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Exploring the fire behaviour of thin intumescent coatings used on timber

Andrea Lucherini[1*], Qazi Samia Razzaque[2] and Cristian Maluk[1]

[1] School of Civil Engineering, The University of Queensland, Australia

[2] Remedial Building Services Australia Pty Ltd, Australia

ABSTRACT

The study presented herein describes an exploratory investigation on the fire performance of intumescent coatings used on timber elements. Timber samples, uncoated or coated with three different thicknesses of a commercially available thin intumescent coating, were tested using high-performance radiant panels according to the H-TRIS fire test method. Test samples were heated for 60 minutes at a constant incident radiant heat flux of 50 kW/m^2. Uncoated samples quickly ignited, while coated samples showed good adherence between the intumescent coating and the timber substrate and limited flaming. At the start of the heating exposure, the intumescent coating rapidly swelled up to a quasi-steady thickness. The presence of the intumescent coating at the exposed surface of timber samples seemed to delay the onset of timber charring and also to reduce the average charring rate after initiation of charring. The delay is proportional to the WFT of the coating, up to 40 minutes from the start of heating for a WFT of 2.5 mm. The experimental results described herein showed that thin intumescent coatings may be effectively used on timber for delaying the onset of charring and assuming a reduced timber charring rate during heating.

KEYWORDS

Intumescent coatings; timber; charring rate; fire testing; H-TRIS; fire safety.

* Corresponding author at: School of Civil Engineering, Advanced Engineering Building (#49), Staff Road House, The University of Queensland, St. Lucia, QLD 4072, Australia.
Email address: a.lucherini@uq.edu.au (Andrea Lucherini).

1 INTRODUCTION AND BACKGROUND

Technological advances and the recent push for sustainable construction have fostered the renaissance of wood as a load-bearing construction material. In particular, the development of engineered wood products has promoted the design of timber structures for accommodating a continuously growing population [1]. Through an optimised manufacturing process, engineered wood products can obtain outstanding and reliable physical and mechanical properties by gluing and combining wooden parts into different configurations. Depending on the type, CLT (Cross Laminated Timber), Glulam (Glue Laminated Timber), LVL (Laminated Veneer Lumber) or other engineered wood products are assembled and used in load-bearing walls, columns, floors or ceilings. However, fire safety has traditionally been a constraint for the adoption of load-bearing timber structures in the built environment [2]. In the event of a fire, timber ignites and chars, resulting in an exothermic reaction that may provide additional fuel to the fire and result in a reduction of the load-bearing cross-section of structural timber elements. Consequently, timber structures must fulfil fire safety requirements to ensure structural integrity and stability during and after a fire [3].

The use of encapsulating thermal barriers (e.g. fire-rated boards) is a common solution to improve the fire performance of timber structures: these systems decrease the temperature rise within the protected material and consequently they slow down or prevent the charring rate within timber elements [4]. More recently, intumescent coatings have been proposed as innovative solution, widely used within the steel industry for avoiding the temperature increase of load-bearing elements during a fire [5]. Intumescent coatings are thermally reactive materials that, when exposed to heat, swell to form a thick porous carbonaceous layer characterized by low density and low thermal conductivity [6]. They are usually applied to a Dry Film Thickness (DFT) in the order of a few millimetres and they can swell up to 100 times its original thickness [7]. The success of intumescent coatings is associated with their attractive architectural appearance of visible structures, along with their ability to be applied on-site and off-site. Particularly, modern transparent formulations of intumescent coatings can even maintain the natural appearance of wood surfaces: these coatings are suitable for exceptional applications, such as the rehabilitation and conservation of heritage wooden buildings in need of an improved fire performance [8].

The use of intumescent coatings on timber can bring multiple advantages. Past researchers gave experimental evidence of the fire-retardant characteristics of intumescent coatings applied on wooden substrate. The coating application usually results in a delay of the time to ignition, a reduction of the heat release rate (total and peak) during combustion, the flame spread and/or smoke emissions. In a few studies, a thin layer of intumescent coatings has prevented the occurrence of timber ignition [9]. In addition, swelled intumescent coatings provide a thermal barrier to reduce the temperature rise, delay the onset of charring and decrease the charring rate within the wooden elements and a physical barrier to limit the pyrolysis gases and access of oxygen [10, 11].

Most of the experimental fire studies available in the literature have been performed using a cone calorimeter under heat fluxes included between 35 and 50 kW/m^2 [8, 10, 12-17]. Particularly, researchers have found that intumescent compositions based on amino-resins can be successfully applied on wooden substrates [8, 14, 15]. However, in the available literature there are limited research studies that have performed detailed characterization and quantification of the overall effectiveness of thin intumescent coatings applied on timber. Since the practitioners charged with the design and construction of fire safe timber structures have reservations and only a few research studies focused on this topic have been published so far, the engineering community has several concerns for their applicability and reliability [18]. For instance, the adherence of the coating to the wooden substrate, the potential for delamination and the true influence on time-to-ignition and charring rate are matters of great debate.

The study presented herein describes an exploratory investigation of the protecting performance of intumescent coatings to structural timber elements exposed to fire. For a range of applied thicknesses of the intumescent coating, the study investigates the effects on surface ignition, onset of timber charring and charring rate.

2 EXPERIMENTAL INVESTIGATION

2.1 Fire testing methodology

The fire testing methodology used in this experimental study is based on a test method/procedure known as Heat-Transfer Rate Inducing System (H-TRIS) [19-22]. The methodology utilizes high-performance radiant panels and it enables the accurate control of the heating conditions imposed on the test samples with high repeatability and low costs [19]. Using a computer-controlled linear motion system, H-TRIS controls the relative position between the target exposed surface of the test sample and an array of radiant panels. In this way, within the limits of minimum proximity to the exposed surface, test samples can be exposed to any specified time-history of incident radiant heat flux. The test setup used within the scope of this work was assembled by combining four high-performance natural-gas-fired radiant heater mounted on a supporting frame, forming a 300x600 mm^2 radiant heat source and able to impose incident radiant heat fluxes up to 100 kW/m^2 (see Figure 1). Moreover, the fire test methodology enables the visual inspection of the test samples during testing (e.g. for gauging the rate of coating swelling), technically challenging during a conventional standard furnace test [21, 22].

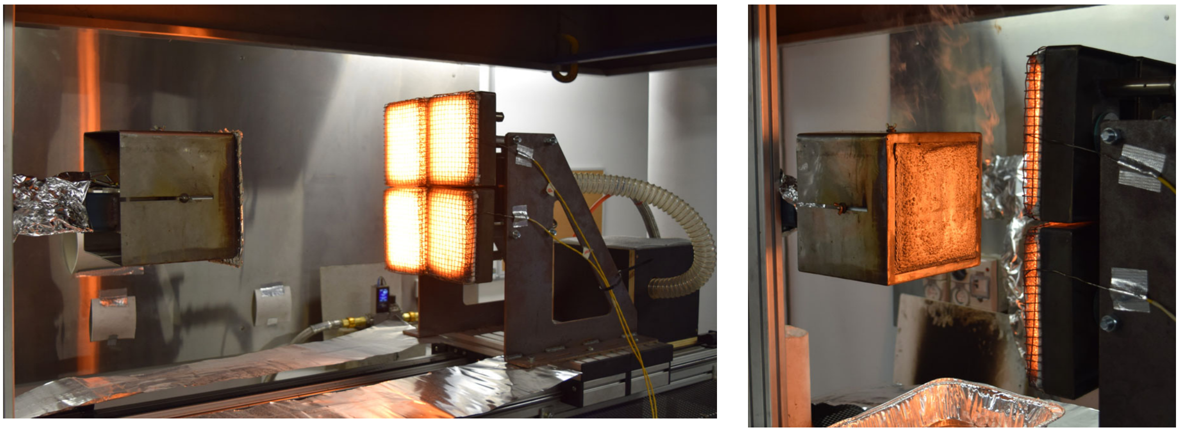


Figure 1. Experimental setup based on H-TRIS test method (left) and fire testing of coated timber samples (right).

2.2 Test samples

The test samples used in this experimental study were twelve 200x200 mm^2, 100 mm thick, Cross-Laminated Timber (CLT) blocks, composed of 5 lamellae (20 mm thick each) of Australian softwood. Three uncoated test samples were used as reference/control. Other nine test samples were prepared and coated by a registered professional contractor with a commercially available solvent-based thin intumescent coating (see Figure 2): three test samples at three different thicknesses of the intumescent coating. The product is a fast-track and self-priming coating, therefore the intumescent coating was applied in one hand using airless spray equipment, without the use of any primer or topcoat. After application, the test samples were stored for about a month inside an environmental chamber at a temperature of 23°C and relative humidity 50%.

Figure 2. Uncoated and coated timber test samples.

The average applied WFT (Wet Film Thickness) and DFT (Dry Film Thickness) for each of the test samples was measured with a non-destructive film thickness gauge, right after application and before fire testing respectively. Test samples were categorised into four groups and the sample ID shown herein was associated with the WFT for each of the samples (refer to Table 1). The letter in the sample label is related to the test repetition (A, B and C).

Table 1. Test matrix of the experimental study.

Sample ID	Applied Thin Intumescent Coating		Initial Weight [gr]
	Average WTF [mm]	Average DFT [mm]	
S00-A			1743
S00-B	n/a	n/a	1751
S00-C			1753
S06-A			1793
S06-B	0.60	0.51	1753
S06-C			1868
S16-A			1911
S16-B	1.60	1.31	1908
S16-C			1904
S25-A			1877
S25-B	2.50	2.13	1905
S25-C			1969

2.3 Testing methodology

Uncoated and coated test samples were individually tested using the H-TRIS test method. Test samples were fire tested to a constant incident radiant heat flux of 50 kW/m^2. The heating condition was selected to yield an onerous thermal condition at exposed surface of test samples and one for which it could be assured that no extinction (for uncoated samples) would occur during testing [23]. All test samples were tested for 60 minutes. The only exception was with uncoated sample S00-A, where the test was stopped at 28 minutes due to the risks of falling of charred material onto the experimental setup. This was the first test performed and the effect of falling charred material was mitigated with a pan placed in front of the sample for the remaining experiments.

During testing, a custom-built steel frame was used in order to hold the test sample aligned with the centre-point of the array of radiant panels, in vertical orientation (see Figure 1). At the end of each fire test, the array of radiant panels was moved away from the test sample and turned off. Afterwards, the sample was cooled down and then cut at mid-height in order to visually assess the swelling depth of the intumescent coating and the charring depth within the timber sample.

2.4 Instrumentation

Prior to testing, test samples were drilled from the back (unexposed) surface in order to place type-K thermocouples (2mm diameter) located at seven various depths from the exposed surface of the sample: 2, 5, 10, 20, 30, 40, 70 mm (Figure 3). The in-depth thermocouples were positioned from the rear of the sample. An additional thermocouple was placed at the back (unexposed) surface of the sample to measure the unexposed surface temperature (100 mm from the exposed surface); this thermocouple was taped onto the back surface to ensure good contact.

The transient rate of swelling of the coating was measured by image processing of videos taken using a high-resolution camera placed at the side of the test sample, aligned with the surface of the test sample. The real-time measurement of the coating swelling was also used for continuously controlling the relative distance between the coating swelling front and the array of radiant panels during testing. This was done to assure that incident radiant heat flux at the exposed surface of test samples was maintained to the specified level during the full duration of the test.

In addition, the lateral faces of the sample were covered with thin sheets of insulation material (mineral wool) in order to minimise the potential of transversal heat transfer between the sample and the metallic sample holder (Figure 4).

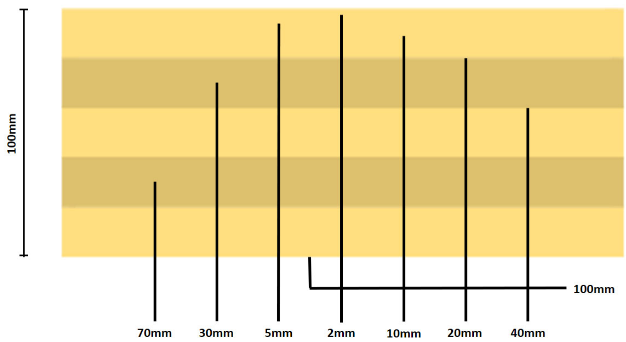


Figure 3. Schematic illustration of the in-depth thermocouples.

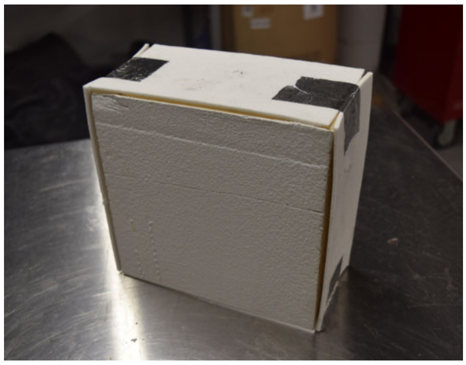


Figure 4. Test sample preparation.

3 ANALYSIS AND RESULTS

3.1 General observations

The experimental setup allowed for continuous visual inspection of the test samples during testing. In this way, it was possible to visually examine the behaviour of uncoated and coated test samples under fire exposure. Table 2 reports the time-to-ignition and time-to-extinction of all tests samples. The reference uncoated test samples (S00) ignited between 30 and 40 seconds from the start of the fire test: the applied incident radiant heat flux was in fact above the critical heat flux for ignition of wood (around 13-14 kW/m^2) [24]. The samples kept burning for the whole duration of the test: no flame extinction was recorded for any of the uncoated samples during the fire test (see Figure 5). Indeed, the applied incident radiant heat flux was higher than the critical heat flux for self-extinguishment of typical CLT products, around 45 kW/m^2 [23]. As regards coated test samples (S06, S16, S25), ignition was only observed for two of three samples protected with a 0.6 mm WFT of intumescent coating (S06-

A and S06-C). Flaming of pyrolysis gases coming out from the cracks on the coating char was observed at very late stages of the fire test (see Figure 5). At the end of the fire test, flames rapidly extinguished after the removal of the applied heat flux.

Table 2. Time-to-ignition and time-to-extinction of uncoated and coated test samples.

Sample ID	Time-to-Ignition	Time-to-Extinction
S00-A	35 sec	No extinction
S00-B	41 sec	No extinction
S00-C	37 sec	No extinction
S06-A	54 min	65 min
S06-B	-	-
S06-C	54 min	65 min
S16-A	-	-
S16-B	-	-
S16-C	-	-
S25-A	-	-
S25-B	-	-
S25-C	-	-

Figure 5. Flaming at the exposed surface of uncoated (S00-B) and coated (S06-A) samples during fire testing.

Testing using the H-TRIS fire test method also enabled a close investigation of the swelling process of the intumescent coatings. As shown in Figure 6, when exposed to heat, the coating underwent different phases, typical of intumescent reaction processes [25]. First, the virgin intumescent coating softens and gradually degrade: this can be observed by the change in colour from white to dark and the release of pyrolysis gases. Then, the coating gradually swells until it reaches a maximum thickness, controlled by the initial applied thickness. Finally, the oxidation reactions occur at the surface of the coating: the intumescent char progressively turns into a white/grey colour. Figure 7 reports frontal photographs of uncoated and coated test samples after completion of the heating regime. The coated samples developed a thick compact porous char with visual cracks at the exposed surface. On the contrary, the uncoated test samples experienced significant charring and detachment of burnt timber char during the fire testing.

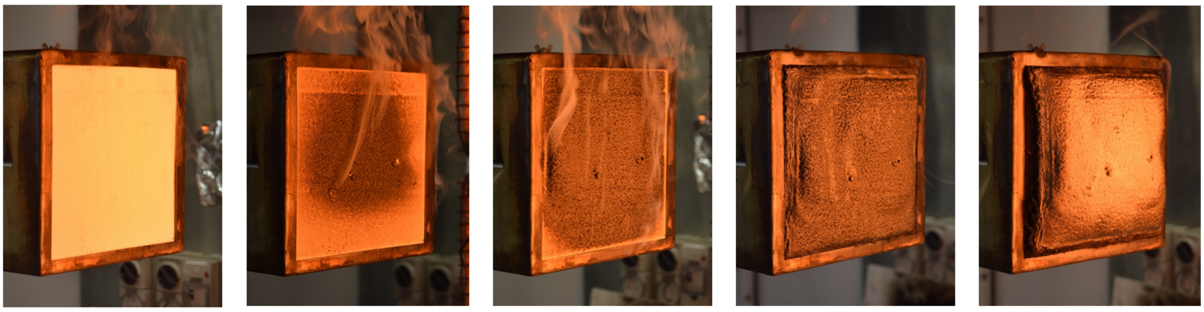


Figure 6. Different phases of the coating swelling during fire testing (S25-C).

Figure 7. Comparison of uncoated and coated test samples at the end of fire testing.

3.2 Transient swelling of the intumescent coating

The time-history of swelling of the intumescent coating at the centre of each coated sample was measured using image processing of high-resolution videos. Figure 8 shows the evolution of the coating thickness in each of the tested coated samples. Right at the start of the fire exposure, the intumescent coating rapidly swells until it reaches a quasi-steady thickness. The maximum thickness that each coating layer can achieve is limited by the initial applied thickness of the intumescent coating: timber samples coated with a thin, medium or thick coating layer swelled up to char thicknesses around 19 mm, 22 mm or 35 mm, respectively. However, it was also found that the rate of swelling is not influenced by the initial applied coating thickness. Finally, in late stages of the fire test, the swelled coating slowly regresses due to oxidation and thermal degradation of the char.

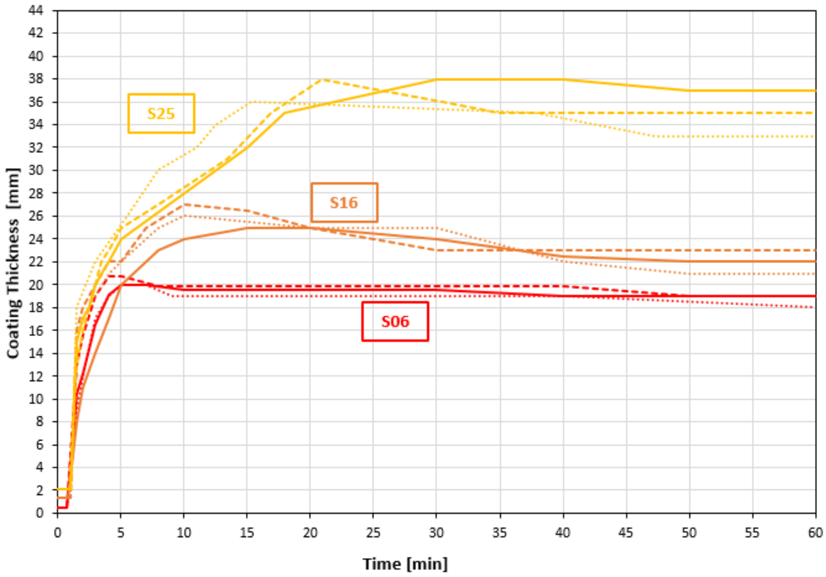


Figure 8. Evolution of coating thickness during testing for coated samples.

3.3 Evolution of the temperature within timber samples

The evolution of temperature within uncoated and coated timber samples was recorded by thermocouples positioned at different depths. Figure 9 compares the evolution of temperatures at four different depths (2, 5, 10, 20 mm) from the exposed surface for each test sample. On the other hand, Figure 10 compares the in-depth temperature profiles within uncoated and coated timber samples at different instants during fire testing (5, 10, 30, 60 minutes). Firstly, the good agreement of the temperature readings obtained in different experiments confirms the high repeatability of the H-TRIS fire test methodology. Secondly, the different plots underline the immediate fire-retardant effect of the applied intumescent coating. Particularly, the temperature within uncoated timber samples rapidly increases due to surface ignition and flaming phenomena at different depths can be observed due to significant noise in thermocouple readings. On the contrary, the temperature within coated timber samples slowly rises and the initial applied thickness of the intumescent coating controls the rate of temperature increment. The fire-retardant and insulating effects of intumescent coatings are highlighted by the substantial temperature difference between uncoated and coated samples. In particular, throughout the fire testing, the temperature at the coating-timber interface (2 mm thermocouple) reached 300°C in 3 minutes for the case of uncoated samples, while samples coated with the thickest layer of intumescent coating (samples series S25) took about 60 minutes to achieve the same condition.

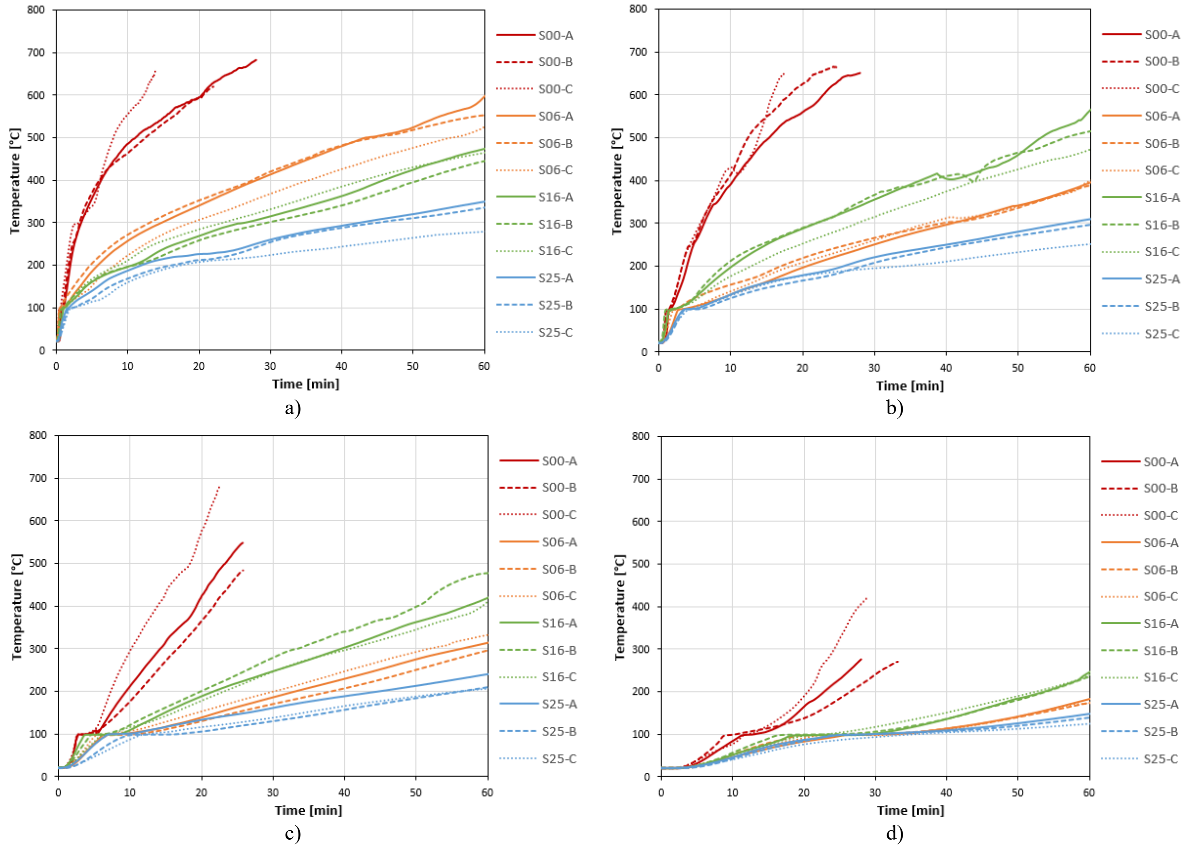


Figure 9. Comparison of the temperature evolution within uncoated and coated timber samples at different depths during fire testing: a) 2 mm; b) 5 mm; c) 10 mm; d) 20 mm.

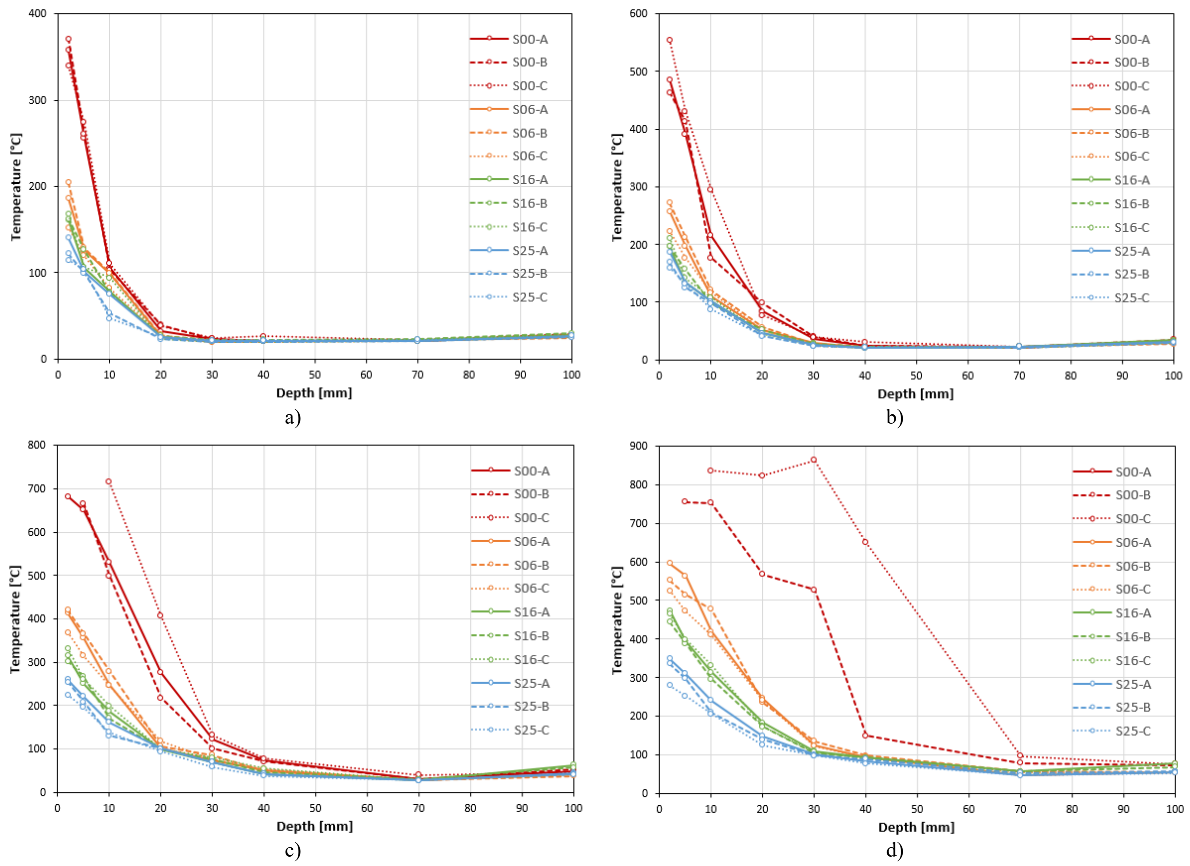
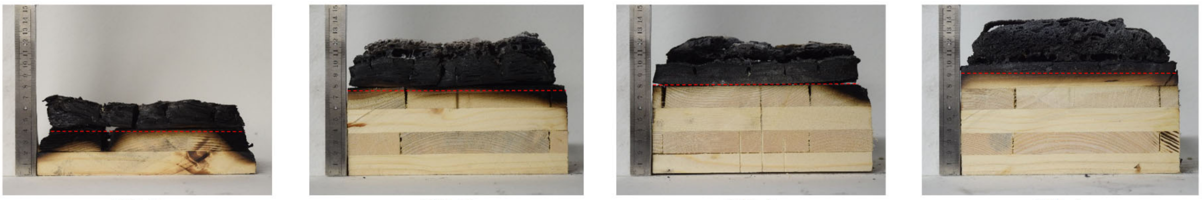


Figure 10. Comparison of in-depth temperature profiles within uncoated and coated timber samples at different instants during fire testing: a) 5 minutes; b) 10 minutes; c) 30 minutes; d) 60 minutes. Notice that the scale for the vertical axis varies for each plot.

3.4 *Effect of applied coating thickness on the timber charring*

Finally, the effect of applied coating thickness on the timber charring was investigated following two different approaches. The first methodology concerns the visual inspection of charring after completion of the fire test. Uncoated and coated samples were sliced horizontally at mid-height. Figure 11 shows photographs of typical sample sections. The charring depth was estimated following the change in colour in the material. Figure 11 also illustrates the projected charring lines and Table 3 reports the values of charring depths experienced by the different test samples.



S00-C S06-B S16-A S25-A

Figure 11. Comparison of charring depths at mid-height cut of the test samples at the end of fire testing.

The second methodology is based on the general assumption that charring line of typical timber may be taken as the position of the 300°C isotherm [3]. Following this approach, the final charring depths experience by the different test samples were calculated by linear interpolation of adjacent thermocouples readings (refer to Table 3). In terms of relative values, general agreement was found for charring depths evaluated following the two different methodologies. However, the values obtained from visual inspection are usually higher: this is likely related to further charring and migration of the thermal wave within the timber sample after the termination of the heating regime [26].

Table 3. Charring depths and charring rates for uncoated and coated timber samples.

Sample ID	Final Charring Depth [mm]		Charring Rate [mm/min]
	Visual Inspection	300°C Isotherm	300°C Isotherm
S00-A	n/a	n/a	0.69
S00-B	55	36.0	0.58
S00-C	60	59.0	1.00
S06-A	21	17.0	0.33
S06-B	22	17.5	0.33
S06-C	22	16.5	0.35
S16-A	20	11.0	0.27
S16-B	14	10.0	0.26
S16-C	20	12.0	0.27
S25-A	10	5.5	0.21
S25-B	8	5.0	0.18
S25-C	5	< 2.0	n/a

Finally, following the same approach based on the 300°C isotherm, the evolution of the charring depth in time was estimated for uncoated and coated timber samples. Figure 12 highlights how the applied intumescent coating delays the onset of charring and decreases the charring rate. However, results shown in Figure 12 indicate that the initial applied thickness of the intumescent coating does not considerably influence the charring rate of coated timber by comparing the slope of S06, S16 and S25 charring depth curves.

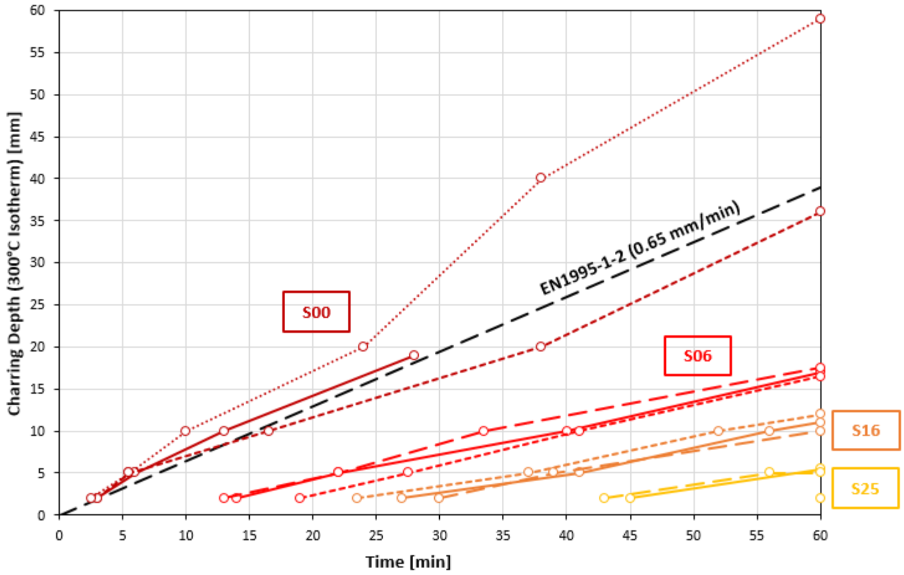


Figure 12. Charring depths comparison according to 300°C isotherm criteria and comparison to the EN1995-1-2 one-dimensional charring rate under standard exposure.

In addition, the average charring rates were calculated based on the temperature evolution of the thermocouple closest to the surface of the timber sample (2 mm) and the final charring depth estimated according to the 300°C isotherm approach (refer to Table 3). In the case of the coated sample S25-C, it was not possible to evaluate the average charring rate because the thermocouple closest to the timber-coating interface (2 mm) did not reach 300°C during the fire test. Test results show that, after initiation of charring, the average charring rate is influenced by the presence and thickness intumescent coating (refer to Table 3 and Figure 12).

Moreover, the obtained values of charring rates were compared to the one-dimensional charring rate for glued laminated timber under standard exposure suggested by Eurocode 5: 0.65 mm/min [3]. The average charring rate for the results testing uncoated timber samples appeared to be in good agreement with Eurocode 5, despite the poor repeatability achieved within the scope of these experiments.

The results presented within this experimental study evidence how the application of intumescent coatings on timber sample reduced the timber charring, even for low initial applied thicknesses. The initial applied thickness of intumescent coating does not appear to influence the charring rate of coated timber samples.

However, a thicker layer of intumescent coating had a higher delaying effect on the onset of charring due to the significant swelling process and the thicker developed char. Indeed, the best improved performance was observed for the thickest layer of intumescent coating (WFT of 2.5 mm): the onset of charring was delayed for more than 40 minutes and the average charring rate was reduced more than 70% (about 0.20 mm/min) compared to the value suggested by Eurocode 5.

4 CONCLUSIONS

The study presented herein describes an exploratory investigation on the fire performance of intumescent coatings used on timber elements. Timber samples, uncoated or coated with three different thicknesses of a commercially available thin intumescent coating, were tested at a constant incident radiant heat flux using the H-TRIS fire test method. The outcomes of the experimental study and the main concluding remarks can be summarized as follows:

- For uncoated timber samples, ignition occurred between 30 and 40 seconds from the start of the test and flame extinction did not occur during the 60 minutes of heating. Time-to-ignition showed to be influenced by the presence and the initial applied thickness of intumescent coating.
- For coated timber samples, upon heating, the intumescent coating rapidly swelled up to a quasi-steady thickness, which was limited by the initial applied thickness. However, the initial applied thickness did not appear to influence the rate of swelling.
- The application of a thick layer of intumescent coating (WFT of 1.6 and 2.5 mm) prevented surface ignition of timber during the full duration of the fire test.
- The presence of the intumescent coating at the exposed surface of timber samples seemed to delay the onset of timber charring: the delay is proportional to the WFT of the coating, up to 40 minutes from the start of heating for a WFT of 2.5 mm.
- The presence of the intumescent coating at the exposed surface of timber samples seemed to reduce the average charring rate after initiation of charring: down to 0.18-0.21 mm/min for a WFT of 2.5 mm.

The work described herein does not investigate at the potential and consequences of delamination of timber samples during heating. Future studies are necessary to extensively quantify the effectiveness of intumescent coatings applied on timber substrates, taking into account the influence of different heating scenarios, potential for loss of adherence between the two materials, potential for delamination of laminated timber, among others.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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