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IMPACT OF OPAQUE AND TRANSPARENT THIN INTUMESCENT COATINGS ON THE HEAT RELEASE RATE OF MASS TIMBER

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ABSTRACT: Exposed timber remains a challenge in the safe construction of mid- to high-rise mass timber buildings. During a fire, heat that is released from the flaming combustion of timber elements can significantly alter the intensity and duration of the fire event. Therefore, understanding the Heat Release Rate (HRR) of mass timber during the different phases of a fire is key, as it can impact both the fire growth and thermal exposure severity to the structure. This study examines the influence of opaque and transparent thin intumescent coatings on the HRR of timber by deriving critical flammability properties, to provide insights into the fire behaviour of bare and coated timber. Bench-scale fire experiments of CLT (cross-laminated timber) blocks were conducted using a calorimetry apparatus under three constant incident radiant heat fluxes of 25, 50, and 75 kW/m^2. For the coated timber samples, different coating types were used – two opaque (A, B) and one transparent (C) at varied thicknesses. The results suggest that opaque coatings (A, B) contribute to improved fire performance of mass timber during both the early and fully developed fire phases, whereas transparent Coating C is primarily effective in the early phase, delaying ignition, limiting flame spread, and reducing heat release.

KEYWORDS: mass timber, thin intumescent coatings, heat release rate, fire safety, calorimetry

1 – INTRODUCTION

1.1 BACKGROUND

Despite the increased use of engineered wood products such as CLT (cross-laminated timber) and glulam (glue-laminated timber), the presence of exposed timber during and after a fire event remains a major challenge in mid- and high-rise construction. Unprotected timber elements can contribute to flaming combustion even after the movable fuel load is consumed, having a direct impact on the different phases of a fire. The flaming combustion of timber can result not only in rapid spread during the developing phase of a fire, but also in increased fire intensity during the fully developed phase [1, 2]. In addition to these, it could lead to ongoing combustion of mass timber elements during the decay phase of a fire, ultimately prolonging the fire duration [2].

The current industry practice to address these challenges is to either partially or completely encapsulate mass timber surfaces with fire-rated plasterboard, to prevent its ignition and thereby timber's contribution to flame spread and fire severity. A secondary effect of encapsulation is the delay or prevention of charring in timber, occurring at temperatures close to 300 °C [3]. Charred sections are attributed negligible mechanical properties, with the char depth used as an indicator of the loss of structural capacity. Therefore, in a mass timber building fire event, timber elements are not only required to maintain their structural integrity, but their likelihood of ignition and subsequent heat release is paramount to fire safety.

Thin intumescent coatings could offer an alternative fire protection measure for mass timber members, with benefits such as improved aesthetics and greater flexibility in application [4, 5]. These coatings are generally opaque and

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are widely applied on steel structures to limit their temperatures below critical values during a fire [6]. More recently, new formulations with a transparent finish have been developed for timber substrates [7], which would allow expression of timber in addition to its protection. Intumescent coatings are generally applied as a very thin layer on the treated surface – up to 3 mm in Dry Film Thickness (DFT). When exposed to heat, they swell, expanding to about 50 to 100 times their original thickness [8, 9], creating a thick, stratified layer of low density and thermal conductivity that insulates the substrate [10, 11], thus preserving its mechanical properties in a fire. Herein, this ability of an intumescent coating to reduce heat transfer into the substrate and thus slow the temperature rise of the material is referred to as insulating efficacy.

Another fire protection option for mass timber could be the use of fire-retardants, which would normally require the impregnation of the timber with substances that alter its fire behaviour by acting in the solid or gas phase to inhibit combustion [12]. Fire-retardants contain compounds that modify the thermal decomposition (pyrolysis) of timber to reduce heat transfer and limit the release of volatile gases, or act in the gas phase to suppress ignition or impede flame propagation [12-14]. While fire-retardants can be applied in both structural and non-structural timber to reduce its flammability, these substances contain acids resulting in a significant strength reduction in timber [15, 16], thus making them a less optimal option for mass timber. In fact, building design codes such as the International Building Code – IBC (US) [17] require strength adjustments to design values for fire-retardant-treated structural timber elements. Hence, fire-retardant-treated timber is often used in non-structural applications [16].

Impregnating mass timber would also need to occur prior to the lamination of individual timber boards, which could interfere with adhesive bonding and potentially increase costs. Unlike most fire retardants, intumescent coatings can be directly applied to the surface of the finished engineered wood product and do not negatively impact structural properties. As such, thin intumescent coatings, particularly transparent ones, could see a wider adoption for the fire protection of mid- to high-rise mass timber construction.

1.2 MOTIVATION

Currently, there is no industry test standard that specifically evaluates the fire behaviour of structural materials during both the early and fully developed phase of a fire. The behaviour in the early phase is evaluated based on the "reaction-to-fire standards" [18-20], which mainly assess flammability properties such as ignition likelihood, flame spread, and heat release – all of which can contribute to flashover conditions (near-simultaneous combustion of cellulosic materials) in the compartment of fire origin. In contrast, the acceptable performance in the fully developed phase (post-flashover) is evaluated by the "fire resistance standards" [21-23], which rely on furnace tests to assess the capacity of building components to prevent fire spread beyond the compartment of origin and structural failure. Indeed, there is no single testing mechanism or apparatus that allows for the assessment of both the flammability properties and thermal degradation (structural integrity) of timber [24]. This is more complex when assessing the fire behaviour of intumescent-coated mass timber as a system.

Reaction-to-fire standards typically require samples to be tested at radiant heat fluxes of 35 or 50 kW/m^2, with the latter widely adopted in standards such AS 5637.1 [19]. These heat flux levels are likely to replicate fire conditions between the onset of flashover (e.g., ≥ 20 kW/m^2 at floor level and 600 °C at ceiling level [25, 26]) and the beginning of the fully developed phase of a fire, in which the heat fluxes are usually greater than 50 kW/m^2 [27]. These standards address the rate of fire growth and thus the time available for egress, while the fire resistance standards are prescribed with the aim of maintaining compartmentation at all stages of a fire.

Historically, there has not been a great need to assess a material simultaneously for flammability and structural capacity, as mid- to high-rise construction has traditionally relied on non-combustible materials such as concrete and steel. However, with the rise of mass timber construction as a more sustainable structural material [28], new and emerging research is essential to comprehensively bridge the gap and link the fire behaviour of both bare and coated mass timber between pre- and post-flashover conditions. A key question thus remains as to whether thin intumescent coatings can improve the fire behaviour of mass timber during both the early and fully developed phases of a fire.

Although there have been some recent experimental studies using cone calorimetry to derive flammability properties of bare and intumescent-coated timber, their premise was not to assess performance across the early and fully developed phases of a fire in a building. These studies either exposed the samples to a single heat flux (typically at 50 kW/m^2 [29]) to compare impregnated and coated timber, tested a limited combination of coating types and DFTs [30], focused on non-intumescent coatings (e.g., mortar coatings [31]), or studied the response to heat fluxes below 30 kW/m^2 to account for fire conditions such as bush (wild) fires [32]. The study herein investigates the Heat Release Rate (HRR) profile of both coated and bare mass timber

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(CLT) samples for different thin intumescent coating types (two opaque, one transparent) and individual DFTs, as well as varied heating conditions. Specifically, samples were exposed to three incident radiant heat fluxes of 25, 50, and 75 kW/m^2. Assuming no convective heat transfer, an emissivity of 1 (black body) [26], and an ambient temperature of 23 °C, these fluxes correspond to radiation temperatures of approximately 550 °C, 700 °C, and 800 °C.

A pilot (igniter) source was not used due to apparatus constraints (discussed in Section 2). However, the selected heat fluxes span from the auto-ignition threshold of bare timber (25-33 kW/m^2 [33]) to above conditions for flaming self-extinction (> 45 kW/m^2 [34]). The highest heat flux aimed to induce temperatures within the range where key components of the coatings undergo thermal degradation (400-800 °C [11, 35]). Cone calorimetry was utilised to derive the following critical flammability properties for the tested samples: (1) time-to-ignition (t_{ig}), (2) peak HRR (*pHRR*), (3) time-to-pHRR (t_{pHRR}), (4) Mean HRR (*αHRR*), and (5) Total Heat Released (*THR*). These properties provide key insights into the fire behaviour of bare and coated mass timber and how they influence fire dynamics. Specifically, they allow for assessing and comparing:

(1) Early flame spread in the developing phase of a fire;
(2) Fire intensity and the likelihood of reaching flashover;
(3) Fire growth rate in relation to flashover conditions;
(4) Sustained burning in the fully developed fire phase;
(5) Prolonged fire duration due to ongoing combustion.

2 – EXPERIMENTAL PROCEDURE

2.1 SAMPLES AND PREPARATION

Timber samples, 100 mm × 100 mm, were prepared from commercially available radiata pine CLT panels. Each sample had a thickness of 110 mm and consisted of three lamellas: top and bottom being 32.5 mm thick and the middle one 45 mm. The opaque coatings are commercially available products, with Coating A used for protecting steel and Coating B for concrete, the latter having a revised formulation for use on timber in this study. Transparent Coating C is a commercial product for timber substrates. The coatings were directly applied to one side of each sample with an airless spray gun at different intervals, to allow fresh paint to cure before the next application until the desired DFT was achieved. Prior to testing, an insulative wrapping (ceramic paper and aluminium tape) was used to minimise any lateral heating to induce one-dimensional heat transfer, as would be expected for full-sized CLT panels.

A total of 36 samples were tested across two experimental campaigns, with each campaign consisting of 18 samples. As seen in Table 1, the first campaign involved testing bare timber and Coating C samples (single DFT) across all heat fluxes, with a mean bulk timber density and standard deviation of 504.6 ± 10.6 kg/m^3. The second campaign (520.3 ± 22.6 kg/m^3) focused on coating type and DFT variation at the most onerous heat flux (75 kW/m^2), as shown in Table 2. In addition, the moisture content was measured weekly using additional sacrificial samples and following the oven-dry method [36], with the mean moisture content and standard error being 10.1 ± 0.3%.

Table 1. Campaign #1 samples: bare timber (BT) vs. transparent Coating (C) at varied heat fluxes.

Sample ID*	DFT [mm]	Heat Flux [kW/m^2]	Density [kg/m^3]	MC [%]
BT-25	N/A	25	511.3	9.3
C-M-25	0.28 (± 0.01)		503.3	
BT-50	N/A	50	499.6	
C-M-50	0.29 (± 0.02)		497.8	
BT-75	N/A	75	505.7	10.3
C-M-75	0.30 (± 0.02)		509.9	

*Each row consisting of three repeats refers to the surface type (bare or coated – Medium DFT) and heat flux level. C-M-25, for example, refers to a coated sample with a medium DFT and a heat flux of 25 kW/m^2.

Table 2. Campaign #2 samples: opaque (A, B) vs. transparent (C) coatings for varied DFTs at most onerous heat flux.

Sample ID*	DFT [mm]	Heat Flux [kW/m^2]	Density [kg/m^3]	MC [%]
A-L-75	0.61 (± 0.06)	75	518.9	10.4
A-H-75	2.56 (± 0.03)		536.2	
B-L-75	1.01 (± 0.03)		510.5	
B-H-75	2.26 (± 0.05)		534.1	
C-L-75	0.20 (± 0.02)		518.1	10.3
C-H-75	0.41 (± 0.02)		505.7	

*Each row consisting of three repeats refers to the DFT level (Low or High) per type of coating tested at 75 kW/m^2.

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For consistency between the two opaque coatings, their upper DFT was based on the maximum recommended by the Coating B manufacturer. Coating C (transparent) required a topcoat for curing and durability purposes, with its DFT not exceeding 0.3-0.4 mm – a typical range for the "clear-type" coating products currently on the market. A coating thickness gauge for timber surfaces was used to measure each DFT. The mean DFT for Coating C in the first experimental campaign was ~0.3 ± 0.04 mm, defined as "M" (Medium), with DFT levels in the second campaign below ("L" for Low) and above ("H" for High) this value. Similarly, for the opaque coatings (A, B) the "L" and "H" DFTs represent their minimum and maximum target thickness values. Typical sample photos of bare and coated samples are shown in Figure 1.

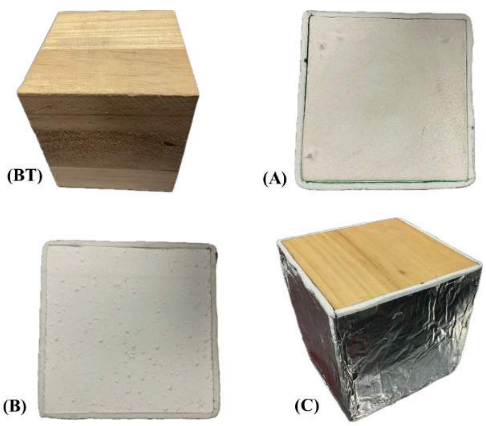


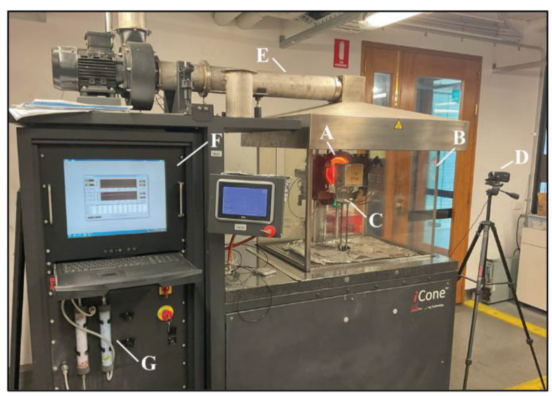
Figure 1. Typical samples before testing showing: (BT) Bare timber; (A) Coating A, (B) Coating B, (C) Coating C with insulative wrapping.

2.2 TESTING SETUP AND RATIONALE

Bench-scale cone calorimetry tests (ISO 5660.1 [18]) were conducted using a Cone calorimeter apparatus (Figure 2), following the oxygen consumption method [16, 37]. This method estimates the HRR of a sample based on the amount of oxygen consumed during its combustion, following the principle that a nearly constant amount of heat is released – typically 13.1 MJ/kg of oxygen for most organic solids [38, 39]. Fire tests were run for at least 20 minutes past ignition of bare timber samples and up to 40 minutes for coated samples. Preliminary testing was undertaken to verify that the HRR plateaus within the specified periods, indicating steady-state combustion. All tests were carried out in the vertical orientation using a modified sample holder, to allow testing of the 110 mm thick samples (Figure 3).

The samples were offset from the cone heater by 42 mm. This offset limited the highest measured heat flux during calibration to 80 kW/m^2. Offsetting was necessary to allow the intumescent coatings to fully swell without impinging on the plate or coil parts of the heater. This was verified during trial testing of sacrificial coated samples with High DFTs, reaching a swelled thickness of up to 35-40 mm for opaque (A, B) and 30-40 mm for the transparent (C). Additionally, there was no practical use for the spark igniter (fixed at ~15 mm from the heater), as its tip was beyond the gas plume of the offset timber surface.

The purpose of the first experimental campaign was to assess the effect of heat flux for bare versus coated timber with Coating C, while the second campaign focused on the effect of DFT variation for all coatings at the highest selected heat flux condition. The rationale for these campaigns to derive critical flammability properties for the selected coated and bare timber samples originates from a separate study by the authors on the charring behaviour of mass timber coated with the selected opaque (A, B) and transparent (C) coatings. This study has shown that the insulating efficacy of Coating C markedly reduces at heat fluxes greater than 25 kW/m^2, while for coatings A and B their integrity and thus insulating efficacy is particularly challenged at 75 kW/m^2 [40-42].



A. Conical heater in vertical position **B.** Glass protective screen
C. Bespoke sample holder on load cell **D.** Video camera
E. Exhaust hood with sampling and smoke management system
F. Computer system **G.** Drying agent (drierite) to absorb water

Figure 2. Experimental apparatus (Cone) showing key components.

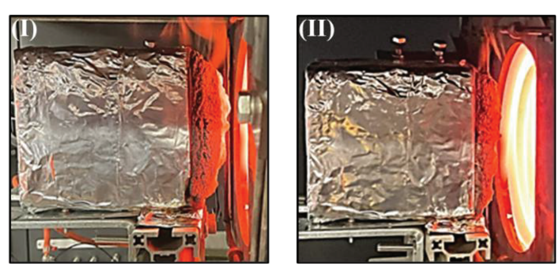


Figure 3. Photos of typical coated timber samples during testing (High DFTs, swelled), where (I) corresponds to opaque and (II) transparent.

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3 – RESULTS AND DISCUSSION

3.1 CAMPAIGN #1 – RESULTS OVERVIEW

Table 3 presents the mean values (three sample repeats) of the flammability properties for both bare and Coating C timber samples, with maximum and minimum intervals indicated by plus and minus notation – derived as follows:

- **t_{ig}:** Time when flaming ignition was first observed.
- **pHRR:** Highest HRR value within 1,200 s.
- **t_{pHRR}:** Time recorded at the highest HRR value.
- **αHRR:** HRR during steady-state burning conditions (curves plateau) observed for at least 200 s.
- **THR_f:** Total heat released at the end of the test.

The HRR and THR profiles for bare and coated timber samples are shown in Figure 4 and Figure 5, respectively. The THR is calculated as the integral of HRR over time using the trapezoid rule, to derive THR values at each HRR data point. A t_{ig} was not recorded at 25 kW/m², as no samples (bare or coated) ignited but instead exhibited oxidative solid phase combustion (smouldering).

Table 3. Experimental data for Campaign #1 samples.

Sample ID	t_{ig} [seconds]	pHRR [kW/m²]	t_{pHRR} [seconds]	αHRR [kW/m²]	THR_f [MJ/m²]
BT-25*	N/A	$22.0^{+2.2}_{-1.2}$	871^{+105}_{-175}	$19.5^{+1.6}_{-0.9}$	$15.8^{+2.7}_{-2.0}$
C-M-25*		$3.6^{+0.9}_{-0.7}$	553^{+456}_{-413}	$1.5^{+0.7}_{-1.0}$	$1.5^{+0.9}_{-0.8}$
BT-50	67^{+08}_{-11}	$105.3^{+13.2}_{-13.4}$	77^{+07}_{-12}	$36.6^{+2.4}_{-1.5}$	$50.8^{+1.1}_{-1.9}$
C-M-50	268^{+142}_{-125}	$41.6^{+7.2}_{-6.9}$	369^{+65}_{-88}	$23.3^{+3.3}_{-4.8}$	$25.3^{+4.3}_{-3.3}$
BT-75	19^{+02}_{-02}	$153.6^{+10.0}_{-12.5}$	26^{+01}_{-02}	$43.6^{+1.1}_{-2.0}$	$63.7^{+2.3}_{-3.7}$
C-M-75	72^{+15}_{-09}	$111.3^{+2.4}_{-1.9}$	230^{+57}_{-65}	$67.7^{+3.0}_{-3.2}$	$88.8^{+3.5}_{-2.2}$

*No t_{ig} recorded, with *pHRR* and *αHRR* having a similar profile. Variability in t_{pHRR} is due to the absence of an actual *pHRR*.

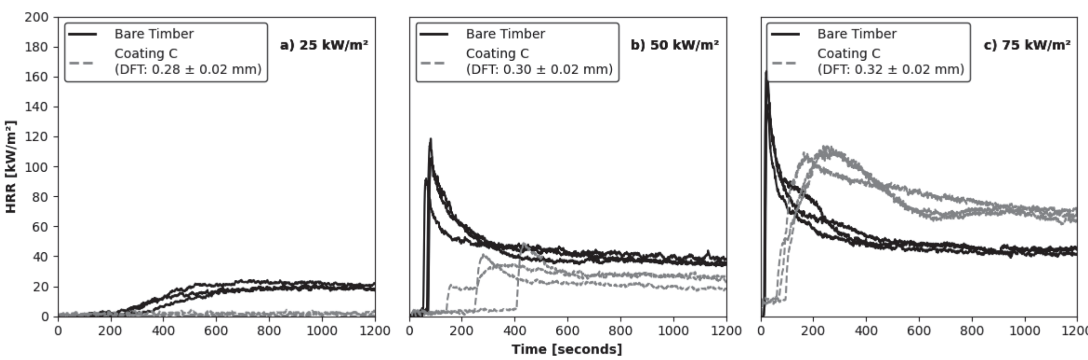

Figure 4. HRR of bare vs. Coating C (Med DFT) timber based on three repeat tests each at a) 25 kW/m², b) 50 kW/m², and c) 75 kW/m².

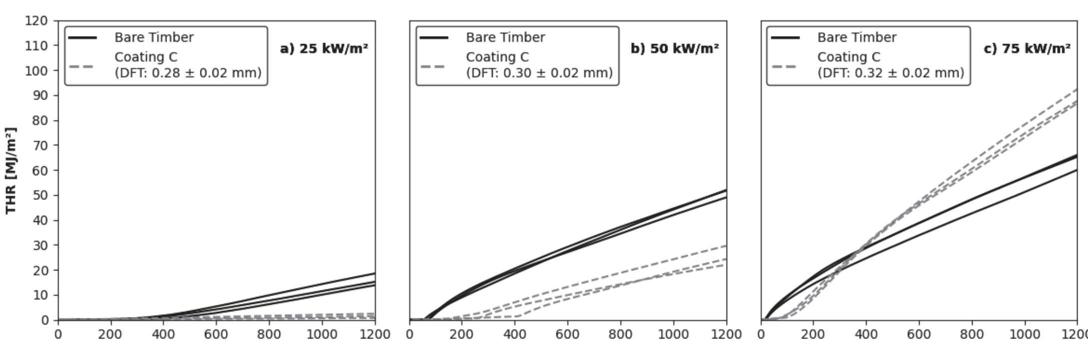

Figure 5. THR of bare vs. Coating C (Med DFT) timber based on three repeat tests each at a) 25 kW/m², b) 50 kW/m², and c) 75 kW/m².

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Considering the wide range of reported critical heat flux values for the unpiloted ignition of timber (25-33 kW/m^2 [33]), with a typical auto-ignition heat flux of 28 kW/m^2 [26, 43], the bare timber samples were unlikely to ignite at 25 kW/m^2. However, they underwent more extensive smouldering compared to Coating C samples, as shown in Figure 6. Specifically, the first lamella of the bare timber samples exhibited a greater volumetric loss and char line progression compared to a Coating C sample, indicating a higher degree of char oxidation. Although Coating C thermally degraded as observed by its fragmented swelled layer, it reduced to a large degree the heat transferred into the timber at 25 kW/m^2.

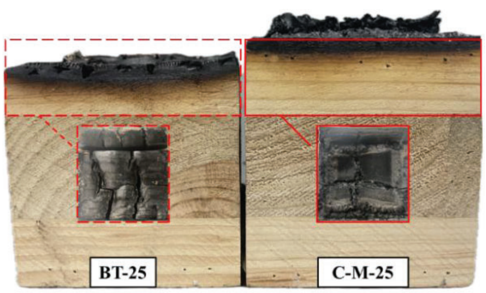

Figure 6. Tested samples of Bare vs. Coating C timber at 25 kW/m^2.

3.2 CAMPAIGN #2 – RESULTS OVERVIEW

For the second experimental campaign, the flammability properties for coated timber samples with different DFT levels tested at 75 kW/m^2 are shown in Table 4. The HRR and THR profiles are graphically presented in Figure 7 and Figure 8, respectively. As seen in Figure 7a, the HRR at one of the Low DFT samples for Coating A decreased between 200-700 s, returning afterward to a similar HRR profile as the other two samples during the steady-state burning phase. The temporary reduction in the HRR for that sample was due to reduced cracking of the coating and thus less exposed timber compared to the other two Low DFT repeat samples. Nevertheless, the coating of that sample degraded further by 600 s due to oxidation of its top surface (intumescent char layer turned to ash), exposing more timber to direct heat (at ~700 s) through new cracked areas – leading to new pockets of flaming.

For the High DFT timber samples of the opaque coatings, 1/3 of the samples ignited for Coating A (Figure 7a) and 2/3 for Coating B (Figure 7b). However, Coating A's flaming self-extinguished within a minute, while flaming for Coating B was observed in two isolated pockets on the edges of the sample's surface, where the coating had shrunk and exposed the bare timber to direct radiant heat. In both instances, flaming was weak – particularly for Coating B timber samples, as evidenced by their THR curve profiles (Figure 8a/b), which remained nearly constant throughout the exposure. In contrast, all Low and High DFT timber samples of Coating C flamed.

As shown in Table 4, no t_{ig} was recorded for Coating A timber samples with High DFT (A-H-75), due to lack of established flaming – defined herein as samples that either did not flame at all or flamed for less than one minute. The latter was the case for the one Coating A sample that flamed. For simplicity, Coating A *pHRR* and t_{pHRR} were based on the other two samples, while *αHRR* and THR_f were derived for all three samples. Similarly, for the Coating B High DFT samples (B-H-75), t_{ig}, *pHRR,* and t_{pHRR} were derived from the two samples that flamed, while the rest of the data were based on all three samples. This irregularity arising from the propensity of the opaque coatings (A, B) to thermally degrade and expose pockets of timber to direct radiant heat is also reflected in the variability of their t_{ig} and t_{pHRR} data (High DFT samples), highlighting the difficulty in defining a specific range for their flaming ignition. This was not the case for Coating C samples (Low and High DFTs), where its early thermal degradation led to full surface flaming of the timber.

Table 4. Experimental data for Campaign #2 samples.

Sample ID	t_{ig} [seconds]	pHRR [kW/m^2]	t_{pHRR} [seconds]	αHRR [kW/m^2]	THR_f [MJ/m^2]
A-L-75	78^{+32}_{-22}	$70.7^{+7.2}_{-6.4}$	180^{+10}_{-11}	$44.2^{+4.5}_{-5.6}$	$50.9^{+7.7}_{-12.2}$
A-H-75*	N/A	$9.1^{+0.1}_{-0.1}$	775^{+81}_{-81}	$6.6^{+1.0}_{-0.6}$	$7.3^{+0.4}_{-0.2}$
B-L-75	345^{+97}_{-108}	$51.5^{+4.3}_{-5.6}$	590^{+36}_{-34}	$37.1^{+7.6}_{-7.1}$	$37.5^{+5.6}_{-6.3}$
B-H-75**	873^{+142}_{-142}	$8.6^{+0.3}_{-0.3}$	1013^{+170}_{-170}	$5.1^{+2.0}_{-2.6}$	$3.9^{+1.1}_{-1.5}$
C-L-75	27^{+06}_{-07}	$130.6^{+18.5}_{-18.6}$	60^{+17}_{-22}	$62.4^{+1.6}_{-1.2}$	$88.8^{+9.6}_{-10.2}$
C-H-75	213^{+34}_{-31}	$93.3^{+6.7}_{-6.4}$	420^{+37}_{-44}	$65.9^{+2.9}_{-1.7}$	$72.8^{+6.2}_{-3.4}$

*1/3 of samples flamed for ≤ 1 minute – i.e., no established ignition; **2/3 of samples flamed (established ignition) within the 20-minute exposure.

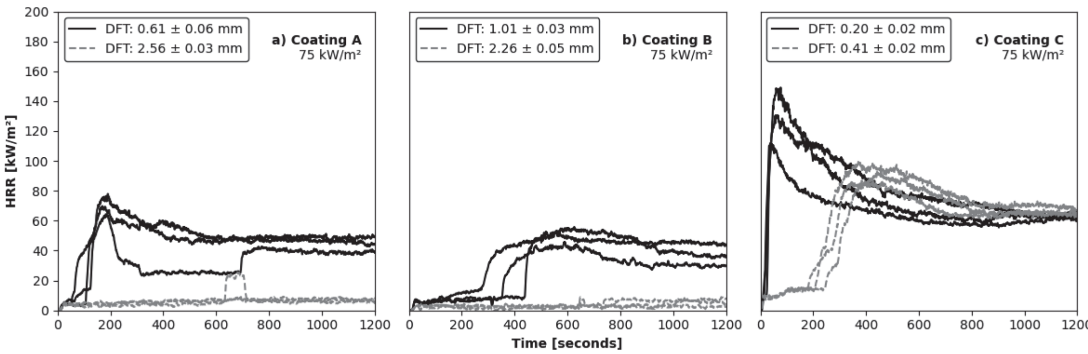

Figure 7. HRR of coated timber samples (Low and High DFTs, three repeat tests each) at 75 kW/m^2 for a) Coating A, b) Coating B, and c) Coating C.

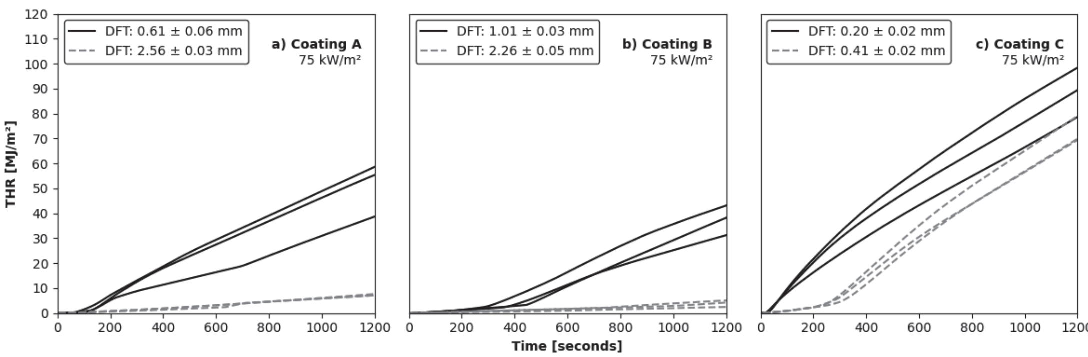

Figure 8. THR of coated timber samples (Low and High DFTs, three repeat tests each) at 75 kW/m^2 for a) Coating A, b) Coating B, and c) Coating C.

3.3 FINDINGS – ANALYSIS AND INSIGHTS

Bare Timber versus Transparent Coating C

As shown in Figure 4 and Figure 5, Coating C timber samples exhibited overall reduced HRR and THR profiles at 25 and 50 kW/m^2 compared to bare timber. Typical sample photos at different time intervals during testing are shown in Figure 9 for samples exposed to 50 kW/m^2. Coating C improved the fire performance of timber by limiting its likelihood to contribute to early flame spread (delayed t_{ig}) and flashover (lower *pHRR* and longer t_{pHRR}) conditions, as well as the prolonged severity and burnout duration (reduced *αHRR* and THR_f) of the fire.

In contrast, the *αHRR* and THR_f of Coating C samples were greater than those for bare timber at 75 kW/m^2 (post-flashover conditions), despite having a delayed ignition and reduced *pHRR*. An early char layer formation in bare timber reduced the extent of flaming during steady-state and thus lowered the HRR severity. In contrast, Coating C timber samples are considered to have experienced deeper thermal penetration due to a larger volume of preheated timber, particularly during degradation of the swelled coating layer, which subsequently led to a greater release of pyrolysis gases once timber was exposed to direct heat.

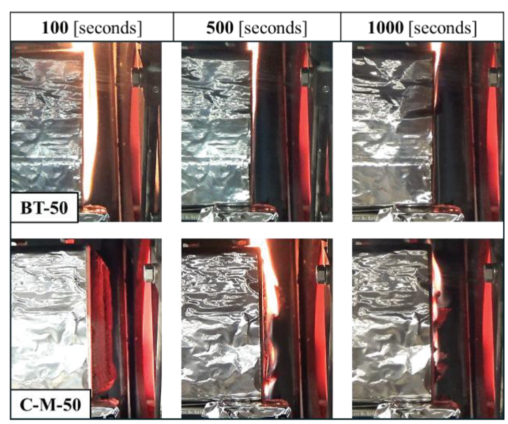

Figure 9. Bare vs. Coating C timber samples during a 50 kW/m^2 test.

Past studies on fire tests of mass timber compartments have reported heat fluxes in the fully developed phase of the fire in the range of 50-250 kW/m^2 [44-46]. Therefore, due to its degradation at higher heat fluxes, transparent Coating C is unlikely to provide adequate passive fire protection for mass timber. However, it may benefit designers and engineers seeking to delay ignition and limit flame spread in the early (growth and developing) phase of a fire, aiding occupant evacuation in the fire origin compartment, while relying on sacrificial timber to provide the required structural performance in the fully

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developed phase. That said, more sacrificial timber would ultimately be required compared to bare timber, given the preheating effect and delayed char layer formation in Coating C timber samples.

Opaque (A, B) versus Transparent Coating C

It was demonstrated in the first experimental campaign that, despite the improved flammability properties of the Coating C samples over bare timber at 25 and 50 kW/m^2, there was no meaningful protection at the most onerous heat flux (i.e., 75 kW/m^2). The second campaign explored the effect of DFT variation for Coating C and the opaque coatings at 75 kW/m^2 and compared the different types.

According to the data for Coating C timber samples, High DFT (~0.41 ± 0.02 mm) at 75 kW/m^2 resulted in nearly eight times the ignition delay of the timber compared to Low DFT, a lower *pHRR*, and a longer t_{pHRR}. Despite a lower *pHRR* and delayed ignition, DFT variation had a minor effect on the *αHRR* and THR_f during the steady-state combustion of the samples. During steady burning, the swelled coating had completely degraded and thus the HRR was solely dependent on the burning timber.

It is expected that deeper thermal penetration occurred due to preheating of the timber for all Coating C DFTs under a 75 kW/m^2 heat flux, leading to higher *αHRR* and THR_f than bare timber, despite delayed ignition and an initially smaller *pHRR*. These findings confirm that for Coating C, heat flux severity governs its insulating efficacy due to the low durability of the swelled coating layer, with its maximum DFT providing no practical improvement in the fire behaviour of timber during the fully developed phase of a fire.

Compared to Coating C, opaque coatings (A, B) led to further reduced HRR and THR profiles, as shown earlier in Figure 7 and Figure 8. Coatings A, B either prevented or significantly delayed the flaming ignition of timber and subsequent t_{pHRR}. Higher DFT improved their insulating efficacy, with High DFT (~2.4 ± 0.2 mm) resulting in the lowest *pHRR, αHRR*, and THR_f relative to Coating C and bare timber. Eventually, timber samples protected with coatings A and B exhibited the least thermal degradation by the end of the 75 kW/m^2 tests (1,200 s), leading to negligible volumetric loss of their first lamella and limited char line progression, as illustrated in Figure 10. As such, the opaque coating can provide meaningful passive fire protection for timber in the fully developed phase of a fire, subject to exposure conditions (e.g., extent and severity).

It is thus evident that opaque coatings (A, B) resulted in an overall improved fire behaviour of timber at the most onerous selected heat flux. In fact, the mean *pHRR* and *αHRR* for High DFT samples, relative to bare timber, were reduced by 94.1% and 84.9% for Coating A and 94.3% and 88.3% for Coating B. Similarly, the THR_f at the end of the test (1,200 s) for Coating A and Coating B samples decreased by 88.5% and 93.9%, respectively. Given their effectiveness at 75 kW/m^2, opaque coatings are also expected to mitigate the flammability of timber during the growth and developing phases of a fire, where heat fluxes are typically lower, by preventing or reducing ignition likelihood and thus limiting timber's contribution to flame spread and the onset of flashover.

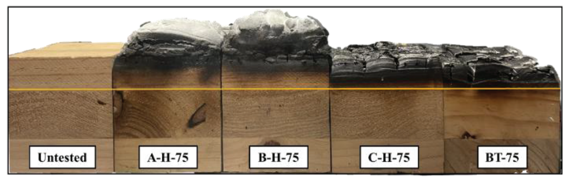

Figure 10. Photos of an untested sample, including Coated (Opaque & Transparent) and Bare Timber samples after testing at 75 kW/m^2.

4 – CONCLUSION

For the selected thin intumescent coating types, DFTs, and heat fluxes, the following key points are drawn:

- Coated samples exhibited an overall reduced HRR profile compared to bare timber, effectively delaying ignition and limiting the peak, rate, and total heat output during combustion of the timber. However, this effect was limited to 50 kW/m^2 (radiation ~700 °C) for transparent Coating C timber samples.
- The insulating efficacy of Coating C was markedly reduced at 75 kW/m^2 (radiation ~800 °C) due to early thermal degradation of the swelled coating, leading to increased heat release over time from the preheated timber with a smaller char layer relative to bare timber. This occurred despite Coating C timber samples experiencing delayed ignition and an initially lower HRR.
- Opaque coatings A and B further reduced the HRR profile of bare timber when compared to transparent Coating C across all heat fluxes (25, 50, and 75 kW/m^2). Higher DFT enhanced their insulating efficacy, whereas the performance of Coating C was primarily governed by heat flux severity.

These findings indicate that opaque intumescent coatings (A, B) are effective in improving the fire performance of mass timber structures during both the early and fully developed phases of a fire, while transparent Coating C is primarily suitable for the early phase to delay ignition, limit flame spread, and reduce heat release.

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