Properties of Tropically Sourced Timber

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Properties of tropically sourced timber subjected to elevated temperature

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Abstract. Char layer is an important parameter for the fire-resistance design of timber. The char-layer insulates the inner layer (core) from high temperature to prevent further damage due to fire. This paper assesses the post-fire properties of tropical solid and laminated timber originating from Indonesia. The species are white teak, bayur, rajumas, and sengon. The timber was exposed to fire at time interval of 30, 45, and 60 min. The temperature growth was set according to ISO 834 standard heating curve. The result shows that the average of charring rate of species with greater density and longer time of exposure is smaller than that of species with smaller density and shorter time of exposure. The charring rate of tropical solid and glulam timber has a linear inverse relationship to the density at each time of exposure. The average experimental data linear regression suggests that tropically sourced timber with a density of more than 400 kg/m^3 meets the charring rate of European standard. However, all experimental results agree with the Australian standard. Furthermore, according to post-fire mechanical properties examination, the solid timber core shows increased strength after fire; meanwhile, a strength decrease exists in glulam core.

1. Introduction

Wood is one of the preferred construction materials because of the advantages offered such as high stiffness and strength-to-weight ratio, eye-pleasing, and renewable resources, relatively compared to other construction materials. Therefore, the tendency of using wood has been continuing to increase, both for structural and industrial purposes [1–4]. However, due to the natural substance, several challenges must be considered in wood application especially the behavior of being exposed to elevated temperature. Wood is a combustible material consisting of cellulose, lignin, and hemicellulose. The basic form of those compositions is carbon, hydrogen, and oxygen which are combustible when there is room temperature increase excessively [5–9].

When the temperature rises and starts from 150 °C, the surface of the wood structures will experience a degradation thermal process (pyrolysis). As the temperature increases, the outside part of wood decomposes into a char layer. The char layer does not have any strength or stiffness, but it acts as an insulating material to inhibit further degradation to the inner layer (core). The char-layer insulates the core from high temperature to prevent further damage due to fire. Char-line is a boundary between pyrolysis, the thermal degradation of wood, and the actual char. This interface is generally characterized by a temperature of 300 °C [10]. The depth of charring is measured from the outer surface of the undamaged cross-section to the char-line position. The growth of charring depth during a fire is called the charring rate. Within fire safety design, the charring rate is the significant factor for calculating the remaining strength of the core, that is an intact cross-section of the timber [11, 12]. Some methods have been established to calculate the residual strength of timber to sustain load continuously after a fire. The concept of calculation is based on a reduction in the cross-sectional area in which the char layer has no strength

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[10, 13–15]. The thickness of the char depends on wood species, density, moisture, permeability, composition, or direction of fire [11]. Char layer of wood species from the tropical country is discussed in this paper. Studies on solid and lamination timber with species which widely used in many western countries have been conducted by many researchers [6, 11, 16–21]. Char-layer thickness of pine wood, which is commonly used for construction in Portugal has been determined. It is found that after 30 minutes exposed to high temperature, char thickness of 1 cm existed on the top surface of specimens. For this position, the temperature was investigated around 250-300 °C [11]. In addition, a study on the mechanical properties of Parica wood from the cultivated forest in Brazil was conducted. At the highest temperature level (230 °C) caused a decrease of 35 % of the compression strength at ambient temperature and a decrease in the strain as well. The exposure of the specimens to high temperatures resulted in changes in the wood color, internal and externally, which were more pronounced at temperatures above 150 °C [18]. Furthermore, the charring rate of seven species of tropical wood has been examined under fire by [17]. The species are azobe (*lophira alata*), afzelia (*afzelia bipindensis*), balau (*shorea spp.*), bilinga (*nauclea diderrichi*), meranti (*shorea rubro*), merbau (*intsia*), and wenge (*millettia laurentti*). The woods are the type of hardwood which frequently being used in construction. The density of wood determines the behavior during the fire and the new model of charring is proposed. The charring rate model of tropical woods are compared to various standards such as EC5, however, the standards are not entirely satisfactory the tropical wood charring rates. Due to the limited study provided on the charring rate of tropical hardwood species, therefore, more research on the tropical wood charring rate is on demand.

There are various species of tropical wood. Indonesia has a forest potential of around 4,000 types of wood. Among them have been widely studied. The physical and mechanical properties of 15 tropical wood species that were commonly used in Indonesia have been reported [22]. The wood ranging from softwood to hardwood. The hardwood is widely used in construction meanwhile softwood to be used in structural should be associated with hardwood in form of glued-laminated timber (glulam). One of the research on the properties of tropical glulam wood at ambient temperature has been conducted by [23]. However, there is limited research is available on the tropical wood species of solid and glulam timber at high temperature and the charring rate is not covered yet in the Indonesian national code for timber structures design [24]. Therefore, the properties of solid and glulam produced from some local woods after a fire are discussed in this paper.

2. *Methods*

2.1. Charring Rate Determination

A national code for wood structures must consider the fire resistance required for a structure when a fire occurs, both in the form of a protective material (insulation) and in the analysis of dimensions. Fire resistance in wood is based on standard fire test procedures and allows identifying the amount of time for the structure to carry enough load [13]. Eurocode 5 provides notional charring rates for multi-face exposure of solid and glulam hardwood which are 0.7 and 0.55 for the density of 290 kg/m^3 and 450 kg/m^3 respectively. In addition, the code sets a linear interpolation that may be used to obtain the charring rates of solid hardwoods for densities between 290 and 450 kg/m^3 [14].

Similar to Eurocode 5, the Australian standard gives a charring rate of woods which depends on the density. The relationship between the density and charring rate as given by Eq. 1.

$$\beta = 0.4 + \left(\frac{280}{\rho}\right)^2, \quad (1)$$

where β is the charring rate of wood (mm/min) and ρ the density of the wood (kg/m^3) [25].

Another standard provides a charring rate based on the timber type and species. British standard (BS 5268) states that the value of the notional charring rate for hardwood is 0.5. Meanwhile according to Forest Research Institute Malaysia, Malaysian tropical wood of balau and merbau possess a charring rate of 0.3 and 0.33 respectively [17]. In this paper, the charring rate of some tropical solid and glulam timber is calculated based on the depth of charring and the time of exposure experimentally.

2.2. Materials

The main materials used in this research were tropical woods obtained from the area of West Nusa Tenggara Region-Indonesia that has just been cut down and free from defects. The species are commonly found as well in South-East Asia Region and India. Solid and glulam timber were used in this study. Species of hardwood, which were white teak wood, bayur, and rajumas are the types of wood that are often used by the community in the form of a solid structure [22] and these solid woods were used in the previous study of pyrolysis and charring depth [26, 27]. Meanwhile, sengon is a softwood that is often used as the inner lamina in glulam timber [23]. Therefore, white teak wood, bayur, rajumas, and sengon were considered as the specimens in the form of solid and glued laminated timber. The average physical properties and mechanical properties of these materials are shown in Table 2. The properties of the wood presented in Table 1 are obtained experimentally according to Indonesian National Code for timber structures [24] and were measured at 12–15 % moisture content.

The mechanical properties of the woods indicate that the quality of the woods between *E15-E26*, according to National Standard [24]; therefore, these local woods are considered to be strong and stiff to be utilized as building structural materials. The average density of white teak wood: 0.462, bayur: 0.407, rajumas: 0.381. This indicates that these woods are included in the category of wood with moderate weight because of the specific gravity of the wood in the ranges from 0.36 to 0.56. Meanwhile, sengon is recognized as softwood with an average density of 0.282.

Table 1. The average of physical and mechanical properties of wood.

Species	Specific gravity	Compressive strength (MPa)	Tensile strength (MPa)	Shear strength (MPa)	Bending strength (MPa)
White Teak (*Gmelina arborea*)	0.462	28.3	65.51	5.53	53.19
Bayur (*Pterospermum*	0.407	39.25	41.54	5.47	56.76
Rajumas (*Duabanga mollucana*)	0.381	32.53	53.95	4.46	48.92
Sengon (*Paraserianthes falcataria*)	0.282	23.86	26.2	5.27	37.34

The size of the specimens for high temperatures was 80 mm by 120 mm by 500 mm in thickness, width, and length, respectively [11]. Solid timber was produced from hardwood (*S-1*: white teak wood, *S-2*: bayur, and *S-3*: rajumas). Meanwhile, the glulam timber consisted of sengon as the core lamina and the face laminas were the hardwoods. All laminas were constructed with parallel fiber orientation. Laminas with a thickness of 40 mm were used for three-layer construction (*G-1*: white teak-sengon-white teak; and *G-2*: rajumas-sengon-rajumas). The number of specimens was three pieces for each variation of solid and glulam timber. The cross-section of the specimen can be seen in Fig. 1. The adhesive was applied to bond the laminas according to the technical standards specified by the manufacturer. The cold press was applied for 24 hours at 1 N/mm^2 pressure, followed by conditioning for 1 week and finishing. The average specific gravity of *G-1* and *G-2* was 0.401 and 0.357 respectively. The average of shear strength and modulus of rupture (*MoR*) of glulam is presented in Table 2.

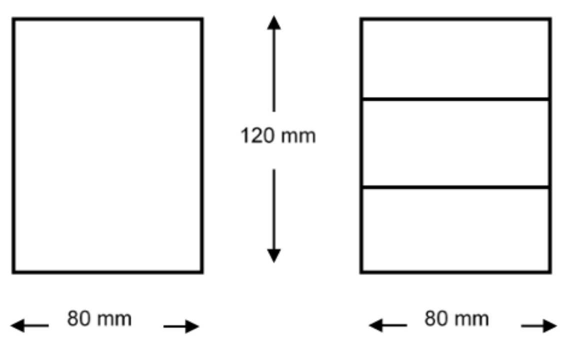

Figure 1. Solid and glulam cross section.

Table 2. The average of mechanical properties of glulam timber.

Glulam specimen	Shear strength (MPa)	*MoR* (MPa)
G-1	5.38	26.39
G-2	5.37	25.98

2.3. Fire Experiments

The heating periods were in the interval of 30, 45, and 60 min. The temperature growth is according to standard furnace test which is regulated on an international basis by ISO 834 [14]. The temperature-time relationship given in Eq. 2 and Fig. 2. The standard curve gives temperatures of 842 °C at 30 min, 902 °C at 45 min, and 945 °C at 60 min and 1049 °C at 120 min.

$$T = 345\log(8t+1) + 20, \qquad (2)$$

where T is temperature (°C) and t is time period of fire (minute).

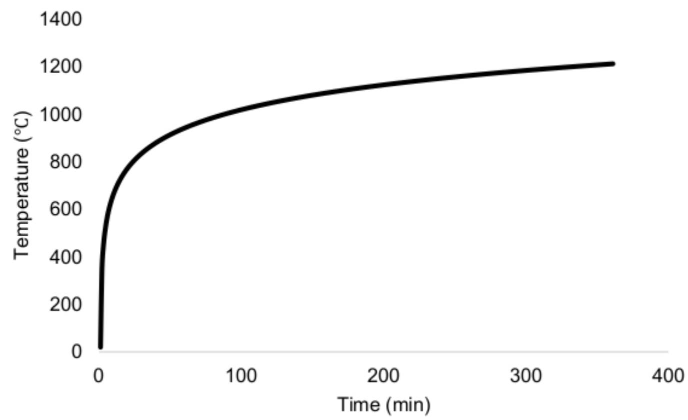

Figure 2. Temperature growth curve according to ISO 834 [14].

Fig. 3 shows the experimental fire test set up in the laboratory. The furnace is equipped by four burners, however, to meet the temperature growth required by the code, only two burners have been set up. The positioning of the wood in the furnace allowed the wood surface exposed to fire in the lateral direction. During the fire, the furnace was locked and two thermocouples were attached to control the temperature inside the furnace. After being exposed to elevated temperature, the depth of char layer and pyrolysis zone was investigated in five different points of the specimens by cutting the cross-section of the timber at 1 cm, 2 cm, 3 cm, 5 cm, and 25 cm apart from the top surface of the specimen as shown in Fig. 4 [11]. To determine the residual strength, the char layer was removed. The intact cross-section was then set for mechanical properties examination.

Figure 3. Fire test set up.

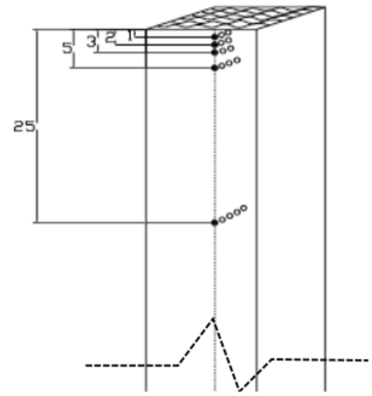

Figure 4. Char position observation [11].

3. Result and Discussion

3.1. Depth of charring

During the fire test, the solid and glulam timbers were exposed from lateral sides. The heating temperature inside the furnace reached 900 °C, 970 °C, and 1000 °C after 30 min, 45 min, and 60 min respectively. The maximum temperature on each heating was higher the those of the standard. The maximum temperature ratio between the experimental and the standard was 1.07, 1.07, and 1.06 respectively for 30 min, 45 min, and 60 min period of exposure.

To examine the depth of char, the timber was cooled to room temperatures naturally. Calculation of the charcoal depth was done by measuring the average thickness of the char laterally from each side. The cross-section that closer to the top surface of the specimen and with longer time interval of exposure experiences thicker char layer as shown in Table 3 and Fig. 5.

Table 3. Average depth of charring.

Species	Time (min)	Distance from top surface (mm)				
		10	20	30	50	250
	30	6.33	0.00	0.00	0.00	0.00
S-1	45	12.24	5.90	0.00	0.00	0.00
	60	21.30	10.08	7.50	6.96	6.36
	30	9.51	0.00	0.00	0.00	0.00
S-2	45	19.13	13.23	5.74	0.00	0.00
	60	35.88	22.41	16.08	16.62	10.01
	30	11.25	6.51	0.00	0.00	0.00
S-3	45	23.72	14.80	11.52	10.67	0.00
	60	40.56	24.88	16.49	14.84	11.86
	30	8.01	7.77	7.23	5.76	4.69
G-1	45	16.79	14.19	9.45	9.05	8.24
	60	28.50	26.46	35.45	28.49	22.11
	30	14.19	12.69	8.16	7.68	6.64
G-2	45	29.16	24.84	19.76	15.28	13.43
	60	47.52	42.69	38.28	31.92	28.86

Figure 5. Charring depth at some positions.

In general, the char thickness increases due to increased fire exposure time. Less char thickness is observed in solid wood than glulam wood. White teak wood (*S-1*) does not show a significant char layer after 30 min exposure, even after exposure of 45 min, the char-layer is at the position of 10 and 20 mm from the top surface. Similar to *S-1*, bayur (*S-2*) shows a char layer only at a position nearby top surface after 30 min exposure, and no char-layer is found anymore beyond the position. And from 45 to 60 minutes of exposure, the char-layer is found until the position of 20 mm and 250 mm respectively from the top surface. For species *S-3*, char begins to exist at 30 min of fire and continued until the distance of 20 mm from the top, and it becomes thicker until exposure time of 45 and 60 min, where char is found up to position of 50 and 250 mm from the top surface.

Charcoal formation behavior in glulam is more severe compared to solid wood. *G-1* glulam wood shows a thinner char-layer than *G-2* because the resistance behavior to fire of white teak is better than rajumas wood. Even the *G-2* glulam char has covered all wood surfaces after the time of 45 minutes. The surface area of the total cross-section turns into char was found up to a position of 20 mm from the top surface.

3.2. Charring rate

Calculation of the charring rate is evaluated at the position of 10 mm from the top because this condition generates the worst effect of fire. Table 4 shows the charring depth and charring rate of the species along with the density. In general, both for solid and glulam timber, the greater density shows lower charring depth and charring rate as suggested by many studies [10, 17, 25]. For solid timber, white teak has the greatest density presents the lowest charring rate. Meanwhile, glulam timber with density bigger than 400 kg/m^3 show smaller charring rate than the glulam with a density of less than 400 kg/m^3.

Table 4. Charring rate.

Spesies	Density (kg/m^3)	Fire exposure Time (min)	Average char depth (mm)	Char rate (mm/min)
		30	6.33	0.211
S-1	462	45	12.24	0.272
		60	21.30	0.355
		30	9.51	0.317
S-2	407	45	19.13	0.425
		60	35.88	0.598
		30	11.25	0.375
S-3	381	45	23.72	0.527
		60	40.56	0.676
		30	8.01	0.267
G-1	401	45	16.79	0.373
		60	28.50	0.475
		30	14.19	0.473
G-2	357	45	29.16	0.648
		60	47.52	0.792

Fig. 6 reveals that the development of char is almost constant from the initial (30 min) to final (60 min) heating time found in the species with greater density (solid wood: *S-1* and *S-2*). Conversely, for the species with lower density (solid wood: *S-1* and glulam wood: *G-1* and *G-2*), the charring rate at the heating time of 45 min to 60 min develops faster than those charring rate at the heating time of 30 min to 45 min. The wood density not only determines the value of the charring rate but also influences the development of the charring rate itself over the fire exposure time. This finding agrees with [25], where the charring rate after a fire exposure of 60 min is greater than that after a fire exposure of 45 min due to increasing temperature inside the wood.

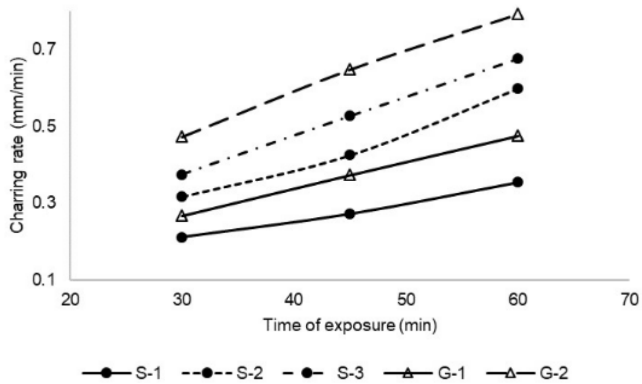

Figure 6. Development of charring rate.

In addition, the result shows that the average of charring rate of species with greater density and longer time of exposure, is smaller than that of species with smaller density and shorter time of exposure, for example species *S-1* with a density of 462 kg/m^3 and exposure time of 60 min has a charring rate of 0.355 compared to species *S-3* with a density of 381 kg/m^3 and exposure time of 30 min shows a charring rate of 0.375. Wood with a density greater than 400 kg/m^3 has more fire resistance over the fire exposure time. After a fire exposure of 60 min, the charring rate of solid and glulam timber has the inverse order to the density. The charring rate order of solid wood: *S-1* < *S-2* < *S-3* and the density order: *S-1* > *S-2* > *S-3*. Similarly, for glulam timber, the order of charring rate: *G-2* < *G-1* and the order of density *G-1* > *G-2*.

The value of charring rates are approaching with the finding of [17], where the tropical hardwood species, balau and merbau with the density range of 500–1000 kg/m^3 show the charring rate of 0.3 and 0.33 respectively. In this research, the hardwood species which has the largest density (*S-1*) show about the same value of the charring rate (0.355).

3.3. Influence of density on charring rate

Many researchers have been published the relationship between wood density and the charring rate, however, there are a few related to tropical wood. Fig. 7 presents the relationship between the density of timber and the charring rate of solid and glulam timber.

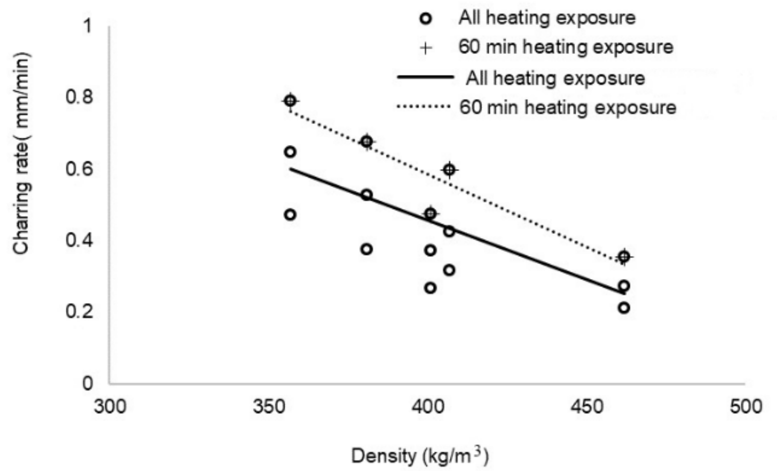

Figure 7. Relationship between density and charring rate.

A linear shape is obtained from the experimental result for the relationship between density and charring rate in all heating period of exposure (solid line), which is inline as stated in EN 1992-1-2 that a linear interpolation may be used to obtain the charring rates of solid hardwoods for densities between 240 and 450 kg/m^3 [14]. Due to the nearly linear character of the curves of the average charring rates for the exposure time of 30, 45 and 60 minutes, the charring rate presented in that figure is the charring rate at 60 minutes (dashed line) [10]. The following linear regression (Eq. 3–6) is obtained for 30, 45, and 60 min and the average of 30, 45, and 60 min exposure time.

$$\text{Charring rate}_{(30)} = (-2.385 \times \text{density}) + 1.286, \quad (3)$$

$$\text{Charring rate}_{(45)} = (-3.490 \times \text{density}) + 1.851, \quad (4)$$

$$\text{Charring rate}_{(60)} = (-4.082 \times \text{density}) + 2.218, \quad (5)$$

$$\text{Charring rate}_{(\text{average})} = (-0.003 \times \text{density}) + 1.785. \quad (6)$$

Eurocode 5 recommends charring rates according to timber type for fire safety in building design. It is recommended a charring rate of 0.70 mm/min for solid and glulam hardwood for the density of 290 kg/m^3 and a charring rate of 0.55 for the density of more than 450 kg/m^3 [14]. Australian standard gives the relationship between the density and charring rate in a quadratic relationship and similar to Eurocode 5, it also reveals the negative relationship between density and charring rate. Fig. 8 illustrates the comparison of the experimental data of charring rates with Eurocode and Australian standard. The experimental regression which is discussed earlier is also attached in this figure.

Compared to European standard recommendation, in general, the solid and glulam timber are safe except timber with the lowest density (solid: *S-3* and glulam: *G-2*) result in unsafe conditions due to higher charring rate. The average experimental data linear regression suggests that tropically sourced timber with a density of more than 350 kg/m^3 meets the charring rate of European standard. However, according to the Australian standard, all experimental result agrees to the standard.

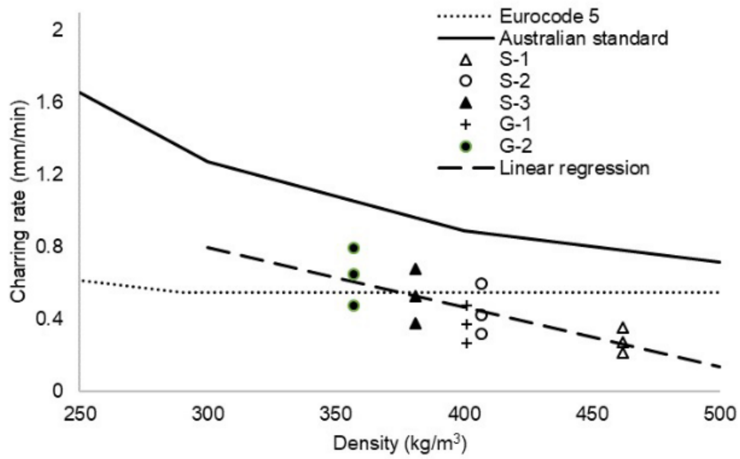

Figure 8. Comparison charring rate with other standard.

3.4. Post-fire mechanical properties

To investigate the properties of wood after elevated temperature can be approached by several methods. Principally, the concept is the same which is the char has no strength [14]. To examine the residual strength, the char layer was removed completely. The core was the inner part which was not affected by the fire due to the char insulation. The mechanical properties testing was conducted for the specimens which were affected by 60 min fire exposure because it was considered as the most severe condition of the timber. This core was prepared to determine the representative of the mechanical properties Shear test was conducted on solid timber which required a small specimen size which enables to be obtained from the post-fire timber to observed post-fire shear strength. Meanwhile, the flexure test was conducted to glulam specimens. The same cross-section of intact specimens as the char removed cross-section was provided in advance as a comparison. Fig. 9 shows post-fire shear strength compared to the actual one.

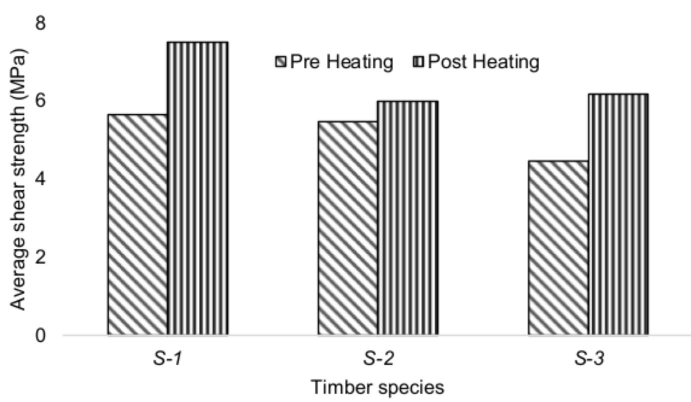

Figure 9. Shear strength comparison.

It is clearly can be seen that solid timber shows an increase in the shear strength after combustion. The timber gained strength around 1.3 times on average compared to the previous strength. The biggest increase occurred in *S-3* which has the smallest density. The increase in properties in wood is assumed to be similar to wood given a heating treatment to improve its properties. The heat treatment usually does not exceed a temperature of 200 °C [1], [28], so it is assumed that the cores experience such temperatures because the inside core is protected by the char layer; thus, the properties of the core increase. Conversely, in the case of the glulam residual cross-section, there is a decrease of flexural load about 22.11 % and 18.45 % for *G-1* and *G-2* respectively after high temperature exposure. The decrease is assumed due to the bonding between the lamina being worsened after the fire [20].

4. Conclusion

The experimental procedures conducted in this paper are for assessing the post-fire properties of solid and glulam timber from tropical wood species. The following points can be drawn.

a. The wood density not only determines the value of the charring rate but also influences the development of the charring rate itself over the fire exposure time.

b. The average of charring rate of species with greater density and longer time of exposure is smaller than that of species with smaller density and shorter time of exposure

c. After a fire exposure of 60 min, the charring rate of tropical solid and glulam timber have the inverse order as the density. The charring rate of solid wood in increasing order: white teak < bayur < < rajumas and the density in decreasing order: white teak > bayur > rajumas. Similarly, for glulam timber, the charring rate in increasing order: white teak-sengon-white teak < rajumas-sengon-rajumas and the density in decreasing order: white teak-sengon-white teak > rajumas-sengon-rajumas.

d. A linear relationship is obtained between wood specific gravity and charring rate at each exposure temperature

e. The average experimental data linear regression suggests that tropically sourced timber with a density of more than 400 kg/m^3 meets the charring rate of European standard. However, according to the Australian standard, all experimental result agrees to the standard.

f. According to post-fire mechanical properties examination, the solid timber shows increased strength after fire; meanwhile, glulam timber does not.

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