COMPARATIVE PERFORMANCE OF PROTECTIVE COATINGS FOR MASS TIMBER STRUCTURES

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ABSTRACT: The use of engineered mass timber in large scale structures is increasing due to the demand for low carbon, sustainable building design. The potential for structural timber to combust and contribute to a fire event adds hazards and complexity to the design of mass timber buildings. To address these issues, various surface treatments are available aiming to protect or alter the reaction to fire behaviour, relevant during early stages of a fire, and charring behaviour of fire exposed timber which is relevant during the developed stage of a fire. The performance of three specific commercially available fire protective coatings for timber was studied by exposing coated 95mm x 95mm x 45mm horizontal softwood samples to radiant heat flux of 35 and 60 kW/m^2 in a cone calorimeter from above, a level of radiation representative of a developing fire. Ignition time, heat release rate, mass loss rate, gas species emissions, in-depth temperatures, and char progression were recorded to study sample performance when compared against uncoated timber. Results indicate that two of the protective coatings used successfully developed a protective intumescent char layer, while one product did not. The former two displayed significantly reduced mass loss and heat release rates, as well as reduced in-depth thermal penetration when compared to uncoated timber. One coating did not intumesce and performed similarly to uncoated timber. These results illustrate the importance of not extrapolating from reaction to fire classifications to make assumptions about improved fire performance outside the scope of such classifications, without substantial further testing and validation of those assumptions.

KEYWORDS: Protective coatings, intumescent coatings, fire performance, mass timber, cone calorimeter

1 MOTIVATION AND BACKGROUND

1.1 INTRODUCTION

The use of engineered mass timber in large scale structures is rising due to the demand for low carbon, sustainable buildings [1]. Mass timber offers benefits such as being lightweight and less constrained by size or shape in comparison to concrete and steel. However, the potential for structural timber to ignite and contribute fuel to a fire, as well as timbers comparatively higher susceptibility to reductions in mechanical properties at elevated temperatures, necessarily adds complexity to the design of mass timber buildings. To address these issues, surface treatments are available aiming to alter the reaction-to-fire [2-4] and/or the charring behaviour of fire exposed timber to achieve a higher fire resistance period than untreated timber. Unlike structural steelwork, with which intumescent coatings are more commonly used, timber structural elements will char and can fail at comparatively low temperatures due to thermal decomposition (i.e., pyrolysis) and timber strength degradation at elevated temperatures when exposed to

sufficient heating. Intumescents are passive fire protection coatings that react when exposed to heating and swell to form a protective char layer which can reduce heat transfer to the substrate materials [5] and hence, in the case of a timber substrate, reduce mass flow of pyrolysates from the exposed surface. Intumescent coatings are typically specified to achieve a better reaction to fire classification than untreated timber would achieve, but may also be relied upon to reduce charring rates which would be determined by the relevant standardised testing method. Transparent protective coatings are appealing for mass timber designers, compared with rigid encapsulation alternatives, due to the aesthetics of exposed timber surfaces. However, experimental data (as opposed to compliance classifications) for such coatings are extremely scarce for a range of relevant heating scenarios. A greater understanding of intumescent products for mass timber is therefore required since many such products are already in widespread use in the built environment. The study presented in this paper aims to quantify and compare the behaviour of timber specimens coated with three different commercially available transparent fire

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protection coatings, achieving European reaction to fire Class B, under various heating conditions. These coatings have been independently obtained, and the authors make no attempt herein to endorse (or otherwise) any of them; we simply present and discuss experimental outcomes under the scenarios investigated.

1.2 PROTECTION OF WOOD

Key concerns for safe structural design of timber are related to the potential fuel contribution of timber elements in a fire (fire dynamics), in combination with reductions in mechanical properties on heating (fire resistance). In order to specify the dimensions of timber structural components, whilst complying with building stability, integrity, and insulation requirements, multiple forms of passive fire protection are available to designers [6-7]. These passive protection measures may include board/encapsulation products, intumescent coatings, and impregnation treatments, all of which aim to reduce the heat transfer to the underlying timber. Gypsum plasterboards are a common, albeit often architecturally undesirable, passive fire protective measure where the thickness or number of layers of board can be adjusted to provide differing levels of protection. Intumescent coatings have the advantage that they can be applied in thin layers whilst maintaining the aesthetic qualities of the unprotected mass timber; however, may require re-application to maintain their performance, and may not function as intended when combined with other surface treatments.

1.3 INTUMESCENT COATINGS

When sufficiently heated, intumescent coatings swell and form a protective char layer [5]. These coatings commonly incorporate various chemical components which react to ensure intumescence and char formation [5,8] under standardised heating scenarios. The interactions of these components in the "correct" sequence is key to ensuring successful formation of an intumescent char, and therefore to the protection of the substrate from fire [5]. A char begins to form when the intumescent compounds decompose and release gases within the melted substance, forming a 'multi-cellular' char layer [5]. Trapped bubbles provide a low density, protective char layer which reduces heat transfer to the structural member and therefore postpones the conditions (i.e., temperatures) favourable for timber to pyrolyze. The mixture of chemical compounds used in intumescent coatings formulated specifically for wood is likely to be unique to each specific commercially available product. Hence, the speed of intumescent char growth, thickness, density, and porosity distribution within the intumescent char all depends on the specific product formulation (and, critically, on the heating conditions). Due to the different chemical compositions of intumescents, and therefore different activation temperatures of their chemical groups, there is a critical temperature required for an intumescent coating to react, char, and provide altered properties that are relevant to the intended substrate material [9].

Possibilities for transparent or coloured coatings make intumescents aesthetically desirable, and their thin, lightweight nature minimises additional structural loads and structural member sizes. However, care must be taken that coatings are applied appropriately; relevant conditions as specified by the manufacturer are required in order to ensure products perform as intended. Factors such as humidity, moisture, and thickness must be considered to ensure their durability, longevity, and performance in fire.

1.4 INTUMESCENT COATINGS FOR WOOD

Popescu et al. [10] describe that in addition to insulating a timber element, intumescent coatings can enhance fire performance by 'reducing the amount of heat released during the initial stages of fire, by retarding the spread of flame and by limiting the production of smoke and flammable volatiles'. The effectiveness of the intumescent coating also depends on the thermal boundary conditions, including the temperatures of the substrate material. A challenge for intumescent coatings applied to timber is that they must have a lower critical temperature (i.e., the temperature that initiates the expansion of the intumescent) than those used for other materials, such as steel, in order to provide protection before significant pyrolysis occurs. This may mean that intumescents for timber are quickly impaired at a higher temperatures [10].

The performance of intumescent coatings (in terms of reaction-to-fire response) is typically determined using standard test methods such as European reaction to fire 'single burning item test' and 'single flame source test' (BS EN 13501-1, BS EN 13823 and BS EN ISO 11925-2 as described in Section 2.2) [2-4]. However, some variables of potential importance in fire are not directly measured or reported in most standard tests, including gas species generation, char depths and rates, mass loss rates, and toxicity. This limits a holistic understanding of the fire performance of intumescent coatings generally, and specifically for those used to provide fire protection of wood [7].

Experimental studies involving intumescent coatings for wood have been presented by, for example, Wladyka-Przybylak, Hassan et al., Bahrani et al., Hartl et al., Lucherini et al. and Xu et al. [8, 11-15] in relation to different coating formulations, durability and the effects of external weathering, and their performance when compared to other passive fire protection methods (e.g., gypsum plasterboards). However, there remains a need for rigorous fire science data regarding the fire performance of existing timber intumescent coatings under a range of relevant heating conditions. This is in order to better understand the performance of reaction to fire coatings, coatings seeking to impact on the resultant fire dynamics and/or slow char rates to improve fire resistance of timber under more severe fire conditions, and to establish their reliability under natural fire conditions.

This paper aims to characterise the fire performance of different reaction to fire treatments under a range of

relevant heating conditions so as to better understand a broader range of impacts of some commercially available coatings when placed under more onerous heating regimes.

2 METHODS

The performance of three commercially available intumescent fire protection coatings for timber was studied by exposing coated samples of softwood to radiant heating. The coatings were then compared against untreated wood to quantify their influence on ignition and burning behaviour. This was done qualitatively by visual observation and quantitatively in terms of heat release rate (HRR), in-depth temperatures, mass loss rate (MLR), and gas species production.

2.1 TEST SAMPLES

Timber samples tested were cut from solid Norway Spruce and had 95 x 95 mm cross sections with 45mm thickness. Three in-depth 1.5 mm diameter K-type thermocouples were installed from the side of the sample and were positioned at 5mm depth intervals from the exposed surface to allow for in-depth temperature measurements at depths of 5, 10, and 15 mm.

All samples were surrounded by aluminium foil and ceramic fibre paper to mitigate mass transport, reduce pyrolysis gas escape from the sides, and reduce heat transfer to the sides of the sample (see Figure 1).
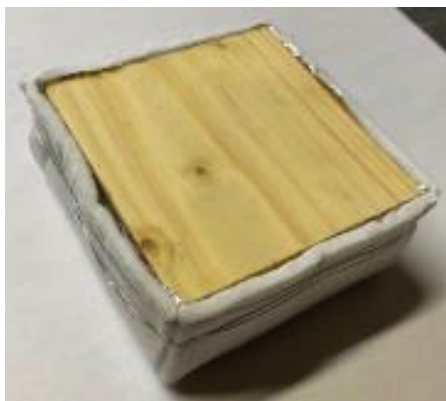
Figure 1: Coating A timber sample preparation.

2.2 INTUMESCENT COATINGS

The three products used in this study are commercially available in the UK and designed for the fire protection of timber; advertising a "reduction of ignitability" and to "insulate against heat", "prevent propagation of fire and spread of flame" and "suppress emission of deadly smoke & gases" whilst providing a reaction to fire classification and/or fire resistance period [16-18].

Each coating system consists of an intumescent base coat and top coat. No primer was used for application of these coatings, as specified by manufacturers for clean softwood. The respective coating systems were applied in thin layers and allowed to dry between each application, as per the respective manufacturers' instructions.

It was noted that despite all coatings being described as transparent, each had a slightly different appearance once all layers had been applied and dried (Figure 2).

Figure 2: Comparison of intumescent coating appearance. From left to right; Coating B, C, A and uncoated.

Coating A (sold as HW Envirograf) is a water-based intumescent system which is advertised on their website as achieving European classification B-s1, d0; on the basis of testing to the 'single burning item test' and 'single flame source test' [2-4, 16]. Such tests are designed to measure production of heat, production of smoke, horizontal flame spread, ignition, and the falling of flaming droplets and particles in controlled fire conditions. The product is also advertised for application e.g. on fire doors for fire resistance periods using standard furnace tests, for 30 and 60 minute fire resistance ratings based on BS 476-20 and BS 476-22 tests for non-/load-bearing elements, and 66 minutes integrity is claimed with reference to a BS EN 1364-1 wall test [16]. No fire classification or fire test reports were available for download from the website to provide further detail and limitations of the fire performance of the product.

Coating B (sold as Sika Pyroplast) is a water-based intumescent system advertised to achieve European classification B-s1, d0 [17]. The manufacturer does not advertise any ability to provide fire resistance with their product.

Coating C (sold as Thermoguard Fire Varnish) is a combined resin-acid catalyst and white spirit based intumescent system. This coating is advertised to achieve European reaction to fire classification B-s2, d0 (thus greater smoke production than coatings A and B) [18]. Coating C's manufacturer also state that fire resistance classifications are possible using their product but that this requires further consultation.

Each of the coatings used in the current study are sold on the basis of improving the fire performance of timber, either in relation to the reaction to fire classification or fire resistance classification.

The proprietary nature of each product likely results in different reactions under heating and therefore different intumescent performance in real fire scenarios.

2.3 APPARATUS AND MEASUREMENTS

Each sample was exposed to a constant radiant heat flux in a cone calorimeter for 30 minutes, since initial investigations determined that this provided sufficient time to develop the protective char layer. Experiments were performed at two nominal incident heat fluxes (35 and 60 kW/m^2) aiming to span a range of heat fluxes that is broadly representative for a compartment fire scenario. Gas species, heat release rate, mass loss rate, and in-depth temperatures were recorded. Measurements of ignition, char thickness (i.e., swelling), and char depth were also recorded so as to further characterise the coating response. Guidance for the testing was taken from BS ISO 5660-1. The surface of the sample was separated from the lowest point of the cone heater by 50 mm to prevent contact between the intumescing coating and the cone heater [19]. However, due to the use of intumescent coatings and their unpredictable behaviour, the samples were not placed in a standard sample holder and instead wrapped (as previously described) and then placed directly onto a load cell [19].

3 RESULTS

3.1 IGNITION

Ignition times for each product are given in Table 1. Both the uncoated and coated samples were observed to ignite under the heat flux conditions used in this work. The uncoated samples experienced continued flaming, after ignition, throughout the experiments, while Coating B and Coating C treated samples experienced extinction shortly after ignition. Later re-ignition was observed for coating B and C samples exposed to 60 kW/m^2; however, this was not observed for 35 kW/m^2. The ignition times for Coating C samples were found to be less than for the uncoated samples at both heat fluxes used. Coating A was found to delay ignition compared to the uncoated sample, however this product displayed continued flaming, after ignition, throughout the experiments.

The earlier ignition of Coating B and Coating C appeared to result in the formation of a protective char *before* the majority of the underlying wood surface reached its pyrolysis temperature, hence protecting the wood substrate once the swollen intumescent layer had formed.

Table 1: Times to ignition, extinction, and re-ignition of flames for each coating and heat flux tested.

Coating Type	Heat Flux (kW/m^2)	Time to Ignition (s)	Time to Extinction (s)	Time to Re-Ignition (s)
Coating A	*35*	71	n/a	-
	60	6	n/a	-
Coating B	*35*	39	61	n/a
	60	9	28	152
Coating C	*35*	12	63	n/a
	60	3	37	159
Uncoated	*35*	65	n/a	-
	60	6	n/a	-

3.2 VISUAL OBSERVATIONS

Observation of the intumescent coatings during testing suggested that only two of the three coatings expanded significantly when exposed to the heat flux conditions used in the current study. Coating B and Coating C, both of which swelled, produced insulating char layers with maximum depths of 12 mm from the exposed surface of the sample. Thus, each of these two coatings grew to approximately 10 times the original applied dry film thickness. Coating A did not swell.

Although successful at extinguishing flames shortly after early ignition, both coatings B and C demonstrated different char growth phases (uniform/non-uniform as further explained), presumably due to their unique chemical formulations. Given the proprietary nature of these products, the exact formulations and hence reactions that occur upon exposure to heating are not known.

The differing swelling phases of the intumescents can, however, be visually correlated to phenomena that were observed during the experiments. Phases of intumescent coating thermal resistance correspond to the growth and decay phases of the char layer; thermal resistance being the ratio of expanded thickness to thermal conductivity of the intumescent layer (Li et al. and Lucherini et al.) [14,20].
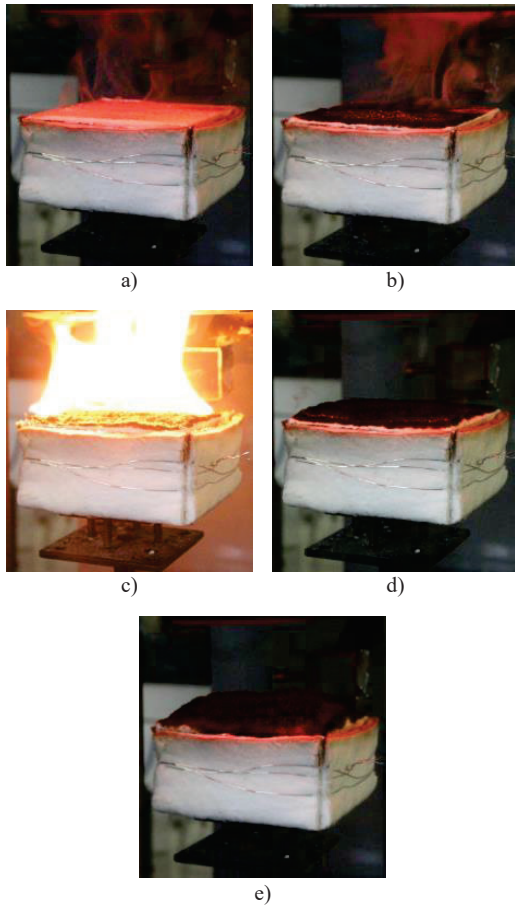
COATING B

The growth of Coating B slowly developed as an unevenly distributed white char across the sample surface (Figure 3a), which then blackened (Figure 3b). Ignition of the volatiles produced during coating pyrolysis occurred soon after heating (see Section 3.1).

Once ignited (Figure 3c), surface flaming then contributed additional heat feedback to the surface, which increased the rate of pyrolysis (evidenced by the mass loss rate in Section 3.3). This accelerated pyrolysis rate also accelerated the rate at which the intumescent char layer developed. The growing char layer served to reduce the rate of heat transfer to the underlying timber substrate, and thus to a decrease in the pyrolysis rate. The pyrolysis rate then decreased below the critical rate to sustain flaming and the flame extinguished (Figure 3d).

Upon completion of the swelling of the intumescent and the oxidation of its char, its thermal resistance peaked [14]. Hence, this was the upper limit of its insulating capability (Figure 3e). Regression of the intumescent char then slowly occurred, resulting in a reduction in thermal resistance. This coating reached a maximum char thickness of 12mm above the surface of the sample.

Figure 3: *Phases of Coating B (Sika Pyroplast) intumescent growth at 35 kW/m².*

Coating B displayed significant variation in intumescent blister shape and distribution across the surface; this can be seen clearly in Figure 4.

Figure 4: *Intumescent char formations for Coating B (Sika Pyroplast) sample removed from apparatus at 35 kW/m².*

COATING C

Coating C did not behave as expected based on the existing literature [7,14]. Before growth of the char bubble matrix, an outermost layer of the coating appeared to trap a portion of intumescent pyrolysis gases and formed a single large (approximately 16mm deep) bubble over the entire surface of the coated sample. Ignition of volatiles released from this bubble caused a large initial flame on ignition, resulting in significant heat feedback to the sample surface. The coating then entered a transient phase by forming a multitude of small bubbles that developed into a protective char layer. This coating reached a maximum char thickness of 8mm, and then – as for Coating B – it gradually regressed.
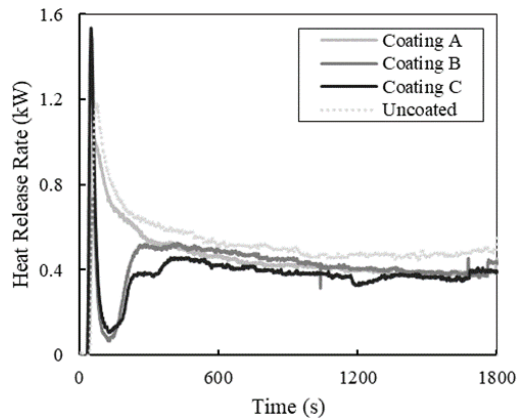
COATING A

When exposed to heating, Coating A immediately melted, pyrolysed, and changed to a blackened colour. Upon ignition however, this coating appeared to immediately disintegrate, cracking, and peeling away in thin curling leaves to reveal the underlying substrate. Little initial bubbling and no obvious intumescent growth were observed. The timber then began to char and fracture as if uncoated. Flaming of Coating A samples continued until the end of the experiments.

3.3 BURNING BEHAVIOUR

The heat release rate (HRR) for the samples was measured using oxygen consumption calorimetry. The mass loss rate was also determined via cone calorimetry and provides an indication of thermal decomposition of the samples. Mass loss can evidence drying of timber, decay by pyrolysis, or oxidation of the carbon-rich char [21]. The heating process that causes the greatest loss of timber substrate mass is pyrolysis, generating ash and gaseous products. Both the time-resolved HRR data and MLR data are given in Figure 5 to Figure 9.
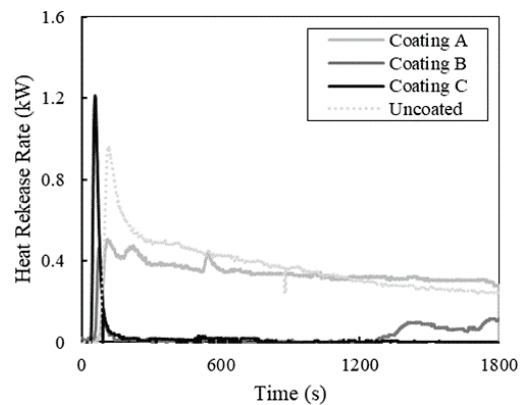
Figure 5: *Stages of intumescent burning at 35 kW/m².*

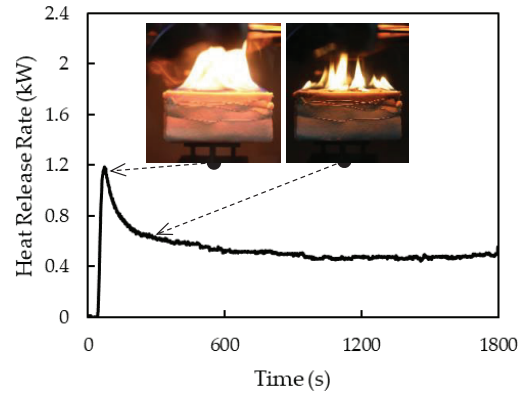*Figure 6: Stages of intumescent burning at 60 kW/m².*

Figure 7: Phases of flaming and heat release rate at 60 kW/m² for uncoated samples.

Figure 8: Phases of flaming and heat release rate at 60 kW/m² for Coating C (Thermoguard Fire Varnish) coated samples.
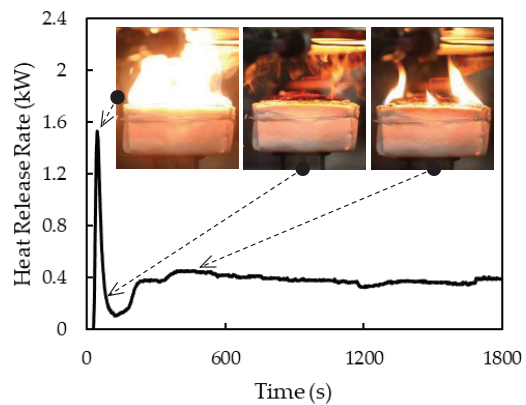
Across the exposure conditions used, the two coatings that swelled (coatings B and C) displayed distinctly different burning behaviour as compared with uncoated wood. The time resolved HRR data for an uncoated sample exposed to 60 kW/m² is given in Figure 7. The early stages of the experiment displayed high rates of pyrolysis prior to ignition, then a rapid increase in the HRR after ignition. The HRR then increased to a peak value which gradually decreased as the char layer developed and heat transfer was reduced in-depth in the timber (as expected).

The HRR with time for a typical intumescent coating (Coating C) exposed to 60 kW/m² is given in Figure 8. A peak HRR value was observed soon after ignition of the intumescent coating. The HRR then reduced to well below the value recorded for uncoated timber. For trials at 60 kW/m², the intumescent char then began to degrade after about 150 seconds; the surface then eventually reignited, with commensurate increase in the HRR (Figure 6).

For experiments conducted at 35 kW/m², re-ignition did not occur and HRR did not increase after the initial peak (Figure 5). The discrepancy between the behaviours across the two heat fluxes illustrates the potential importance of the heating conditions when studying the performance of intumescents, as previously suggested in the available literature [13-14]. The heat fluxes to which such coatings are subjected when assessed via regulatory tests is therefore potentially very important in terms of the credibility of assessment for performance in real (rather than regulatory) fire scenarios.

Figure 5 to Figure 9 show that Coating C had the fastest and largest HRR and MLR peak for all coatings and heat fluxes. This peak occurred in less than 20 seconds at 35 kW/m² and less than 10 seconds at 60 kW/m². HRR then declined rapidly, suggesting there was a sudden release and then ignition of combustion products – this aligns with the observation of a single large bubble on the surface of the Coating C samples. After this initial growth the intumescent char layer protected the timber and therefore HRR and MLR declined. After approximately five minutes, the HRR behaviour for trials conducted at 60 kW/m² was observed to converge to similar general behaviours as the samples transitioned into a regime of predominantly char oxidation. All ignition, extinction, or re-ignitions occurred within the first three minutes of each experiment.
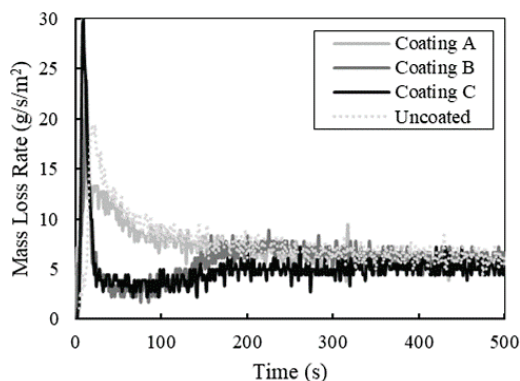
Figure 9: First 500 seconds of mass loss at 60 kW/m^2.

Despite the behaviour of each sample within the first 500 seconds being distinctive, all data began to converge to a mass loss rate of approximately 4 g/s/m^2 at 35 kW/m^2 and 5 g/s/m^2 at 60 kW/m^2, once 1500 seconds had elapsed.

The results for heat release rate and mass loss rate correlate well, as expected given that both are manifestations of the burning rate. The trends of mass loss therefore correspond to those described for HRR, i.e., the initial mass loss rate is higher due to the added presence of more volatile products.

For coatings B and C which swelled, the peak in mass loss rate occurred as the intumescent blisters were forming. This occurred more quickly than for Coating A or uncoated samples and can likely be attributed to the reduced reactional temperature of the intumescent in comparison to the pyrolysis temperature for timber. The reduced mass loss and heat release rate after the initial peak supports the idea that the intumescent char layer does protect the underlying timber.

3.4 GAS SPECIES

Recorded values of carbon monoxide (CO) and carbon dioxide (CO_2) in the cone calorimeter flue gases provide insight into the emissions from both the timber substrate and each of the protective coatings; the CO results are shown in Figure 10. The pyrolysis and burning of timber can be expected to produce CO, CO_2, and various other products. The intumescent coatings will also contribute combustion products, including CO and CO_2. The rate of CO and CO_2 generation will vary with the presence of a flame or with the presence of solid phase char oxidation. Therefore, the measurement of CO and CO_2 lend insights into the global combustion conditions of the tested specimen. Periods of high CO_2 generation tend to indicate periods of sustained flaming, as a result of the flame sheet rapidly oxidizing CO produced during pyrolysis to CO_2 [22]. The CO values found in this study, however, varied significantly between coatings and heat fluxes, following differing trends throughout the 30 minute exposures.

High generation of CO has been associated with both pyrolysis and solid phase char oxidation [23]. The CO production for samples coated with coatings B and C were significantly higher than for uncoated wood, suggesting that the increased CO yield may be a result of the

oxidation of the intumescent char. Intumescent products commonly incorporate carbonising agents, and it is possible that decomposition of these elements leads to the production of CO in the early stages of intumescent growth [8]. It is also likely that char oxidation dominates the production of CO in the later stages of the experiments presented herein [24].

For coatings B and C exposed to 35 kW/m^2, the CO value grew significantly after an initial peak, peaking for a second time after 20 minutes and 30 minutes, respectively. At 60 kW/m^2 the initial CO peak was much higher, and production then rapidly decreased. This variation of gas species generation between the two heat fluxes supports the idea that different chemical reactions may occur within the intumescents at different temperatures. It is also noteworthy that production of these gases only occurred after the thermal decomposition of the protective layer had been initiated.

The CO_2 and CO concentrations varied considerably between each Coating B repeat test. This suggests that even with the same application of coating and heat flux, the behaviour of this intumescent may differ in terms of both char formation and reaction products.

As with the previous results, the Coating A samples behaved similarly to uncoated wood in relation to both CO_2 and CO concentrations at both 35 and 60 kW/m^2.
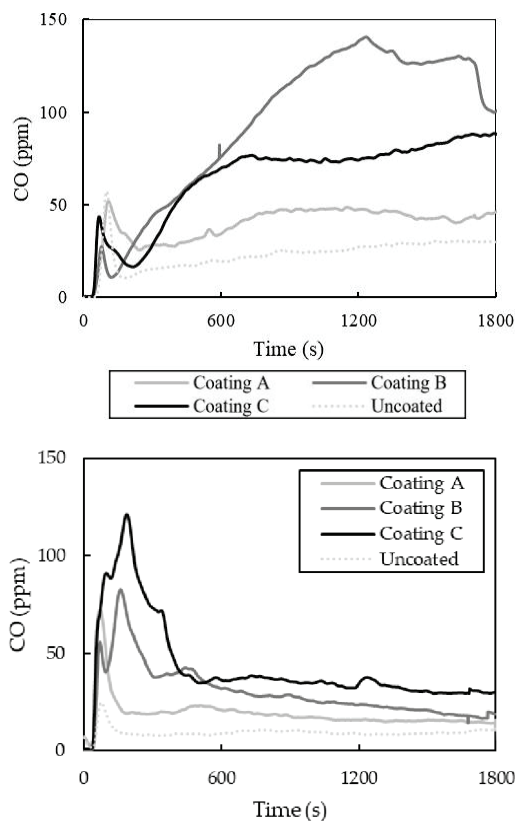
Figure 10: CO gas concentrations in exhaust gases at 35 kW/m^2 (top) and 60 kW/m^2 (bottom), respectively.

3.5 TEMPERATURE AND CHAR DEPTH

The in-depth temperature gradients in the samples provide indications of the degree of thermal penetration in the timber. Dominating burning regimes correlate with different temperature bounds, therefore, a profile of temperature through the depth of the sample can elucidate the processes occurring at any one time and suggest the degree to which the overall strength of the timber section would have been reduced due to in-depth heating. At approximately 100°C moisture vaporization and transport will occur variably throughout a timber cross section, causing dehydrated wood to become more brittle and saturated wood layers to soften [21]. At 100°C, timber is typically assumed to lose 75% of its flexural strength [25]. At about 200°C, the timber will begin to pyrolyze [26] which not only further reduces the structural capacity of the member but also produces flammable gases which may ignite. At temperatures in the range of 400-600°C, any char is likely to experience solid phase char oxidation. The 300°C in-depth isotherm is typically assumed to represent the effective depth of the "char layer" (i.e., the position at which timber has lost effectively all of its mechanical strength). However, mechanical properties are also lost in thermally-affected regions at temperatures below 300°C [25].

The samples that most rapidly reached 300°C, both at the surface and at locations in-depth, were the uncoated samples. These were closely followed by samples with Coating A.

Coatings B and C, both of which insulated the timber as already discussed, resulted in consistently lower in-depth temperatures compared against uncoated trials.

At 35 kW/m², the surface of the timber protected by Coating C was up to 300°C less than for uncoated timber samples. The char depth after 30 minutes of exposure was reduced by 4-7 mm for coatings B and C.

Figure 11 shows the thermal gradients developed through the depth of exposed uncoated and Coating B specimens. This thermal gradient can then be compared across products to assess the rates and degree of thermal penetration experienced.

In addition to in-depth temperature results, the impact of each coating on final char depth of the timber was evaluated by visual examination of the samples after testing. Samples were cut vertically in half to observe the char depth and unpyrolysed wood, where distinction was made by qualitatively reviewing the colour change of the cross section. By measuring the remaining depth of wood, the loss of material was quantified in thickness (as well as mass from the mass loss readings).

As should be expected, the greatest loss of timber substrate was found for the uncoated timber when tested at 60 kW/m².

4 DISCUSSION

The data presented in the preceding sections provide insights into timber and intumescent coating response

(a) 5 minutes

(b) 15 minutes

(c) 25 minutes
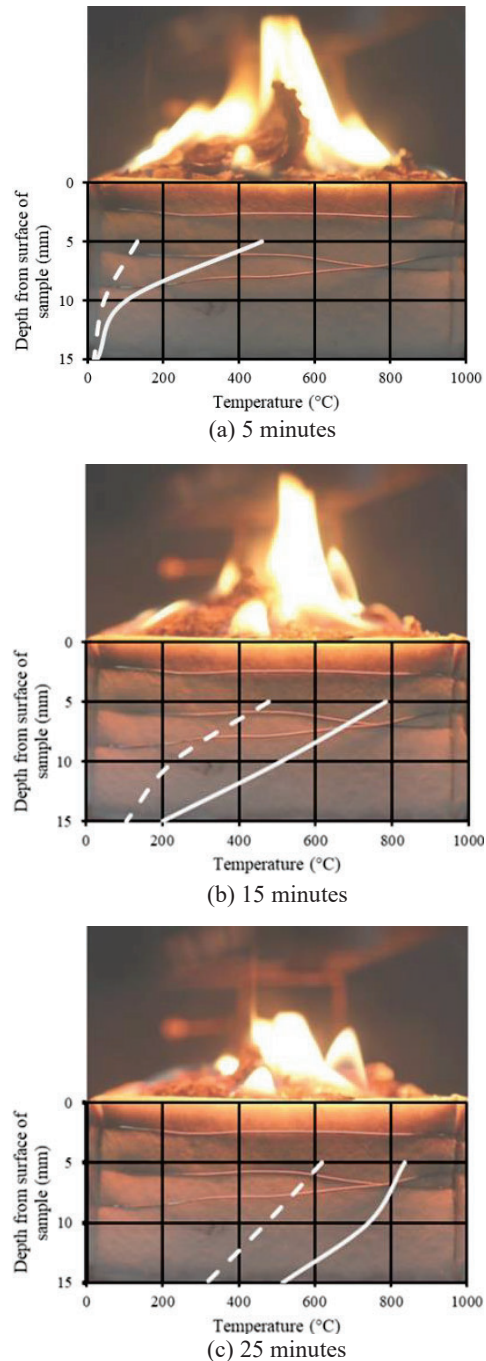
Figure 11: *Temperature distribution through the depth of samples at 60 kW/m². Solid line: uncoated sample. Dashed line: Coating B (Sika Pyroplast) (TCs at 5, 10, 15 mm).*

when exposed to radiant heating at small scale. The behaviours observed allow a comparison of the coatings' performance in terms of the intumescent growth phases, burning behaviour, products of combustion, thermal penetration, and char depth. These measurements allow for the evaluation of the product performance alongside

claims made by each product manufacturer, and hence their potential effectiveness in regard to a range of potential applications in mass timber buildings.

4.1 HEAT FLUX

All samples were tested at both 35 kW/m^2 and 60 kW/m^2 and it was confirmed – as expected – that a higher initial incident heat flux consistently resulted in earlier ignition, greater heat release rates, greater mass loss rates, acceleration of in-depth temperature increase, greater in-depth temperature, and greater final char depth. This was seen both in uncoated and coated samples (all other factors being equal).

4.2 COATING A

The data presented consistently suggests that the performance of Coating A samples resembled that of uncoated wood. It was observed that instead of the intumescent layer growing from the surface of the timber when exposed to heating, the coating peeled away to reveal the timber underneath. Albeit time to ignition was mildly extended using this coating.

It is possible that the comparative ineffectiveness of this coating has been caused by the uncontrolled moisture content of samples before application. The manufacturers 14% maximum moisture content, however, is extremely difficult to achieve for existing structural elements which the coating is advertised for, suggesting that successful protection using this intumescent would be very difficult to attain if conditioning is absolutely necessary.

4.3 COATING B

The data for Coating B confirmed that it performed as expected for a typical intumescent coating, forming a cellular char layer that extinguished flames at both heat fluxes tested. The depth of the intumescent char was the greatest of all coatings tested; this resulted in decreased HRR, MLR, flaming, in-depth temperatures, and char depth in comparison with uncoated wood.

The behaviour of this coating during testing confirms that it has beneficial impacts on the HRR and insulation of underlying timber.

The inconsistent performance of Coating B across the surface of the sample and between repeat tests may be an indication that the product protection may be prone to variation in practice. It is suggested that further repeat experiments are completed to ensure the overall performance of Coating B is quantified. Furthermore, large scale and realistic orientation tests should be completed to observe whether the variation of intumescent growth is significant over larger surface areas and whether it maintains intumescent char structure when vertical.

4.4 COATING C

Coating C was successful in reducing HRR, MLR, flaming, in-depth temperatures and char depths in comparison with uncoated wood. Moreover, Coating C samples demonstrated the least amount of flaming after

the initial peak in heat release rate, and consistently gave the lowest in-depth temperatures amongst all coatings.

Early ignition in comparison to uncoated wood was observed for Coating C; however, as early ignition then promoted the rapid growth of the intumescent char layer, early ignition is not necessarily in itself a negative result in terms of fire performance. Large scale testing at various orientations is recommended to understand the consequences of ignition and flame spread over an intumescent coated surface and hence fire growth rates for timber surfaces within realistic fire compartments in buildings.

5 CONCLUSIONS

The research presented within this paper serves as a preliminary study investigating the reaction-to-fire performance of three transparent passive fire protective coatings for wood, when exposed to more severe heat flux conditions from above, with the sample in a horizontal orientation. The testing results indicate that Coating A did not swell and therefore performed similarly to that of uncoated samples. The two remaining intumescent coatings (B and C) produced multi-cellular char layers that reduced the heat release rate, mass loss rate, CO_2 concentrations, in-depth temperatures, and char depths under the experimental conditions used in the current study. The potential for these products to improve the reaction-to-fire and burning behaviour and wood is therefore promising. However, their widespread application in mass timber buildings with exposed timber surfaces requires further study to better understand the influence of e.g. scale, orientation and much higher heat fluxes seen in natural fire conditions in large timber-lined compartments [27].

Research and experimentation has highlighted the importance of a range of parameters for evaluating the effectiveness of an intumescent product for wood. Additional research is needed to determine the suitable applied surface treatments across the relevant range of fire safety strategy considerations, where they are intended to improve e.g. char rates, or be used as a justification for slower fire spread rates in large compartments. The current fire classifications of reaction to fire classification and fire resistance derived from standard tests are unlikely to be suitable for that purpose.

To accurately predict the behaviour of an intumescent in a real fire scenario, further experimentation involving the exposure of intumescent coatings to transient heat sources, (e.g., increasing heat flux, interactions within a real compartment, etc.) in a realistic orientation that accounts also for the impact of gravity (as products are usually applied to walls or ceilings) would be necessary to better represent the changing conditions.

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