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TIME TO IGNITION, HEAT RELEASE RATE, AND MASS LOSS RATE PROPERTIES OF SELECTED MALAYSIAN SOLID TROPICAL HARDWOOD TIMBER FROM CONE CALORIMETER TEST

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This study examined the combustion characteristics of three tropical Malaysian wood species—Keranji, Keruing, and Light Red Meranti—using a cone calorimeter following the ISO 5660-1 standard. The heat release rate (HRR), mass loss rate (MLR), and time to ignition (TTI) were measured under varying fire conditions for each wood species. The results revealed significant differences in the burning behaviour of these species, influenced by their densities and exposure to different heat flux levels. Species with higher densities exhibited elevated HRR and peak heat release rate (PHRR) values, whereas lower-density woods showed decreased MLR values. Additionally, the TTI was longer for woods with higher densities. These findings contribute valuable insights into the combustion properties of tropical wood species, particularly for applications in the construction industry, where understanding fire behaviour is crucial for material selection and safety assessments.

Keywords: Combustion, cone calorimeter, heat release rate, mass loss, tropical timber

INTRODUCTION

The role of timber in sustainable construction has gained considerable interest due to its environmental benefits and structural qualities. However, as a combustible material, timber poses fire safety challenges, especially concerning its reaction-to-fire properties such as time to ignition, heat release, flame spread, mass loss, and smoke production, whether used as furniture or as timber structures (Ali et al. 2020). Understanding these properties is crucial for developing safer timber structures, particularly with the growing use of engineered wood products in modern architecture.

When exposed to heat, wood begins to decompose, releasing fuel gases that flow into the surrounding area and forming a layer of char on the wood's surface. These gases mix with air, creating a flammable mixture that can ignite once the fuel-to-air ratio and gas temperature reach necessary levels. As the surface temperature rises, the char layer reacts with oxygen from the environment. The fire will continue if there is a supply of fuel or oxygen; once either is depleted, the fire will diminish and eventually extinguish itself (Hao et al. 2020). Thermal degradation of wood involves depolymerisation and devolatilisation processes, where significant weight loss occurs between 280–370 °C under inert conditions (Tan 1989). The boundary between the char layer and the unburned wood is well-defined and corresponds to a temperature of 300 °C. In North America, the widely accepted charring temperature is 288 °C. However, Mikkola (1990) identifies the char front at 360 °C in his research, as the wood retains some strength up to this temperature.

Reaction to fire testing is essential for understanding timber's role in fire dynamics, aiding engineers, architects, and fire safety professionals in designing safer buildings. Numerous studies have investigated timber's reaction-to-fire characteristics, emphasising critical properties such as heat release rate (HRR), time to ignition (TTI), mass loss rate (MLR), and charring behaviour. Babrauskas and Grayson (1992) identified HRR as the key parameter for assessing how materials influence fire severity, showing that the cone calorimeter can effectively measure HHR across various materials, including timber. Heat release rate is particularly important in evaluating the fire behaviour of wood, as it represents the amount of heat released per unit surface area and serves as a primary indicator of the fire risk posed by burning materials (Grexa & Lubke 2001, Lee et al. 2011). Yang et al. (2003) further reported that as external heat flux increases, both the surface and internal temperatures of wood rise, initiating pyrolysis and leading to char formation on the wood's surface.

Time to ignition is an important parameter for evaluating the fire characteristics and flammability of materials (Li 2003, Lee et al. 2011). Seo et al. (2016) investigated the combustion of softwood (red pine, Japanese larch, Japanese cedar, and Korean fir) and hardwood timber (Manchurian ash and giant dogwood) and found that the TTI was faster for softwoods than for hardwoods. Wood is a porous material, so the emitted heat from the flame can be absorbed into the pores and pits of the wood (Evans 1991).

The cone calorimeter, a widely adopted instrument for reaction-to-fire testing, enables precise quantification of fire behaviour under well-controlled heat-flux conditions, producing results that show strong correlation with large-scale fire test outcomes (White & Sumathipala 2013). In this study, the wood specimens measuring 100 mm x 100 mm x 50 mm were subjected to a constant radiant heat flux, simulating fire exposure. The test measures key parameters, including HRR, the rate of heat emitted by burning wood; MLR, the rate of material mass reduction; TTI, the time until sustained burning begins; and smoke production (SP), which quantifies smoke output. With only a small sample required for each test, the cone calorimeter is ideal for research and development. Following standardised testing methods that comply with global standards (ASTM E1354, ISO 5660), the cone calorimeter provides reliable comparisons across studies. This versatile tool is used to assess untreated wood, fire-retardant-treated wood, and composite wood products. This study uses cone calorimetry to investigate timber's reaction-to-fire characteristics, analysing species variations in HRR, mass loss, and ignition time.

MATERIALS AND METHODS

Material preparation

Three hardwood species in various densities were used in this study, namely Keranji (*Dialium* spp.), Keruing (*Dipterocarpus* spp.), and Light Red Meranti (*Shorea* spp.). The woods were obtained from a sawmill in Terengganu, Malaysia. The received wood samples were pre-dried to below 19% moisture content to simulate dry-use conditions, reduce moisture-related variability, and ensure repeatability and comparability of the experimental results. The dried densities of Keranji, Keruing, and Light Red Meranti are 975.1 kg m^{-3}, 756.1 kg m^{-3}, and 545.4 kg m^{-3}, respectively. The samples were prepared in the form of a block with dimensions of 100 x 100 x 50 mm as shown in Figure 1.

Specimens for the cone calorimeter test were prepared according to the ISO 5660-1:2015 method. Following the standard, each specimen was wrapped in aluminum foil along the sides and bottom (Figure 2a), then placed on a ceramic fibre blanket within the sample holder (Figure 2b). A retainer frame, without a wire grid (Figure 2c), was used to secure the sample, leaving an exposed surface area of 88.0 cm^2. Before testing, the mass and moisture content of all specimens were measured and recorded.

Cone calorimeter experiment

A cone calorimeter (Figure 3a) was employed to evaluate the combustion properties of the specimens according to ISO 5660-1:2002. In a cone calorimeter test, HRR was determined based on the oxygen depletion principle, utilising

Figure 1 Wood samples used in the study; (a) Keruing (KG), Light Red Meranti (LM), and Keranji (KR), (b) plan view of Light Red Meranti samples

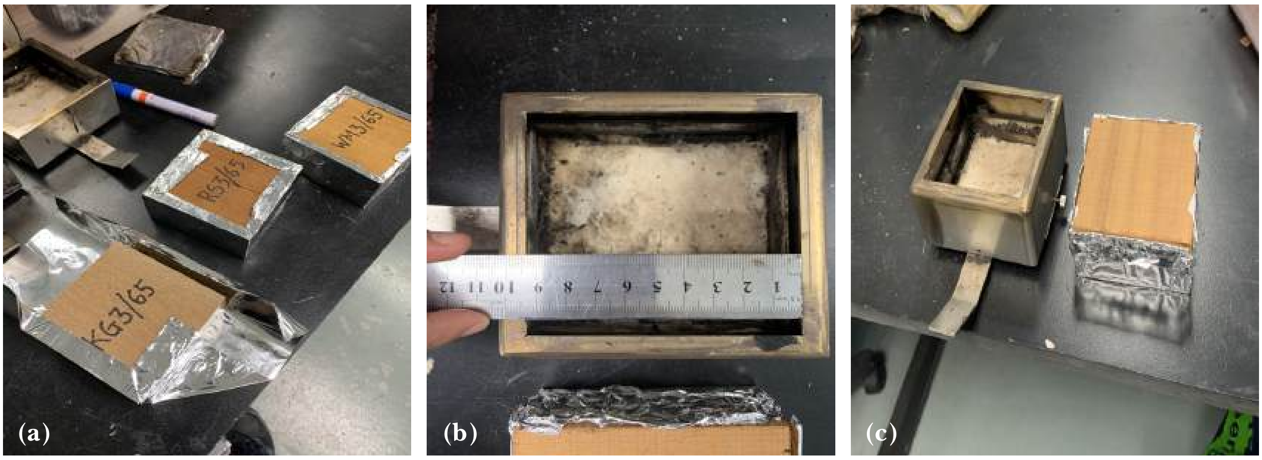


Figure 2 Preparation of specimen for cone calorimeter test; (a) wrapping the specimen with aluminium foil, (b) sample holder with retainer with ceramic fibre blanket, (c) ready sample holder before placing the specimen

the fact that heat release per unit mass of oxygen consumed is approximately independent of the type of fuel. The prepared specimens were exposed to incident heat flux in their horizontal orientation parallel to the grain, with a conical radiant electric heater positioned 25 mm above. The heater was set at various heat flux intensities of 35, 45, 50, 55, and 65 kW m^{-2}, directed horizontally. Under each level of incident heat flux, samples were heated for 30 min. In all cases, none of the samples were completely burned after 30 min of heating. To initiate ignition, a pilot flame was applied 10 mm above the center of each specimen, igniting any volatile gases emitted from the surface (Figure 3b) and Figure 3c shows the ignition of the specimen.

Observations were made to record the time needed to achieve a steady flame, using a 5-second criterion to determine sustained ignition. Each species was evaluated using one specimen per heat-flux level, resulting in a total of 15 specimens tested. During the cone calorimeter test, key flammability parameters such as TTI for flaming combustion were recorded, along with HRR and MLR.

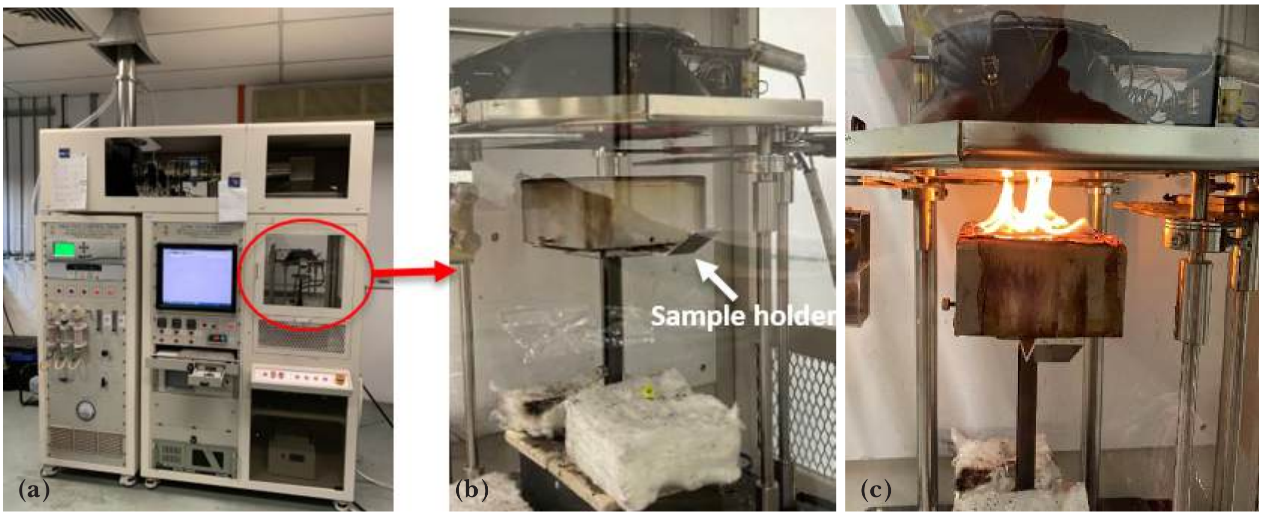


Figure 3 Test set up; (a) cone calorimeter test equipment, (b) sample holder position at 25 mm distant from the cone heater, (c) ignition occurred

RESULTS AND DISCUSSION

During the cone calorimeter tests, the following parameters were recorded: TTI, HRR, MLR. A summary of all test results is presented in Table 1, and the respective discussion is provided in the following sections.

Time to ignition

Time to ignition (TTI) refers to the period of heat exposure required to produce continuous flaming, indicated by smouldering, glowing, or visible flames on the wood sample surface, driven by wood pyrolysis (Dietenberger & Hasburgh 2016). The time was measured from the start of exposure until sustained flaming persists for at least 5 s (ISO 5660). Table 1 lists the ignition times and heat fluxes for various wood species, while Figure 4a shows the relationship between TTI and species. Generally, Light Red Meranti ignites faster, whereas Keranji has a longer ignition time, suggesting that the former timber species is more readily ignitable than Keruing and Keranji under the same heat flux. As heat flux increases, TTI generally decreases, although the Light Red Meranti showed an increase at 50 kW m^{-2} (Figure 4b). Under an exposure to 50 kW m^{-2} heat flux intensity, the Light Red Meranti specimen may have undergone rapid early devolatilisation without immediate ignition due to dilution or dispersion of released gases prior to the establishment of a stable flame, thereby delaying ignition (Di Blasi 2008, Drysdale 2011).

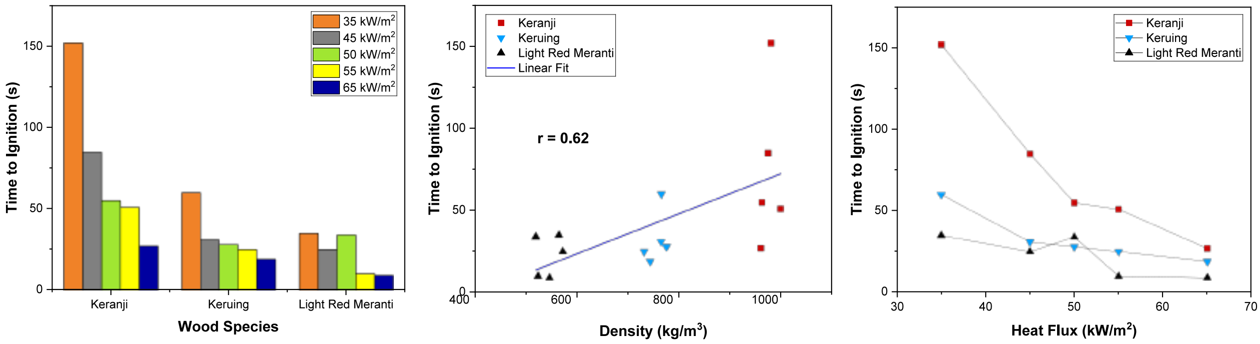
Across all heat fluxes, the TTI values remain below the 5 min limit set by ISO 5660. At 35 kW m^{-2}, Light Red Meranti was the most flammable with a TTI of 35 s, while Keranji was the least flammable with a TTI of 152 s. This trend persists as the heat flux increases even at 65 kW m^{-2}, Keranji maintains a higher ignition resistance (27 s) compared with Keruing (19 s) and Light Red Meranti (9 s).

Figure 4(c) shows the relationship between time to ignition (TTI) and density. Based on the Pearson correlation coefficient (), there is evidence of a relatively strong positive linear correlation between TTI and density. Keranji, which has the highest density, exhibits a TTI of 27 s, whereas Light Red Meranti, with the lowest density, shows a TTI of 9 s at a heat flux of 65 kW m^{-2}. This suggests that higher-density species take longer to ignite. Similar findings have been reported by other researchers (Boonstra et al. 2006, Kim & Kwon 2009, Izran et al. 2010, Seo et al. 2016, Hurley 2016). However, other studies indicated that ignition temperature remains relatively constant regardless of density, with minimal variation in specific heat capacity due to wood density (Nagaoka et al. 1998, Babrauskas 2002, Wen et al. 2018).

Table 1 The combustion properties of different wood species including ingnition time (TTI), peak HRR, average HRR, mass loss (ML) and average MLR

Species		Keranji					Keruing					Light Red Meranti				
Calorimeter heat flux	kW m^{-2}	35	45	50	55	65	35	45	50	55	65	35	45	50	55	65
Density	Kg m^{-3}			975.1 (15.6)[a]					756.1 (18.1)					545.4 (23.6)		
Time to Ignition (TTI)	s	152	85	55	51	27	60	31	28	25	19	35	25	34	10	9
Peak HRR	kW m^{-2}	140.7	137.2	159.7	152.6	178.2	120.7	130.8	140.5	154.7	182.7	104.3	112.6	125.5	132.1	151.6
Time at peak heat release	s	192	125	100	93	75	106	73	60	64	54	71	61	69	45	47
Average HRR in 5 min	kW m^{-2}	83.4	91.3	103.3	102.7	120.9	76.7	86.8	85.6	97.1	110.8	57.6	64.1	72.2	73.4	84.7
Mass loss	g	107.0	125.4	141.2	145.7	159.0	111.4	123.7	140.9	138.4	149.1	71.1	77.9	93.0	89.5	96.9
Average MLR in 5 min	(g s^{-1})	0.075	0.085	0.090	0.095	0.110	0.071	0.083	0.096	0.092	0.105	0.049	0.054	0.066	0.062	0.07

[a] Value in the bracket is standard deviation



(a) (b) (c)

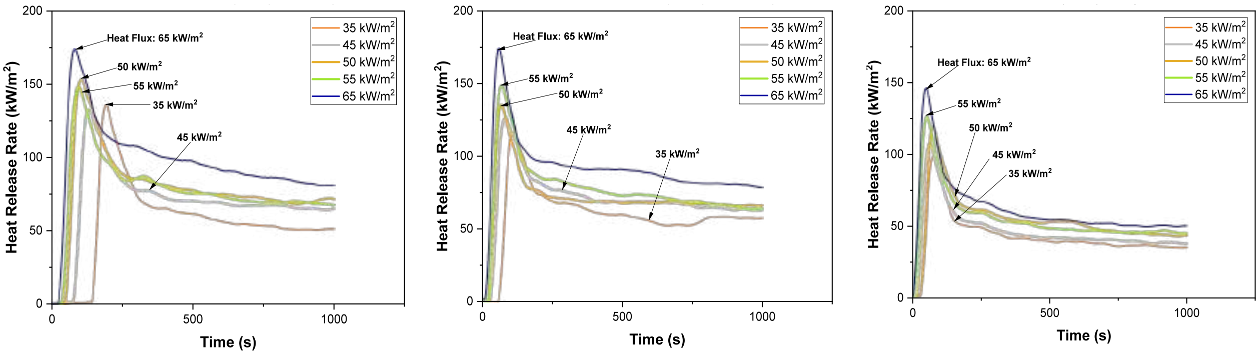
Figure 4 Relationship between time to ignition (TTI) and; (a) wood species, (b) density, (c) heat flux

Heat release rate

The heat release rate (HRR) quantifies how quickly a material emits heat energy when it burns and is essential for understanding fire behaviour and its impact on fire spread (Xu et al. 2015). Figure 5 illustrates the HRR of various wood species subjected to different heat flux levels, with the data obtained from the cone calorimeter data logger. Although the actual exposure time was 1800 s (30 min), the graphs were plotted with limited time to 1000 s to highlight HRR data at earlier exposure times since after 1000 s the graphs remain plateau. All specimens showed similar HRR patterns, with a single peak occurring shortly after ignition.

For thermally thick, charring materials like wood, this single HRR curve pattern is typical. However, two distinct HRR peaks are also commonly observed: the first at the onset of burning, and a secondary peak shortly before flameout. The second peak is generally attributed to cracking or rupture of the char layer, which reduces its insulating effectiveness, hence exposes underlying uncharred material and accelerates heat transfer to the pyrolysis front. This results in a transient increase in the release of combustible volatiles and oxygen consumption (Grexa & Lubke 2001, Chung 2010, Kim et al. 2011).

In cone calorimeter tests, the HRR is directly influenced by the amount of oxygen consumed. For all tested species, the HRR versus time graphs show a sharp increase immediately after ignition, indicating a substantial oxygen intake that results in a peak in HRR. At this peak, smouldering combustion begins, driven largely by the oxidation of residual carbon. Following this initial spike, a char layer gradually forms as the pyrolysis front moves inward. This char layer restricts oxygen and volatile gas exchange, creating a thermal barrier that insulates the pyrolysis zone from the surface. This insulating effect, due to thermal degradation, is essential



(a) (b) (c)

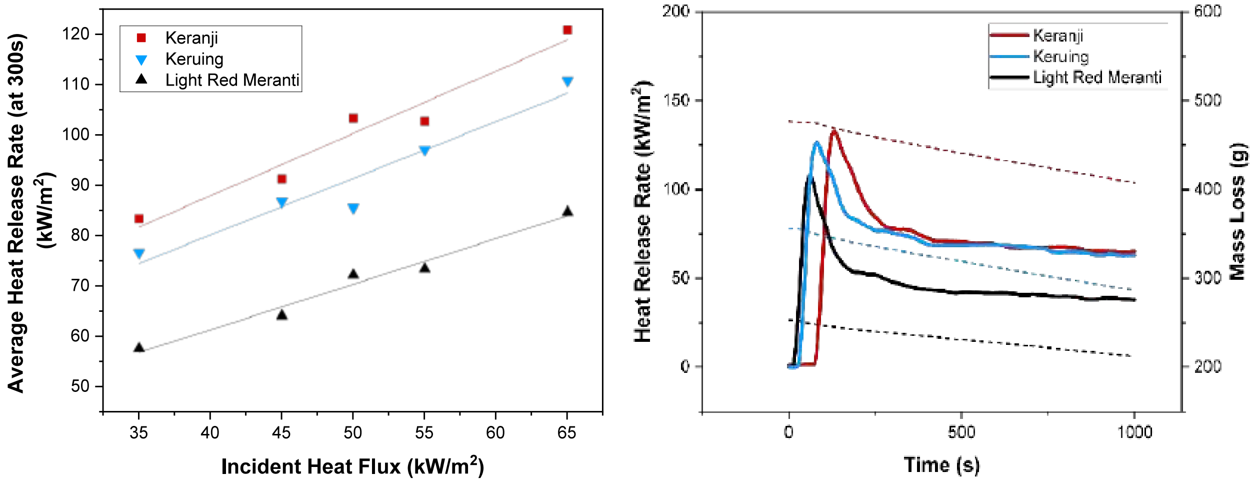
Figure 5 Heat release rate (HRR) behaviour for three tropical hardwood timbers in different heat flux rates; (a) Keranji, (b) Keruing, (c) Light Red Meranti in slowing down the combustion rate (White & Sumathipala 2013). As the char layer thickens, it further isolates the pyrolysis front, causing the HRR to decline, following a roughly negative exponential decay. Once all flammable volatiles have been exhausted and flame combustion ceases, the HRR stabilises at a low, steady level, indicating minimal heat generation and the depletion of combustible material. Across all tested wood species, there is minimal variation in the time taken to reach this steady state, with each species stabilising within approximately 5 min.

Figure 5 shows notable differences in the HRR among various timber species, with Keranji displaying higher peak HRR values compared to Keruing and Light Red Meranti. The peak heat release rate (PHRR) represents a critical parameter that indicates the highest intensity within the HRR curve, serving as an indicator of the material's maximum fire intensity (Li et al. 2015). For each timber species, as the heat flux increases, the PHRR also rises, while the time required to reach the PHRR decreases.

Table 1 shows the average heat release rate (AHRR), determined as the area under the HRR curve over a specific period. The AHRR over the first 5 min after ignition is suggested as an indicator for predicting the time to flashover in an ISO 9705 room corner test (Delichatsios 1999). As heat flux increases, AHRR values range from 83.4–129.9 kW m^{-2} for Keranji, 76.7–110.8 kW m^{-2} for Keruing, and 57.6–84.7 kW m^{-2} for Light Red Meranti. Correspondingly, the time to reach peak HRR (PHRR) shortens across these species, ranging from 192 to 75 s for Keranji, 106 to 54 s for Keruing, and 71 to 47 s for Light Red Meranti. In Figure 6a, AHRR values were plotted against various flux levels, showing a fairly linear trend of AHRR with increasing flux for each timber species. This linearity indicates a predictable relationship between heat flux and average combustion intensity, providing insights into how these materials behave under varying heat exposures.

At a heat flux of 45 kW m^{-2} (Figure 6b), a comparison of the PHRR across different species revealed that Keranji takes longer to reach its PHRR and has a significantly higher PHRR than both Keruing and Light Red Meranti, consistent with its higher density. As anticipated, the total burning duration is also influenced by the sample's mass.

In this study, at a heat flux of 45 kW m^{-2}, Keranji achieved a peak HRR of 137.2 kW m^{-2} at 125 s, while Keruing showed a PHRR of approximately 140.5 kW m^{-2} at 73 s, and Light Red Meranti reached a PHRR of 125.5 kW m^{-2} at 62 s. These observations are consistent with previous research suggesting that denser woods release energy more gradually due to their compact structure, which limits oxygen availability and slows thermal decomposition (Babrauskas 2005).



(a) (b)

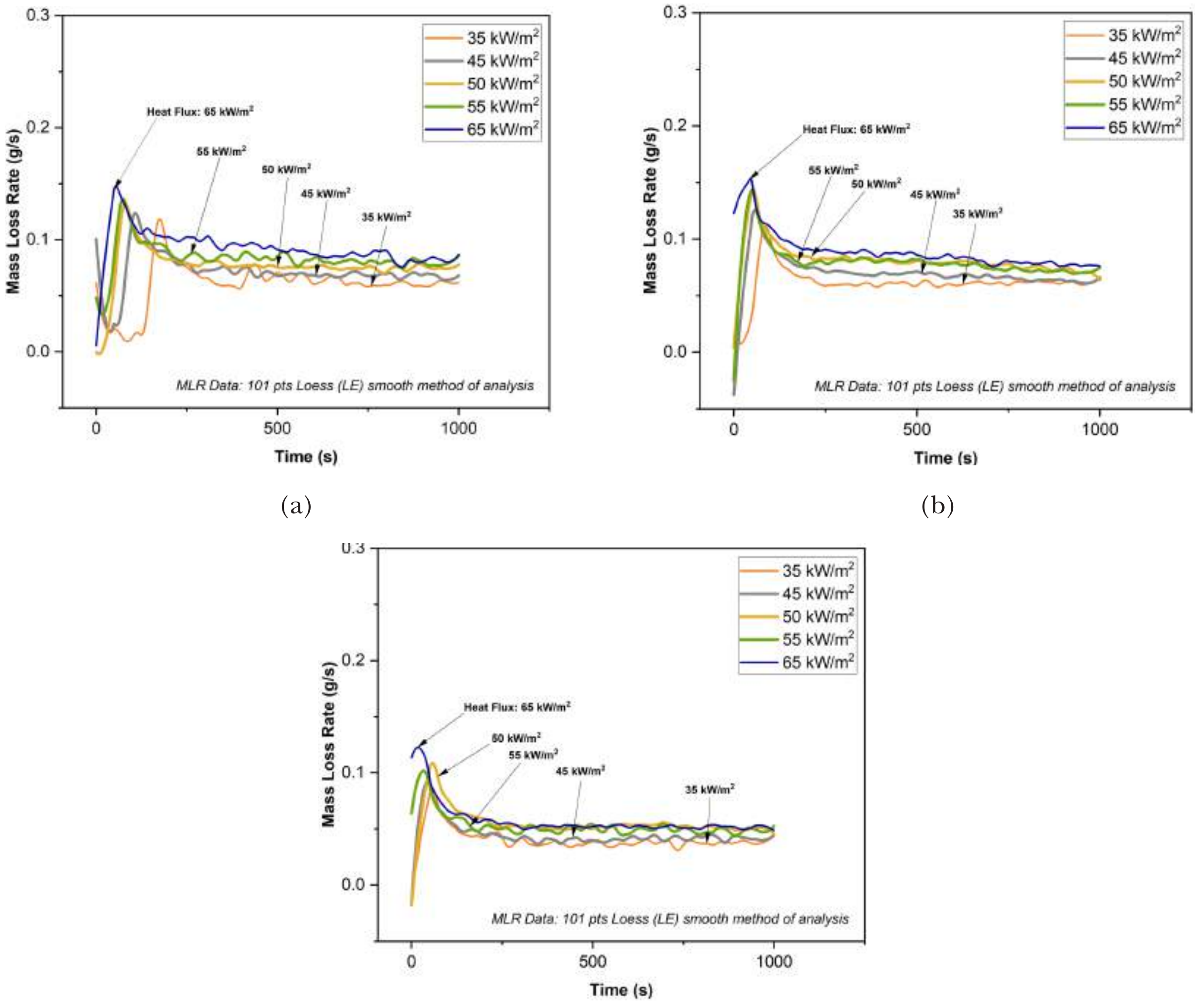
Figure 6 Relationship of; (a) average heat release rate (AHRR) at 300 s versus incident heat flux for all three species, (b) heat release rate and mass loss versus time for all species at 45 kW m^{-2}

Mass loss

When exposed to heat flux, the wood underwent thermal degradation, releasing volatiles and combustible products at concentrations sufficient for ignition. This initiated flaming combustion, which led to a loss of mass. Figure 7 presents the mass loss rate (MLR) for each wood species at various heat flux levels, with the data obtained from the cone calorimeter data logger.

The parameters, such as sample mass loss (g m^{-2}) and average mass loss rate at 5 min (AMLR-300), are presented in Table 1. Those values were calculated based on an exposed surface area of 0.008836 m^2 on a per m^2 basis. Upon ignition, the MLR rises sharply and then gradually decreases to stable values, mirroring the changes in the HRR.

The net mass loss was not zero, as none of the specimens fully disintegrated by the end of the test, as shown in Figure 8. A higher MLR reflects a faster pyrolysis rate, leading to the release of more combustible volatiles and, consequently, greater heat production from their oxidation (Paál et al. 2023). The mass loss of all timber species under various heat flux levels is shown in Table 1. The range of mass loss varied noticeably for each species. Mass loss was shown to be rising in two species, with the greatest mass loss occurring at an inducing heat flux of 65 kW m^{-2}, with Keruing at 42% and Keranji at 33% for mass loss. The average mass loss rate (AMLR) decreases as exposure time increases for each wood species (Figure 9a), while AMLR increases with denser materials as shown in Figure 9b.



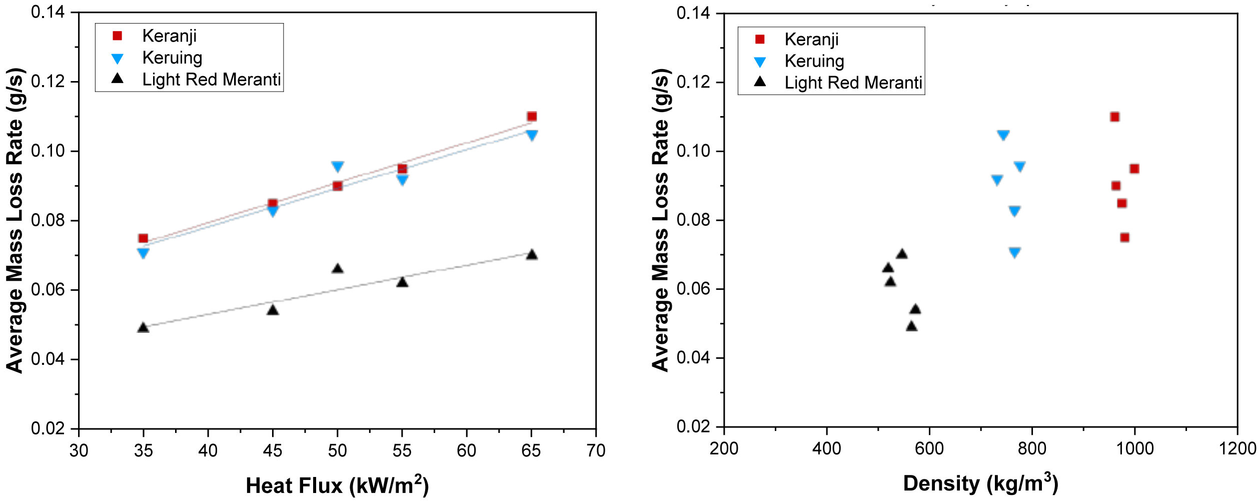
(a) (b)

(c)

Figure 7 Mass loss rate (MLR) behaviour of tropical hardwood solid timbers (a) Keranji, (b) Keruing, and (c) Light Red Meranti in different heat flux rates

(a) (b) (c)

Figure 8 Charred samples after being exposed to 50 kW m^{-2} heat flux; (a) Keranji, (b) Keruing, (c) Light Red Meranti



(a) (b)

Figure 9 Average mass loss rate (at 300 s) for all species versus; (a) heat flux, (b) density

At a heat flux of 50 kW m^{-2}, Keranji exhibits the highest AMLR, while Light Red Meranti shows the lowest, with a notable difference of 36.4%. The AMLR ranges are as follows: 0.075–0.11 g s^{-1} for Keranji, 0.071–0.105 g s^{-1} for Keruing, and 0.049–0.07 g s^{-1} for Light Red Meranti. This study demonstrated that higher density materials char more slowly, as more energy is required to pyrolyse a larger material mass (Figure 6b). However, as shown in Figure 8b, the MLR increases with material density. This suggests that overall pyrolysis accelerates, leading to a greater release of combustible gases (Bartlett et al. 2019), where MLR correlates closely with the HRR, indicating that higher density results in a higher HRR.

CONCLUSIONS

Three wood species (Keranji, Keruing, and Light Red Meranti) were tested in cone calorimeter experiments to evaluate their combustion properties, specifically focusing on TTI, HRR, and mass loss under increasing heat flux (35, 45, 50, 55, 60 kW m^{-2}). The following conclusions are drawn:

1. TTI decreased as heat flux increased. Among the three species, Light Red Meranti had the shortest TTI, while Keranji had the longest. TTI was positively correlated with density.
2. Both the PHRR and the AHRR over the 5 min following ignition, rose with increasing heat flux. Keranji exhibited higher AHRR and PHRR than Keruing, followed by Light Red Meranti. The time to reach PHRR decreased

as heat flux increased, with Keranji taking longer to reach PHRR compared to Keruing and Light Red Meranti.

3. MLR increased with rising heat flux, with Keranji displaying a higher AMLR than Keruing, followed by Light Red Meranti.

Among the three species tested, Light Red Meranti (545.4 kg m^{-3}) demonstrated the greatest resistance to fire, although it has a significantly lower density than that of Keruing (756 kg m^{-3}) and Keranji (975 kg m^{-3}). While Light Red Meranti has shorter TTI values (faster ignition rates) than the other two species, it has lower HRR and MLR, reducing the pyrolysis rate and making it less prone to rapid mass loss. This result may be due to the chemical composition of the species, where species with higher lignin content may contribute to greater fire resistance. The correlation between fire performance and chemical composition raises safety concerns as well (Hao et al. 2020). Consequently, Light Red Meranti's criteria in reaction to fire properties contribute to its suitability for applications where enhanced fire resistance is required.

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