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RESEARCH NOTE

Fire Resistance Properties of Low-density *Neolamarckia cadamba* (Roxb.) Bosser Timber

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The inherent flammability of timber rises the concern of society about the stability and firmness of timber materials when exposed to fire. This study illustrated the fire resistance properties of low-density *Neolamarckia cadamba* timber to evaluate its charred area (CA), charred depth (CD), mass loss rate (MLR), and charring rate (CR). Three different burning durations – 60, 90, and 120 min – were subjected to the timber test pieces following the NIST PS1-09 2010 standard. The CA and CD of the test pieces were measured using ImageJ before the determination of MLR and CR. *N. cadamba* showed a statistically significant difference on the top CA (14040.56 mm^2) at 90 min compared to its side CA (1957.93 mm^2). CD remained statistically unchanged for three burning durations. Top CA increased gradually with burning durations. Side CA and CD, however, were reduced to 1957.93 and 17.84 mm^2, respectively, for 90 min, before being increased back to 120 min. For CR and MLR, a gradual dropped in trend can be seen in the burning durations. Significant differences were detected when comparing the CR (0.30 mm/min) at 60 min with that in 90 min (0.20 mm/min), whereas the MLR was 2.15 g/m^{2}s at 60 min with 1.42 g/m^{2}s at 120 min. Generally, top CA, side CA, and CD showed an increased trend in the area and depth value. whereas CR and MLR showed the opposite.

Keywords: CA, CD, CR, fire resistance, MLR

Timber is a sustainable, stiff, and aesthetically pleasing material. However, its utilization to become building materials was deemed to put the civil engineering work at risk of burning because timber is ignitable and combustible.

Contrary to the apprehension from many people, the timber used for construction purposes can perform very well under fire hazards. Formation of the char layer protected the timber material from further decomposing by removing the water vapor, oxygen, and hydrogen from its matrix and effectively prevented further spreading of the flame as well as lowering the thermal conductivity of the fire-exposed area. According to Schaffer (1980), the char is formed when timber is exposed to fire and combustible volatiles below the timber surface thus providing fuel for continuation in combustion. The growth of flame and heat conductivity decreases when the liberation of volatile is reduced until the flame extinguished itself. With the protection from the char, the integrity and stiffness of the material or construction can be maintained under near-ambient temperatures over a long duration of fire exposures (Havel 2016). Therefore, in this study, the fire resistance test on low-density *N. cadamba* timber was evaluated at different burning durations – 60, 90, and 120 min – for its charred area (CA), charred depth (CD), mass loss rate (MLR), and charring rate (CR). *N. cadamba* is categorized under low-density timber with a density of around 290–465 kg/m^3. It is from the family of Rubiaceae and is enlisted as one of the key species under Malaysia's Forest Plantation Programme. The local name

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is *laran* with trading names such as *jabon*, *kadam*, and *kalempayan* (Useful Tropical Plats Database 2019). This fast-growing tree is able to grow up to 40–45 m tall with a trunk diameter ranging from 100–160 cm and is able to grow well in regions with rainfall of around 1600 mm or more (Joker 2000). Commercially, it is felled around the age of 10–15 yr and used in making plywood, picture frame, boxes, or pulp and paper (Patel and Kumar 2008).

N. cadamba timber laminas with dimensions of 200 mm (length) x 50 mm (width) x 20 mm (thickness) were prepared and supplied by Sapulut Forest Development Sdn. Bhd. Three pieces of timber laminas were glued together side-by-side using 400 g/m^2 polyvinyl acetate and clamped for 24 h. Test pieces were prepared at 200 mm (length) x 150 mm (width) x 20 mm (thickness) for burning durations of 60, 90, and 120 min. Each duration had three replicates.

The apparatus setup for the fire resistance test was done according to the National Institute of Standards and Technology standard (NIST PS1-09 2010), as in Figure 1. Type-K thermocouple was used to ensure the flame temperature and maintained in the range of 800–900 °C. After the fire resistance test, the test pieces were sawn along the middle of the test piece in half before the images were taken for all the burning durations. Images were processed by converting into an 8-bit color threshold to increase visibility and determined the CA (mm^2) and CD (mm) using the ROI manager available in ImageJ V1.8.0 software. MLR and CR were calculated using Equations 1 and 2, respectively (Emberly 2017).

$$MLR\ (g/m^2 s) = \frac{(m_i - m_f)}{tA} \qquad (1)$$

where:

MLR	=	MLR
m_i	=	initial mass of test piece
m_f	=	final mass of test piece
t	=	time for fire exposure
A	=	exposed surface area

$$\beta_0\ (mm/min) = \frac{d_{char}}{t} \qquad (2)$$

where:

β_0	=	CR
d_{char}	=	CD
t	=	time for fire exposure

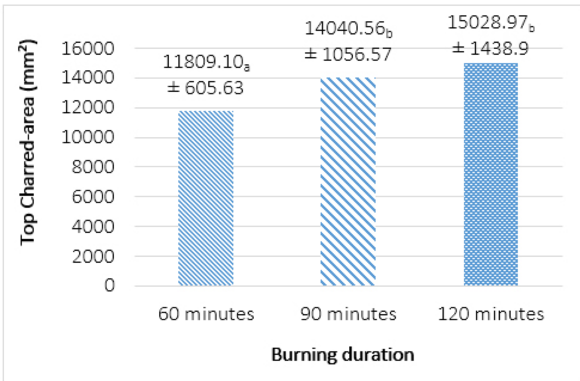
Data gathered were statistically analyzed using a one-way analysis of variance and the least significant difference *post hoc* test at $p \leq 0.05$.

Figure 1. Fire testing setup with the height of flame maintained in the range of 25.4–38.1 mm.

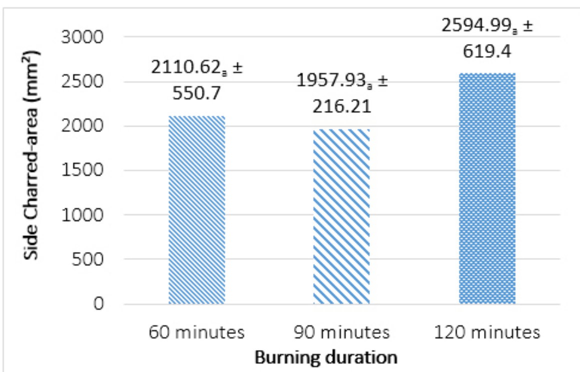
The fire resistance properties of the low-density *N. cadamba* timber were presented as CA, CD, MLR, and CR. The moisture content and density of the test pieces were obtained experimentally at 12.81 ± 0.38 % and 351.11 ± 35.60 kg/m^3, respectively, from the average value of nine replicate test pieces. The effect of different burning durations on the top CA, Side CA, CD, MLR, and CR of *N. cadamba* was shown in Figures 2a–e, respectively.

In Figure 2a, top CA increased in area as the burning duration proceeded longer can be observed, with the lowest value at 60 min (11809.10 mm^2) and the largest at 120 min (15028.97 mm^2). Meanwhile, in Figure 2b for side CA, the burning duration of 90 min had the lowest value (1957.93 mm^2) but had the highest value at 120 min (2594.99 mm^2). Figure 3 shows the top CA and side CA for the *N. cadamba* test pieces.

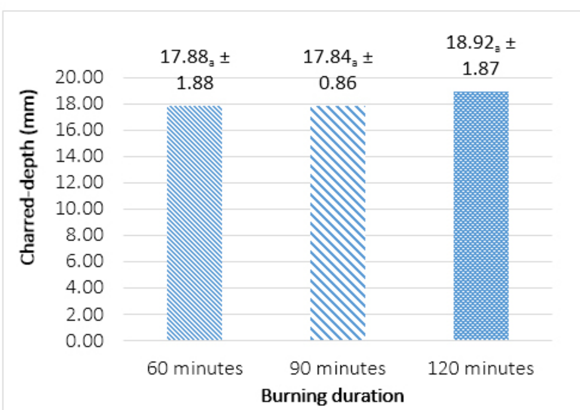
Emberly (2017) said that the thermal deterioration of wood is highly dependent on the chemical composition of the wood itself. Wood species with high content of lignin will have high resistance toward thermal degradation, as lignin



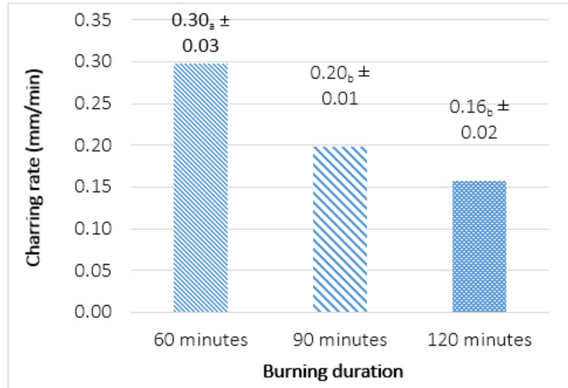
(a)



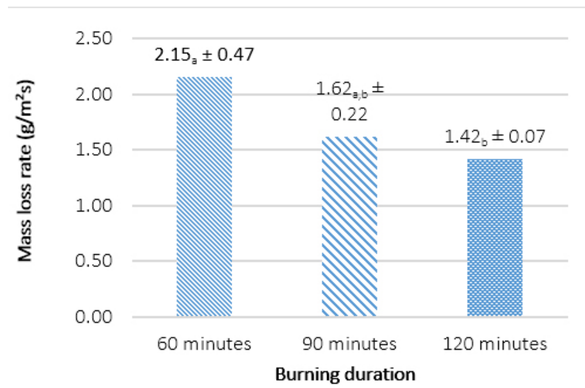
(b)



(c)



(d)



(e)

Figure 2. The mean values and standard deviations (±) for *N. cadamba* at different burning durations (60, 90, and 120 min): [a] top CA, [b] side CA, [c] CD, [d] CR, and [e] MLR. Subscript alphabets (a and b) beside the mean values show that the different alphabets indicate statistical difference among the burning durations for each test at $p \leq 0.05$ least significant difference.

will act as a barrier to defend the fire from penetrating and its decomposition temperature is very high, which is above 320 °C until 500 °C. Its high molecular weight and strong chemical linkage produced strong thermal resistance properties. Higher temperature breaks its glycosidic linkages to form lighter and smaller molecules (Wretborn 2016).

According to Bartlett *et al.* (2018), the burning behavior of the wood depends on moisture transport. When wood is exposed to heat, the moisture at the fire-exposed site will be evaporated as free water, whereas some of the water vapor will migrate into the deeper side of the wood matrix and be re-condensed. The re-condensed moisture will rise the local moisture content of the wood. Three different zones – which are the pyrolysis, dehydration, and wet zones – will be formed. The lower accumulated heat energy at the initial stage of burning will cause pyrolysis and dehydration to occur independently. The condensed moisture stored in the wet zone will cause the mid-burning stage to become weaker and further absorption of heat energy from the heating source will reinstate the burning performance. High accumulation of heat energy at the final stage of burning causes pyrolysis and moisture evaporation to occur simultaneously and eventually increase the thermal degradation of the wood.

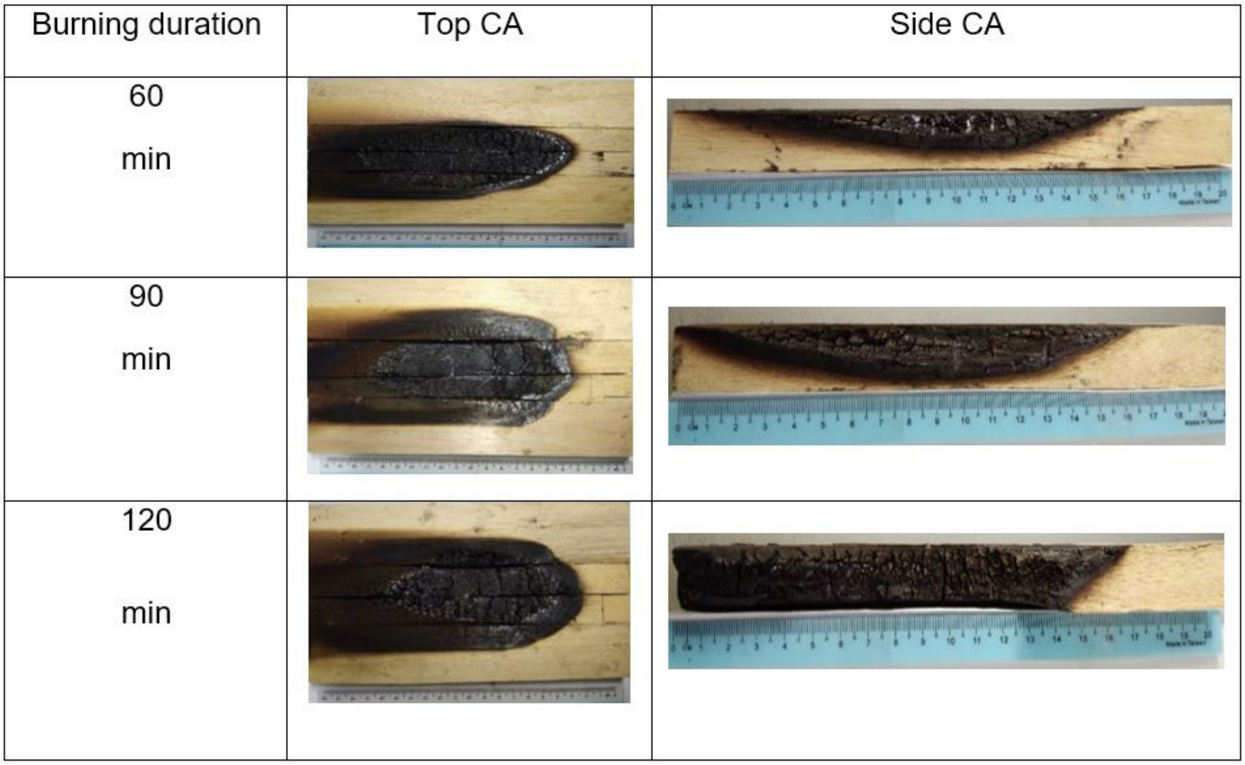


Figure 3. The top CA and side CA of the *N. cadamba* test pieces at three different burning durations.

Figure 2c shows that the burning duration of 120 min had the deepest CD (18.92 mm), whereas the 90 min had the shallowest (17.84 mm). Charred -depth is a revealer of the burning performance of the fire, which makes it have a close correlation with the factors that influence fire development. The factors that affect the growth of fire include the wood species, moisture content, duration of heating, ventilation effects, and nature of the surface coating. Su *et al.* (2018) found that the extent of CD does not have a significant correlation with the density. The thermal conductivity of low-density wood is weak as the presence of vast porous spaces in the wood matrix. Thus, localized heating and heat accumulation will be produced and rises the rate of flame spreading. However, an increase in the density of wood did not have a positive impact on the combustion efficiency because the dense structure had a prohibited effect against thermal degradation. The wood with higher density will make the fire difficult to penetrate due to the greater mass of material that needs to be pyrolyzed and more heat energy was required for the endothermic process (Bartlett *et al.* 2018). According to Shen *et al.* (2007), the moisture content is also a key factor that influenced the CD. Free water and bound water were the existing forms of moisture in the wood. Free water was a type of moisture that can be mainly found in the void of wood and it can be evaporated at the temperature of 100 °C, whereas bound water was required a higher temperature to be evaporated, as it was bonded to the hydroxyl group present inside the cell wall. The wood with high moisture content will have a high fiber saturation point, and the excess moisture diffused into the wood and raised the internal moisture content of the wood. The high moisture content retarded the heat spreading and diffusion. This would delay the rise of temperature on the wood and more heat energy was needed to be consumed to vaporize the water.

In Figure 2d, the trend of CR decreases with the rising in burning duration has shown. The burning duration of 60 min achieved the highest rate of charring (0.30 mm/min), whereas 120 min had the lowest (0.16 mm/min). The unsuccessful formation of the char layer during the initial burning period caused the CR to become higher (Fong 2019). CR decreases with the rising density. Low permeability level is the effect of high density. Permeability controls the rate of moisture evaporation and pressure gradient. The highly permeable wood will have a low-pressure gradient, which allows the rapid loss of moisture and thus increase the CR (Collier 1992). Increased CR after ignition caused the rate of heat release to decrease as the char layer formed on the fire-exposed site reduce the thermal conductivity between the exposed site and the pyrolysis zone. Smoldering combustion might occur when the char layer has formed on the fire-exposed site, as char prevent the emission of volatile gases and, thus, stable flaming combustion (Inghelbrecht 2014). The insulating temperature on the core of the test piece was risen due to the formation of a thicker char layer when the wood structure had exposed to the high external heat (Fonseca and Barreira 2009). According to Fong (2019), the regression away of the heated surface from the external fire flux greatly affected the CR. Continuously exposing the wood to the flame caused the wood to degrade and decompose into a char. The decay char layer will increase the distance between the heat flux and the exposed surface of test pieces and, thus, reduce the thermal conductivity to the unburned area. CR also depends on the rate of heat transfer and thermal diffusivity. Transferring of heat energy in the wood can be achieved by surface transferring, internal convection, and conduction to the interior. The radius of the unreacted core and temperature gradient ensures thermal diffusivity. Gross heat transferring and retaining increase the rate of pyrolysis and, thus, the CR (Sinha *et al.* 2000).

Figure 2e shows the result of the MLR. A critical MLR (2.15 g/m^2s) was achieved on the burning duration of 60 min, whereas the 120 min had the lowest rate (1.42 g/m^2s). As the wood had exposed to external heat flux, its mass was reduced due to the production of pyrolysis and energy conversion into the form of pyrolysis gases and char (Awad 2020). Peak mass loss occurred in the transient state after ignition as the test pieces lack of the protection of thermal degradation from the char layer that protected the unburned test pieces from the external heat flux. The temperature gradient inside the wood matrix will rise when the wood has been exposed to external heat energy over a long period (Inghelbrecht 2014). This will make a small zone on the fire-exposed site have a relatively high temperature. To heat the whole wood, more pyrolysis heat is needed and, consequently, the MLR in the transient state is found to be higher. The excessive heat energy that assimilated in the transient state accelerated the thermal degradation and contributed to the high mass loss value. The peak in the transient state can be explained as the wood had become dehydrated in high temperatures and diffusing ambient air into the porous char residue. Dehydration and carbon monoxide formation rose the pyrolysis reaction and degree of depolymerization of chemical components present in the wood (White and Dietenberger 2010). After the initial higher CR, the MLR tends to be in a fairly constant state. This is due to the formation of the char layer as an insulator and prevents the test pieces from further degradation. According to Emberly (2017), transferring heat energy is only through conduction from the fire-exposed site to the other unburned site before the char layer has formed. The situation changed once the char formed as the char act as a regulator which moderates the spreading of energy and lowers the rate of mass loss in the steady state.

Increasing the burning duration influenced the fire resistance properties of the *N. cadamba*. The top CA increased with the rising burning duration. Significant expansion of the top CA occurred in the 90 min and remained no significant different until 120 min. The largest top CA was observed on the burning duration of 120 min, but the smallest top CA was on 60 min.

There was no significant difference for the side CA across three burning durations. The side CA was reduced from 60 to 90 min but rose back to 120 min.

As for CD of 60 min to 120 min, a significant difference was not detected in the rising of CD, although it had increased numerically. A burning duration of 120 min had achieved the deepest CD, but 90 min had the shallowest.

The CR of the *N. cadamba* test pieces in this study were decreasing with the rising burning duration. A burning duration of 60 min had the highest CR, but 120 min had the lowest. The CR also decreases but started to remain consistent when going from 90 to 120 min but not significantly different. *N. cadamba* test pieces achieved the requirement in Eurocode 5, which stated that the solid or glue-laminated hardwood with a density of more than 290 kg/m^3 had a CR lower than 0.65 mm/min.

The MLR also decreases with the rising in burning duration. Significant differences occurred when comparing the MLR at 60 and 120 min. The highest MLR was achieved on the burning duration of 60 min, whereas the lowest MLR was on 120 min. The rate in the transient state is significantly higher than the average steady state. This is due to the formation of a char layer in the steady state of burning, which acts as an insulator and protector to prevent the wood from further thermal degradation.

With the overall results in hand, it can be generalized that *N. cadamba* timber material is potentially usable in fire resistance for up to 120 min, which is a requirement for fire-rating products such as fire doors in Malaysia.

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