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Fire Performance of *Endospermum malaccense* Cross Laminated Timber (CLT) Treated with Fire Retardant

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Abstract
This study assessed the fire performance of cross-laminated timber (CLT) made from sesenduk (Endospermum malaccense) painted with a fire retardant. Teknoksafe 2407 (Tk-Exterior) and Teknoksafe 2457 (Tk Interior) fire retardants were prepared and applied to the sesenduk CLT. Fire properties such as surface spread of flame test, charring rate test, fire resistance test, and chemical property changes before and after fire testing were evaluated and compared to Control CLT. The results showed that using fire retardant effectively prevented the fire from spreading.

Keywords: Sesenduk, intumescent paint, fire properties

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1.0 Introduction

Cross-laminated timber, also known as CLT, is widely used in the construction industry; however, one of the challenging aspects that prevents its use is its inability to meet building regulation requirements for fire safety. A general definition of fire resistance for construction elements can be as follows: the amount of time that passes before a component, when exposed to the effects of a fire, stops performing the functions for which it was designed (Rodrigues et al., 2000). These panels, used in European and American construction, have their fire performance specified. To increase its utilisation, the risks associated with working with wood must first be addressed (Ostman, 2010). The length of time that wood is heated can impact the temperature at which it ignites. The ignition temperature for wood is typically between 250 and 300 °C, whereas the spontaneous ignition temperature for wood is approximately 600 °C. Carbonisation of solid wood begins at a rate of 0.8 mm/min, while carbonisation of laminated timber occurs at a slower rate of 0.7 mm/min. The carbonisation rate slows down proportionately based on the density of the timber, the moisture content, and the individual thickness of the wood pieces used. Density is one of the most important characteristics of wood among its other common physical properties (Bowyer et al., 2003).

The sesenduk tree, also known as *Endospermum malaccense*, is a member of the Euphorbiaceae family. When freshly cut, the sesenduk wood is bright yellow, and the heartwood and sapwood of the tree are virtually identical. The colour of the wood changed after it was exposed to air; after some time, it became a light brown colour with a greenish tint. Sesenduk is a light hardwood with an

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air-dried density of 305-655 kg/m^3 (Lee & Ashaari, 2015). Sesenduk wood is categorised as non-durability timber and is considered to have low strength. This is because sesenduk wood belongs to the strength group 7, the weakest group of strength. However, after being treated, in particular with phenol formaldehyde resin, it is possible to convert it into laminated board with satisfactory strength and dimensional stability (Ashaari et al. 2016), excellent natural durability (Nabil et al. 2016), and resistance to the effects of the weather (Mohammad-Fitri et al. 2017). In addition, it has been demonstrated that sesenduk wood is a material suitable for the fabrication of CLT. According to a study by Husain et al. (2020), a CLT structure made of sesenduk offers its occupants a high level of comfort even on the hottest days of the year because it can act as a sound insulation against heat.

2.0 Literature Review

It is critical that adequate protection be applied to the timber in order to provide occupants with confidence in the safety elements incorporated in the building components. While solid wood has inherent fire resistance, there are numerous options available to improve these properties further. According to critics, the primary risks associated with CLT are fire resistance and water damage. When mixed into CLT, a fire retardant produces a building material with a high fire rating. However, the CLT fire-rated assembly details still need to be standardised (Grasberger & Hinton, 2018). Alternatives include structural fire protection, impregnation of wood with fire-retardant compositions, direct application of fire-retardant coatings to the material surface, and the use of combined fire protection such as sheeting and thermal insulation (Aseeva et al., 2013). According to Gerard and Barber (2013), the greater the depth of the section (3, 5, or 7 layers), the greater the fire resistance and fire-resistant linings. To prevent flames from spreading along the ceiling, the underside of the wooden surface can be protected with fireproofing paint (Borgström & Fröbel, 2019).

Enabling the timber to obtain an acceptable level of fire resistance would generally involve applying a chemical formula that will protect the wood and be safe for the end user. There are already available retardants in the market, and several studies have been carried out on the fire performance of CLT panels as a load-bearing wall and floor. Making wood fire-resistant entails applying a chemical formula that will protect the timber. Many studies have been conducted on the effects of surface application and vacuum impregnation with fire retardants on timber structures and components such as load-bearing walls and floors or non-structural members (Chu et al., 1997; Ostman, 2010; Lowden & Hull, 2013). Stora Enso stated that their CLT panels have REI 60 and REI 90 fire resistance if a single-layer plasterboard cladding was attached. Teknos Malaysia, on the other hand, indicated that during a fire, the intumescent paint swells to form a protective foam layer, which partially uses energy during foaming and partially insulates the underlying wood from the fire. If the fire lasts, the wood turns to charcoal, but it will not ignite. Intumescent paint is one of the fire retarding agents that can be applied to wood and wood products to improve their fire resistance. When exposed to high temperatures, intumescent paint undergoes a series of reactions that form a charred carbonaceous compound foam layer with high insulation performance. Under the influence of heat, the coating swells to form a multicellular charred layer that acts as an insulator and slows heat and mass transfer between the condensed and vapour phases. This intumesced char can grow up to 50 times thicker than the original thickness of the applied coatings. Camino et al. (1988) classified intumescent system chemical components into four categories:

i. Inorganic acid, free or originated due to the rise in temperature to 100–250 °C.
ii. Polyhydric compound rich in carbon.
iii. Organic amine or amide.
iv. Halogen compound (usually formed by fluorine or chlorine).

Boric acid, borax, ammonium sulphate, monosodium phosphate, potassium carbonate, and sodium hydroxide are some of the compounds that can be used to lessen the amount of char produced by approximately 20%. In a study that Chou et al. (2009) conducted on intumescent fire-retardant coatings for wood-based materials, they found that the mixture obtained the lowest flammability grade possible under Taiwan Standard CNS 7614 when the proportion of sericite in the fire-retardant composition was more significant than 75%. The chemicals may contain one or more inorganic salts, typically water-based, but some formulations are based on solvents. The water-borne particles have a hygroscopic nature, and as a result, it is advised that they only be used in an indoor setting.

Malaysian authorities are supportive of the use of wood in construction. At the moment, approvals are granted on a project-by-project basis. Local acceptance of CLT is hampered by a lack of supporting data and technical information, such as fire performance and safety assurance. Architects' awareness and knowledge of CLT are relatively low, at 45% and 30%, respectively (Ab Latib et al., 2019). They also concluded that the high cost, perceived poor durability, restrictive building codes and by-laws, and poor fire resistance are all deterrents to using timber products for construction in Malaysia. Existing data on CLT panels tested with temperate wood may not apply to tropical woods such as sesenduk in this study. In Malaysia, very few reports or known standards on CLT panels' fire resistance and performance (Chu et al., 1997). As a result, this research aims to conduct a fire performance test on CLT made from sesenduk that has been treated with a fire retardant, an intumescent paint.

3.0 Methodology

Sesenduk, a light hardwood timber with a density ranging from 305-655 kg/m^3, were obtained from a local sawmill and kiln-dried to about 12% moisture content. Planks of 128 mm x 3050 mm x 30 mm were cut, planed and sized. Fifteen pieces of sesenduk planks were separated and used for the flame spread test. Making a 3-layer CLT panel follows the procedure reported by Hamdan et al. (2016). The CLT panels were then prepared for fire resistance and charring rate tests.

Two types of fire retardant, namely Teknoksafe 2407 (Exterior) and Teknoksafe 2457 (Interior)) were painted onto the CLT panels based on the following protocol. The panels were first sanded with sandpaper Grit 240. Next, 175 gsm fire retardant was sprayed on the samples and left for 2 hours at 30 °C. Light de-nib was applied on the surface with sandpaper Grit 240 before another layer of 175 gsm fire retardant was applied.

Classification of surface spread of flame test was carried out according to BS 476: Part 7: 1997 - Fire Test on Building Materials and Structures. Nine pieces of CLT panel of 270 mm x 88 mm x 19 mm were prepared for every treatment. Untreated CLT panels were denoted as 'Control' while CLT panels treated with Teknoksafe 2407 and Teknoksafe 2457 were marked as `Tk-Exterior' and `Tk-Interior' respectively. The moisture content, weight and size of every sample were recorded. The thickness measurements of the samples after the test across 300 mm were taken.

The charring rate was determined according to BS 476 Part 22:1987 and tested at the Fire Protection Laboratory in Forest Research Institute Malaysia (FRIM), Kepong. The sample size for the charring rate test was 10 mm x 75 mm x 1200 mm. Three replicates for every treatment consisting of CLT Control, Tk-Interior and Tk-Exterior were prepared. Thermocouples were placed at three different locations, with each set having three thermocouples placed at three different depths, namely at the panel's Surface, 20 mm and 38 mm deep. All the thermocouples were linked to a data logger. Experimental charring rates subjected to one side were determined by scrapping away the charred timber and measuring the average depth remaining (char depth) to determine the amount lost through charring. This was divided by the exposure time (min) and is expressed in (mm/min) as the ratio of the char depth (mm) and the exposure time (min). The thickness and weight of the CLT panels before and after the test were taken.

Two criteria of evaluation were determined. Insulation is the ability to prevent excessive increases in temperature. A failure is deemed to occur when the mean temperature of the unexposed face increases by more than 140 °C above the initial value or if the temperature recorded at any position on the unexposed face is more than 180 °C above the initial mean unexposed face temperature. Secondly is integrity, the ability of the CLT panel to resist the development of holes, cracks, fissures or flame penetration. Failure occurs when the CLT panel collapses or sustains flaming for over 10s on the unexposed face.

The layer of coating collected on the CLT panel after the fire test was sent for FTIR characterisation. The samples were homogenised with potassium bromide (KBr) and ground into powder using a mortar and pestle. The mixture was transferred into a mould and pressed to form a 13 mm diameter KBr disc. FTIR spectra were recorded in the range of 4000 to 4500 cm^{-1} with 16 scans employing a PerkinElmer Spectrum 100 Series.

3.0 Finding and discussion

Figure 1 shows the I.R. spectra of the fire retardant before and after the fire resistance test. Generally, the coating before the fire resistance test, peaks representing fire-retardant chemical, foamer and char former can be observed from the I.R. spectra in Figure 1 (Lo et al. 2016). The peak at around 3155 cm^{-1} corresponds to the N-H functional group, while the peak at around 2932 cm^{-1} corresponds to the C-H functional groups. On the other hand, peaks at around 1729 cm^{-1}, 1437 cm^{-1} and 875 cm^{-1}, respectively corresponds to C=O functional group, C-N (ring vibration) and N-H functional group. Meanwhile, the existence of phosphate (P=O) and P-O-P functional groups were represented by the peaks at around 1247 cm^{-1}, 1071 cm^{-1}, and 1013 cm^{-1}.

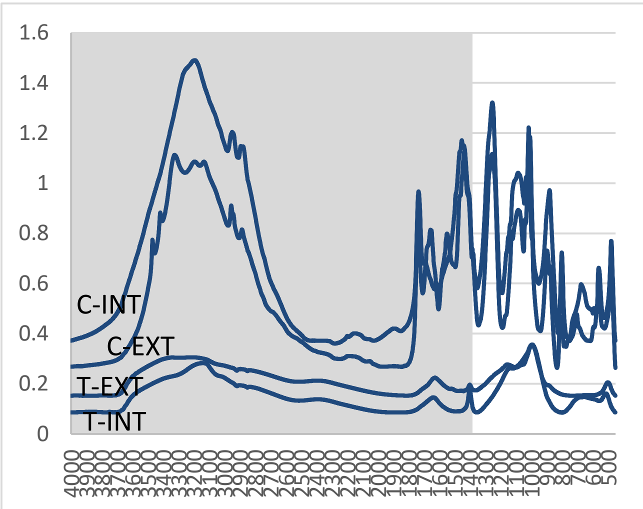

Fig. 1: FTIR spectra of fire retardant applied on the CLT before and the after fire resistance test
Note: C-EXT = Paint Exterior; C-INT = Paint Interior; T-EXT = Paint Exterior Tested (after test); T-INT = Paint Interior Tested (after test)

After the fire resistance test, a new peak appeared near 1171 cm^{-1}, corresponding to the complex P-O-C group produced from phosphate (ester) and the carbon in pentaerythritol (Gu et al., 2007). A small absorption peak observed at around 1609 cm^{-1} indicated the formation of a C=C bond (Wang et al., 2005). The absorption peak of a P-O-C group appeared in the band around 1100–1000 cm^{-1}, and that of the phosphate (P=O) group appeared around 1250–1200 cm^{-1}, while the peak at 1062 cm^{-1} represented a P-O group. According to Wang et al. (2006) and Lv et al. (2005), phosphoric acid, ammonia, and water are the main composition generated during heating. The phosphoric acid will act as a catalyst that promotes the reactions of polyhydric alcohol, producing water and alkene, eventually forming a solid-phase char coating. At a temperature higher than 300 °C, the phosphoric acid further dehydrates to form polyphosphate.

Table 1. Classification of surface spread flame, charring rate, fire resistance test

Panel	Density (kg/m^3)	Class	Charring rate (mm/min)	Integrity (min)	Insulation (min)
Control	468	3	0.76	60	60
Tk-Exterior	483	1	0.59	60	60
Tk-Interior	472	1	0.53	60	60

Table 1 shows the classification for surface spread flame, charring rate, and fire resistance. According to BS 476: Part 7: 1997 for Fire Test on Building Materials and Structures, the Control panel received a Class 3 rating, while Tk-Exterior and Tk-Interior received a Class 1 surface spread flame test. The results showed that using a fire retardant effectively prevented the fire from spreading. The one-dimensional charring rate test results, whereby the calculation of cross-sectional properties was based on the actual charring depth. The charring rate for the Control panel was 0,76 mm/min while Tk-Exterior and Tk-Interior were 0,59 mm/min and 0,53 mm/min, respectively. In comparison, the one-dimensional charring rate according to EN 1995-1-2 is 0,65 mm/min for thick wood layer. According to EC5, the charring rate for hardwoods varies linearly for densities between 290 and 450 kg/m^3 but is independent with density above 450 kg/m^3. With regards to timber density, BS 5268: Part 4: Section 4.1: 1978 indicated that the mean charring rate for hardwoods is 0,50mm/min with the lowest for chengal (Neobalanocarpus heimii) at 0,26mm/min (Anonymous, 1978; Chu et al., 1997). In comparison, the Control with a density of about 460 kg/m^3 recorded a 0,76 mm/min charring rate, which corresponded with the EC5 conductive model after 30 and 60 min, which is between 0,76 mm/min and 0,68 mm/min, respectively. The fire resistance test results showed that the CLT panel met the basic requirements specified in BS 476: Part 22:1987.

Fig. 2: Surface flame spread and cross-section respectively

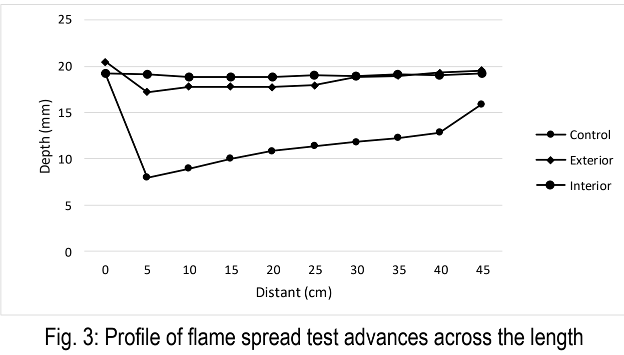

Fig. 3: Profile of flame spread test advances across the length

Figure 2 shows the surface flame spread and the flame profile spread across the length (Fig. 3). The mode of spread from the location of ignition on the control panel was distinctly influenced by the surface treatment. Compared to treated samples, the maximum burnt depth for the Control panel was approximately 60% of its original thickness, with Tk-Interior at about 10%. The control sample's surface exposed to direct fire had distinct scaling and a pronounced fissured surface with thick charring. Smoother surfaces were observed for both treated samples in comparison. When exposed to fire, the retardant effectively insulated the surface, resulting in less charring. Char development was slightly greater in depth at fissure locations and with increasing exposure temperatures and decreasing wood density (U.S. Department of Agriculture, 1967). The treatments also significantly improved the CLT panel's resistance rating by reducing charring formation. Hietaniemi et al. (2004) agreed that protective coatings may effectively prevent wood ignition and charring in general.

The mean weight and thickness loss after the fire resistance test are shown in Table 2. The average thickness loss for the Control panel is approximately 43,2 mm or 61,45%, while the total weight loss is approximately 47,4%. Panels Tk-Exterior and Tk-Interior, on the other hand, experienced a mean thickness loss of 29,2 mm (40,67%) and 31,2 mm, respectively (45,10%loss). The intumescent coating protects by delaying fire spread across both treated panels. This suggests that the painted CLT can extend its strength and overall panel integrity over the same period as compared to the Control. The test also demonstrates that the first and nearly all second layers were burned for the Control panel within 60 minutes.

Table 2. Weight and thickness loss after fire resistance test

Sample	Mean Thickness loss (mm)	Weight loss (kg)
Control	70,3	42,2
Final thickness and wt. after carbon removed	27,1	22,2
Loss of thickness and wt. after test	43,2	20,0
Percentage loss (%)	61,45	47,39
Tk-Exterior	71,8	40,2
Final thickness and wt. after carbon removed	42,6	23,6
Loss of thickness and wt. after test	29,2	16,6
Percentage loss (%)	40,67	41,34
Tk-Interior	71,2	52,4
Final thickness and wt. after carbon removed	39,1	30,6
Loss of thickness and wt. after test	32,1	21,8
Percentage loss (%)	45,10	41,66

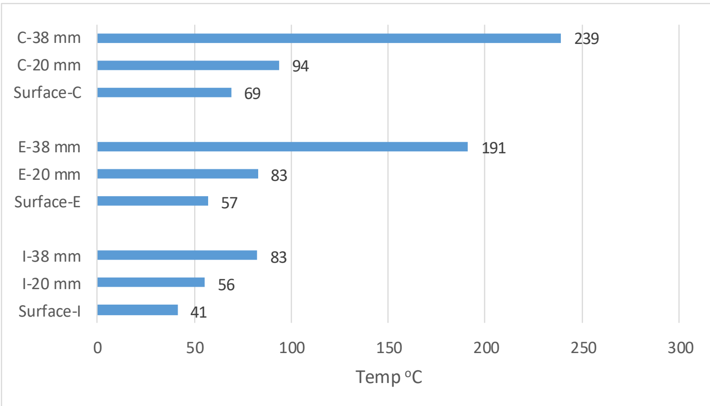

Fig. 4: Maximum temperature at Surface; 20 mm; 38 mm depth

Figure 4 shows the maximum temperature recorded at the Surface: 20 mm; 38 mm deep for Control, Tk-Exterior and Tk-Interior. The National Fire Protection Association (NFPA) states that the upper limit of human temperature tenability is 100 °C. However, in the range of 32 ˚C and 40 ˚C, a person can experience heat cramps and exhaustion. Between 40 ˚C and 54 ˚C, heat exhaustion is more likely. An environmental temperature over 54 ˚C often leads to heatstroke. The temperature for Control recorded at the surface after 60 minutes was about 70 °C while the Surface for Tk-Exterior and Tk-Interior were 57 °C and 41 °C, respectively. The results may suggest that a person confined within a space painted with Tk-Interior may only experience heat exhaustion after 60 minutes compared to Control, who may already experience heatstroke. The test also shows that the temperature recorded at 38 mm deep from the Surface for Control was 239 °C and 191 °C for Tk-Exterior but only 83 °C for Tk-Interior. This again shows that with appropriate coating, heat transfer between the CLT layers could be effectively reduced by introducing surface coating to the CLT surface.

5.0 Conclusions

CLTs are already being used worldwide for various applications, and the general public is very open to the idea of using timber in large structures due to the green building label. Because timber can catch fire, it is essential to take the necessary precautions to protect it to ensure its long-term stability. The research conducted with Tk-Exterior (Tksafe 2407) and Tk-Interior (Tksafe 2457) coated

CLT panels produced outstanding results and outperformed the Control. The rise in temperature versus time of fire initiation was significantly prolonged for both coated samples compared to the Control. This was the case because the coated samples had a higher surface area. The addition of an ash layer that slows pyrolysis is what gives intumescent paint its purpose, which is to make up for the charring that occurs when layers are burned. To achieve performance comparable to that of the coated CLT, the number of layers and thickness of the CLT for Control may need to be increased to at least five to be eligible for use in Type III construction. Although the code in IBC (2021) 2303.2 Fire-Retardant-Treated Wood refers to wood products that have been impregnated with chemicals such as fire retardants or by other means during the manufacturing process, the technique of applying fire retardants by surface coating has demonstrated remarkable potential for future applications. Additional studies and sample tests need to be conducted to meet the requirements for approval by the various authorities in Malaysia.

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