooler concrete core. The temperature difference across the section temporarily restrains the free thermal expansion and produces a redistribution of thermal stresses and deformation. This transient interaction may cause a small initial displacement in the direction of contraction. With the heat progressively penetrating toward the core and the temperature field developing in the whole specimen, the thermally induced expansion dominates and the displacement changes to the positive direction. The exposure temperature and coating thickness therefore mainly affect the magnitude and speed of displacement development and not the general qualitative evolution from initial transient response to later thermal expansion. Also, the displacements histories showed a strong dependence on the thermal exposure conditions. As the exposure temperature increased, the temperature evolution inside the concrete was faster and higher, and the thermally induced deformation was increasing accordingly. This trend can be observed in the final displacement values in Table 10. Surface and core displacements generally increased with increasing exposure temperature. The surface displacement of the 1mm coating increased from 0.1213mm at 100°C to 0.8518mm at 700°C, while the core displacement increased from 0.0557mm to 0.4125mm. The 2- and 4-mm coatings showed the same temperature dependent response. This observation further supports the conclusion that the magnitude of the final displacement was primarily governed by the extent of thermal exposure. It was also obvious the difference between the exposed surface and the core of the cylinder. The core displacement was lower than the corresponding surface displacement for all coating thicknesses and exposure temperatures. This behavior is explained by the non-uniform distribution of the temperature all over the cylinder and the delayed thermal response of the core. The exposed surface responds more directly to the imposed thermal boundary condition, while the core experiences a delayed and reduced temperature increase as heat diffuses inward. Hence, the difference between the surface and core displacement is representative of the developed thermal gradient through the concrete section. The raw displacement histories showed that the difference developed progressively during the analysis, not constantly confirming the transient nature of the coupled thermal and mechanical response. The effect of coating thickness was particularly notable in the severe exposure condition at 700°C given in Figure 14. But all three configurations showed the same general evolution from contraction to expansion, but their displacement magnitudes differed greatly. The maximum final surface displacement of 2-mm coating was 1.2174 mm while the maximum final surface displacement of the 1- and 4-mm coatings were 0.8518 and 0.8245 mm, respectively. Hence, the final surface displacement for the 4-mm coating was reduced by about 32.3% compared to the 2-mm coating and by 3.2% compared to the 1-mm coating. For the 1-, 2-, and 4-mm coatings, the corresponding core displacements were 0.4125, 0.7371, and 0.3803 mm, demonstrating that the 4-mm configuration reduced the final core displacement by approximately 48.4% compared to the 2-mm coating and 7.8% compared to the 1-mm coating. The relatively larger displacement of the 2 mm configuration with respect to the 1 and 4mm configurations should not be interpreted as degradation of the thermal protection provided by the coating. The numerical output was checked, and it was confirmed that this non-monotonic response was not caused by the location of the displacement extraction, as the same concrete surface and core reference locations were used for all three coating thicknesses. Rather, the displacement response is governed by the combined interaction of the transient temperature field, thermal expansion and contraction, temperature gradients and the temperature dependent mechanical behavior of concrete. In particular, the 4-mm coating offered much higher thermal insulation, which highly reduced the heat penetration in the concrete and hence limited the final thermally induced deformation. This interpretation is consistent with the temperature results which demonstrated that the internal thermal field was affected by the coating thickness, but the extent of thermal benefit was not strictly proportional to the coating thickness under all exposure conditions. The results of the displacement measurements thus confirm that the protective coating modifies the mechanical response mainly through its control on transient heat transfer and the resulting thermal field. The displacement histories in general show a consistent thermo-mechanical response for all the configurations investigated while the deformation magnitude was controlled

by the combined effects of exposure temperature and coating thickness. The results indicated that the 4 mm coating was the most effective in reducing the final core displacement under severe thermal exposure, which was confirmed with its superior thermal insulation performance. The displacement response thus confirms the high coupling between heat penetration and thermally induced deformation, while the subsequent tensile-damage contours provide a complementary assessment of the spatial consequences of this thermo-mechanical response.

Table 10. Final displacement response at the concrete surface and core after 5400 s

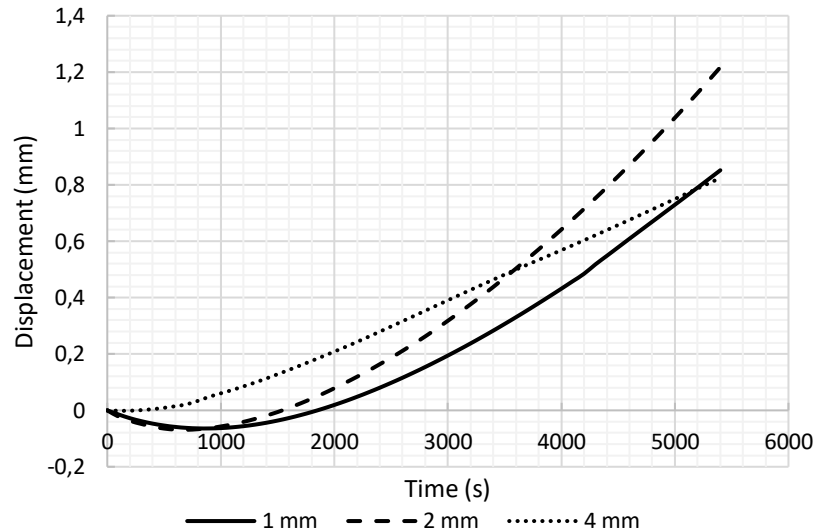


Fig. 14. Displacement histories at surface of concrete cylinders with different intumescent coating thicknesses at 700°C

4.3.2 Tensile Damage Response

The contours of tensile damage, which qualitatively represent the evolution of damage in the concrete cylinders under different thermal exposure conditions and intumescent coating thicknesses, are shown in Figure 15. The contours were chosen to represent the main trends found in the entire analyzed set of configurations, and not to reproduce each individual case. In general, the distribution and intensity of tensile damage increased with increasing temperature of exposure, especially for the uncoated and thinner coated cylinders. The uncoated cylinder with the lower exposure temperature showed only limited localized damage, whereas the severe thermal exposure caused a substantially greater extent and intensity of damage. The results also show the protective effect of the intumescent coating on the evolution of the thermally induced tensile damage. Increasing the coating thickness generally reduced the thermal penetration into the concrete and therefore limited the extent of damage development for a given exposure temperature. This effect was more evident under the more severe thermal exposure, where the thicker protective layers resulted in lower temperatures within the concrete and reduced the thermal severity experienced by the material. The damage contours also show that the damage was not uniformly spread across the cylinder but rather grew preferentially in areas subjected to higher thermal gradients and non-uniform thermally induced deformation. The damage pattern observed is consistent with the thermal results shown earlier, where the temperature within the concrete was considerably reduced as the intumescent coating thickness increased. In the concrete damage-plasticity model, the tensile damage is related to the tensile deformation and the cracking induced by temperature. Therefore, the decrease in temperature penetration by the protective coating led to the corresponding decrease in the development and propagation of tensile damage. Thus, the 4-mm coating demonstrated the best overall damage mitigation of the tested configurations, especially at the highest thermal exposure conditions. The spatially varying temperature field and the corresponding non-uniform thermally induced deformation led to the localization and non-uniformity of tensile damage contours in concrete cylinder. This behavior is in agreement with the thermomechanical response of concrete at elevated temperatures where temperature-dependent

degradation of mechanical properties, thermal gradients and localized cracking mechanisms contribute to spatially heterogeneous damage development. [35, 36]. Thus, the damage distribution observed is expected to be heterogeneous in the cylinder and not to develop homogeneously in the whole concrete domain.

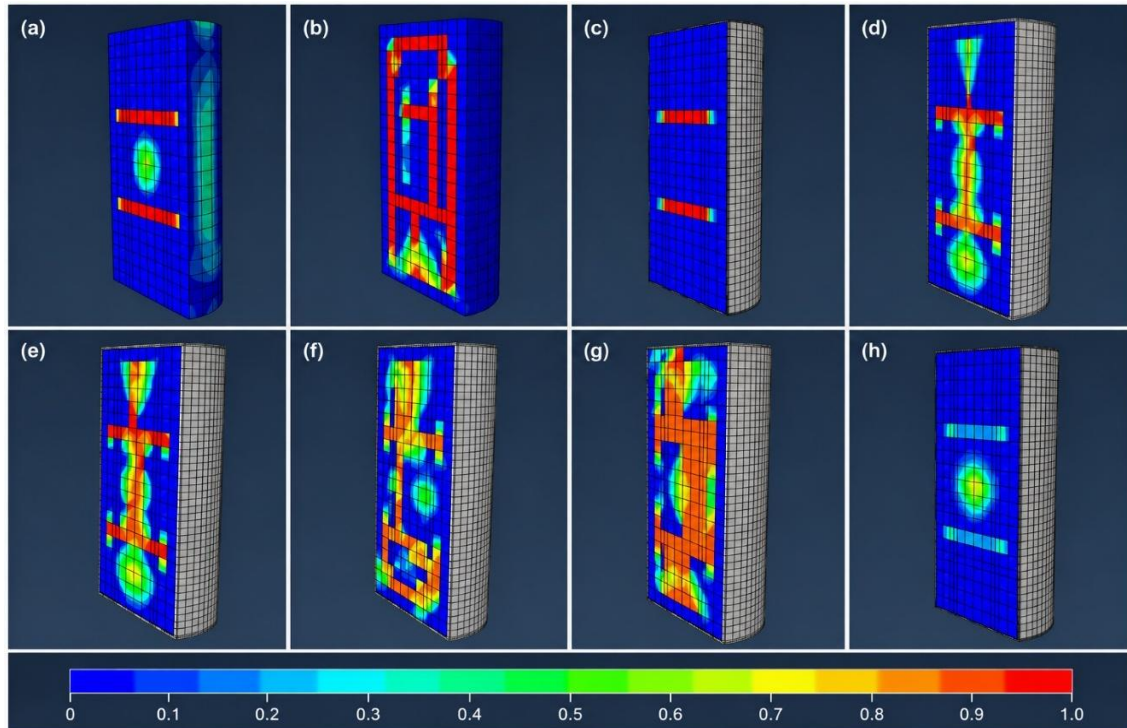


Fig. 15. Representative tensile damage contours illustrating the effects of thermal exposure temperature and intumescent coating thickness. (a) uncoated cylinder at 100 ° C, (b) uncoated cylinder at 700 ° C, (c) 1 mm coated cylinder at 100 ° C, (d) 1 mm coated cylinder at 500 ° C, (e) 1 mm coated cylinder at 700 ° C, (f) 2 mm coated cylinder at 500 ° C, (g) 2 mm coated cylinder at 700 ° C, (h) 4 mm coated cylinder at 500 ° C

This interpretation is in line with previous studies on fire-protected concrete systems that demonstrated that intumescent coatings alter the internal temperature distribution by reducing the heat ingress and consequently the thermal exposure of the concrete . [37, 38]. Therefore, the reduction in thermal severity with increasing coating thickness can help to alleviate the thermally induced tensile damage and maintain the integrity of the concrete core, as also reported in experimental studies of fire-protected concrete exposed to elevated temperatures.[21]. Therefore, the tensile-damage contours for the present study were interpreted qualitatively, based on the overall spatial distribution and severity of damage, rather than based on isolated element values or as mesh-independent predictions of individual crack paths. Some contours exhibit grid-aligned localization, which may be partly due to the sensitivity of strain-softening damage formulations to the finite element discretization. The present analysis does not include a dedicated mesh-objectivity study of the localized damage patterns and an objectivity regularization or damage-stabilization procedure. Thus, the predicted damage bands should not be taken literally in terms of their local width and fine geometry. The contours are primarily used for comparing the gross extent and position of damage for the thermal conditions studied. Future studies should investigate mesh-objective regularizations and damage-stabilization approaches when detailed prediction of localized cracking is desired.

4.3.3 Residual Mechanical Performance

The residual compressive performance of the concrete cylinders was evaluated by the peak compressive stress value after thermal exposure. The retained compressive strength and the corresponding strength loss were calculated with respect to the reference compressive strength of the unheated concrete, and the results are summarized in Table 11. The findings pointed to a clear temperature-dependent decrease in the mechanical capacity of the concrete while the effectiveness

of the intumescent coating was improved with the increase of coating thickness and the intensity of exposure. The mechanical degradation was low for all investigated configurations at the exposure temperature of 100 °C. The uncoated cylinder lost 1.83% of the original compressive strength (98.17% of the original compressive strength). The retained strength slightly increased to 98.43%, 99.0% and 99.98% for the 1-, 2- and 4-mm coatings, respectively. The small differences between the configurations show that the concrete mechanical properties were affected only to a small extent at the low temperature, and therefore the influence of the coating thickness was limited at this temperature. The loss in compression performance was more severe at 300 °C. The uncoated cylinder retained 88.5% of its original strength or had a strength loss of 11.5%. By increasing the coating thickness to 1 and 2 mm, the retained strengths were 89.32% and 90.10%, respectively, while the 4-mm coating increased the retained strength to 94.1% and the strength loss was reduced to 5.9%. The gradual improvement with the increase of coating thickness shows that the thicker protective layer gradually limited the severity of thermal deterioration of the concrete. At 500°C the effect of the coating was much more pronounced. The original compressive strength of the uncoated cylinder was maintained at 75% (a 25% reduction in strength). The retained strength increased to 77, 88 and 93% for 1, 2 and 4mm coatings, respectively. Thus, the 4-mm coating reduced the strength loss from 25% to 7%, which is about 72% reduction in the strength loss, compared to the uncoated configuration. This important improvement shows the higher efficiency of the thicker coating to preserve the mechanical capacity of the concrete with the increase of the thermal attack. The most pronounced difference between studied configurations was observed at 700 °C. The uncoated cylinder lost 63.25% of its compressive strength, retaining only 36.75% of the original. The 1 and 2mm coatings showed only slight improvements with the retained strengths of 41.23% and 43.0% respectively. In contrast, the 4-mm coating retained 84.89% of the initial compressive strength, and the loss of strength was only 15.11%. Thus, the 4-mm coating reduced the strength loss by about 76.1% compared with the uncoated configuration and preserved about 2.31 times the residual compressive capacity of the uncoated cylinder. The small difference in retained compressive strength between the 1-mm and 2-mm coatings at 700°C, despite the better thermal protection offered by the thicker coating, suggests that the relationship between thermal protection and residual mechanical performance is not necessarily linear. The residual compressive strength relates to the combined effect of the internal temperature field, the thermal gradients and the degradation accumulated in the concrete rather than the coating thickness or a single temperature measure. Both the 1-mm and 2-mm configurations were exposed to the severe 700°C exposure, which is within a high temperature regime for significant concrete degradation, so the added thermal protection of increasing the coating thickness from 1 mm to 2 mm provided only a limited improvement in retained strength. However, the 4-mm coating was thermally stable enough to significantly reduce the thermal severity on the concrete, resulting in the substantially higher retained strength of 84.89 %. Coating expansion, interface degradation and potential debonding were not explicitly modelled in the current equivalent-layer formulation and therefore these mechanisms were not used to directly explain the predicted residual strength response. The results showed that the coating thickness effect was highly dependent on the intensity of thermal exposure. At low temperatures, concrete retained most of its original mechanical capacity and the differences between coating thicknesses were limited. The protective effect of the intumescent coating increased with increasing exposure temperature. This is especially true at 700°C where the 4mm coating resulted in a much higher retained strength than either the 1mm or 2mm coatings. The significant improvement at this exposure temperature is attributed to the ability of the thicker protective layer to reduce the thermal intensity experienced by the concrete and, thereby, suppress the degradation of its mechanical capacity. The results on residual strength also provide a quantitative description of the mechanical effects of the thermo-mechanical response discussed above. The results showed that the severity of the thermal exposure led to greater deterioration of the mechanical capacity of concrete, while the thicker intumescent coating significantly mitigated this deterioration. The observed relation between exposure temperature, coating thickness and residual strength is physically consistent with the temperature-dependent deterioration mechanisms reported for concrete subject to elevated temperatures and with the protective role of thermal barrier systems reported in previous studies [13, 22, 24]. The results of these studies support the interpretation that reducing the heat

penetration can decrease the severity of the thermal damage and improve the residual mechanical performance of the concrete. The results demonstrate that the intumescent coating was effective in maintaining the residual compressive performance of concrete cylinders, and its benefit was more significant under severe thermal exposure. The 4 mm coating resulted in the highest retained compressive strength and the lowest strength loss of all investigated configurations. It showed a significant performance at 700°C, reducing the strength loss from 63.25% for the uncoated cylinder to only 15.11%. Therefore, the remaining mechanical results quantitatively show that the increase of the intumescent coating thickness can significantly reduce the degradation of concrete compressive capacity and preserve a larger portion of its original mechanical performance after severe thermal exposure.

Table 11. Summary of the residual compressive performance of the coated concrete cylinders

Exposure Temperature (°C)	Coating Thickness (mm)	Peak Stress (MPa)	Retained Strength (%)	Strength Loss (%)
100	0	29.2873	98.17	1.83
100	1	29.3649	98.43	1.57
100	2	29.535	99	1
100	4	29.83	99.98	0.011
300	0	26.4025	88.5	11.5
300	1	26.6471	89.32	10.68
300	2	26.88	90.10	9.9
300	4	28.0731	94.1	5.9
500	0	22.375	75	25
500	1	22.9716	77	23
500	2	26.2533	88	12
500	4	27.745	93	7
700	0	10.9638	36.75	63.25
700	1	12.3002	41.23	58.77
700	2	12.8283	43	57
700	4	25.3255	84.89	15.11

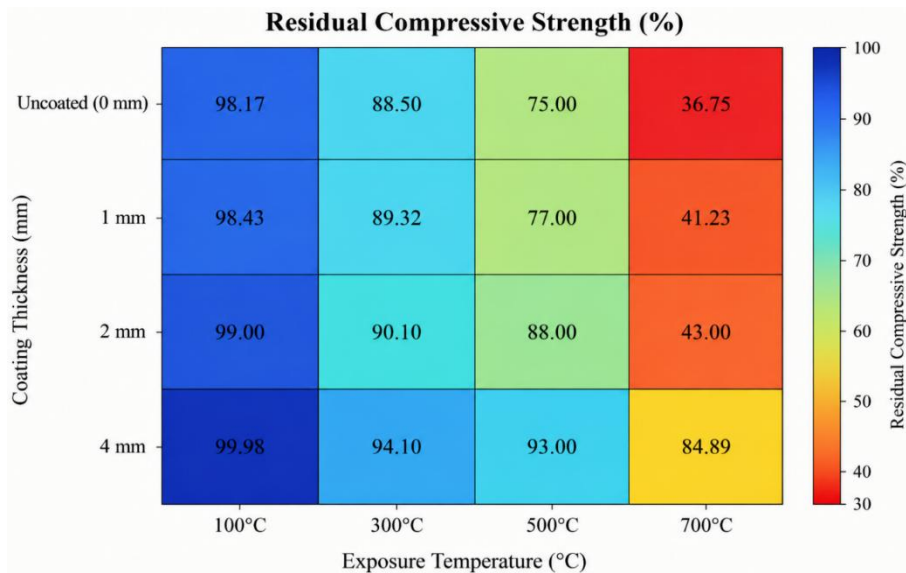


Fig. 16. Heatmap of retained compressive strength as a function of exposure temperature and intumescent coating thickness

As shown in Figure 16, the retained compressive strength generally decreased with the increasing exposure temperature while increasing the thickness of the intumescent coating improved the residual mechanical performance of the concrete. The effect of coating thickness was most evident at the highest exposure temperature, where the 4-mm coating retained significantly higher residual strength compared to the uncoated and thinner-coated cases.

5. Conclusions

The thermo-mechanical response of a concrete structure exposed to fire was studied in the present work using an experimentally validated sequentially coupled finite element framework. The results suggest that the protective effect of the coating is controlled not only by its thickness but also by the interaction between the exposure temperature, the transient heat transfer, thermal gradients and the consequent mechanical response of the concrete. The numerical model has been shown to agree well with the experimentally observed thermal response and has provided a suitable framework to examine the influence of coating thickness when considering the investigated thermal conditions.

The intumescent coating mainly acted to delay the penetration of heat into the concrete and change the evolution of the internal temperature field. In general, increasing the coating thickness improved the thermal protection. The lowest final core temperatures of the coating thickness investigation were obtained for the 4 mm configuration. However, for all exposure conditions the improvement was not strictly proportional to coating thickness. Thus, coating performance should not be assessed solely on the basis of thickness, but also on the time and intensity of thermal exposure and the transient heat-transfer characteristics of the protected system.

The thermo-mechanical results also indicated that the deformation of concrete was closely related to the fluctuating temperature distribution and thermal gradients. The non-monotonic displacement response observed for some coating configurations indicates that a lower temperature at an individual location does not directly translate to a proportionally lower displacement. Instead, the deformation response is due to a combination of spatial temperature gradients, thermal expansion and contraction, and temperature-dependent mechanical behaviour. Similarly, the predicted tensile damage patterns show that controlling heat penetration can decrease the amount of thermally induced damage and hence improve the residual mechanical performance after high temperature exposure.

These results support the application of increased intumescent coating thickness as an effective approach to enhancing the thermal protection of concrete exposed to high temperatures. The best overall combination of thermal protection reduced thermally induced deformation and improved residual response was obtained with the 4 mm coating in the investigated range. However, the results also suggest that the selection of protective coating thickness should be based on the anticipated thermal exposure rather than assuming a linear improvement with increasing thickness. Therefore, the validated modelling framework may be used to facilitate a comparative assessment and preliminary optimization of protective coating configurations under the studied conditions.

5.1 Limitations and Scope of Applicability

The current numerical results are to be understood by considering the studied specimens and modelling assumptions. The model was developed and validated using relatively small unrestrained concrete cylinders under controlled thermal exposure. Therefore, the predicted thermal and thermo-mechanical responses should not be directly extrapolated to full-scale structural members where sustained mechanical loading, restraint conditions, member geometry, reinforcement and non-uniform fire exposure may significantly impact the response. Also, transient creep and other load-temperature interaction effects were not explicitly considered in the present model. The three-dimensional geometry used in this study is representative of the cylindrical specimens tested and does not reflect the more complex heat transfer paths and restraint conditions that may exist in beams, columns, slabs, or structural connections. The results are therefore primarily intended for comparative assessment of the investigated coating thicknesses under the validated conditions rather than for direct structural fire design predictions. Future research should be directed toward the extension of the proposed framework to loaded and restrained reinforced-concrete members, inclusion of transient creep and additional temperature-dependent material behavior, and validation of the predictions against larger-scale fire tests.

6. Recommendations

Based on the results of the present study, the following recommendations are presented:

- The intumescent coating thickness should be considered as an important design parameter for the development of thermal protection systems for concrete subjected to extreme elevated temperatures.
- Thicker protective layers shall be prioritized for the case of severe thermal exposure conditions where the preservation of the concrete core temperature and residual compressive capacity is required.
- The performance of fire-protected concrete should not be judged solely on the basis of the reduction in surface or core temperature but rather considering the coupled thermal and mechanical response.
- Numerical predictions should be supported by experimental thermal and mechanical data in the evaluation of new coating materials or coating thicknesses.

7. Future Work

Future work should aim to validate the predicted thermo-mechanical response experimentally for a wider range of intumescent coating thicknesses and formulations. Further research should also consider other concrete strength classes and aggregate types as well as the influence of coating thermal properties and expansion behavior on heat transfer and damage development. In addition, the effect of elevated temperature in combination with sustained or transient mechanical loading should be studied to extend the present material-level analysis towards more realistic structural conditions. Finally, optimization-based studies could be performed to find coating thicknesses which provide a good balance between thermal protection, residual mechanical performance, material consumption and practical application requirements.

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