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Assessing Fire Resistance Through One-Dimensional Charring Rates of Solid Malaysian Light Hardwoods Using The Reduced Cross-Section Method

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Abstract

In recent decades, timber structures have gained popularity due to their environmental benefits and support for sustainable development goals. They reduce energy demands and pollution, hence making the construction sector greener. However, timber is a combustible material, limiting its use in structural applications due to building regulations, especially for taller and larger buildings, which raise fire safety concerns. Therefore, studying the fire resistance and structural integrity of timber during and after a fire is crucial. This paper presents a study examining the fire performance of timber beams made from Malaysian tropical light hardwoods. To assess the performance in detail, the char depth of timber beams was determined by using the reduced cross-section method for various species, ranging from light hardwoods with densities varying from 450 kg/m^3 to 700 kg/m^3. The beams were tested under one-dimensional fire conditions for varying durations (45 minutes, 60 minutes, and 70 minutes) using standard fire exposure. The charring rate value also been evaluated for these species. The findings indicate that certain species exhibit charring rates of 0.5 mm/min, which align with the guidelines outlined in Eurocode 5 for solid hardwoods with timber densities exceeding 450 kg/m^3.

1. Introduction

Over the past decade, there has been a growing interest in timber as a sustainable and environmentally friendly material. Many countries have even set goals to increase their use. However, timber is a combustible material, leading to the misconception that it is unsuitable for multi-storey buildings. This misconception assumes that buildings with timber frame structures or solid wood members would have poor fire resistance and reduced structural capacity [1]. However, research and test results have proven that wooden structures can indeed have sufficient fire resistance if designed correctly [2].

The ability of timber structures to withstand fires has become a crucial characteristic for ensuring building safety. Furthermore, timber structures are often integrated into buildings constructed using other materials, making the combustion system more complex. Structural elements must retain their load-bearing capacity over an expected duration, and the individual timber components should be capable of enduring high temperatures or fire circulation [3].

According to BS4422:2005, the fire resistance of a structural element is defined as "its ability to satisfy, for a specified duration, the criteria for stability during a fire and/or integrity and/or thermal insulation as specified in fire resistance testing standards." This implies that fire resistance is a characteristic of an element, not the material itself. To ensure that a timber structure remains durable and stable during a fire, it is necessary to consider the burnt or charred portion.

While timber exhibits combustion above a critical temperature, typically around 300°C, this drawback is significantly mitigated by the formation of a char layer. This layer acts as a robust thermal shield, protecting the remaining unburned core of the timber member. Due to the low thermal conductivity of wood, only a narrow zone directly beneath the char layer experiences elevated temperatures. The remainder of the cross-section remains largely unaffected by heat. The most crucial design approach is founded on the notion of the effective cross-section, enabling the utilisation of user-friendly techniques for the fire design of timber structures. By incorporating this concept into the design process, the heat-affected zone beneath the char layer is minimised through the inclusion of a "zero-strength layer" with a thickness (or depth) represented by d_0. Consequently, the remaining residual cross-section retains its original material properties, including its full strength and stiffness [4], [5].

The part of the timber beyond the char layer in the heated zone is commonly referred to as the pyrolysis zone. It is widely accepted that within this zone, the timber undergoes thermal decomposition and pyrolysis. The char layer expands as it is exposed to fire, providing additional insulation, slowing down the burning rate, and reducing the unheated cross-sectional area of the timber [6]. This process continues until the end of heating or until the section has fully combusted [7]. Fig. 1 shows a clearer understanding of this process.

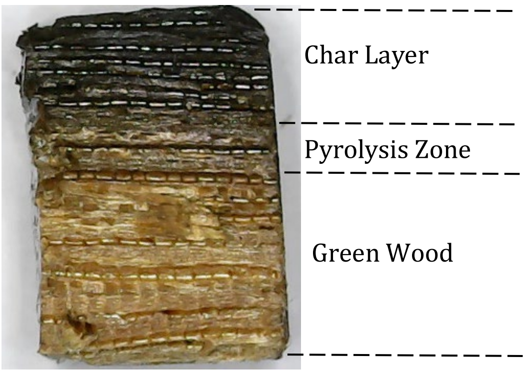


Fig. 1 *Areas of decay in the wood*

In general, timber and its products with larger cross-sectional areas are more resistant to flames. The type of timber used also affects how quickly it chars, primarily determined by its density. Timber with higher density is more fire-resistant and burns more slowly, resulting in a lower charring rate. Conversely, timber with lower density ignites more quickly, resulting in greater charring and a higher charring rate. When exposed to fire, the cross-sectional area of the timber decreases, and its mechanical properties near the char line weaken. As a result, the load is borne by the unburned portion of the timber. Therefore, it is crucial to determine the char rate of the timber used to ensure the structure is appropriately designed and safe in the event of a fire.

Most studies on timber fire resistance have been conducted in foreign countries using timber species from Europe, the United States, New Zealand, Australia, and other regions [8]-[10]. However, the performance of Malaysian-grown timber may differ from timber grown in other countries due to variations in climate, which can affect the growth and density of the timber to varying degrees. The charring rate of solid timber in one dimension, especially in relation to Malaysian tropical species, can vary due to several factors. These factors include the wood species, moisture content, density, and the specific conditions of fire or heat exposure. Different wood species have different levels of fire resistance.

Moreover, the moisture content of wood greatly influences its rate of charring [11], [12]. Dry wood chars at a slower rate compared to wet or green wood, as water effectively absorbs and dissipates heat. In the case of wet wood, the absorption of heat energy hinders the charring process. The one-dimensional charring rate of solid timber is influenced by various factors, including the wood species, moisture content, density, and specific conditions of the fire or heat exposure [13].

To determine the charring rate value, it is necessary to measure the depth of the charring. Understanding the depth of charring in timber is crucial for evaluating its fire resistance and ability to maintain its structural integrity during and after a fire [14]. By determining the charring depth, engineers and architects can make informed decisions about the safe use of timber in construction and design structures that can better withstand the effects of fire. The charring rate can also be calculated to estimate the time it takes for the charred layer to reach a critical depth at which the underlying timber may become compromised and lose its structural integrity. Therefore, this paper aims to determine the char depth of timber using the cross-section method and to evaluate the charring rate value of solid timber under one-dimensional fire exposure.

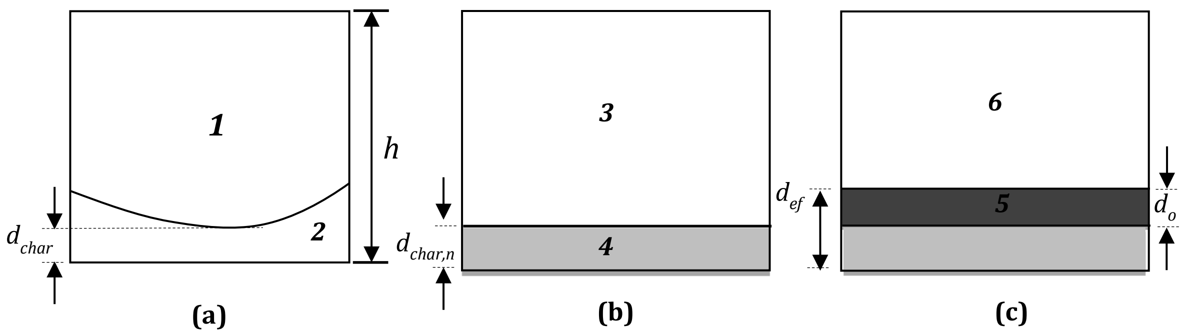
1.1 Reduce Cross-Section Method

Eurocode 5 (EC5) recommends three methods for evaluating the fire resistance of timber structural members: the reduced cross-section method, the reduced properties method, and the advanced calculation method (finite element analysis) [15]. However, this study focuses solely on the reduced cross-section method. This method involves calculating the reduced cross-section by subtracting the effective char depth (d_{ef}) from the initial cross-section, as described in Eq. 1 [16]. The effective depth is determined by adding the notional charring depth to the zero-strength layer (d_0).

$$d_{ef} = d_{char,n} + k_0 d_0 \tag{1}$$

where $d_{char,n}$ represents the reduced section after the fire test, also known as the notional char layer. The value of k_0 is determined as $t/20$ for t < 20 minutes and is equal to 1.0 for t > 20 minutes for unprotected surfaces, as per EC5 guidelines. In this study, since the fire durations were 45 minutes, 60 minutes, and 70 minutes—all exceeding 20 minutes—the k_0 value is taken as 1.0. Meanwhile, the zero-strength layer (d_0) is considered to be 7 mm.

Material near the char line within the k_0d_0 layer is assumed to have no strength or stiffness, while the remaining wood retains its original properties. In this study, only the depth side of the sample cross-section is considered, with no further reduction applied to the wide sides, as the focus is on one-dimensional charring. The depth of charring (d_{ef}) is then used to calculate the charring rate of timber, as specified in EC5. This process follows the flowchart outlined in Appendix 5, EC5. While Fig. 2 was illustrated from König [16], which was summarised from EC5.



1-Residual cross-section (original size)
2-Char layer (real shape)
3-Equivalent residual cross-section (rectangular)
4-Char layer with notional charring depth
5-Zero strength layer
6-Effective cross-section

Fig. 2 *Charring for one-dimensional fire exposure: (a) Real residual cross-section; (b) Notional charring depth; and (c) Effective charring depth and the zero-strength layer of timber*

1.2 One-Dimensional Charring Rate

The charring rate of timber can be categorised into two types: one-dimensional charring rate and notional charring rate. The theoretical basis for these rates is established in EC5, where the one-dimensional charring rate (β_0) is determined under standard fire exposure conditions for an unprotected semi-infinite timber slab without any fissures or gaps. Similar conditions apply to thin slabs or wide timber cross-sections located far from corners [17]. The charring depth, denoted as d_{ef} (continuity from the previous section), represents the extent of timber loss due to fire and can be measured at specific time intervals (see Fig. 2). This charring depth has been measured by reduced cross-section methods as specified in EC5. This charring depth is inferred from the above statement, where β_0 is defined as in Eq. (2).

$$ß_0 = \frac{d}{t} \quad (2)$$

where β_0 is the one-dimensional design charring rate under standard fire exposure, d_{ef} is the charring depth for one-dimensional charring, and t is the time of fire exposure.

Fig. 3 illustrates the determination of one-dimensional charring of a wide cross-section with fire exposure on one side, as per EC5.

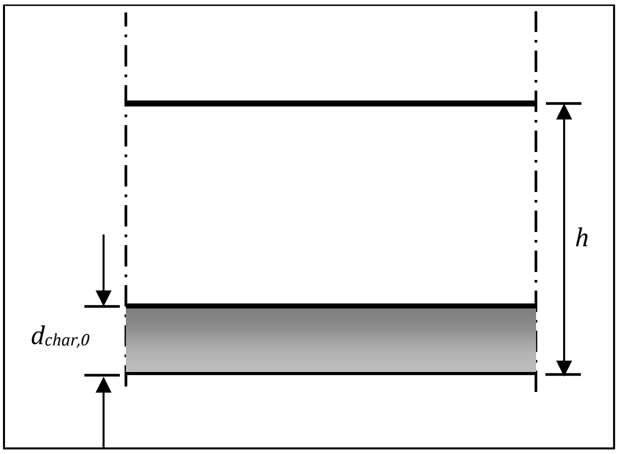


Fig. 3 *One-dimensional charring of wide cross-section with fire exposure on one side as per EC5*

2. Methodology

2.1 Preparation for Sample and Testing Procedure

The timber used in this study was categorised as light hardwood, with a density range of 450 kg/m^3 to 700 kg/m^3. These species were commonly used for structural applications, even in light hardwood categories. The species used in this study were White Meranti (700kg/m^3), Dark Red Meranti (730kg/m^3), Kedondong (600kg/m^3), Light Red Meranti (560kg/m^3), and Jelutong (480kg/m^3). Do note that the densities obtained here are from MS544: Part 2, which may vary depending on the specimens received, as the range for each species can be substantial.

The solid timber used for this study had dimensions of 100 mm x 100 mm x 1400 mm. The length of the timber was based on the frame manufactured for the furnace used in the fire test. The test was conducted at the Fire Protection Laboratory of the Forest Research Institute Malaysia (FRIM) in Kajang, Selangor. Each species was replicated with 6 samples, with 3 samples for different durations of fire test: either 45 min and 60 min, or 60 min and 70 min, as presented in Table 1. Previous studies by Ahmad *et al.* [18], Njankouo et al. [19] and Yang et al. [20] used durations of 30, 45 and 60 minutes for their fire tests. These durations also fulfil the requirements set by the local authority, as mentioned in the Uniform Building By-Law (UBBL) Malaysia, where the required fire resistance times are more than 30 minutes and 60 minutes. The densities listed in Table 1 are from MS544: Part 2. It is worth noting that these values may vary depending on the specimens received, as the range for each species can be substantial. The average density of each species will be presented in the results and discussion section.

Table 1 *Time exposure for furnace fire test in one-dimensional specimens*

Species	Density from MS 544: Part 2 (kg/m^3)	Time of Fire Exposure (min)		
		45	60	70
White Meranti	700	-	✓	✓
Dark Red Meranti	730	✓	✓	-
Kedondong	600	-	✓	✓
Light Red Meranti	560	✓	✓	-
Jelutong	480	✓	✓	-

*Note: Each ✓ represents for 3 specimens

All timber beam samples were graded by graders before any preparation work was carried out. Subsequently, a drilling process was conducted on each sample to create six holes for the positioning of the thermocouple. While the thermocouple installation took place, the specific details concerning its location and conditions will not be thoroughly explained in this paper, as the main focus is on the reduced cross-section method for determining the charring rate.

2.2 Furnace Preparation

During a single fire test session, only three samples could be tested due to the limitations of the frame design. The frame is designed to accommodate three samples per burning cycle, based on the furnace size and surface exposure. Skilled personnel from the Forest Research Institute Malaysia (FRIM) operated the furnace to ensure it achieved the required time-temperature curve as specified by BS 476: Part 20 (equivalent to EN 1363-1 and ISO 834). The fire test employed a small gas-fired furnace covered by the specimen and additional sheets of gypsum plasterboard (Fig. 4(b)). Observations of the test specimens were made through a small glass window in the furnace throughout and following the fire exposure.

The furnace temperature was monitored using three plate thermometers positioned within the furnace: two on the left side (top and bottom) and one on the right side (Fig. 4(a)). Fig. 4(c) shows the furnace frame ready for testing.

(a) (b) (c)

Fig. 4 *Vertical furnace for fire test - (a) plate thermometers positioned within the furnace; and (b) gas-fired furnace covered by the specimen and additional sheets of gypsum plasterboard*

Immediately after reaching the burning duration, the test specimens were removed from the furnace and extinguished with water to prevent further charring (Fig. 5).

(a) (b) (c)

Fig. 5 *Works after fire duration being terminated - (a) Test specimens were immediately taken out from the furnace; (b) The specimens were sprayed with water to ensure that the fire was completely extinguished; and (c) Specimens left for cooling phase*

2.3 Sample Cutting and Scrapping after Fire Test

As mentioned in the earlier section, at the end of the fire test, all specimens were removed from the furnace, and the fire was extinguished with water to prevent further charring. After the specimens had cooled, they were sliced (see Fig. 6(a)) at the exact location where the thermocouple (TC) was placed (see Fig. 6(b)). Subsequently, the char formed on the cutting sample was removed using a scraper.

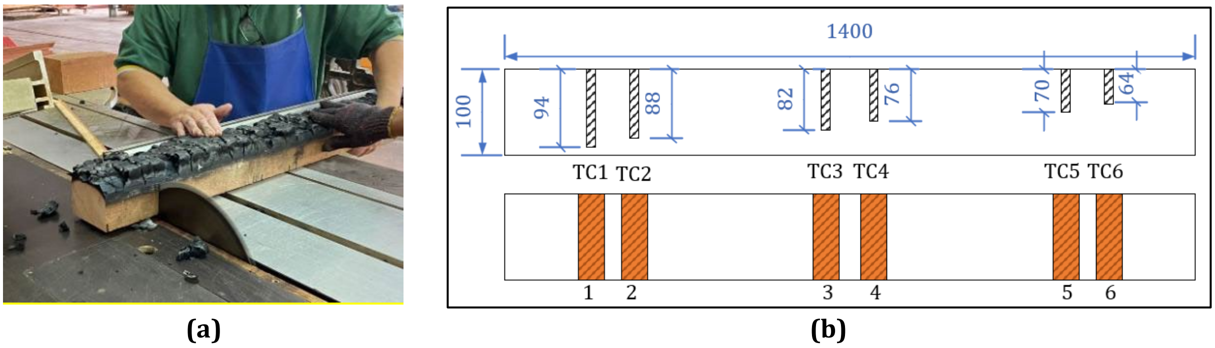


Fig. 6 *(a) Cutting of the sample at a specific location; (b) Schematic diagram for locations where sections were cut from the residual timber*

2.4 Determination of Char Depth

After the char layer had physically been removed, the uncharred section, known as the residual sample of timber, was measured. To determine the char depth value, the thickness of the charred depth (d_{char}) for each slice was measured. Five spots for each slicing sample were measured before being averaged for the final valued charred depth (d_{ef})(effective charring depth and zero-strength layer of timber) as described in Section 1.1. Fig. 7 depicts the analysis of measured char depth and the application of Eq. (3) to determine the effective char depth. This approach is consistent with the methods employed by Bakri [21]. This method, which involves averaging the depth of the section, has also been mentioned by Tsai [22].

$$d_{ef} = \frac{t_1 + t_2 + t_3 + t_4 + t_5}{no.\,of\ point\ taken} \tag{3}$$

where *d* is the effective depth of char and *t* is the thickness of the loosened part of the timber

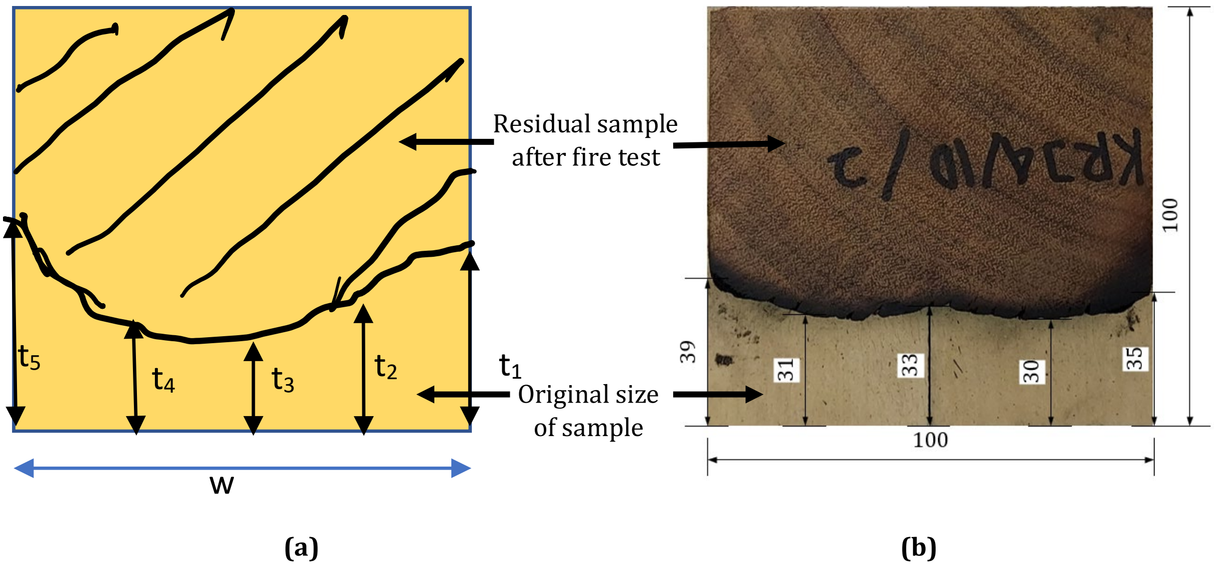


Fig. 7 *Measuring char depth - (a) Illustration of the determination of char depth; and (b) The actual cutting specimen analysed with Visio Professional 2013*

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2.5 Determination of Charring Rate

The charring rate for these one-dimensional specimens was calculated from the char depth gained by the reduced cross-section method. The charring rate of one-dimensional (β_0) generally can then be calculated using Eq. (2).

3. Results and Discussion

Charred cross-sections of the specimens were photographed and imported into Microsoft Visio Professional. The software was then used to measure the char depth for each specimen relative to its original cross-sectional dimensions. This char depth (d_{ef}) for each species was determined using Eq. (3), which incorporates the zero-strength layer into the measurement.

Table 2 *Charring depth and charring rate evaluation via measurement of the residual cross-section*

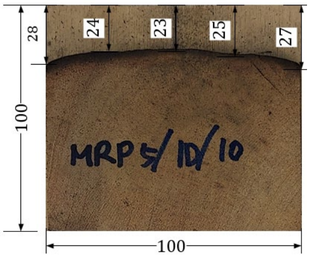
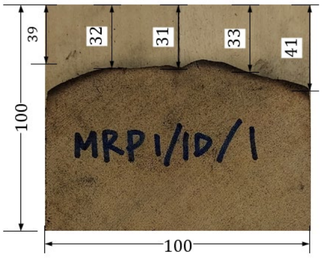
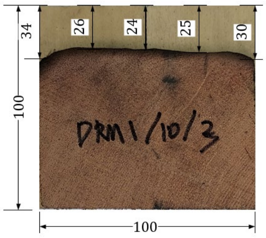
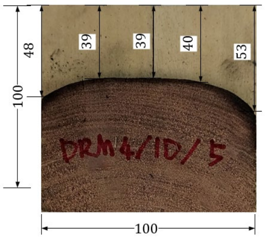
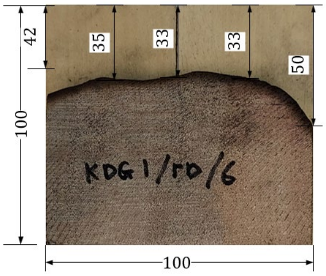
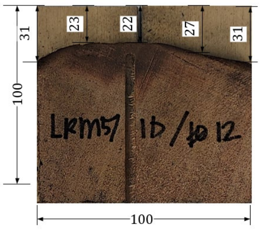
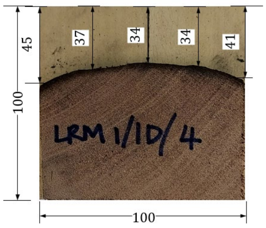
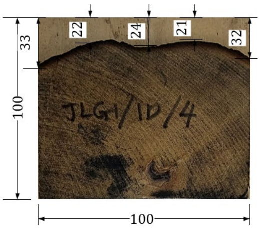
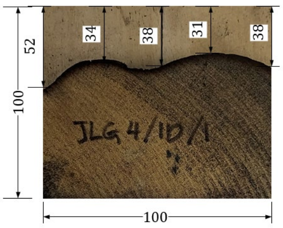
Species	Diagrams of cross-section		
Duration of Fire	45 minutes	60 minutes	70 minutes
White Meranti	n/a		
Dark Red Meranti			n/a
Kedondong	n/a		
Light Red Meranti			n/a
Jelutong			n/a

Table 2 presents images comparing the original and residual cross-sections of each species. As the table shows, even with the same fire exposure duration, the uncharred area varies between species. It reveals clear differences in char depth for the same species exposed to different fire durations. These variations can be attributed to both the density and cellular structure of the timber, which differ significantly across species, as confirmed by Aseeva et al. [6]. Timber is considered a unique material due to its diverse characteristics: some timbers are harder or softer (hardwood and softwood), some are denser or lighter, and they can be more flexible or easier to shape.

Using the char depth (d_{ef}) value, the charring rate for all species can be determined by using Eq. (2) from EC5. Table 3 shows the average char depth and charring rate for each specimen from every species. EC5 states that for solid hardwoods with a density greater than 450 kg/m^3, β_0 is 0.5 mm/min. In this study, three species exceeded the charring rate of 0.5 mm/min, which is Dark Red Meranti with 0.69 mm/min, Light Red Meranti with 0.62 mm/min, and Jelutong with 0.54 mm/min. Meanwhile, the other two species had charring rates below 0.5 mm/min, specifically White Meranti at 0.43 mm/min and Kedondong at 0.46 mm/min.

Table 3 *Charring depth and charring rate evaluation for all species*

Species	Exposure Time (min)	Sample	Density (kg/m^3)	Average Density (kg/m^3)	Charring Depth (mm)	Charring Rate (mm/min)	Average Charring Rate (mm/min)
White Meranti	60	MRP4	870.0	822	34.8	0.58	0.43
		MRP5	871.4		27.4	0.46	
		MRP6	825.7		32.8	0.55	
	70	MRP1	778.6		21.5	0.31	
		MRP2	834.3		23.9	0.34	
		MRP3	751.4		23	0.33	
Dark Red Meranti	45	DRM1	445.7	480	29.5	0.66	0.69
		DRM2	454.3		28.2	0.63	
		DRM3	434.3		25.6	0.57	
	60	DRM4	558.6		45.7	0.76	
		DRM5	508.6		45.4	0.76	
		DRM6	480.0		47	0.78	
Kedondong	60	KDG4	692.9	703	37.4	0.62	0.46
		KDG5	694.3		35.7	0.60	
		KDG6	705.7		24.6	0.41	
	70	KDG1	662.9		26.7	0.38	
		KDG2	664.3		28	0.40	
		KDG3	797.1		24.1	0.34	
Light Red Meranti	45	LRM4	541.4	567	38.1	0.85	0.62
		LRM5	560.0		37.4	0.83	
		LRM6	538.6		27.5	0.61	
	60	LRM1	545.7		32.7	0.55	
		LRM2	517.1		26.5	0.44	
		LRM3	701.4		25.8	0.43	
Jelutong	45	JLG1	534.3	589	27.0	0.60	0.54
		JLG2	610.0		22.0	0.49	
		JLG3	604.3		20.3	0.45	
	60	JLG4	575.7		36.4	0.61	
		JLG5	598.6		34.9	0.58	
		JLG6	612.9		31.6	0.53	

Results show that even the lowest density among these species, which is Jelutong, can also contribute to achieving a good charring rate (which is more than 0.5 mm/min). Against it relates to the structure factor of the species itself. However, although the relationship between charring rate and density appears to fluctuate, it is evident that as the density of the timber increases, the charring rate decreases [23]. The species are ranked by decreasing charring rate as follows: Dark Red Meranti > Light Red Meranti > Jelutong > Kedondong > White Meranti.

König [17], Njankouo et al. [19], White [24], Frangi & Fontana [25] agree that timber density has a significant impact on the rate of charring. However, the relationship between charring rates and densities has been a subject of debate among researchers, as various factors also influence this relationship, including moisture content, chemical composition, grain orientation, and fire exposure. Friquin [13] also stated that the charring rate is affected by the fire growth rate and the maximum temperature, with higher initial growth rates leading to higher charring rates.

Nevertheless, many researchers do not use the uninstrumented or residual cross-section method of measurement to calculate the charring rate value as the final answer. Instead, they commonly use the instrument method [26], [27].

4. Conclusion

This study examined the thermal properties measured using a furnace under one-dimensional fire exposure. The charring rates were analysed based on different exposure times: 45, 60, and 70 minutes. The following key findings were observed:

- The variation in char depth between the specimens is visible, influenced by the different fire exposure times and the species of the timber.
- In this study, three species exceeded the charring rate of 0.5 mm/min, while the other two species had charring rates below 0.5 mm/min but still close to 0.5 mm/min
- The species are ranked by decreasing charring rate as follows: Dark Red Meranti > Light Red Meranti > Jelutong > Kedondong > White Meranti.

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Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Author Contribution

*The authors confirm their contributions to the paper as follows: **Study conception and design:** Hafizah Muhamad Azlan and Zakiah Ahmad; **Data collection:** Hafizah Muhamad Azlan, Norshariza Mohamad Bhkari, and Lannie Francis; **Analysis and interpretation of results:** Hafizah Muhamad Azlan, Norshariza Mohamad Bhkari, and Zakiah Ahmad; **Draft manuscript preparation:** Hafizah Muhamad Azlan, Norshariza Mohamad Bhkari, Zakiah Ahmad, and Lannie Francis. All authors reviewed the results and approved the final version of the manuscript.*

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