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Experimental Study Of Local Solid Wood Post-Fire Behaviour

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A B S T R A C T

When wood structures are exposed to high temperatures, they will decompose to provide a char layer and pyrolysis zone, an insulating material that inhibits further degradation. This experimental study aims to determine the char thickness and pyrolysis of solid wood exposed to fire for 30, 45, and 60 minutes. The post-fire shear strength has also been evaluated. The solid woods were locally from Nusa Tenggara Island, namely Jati Putih, Bajur, and Rajumas. According to the Indonesian National Standard of the heating curve for structures, the temperature growth was SNI-1741: 2008. Obtained The char layer's highest average thickness was within 60 minutes of combustion with the highest temperature of 1055ºC. The char layer for Jati Putih, Bajur, and Rajumas are 2.12 mm, 7.89 mm, and 6.53 mm. Meanwhile, the pyrolysis layers are 8.78 mm, 9.13 mm, and 14.82 mm, respectively, for Jati Putih, Bajur, and Rajumas. Besides, the post-fire shear strength of all wood species shows an increase in shear strength in the core. Wood can still sustain the load during a fire because there is a char layer that is preventing the core section from immediately exposed to the fire.

1. Introduction

The use of wood has increased in structural engineering applications such as buildings that can be placed either interior or exterior applications such as beams, columns, plates, fences, walls, ceilings, retaining walls, and much more. The wood application has proven to be more environmentally friendly and cheaper than other materials, such as steel or concrete. Other advantages of using wood construction relative to other materials are: simpler in construction and maintenance, pleasant appearance, renewable resources, lightweight, and the construction does not depend on the weather [1], [2]. When wood structures are exposed to high temperatures (fires), char layers are formed from a cross-section of exposed wood, causing the layer to lose all strength. But this char layer further protects the remain wood core during fires [3], [4].

When the wood is being exposed to high temperatures, there will be a thermal degradation process that produces gas accompanied by weight loss, and the cross-section is reduced due to the formation of the char layer. The wood's post-fire cross-section consists of several layers: the char layer, pyrolysis zone, and the core. The char layer is part of the cross-section that is turning the color into black, and the pyrolysis zone is a part of the cross-section in which the color is turning into dark brownish. Furthermore, the unburned part of the wood that is still intact or not exposed to fire is the core. This part also maintains the structural load continuously after the fire [5],[7].

Factors that influence wood during high-temperature behavior will determine the layer's depth is turning into char (charring depth). The types of factors considered important to consider are as follows: the degree of temperature, the formation of char, moisture content, species, and dimensions of wood. Wood structures that experience high temperatures shall consider reducing the cross-section due to the char layer's formation. This layer loses strength and stiffness, and strength and stiffness are found only in the remaining parts. The stiffness and strength of wood significantly decrease with increasing temperature. The areas exposed directly to the fire are marked with colors between black and brown, generally have reached a temperature of 300ºC [8], [9].

The behavior of wood exposed to high temperatures has been studied extensively by researchers abroad but is limited to wood species that are commonly found abroad [3], [5], [8], [10]. There are fundamental differences between local wood properties and wood that are generally used abroad [11]. Most research on wood in Indonesia emphasizes mechanical properties at normal temperatures [12], [13]. But the nature of wood at high temperatures, especially the analysis of the char layer's depth, has not been examined.

A study dedicated to determining the characteristics or quality of several local wood types from West Nusa Tenggara has been carried out [12]. The types of wood tested were 15 (fifteen) local wood species such as Bajur, Sentul, Ketapang, Jukut, Bebatu, and others. Characteristics examined are physical properties, including water content and specific gravity, water content, while mechanical properties include modulus of elasticity, tensile strength, compressive strength, flexural strength, and shear strength. The local woods' physical properties in this study show that several types of wood can use several types of wood as structural building materials. Jati Putih, Rajumas, and Bajur are easy to be found and generally applied as structural.

This research aims to study the behavior of local wood after being exposed to high temperature experimentally. The thickness of the char layer and the remaining capacity of the unburnt cross-section are important factors in fire safety design. Therefore, this study emphasizes the study on the thickness of the char layer and evaluates the woods' post-fire strength. The selected solid local wood is Jati Putih, Rajumas, and Bajur because they are widely applied structurally [12].

2. Literature Review

Purkiss J., 2007 in [5] reveals different treatments in assessing post-firewood material compared to other construction materials such as concrete and steel. There is no requirement to calculate the temperature distribution that influences the strength after a fire in post-fire wood evaluation. But the main procedure is to calculate the depth of chars that occurs during a fire.

The behavior of woods under fire is a progressive process; thus, its behavior can study. While wood is exposed to high temperatures, it produces gas, which can cause weight loss. This process depends on the heating rate and temperature. Meanwhile, the internal wood factors that affect the char's depth depend on the moisture, density, and dimension [8]. Furthermore, it is said that the layer of charcoal acts as an insulator, which slows down further degradation. The strength and stiffness are reduced in the section that has become charcoal, thus reducing the wood core dimensions, which is still intact. When the wood is heated to high temperature, three different zones are considered in the analysis, namely the char zone, the pyrolysis zone, and the core.

Several countries have established standards for determining the depth of charcoal from a type of wood that is commonly found in sub-tropical countries. Some of the standards employed are The Eurocode 5, The Australian code, and White's formula. Found that the post-fire behavior of tropical wood did not fully comply with these standards, so proposed a new model. Although new models have been proposed, further experiments are still needed in determining the behavior of post-fire tropical wood [11]. Table 1 shows the depth of charring of some wood species, including tropical wood according to this research.

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Table 1. Depth of char for tropical and sub tropical woods

Type of Woods	Depth of char		
	30 minute	45 minute	60 minute
Meranti	16.35	24.53	32.70
Merbau	15.00	22.50	29.40
Wenge	14.70	22.05	29.40
Balau	12.15	18.23	24.30
Fir	11.61	31.95	42.60
Spruce	17.85	26.78	35.70
Oak	17.70	26.55	35.40
Bilinga	17.40	26.10	34.80
Afzelia	12.96	19.44	25.92
Azobe	12.66	18.99	25.32

Source : [11]

Table 2. Properties of woods

Wood Properties	Jati Putih		Bajur	
	Edge	Middle	Edge	Middle
Moisture content (%)	19.00	21.57	10.01	20.15
Specific gravity	0.417	0.468	0.309	0.345
Compressive strength (MPa)	41.80	46.59	23.50	32.30
Shear strength (MPa)	4.511	6.957	2.887	6.243
Tensile strength (MPa)	27.176	27.716	17.856	17.856
Bending strength (MPa)	58.857	103.129	39.680	57.665

Source : [12]

According to the results of research conducted by Anshari B., et al (2015) that based on the mechanical properties of the local woods studied, one of which is Jati Puth wood, shows that it can apply as a structural building material [12]. Jati Putih wood is included in the quality

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class of E26 in terms of compressive strength, tensile strength, and shear strength parallel to the fibers. However, when viewed from the flexural strength for the two types of wood above, it is slightly lower than that quality, namely E17. Table 2 shows the research results by Anshari B., et al, 2015 in [12], which explains some of the properties of local wood used in this study, namely Jati Putih and Bajur.

3. Methodology

The main materials used in this research were solid woods. Obtained The woods were from the area of West Nusa Tenggara that has just been cut down and are free from defects. According to the previous research on local wood [12], [13], considered Jati Putih, Bajur, and Rajumas were the specimens. The physical properties consisted of specific gravity and examined moisture content in the beginning. The procedures of testing required by the national standard are described as follows.

To examine the moisture content of Jati Putih, Bajur, and Rajumas, the wood cubes with a dimension of 50 mm x 50 mm x 50 mm were prepared. The test was conducted based on SNI 03-6848-2002. The testing of the woods' specific gravity using the same dimensions of the specimens as the specimens for examining the moisture content. This test included determining the initial moisture content and obtaining the moisture content of the woods. They have conducted Testing on moisture content by weighing the specimens, which were still wet as the initial weight. Then put the specimens into the oven, and after 2 hours, removed them from the oven. After being cooled down, they measured the weight of the specimens. Repeated The same method was several times until it reached a constant dry weight. Calculated The moisture content of the wood can be after reaching the constant weight. The dry weight of the specimens was also used to calculate the specific gravity of each wood.

The specimens for high temperatures were wood solid beam prism. The dimensions are 80 mm x 120 mm x 500 mm, and the number of test specimens for each wood is 3 pieces. The heating periods are in intervals of 30 minutes, 45 minutes, and 60 minutes.

During the experimental process of exposing fire to the material, the average furnace temperature must be monitored and controlled. Indonesian National Standard for Method of Fire Resistance Test of Building Structure Components, SNI 1741:2008 [14] follows the International Standard for temperature growth during fire test to the materials, as shown in **Figure 1.**

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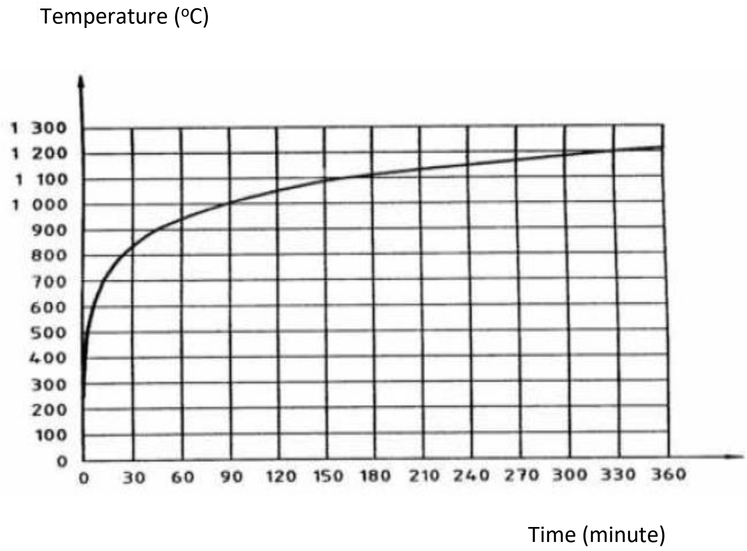

Figure 1. Temperature growth curve (SNI 1741:2008) [14].

Equipment for fire tests consists of furnace, burners, and thermocouples, as shown in Figure 2. The method to investigate the char layers and pyrolysis zones is by cutting the wood cross-section after the fire, by the size of 1 cm, 2 cm, 3 cm, 5 cm, and 25 cm seen from the top side the exposed cross-section. Furthermore, to evaluate the remaining strength after the fire, the char layers are peeled, then set to mechanical properties examination.

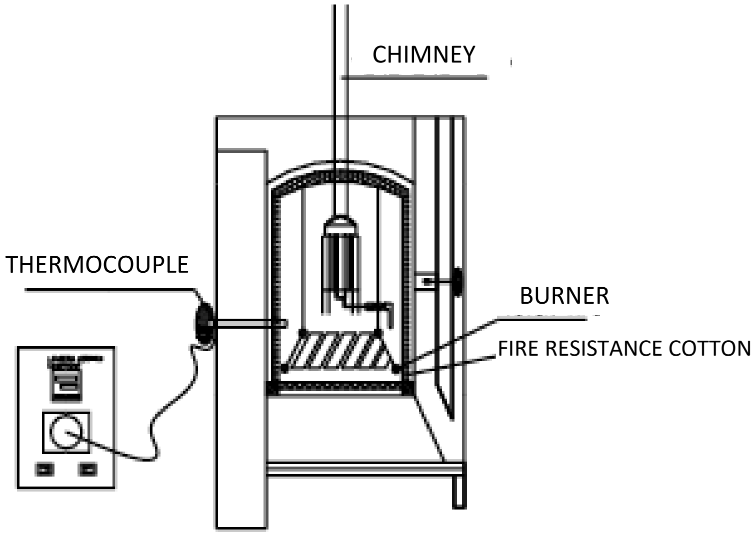

Figure 2. Equipment For Fire Test

Source : *This research*

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4. Results and Discussion

4.1. Physical and Mechanical Properties of Local Wood

Obtained The physical properties and mechanical properties of the wood were experimentally according to the national standard for wood structures (SNI 7973-2013) [15]–[20]. The shear strength of the woods indicates that the quality of the woods between E15-E26, according to SNI 7973-2013, therefore these local woods are strong and stiff to be utilized as building structure materials. The average specific gravity of the woods can be seen in Figure 3. This reveals that these woods are included in the wood category with moderate weight because the specific gravity of the wood is in the ranges from 0.36 to 0.56. Besides, the shear properties are shown in Figure 4. According to shear strength, these local woods include in quality of E15-E26 required by the national standard.

There is a similar property found in this research compared to other studies on the properties of local woods, as shown in Table 3, especially for Jati Putih. Bajur properties exhibit a slight difference. The moisture content of the woods during testing might affects the results. This study provides a better property due to lower moisture content for about 20% during the testing.

Source : This research

Figure 3. Specific Gravity of Wood

Table 3. Comparison of woods properties

Wood Properties	Jati Putih		Bajur	
	This Study	Anshari, B et al.	This Study	Anshari, B et al
Average Specific Gravity	0,46	0.44	0.33	0.41
Average Shear Strength (MPa)	5.53	5.73	5.47	4.57

Source : This research

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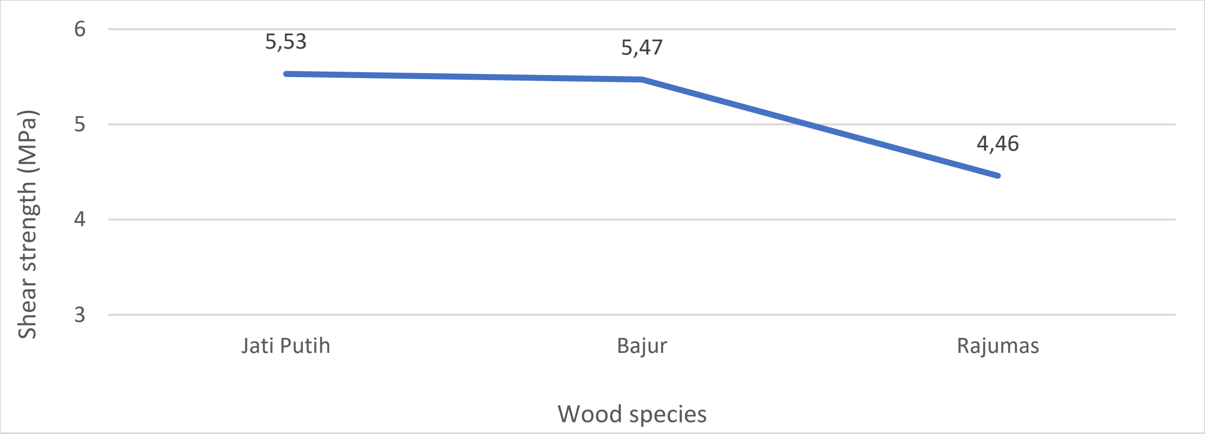

Source : This research

Figure 4. Shear Properties of Wood

4.2. Char Layer and Pyrolysis Zone

Determination of the thickness of the charcoal layer and the pyrolysis zone of wood after burning is done by cutting wood with sizes of 1 cm, 2 cm, 3 cm, 5 cm, and 25 cm from the top. Jati Putih does not show a char layer in the period of exposure of 30 and 45 minutes. However, the pyrolysis zone exists. The char appears during combustion time at 60 minutes. Can see The char layer and pyrolysis' average value in Table 4, Table 5, and Table 6 for Jati Putih, Bajur, and Rajumas, respectively.

Table 4. Char Layer and Pyrolysis of Jati Putih

Distance from Top (mm)	Layer Thickness (mm)	Burning Time (minute)		
		30	45	60
10	Char	0	0	2.12
	Pirolisis	3.45	4.53	8.78
20	Char	0	0	0
	Pirolisis	0	3.40	3.79
30	Char	0	0	0
	Pirolisis	0	0	3.44
50	Char	0	0	0
	Pirolisis	0	0	2.87
250	Char	0	0	0
	Pirolisis	0	0	0

Source : This research

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Table 5. Char Layer and Pyrolysis of Bajur

Distance from Top (mm)	Layer Thickness (mm)	Burning Time (minute)		
		30	45	60
10	Char	0	0	7.89
	Pirolisis	2.02	6.41	9.13
20	Char	0	0	4.02
	Pirolisis	0	4.11	6.18
30	Char	0	0	2.68
	Pirolisis	0	2.60	5.21
50	Char	0	0	2.41
	Pirolisis	0	0	5.02
250	Char	0	0	0.42
	Pirolisis	0	0	4.19

Source : This research

Table 6. Char Layer and Pyrolysis of Rajumas

Distance from Top (mm)	Layer Thickness (mm)	Burning Time (minute)		
		30	45	60
10	Char	0	2.89	6.53
	Pirolisis	5.55	9.81	14.82
20	Char	3.25	1.2	4.56
	Pirolisis	0	7.05	8.46
30	Char	0	0.73	3.09
	Pirolisis	0	5.07	6.42
50	Char	0	0.69	2.33
	Pirolisis	0	5.72	5.79
250	Char	0	0	1.05
	Pirolisis	0	0	5.28

Source : This research

The longer the combustion interval, the thicker the layer of charcoal and pyrolysis formed. The longer of the distance the fire source causes the thinner char layers and pyrolysis. Jati Putih has a greater resistance to fire compared to Bajur and Rajumas. At each fire time

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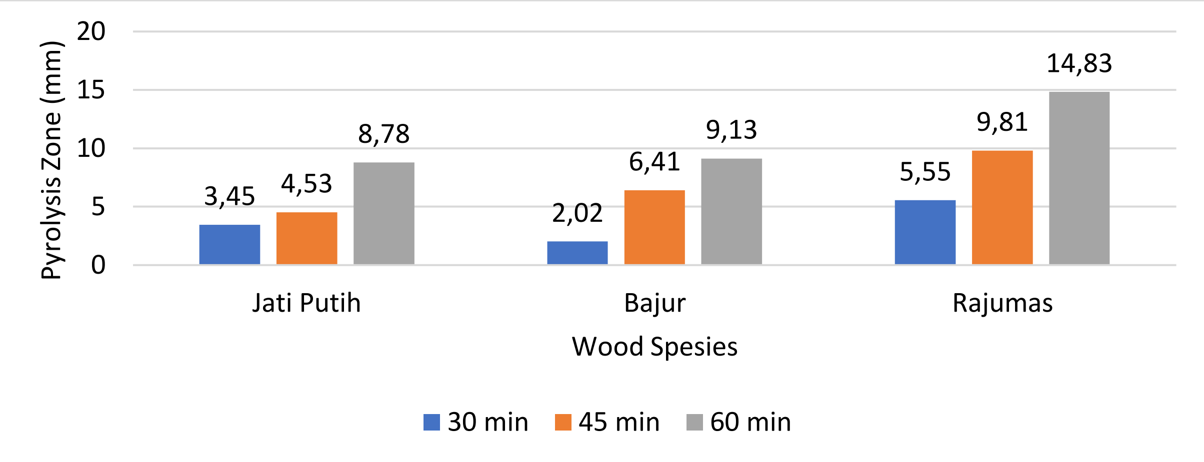
interval, Rajumas has the thickest of pyrolysis and char layer. At intervals of 30 and 45 minutes of fire, Jati Putih and Bajur do not show charcoal layers. After 60 minutes, a new charcoal layer occurs in Bajur, but Jati Putih is still in sound condition. Char has formed when burning 45 minutes on Rajumas, and the condition is getting severe with the increasing of fire intervals.

Can see The depth of the pyrolysis zone in Figure 5. The figure presents the pyrolysis measured at a distance of 10 mm from the top. At each heating level, Rajumas has the greatest depth of the pyrolysis zone, followed by the depth of pyrolysis in Bajur. Meanwhile, the pyrolysis depth in Jati Putih wood shows the lowest value. Similar to the char layer's depth, for this pyrolysis zone, Jati Putih has the best resistance among other woods. This is due to the highest physical and mechanical properties found in this wood. However, when observed according to the increase in the propagation of the pyrolysis zone at 60 minutes, Rajumas shows a similar value to Jati Putih, which is about 2 times the propagation of pyrolysis compared to the period of 30 minutes of fire. Bajur has the fastest pyrolysis growth at 60 minutes, which is about 4.5 times the pyrolysis value at 30 minutes of fire.



Source : This research

Figure 5. Pyrolysis Zone

Figure 6 shows the total char and pyrolysis depths for the three types of wood at each distance measurement of the wood top surfaces. Can see that the farther from the top of the wood surface, the layer of char and pyrolysis becomes less significant. The growth of fire significantly affects the near surfaces area of the wood.

This picture shows that the char and pyrolysis become an insulation layer for a deeper layer of the wood. The curve slope reveals it is very sharp at the beginning where the char and pyrolysis are measured near the surface, in this case, at a distance of 10 mm and 20 mm. Furthermore, this curve slope becomes much to slow down and gentle at a longer measurement

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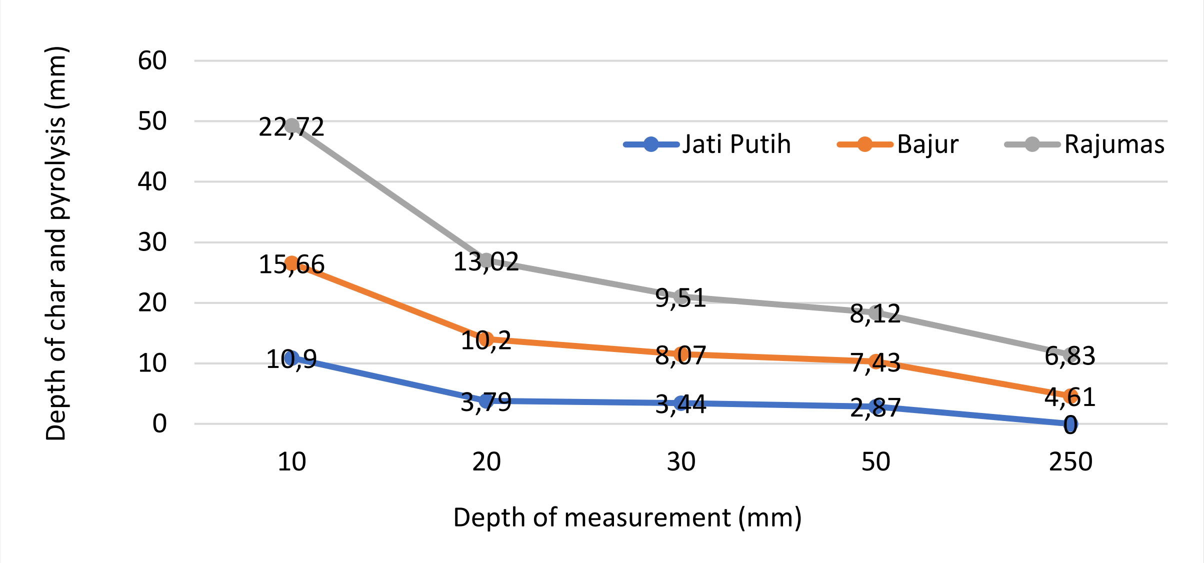
distance from the surface, which is 30 mm, 50 mm, and 250 mm. This result is in line with that of Njankouo JM., Dotreppe J-C., And Franssen J-M., 2005 [11].



Source : This research

Figure 6. Depth of char and pyrolysis at a certain distance

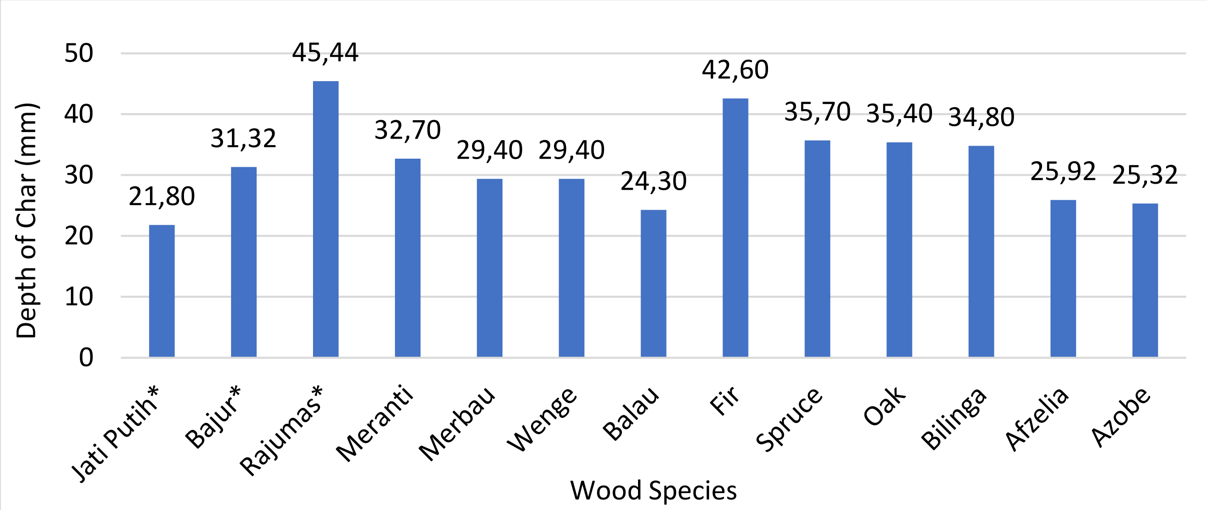
4.3. Comparison with Previous Research

The depth of charring from these three local wood species needs to be compared with the previous research concerned with the wood properties after fire, as shown in Figure 7. The wood species used in this research is labeled by (*) in the figure. Three categories of charring depth have been measured for 60 minutes of fire exposure.

First, 20-30 mm depth of charring. Jati Putih falls in this category along with Merbau, Wenge, Balau, Afzelia, and Azobe. These wood species have been utilized as structural woods in Indonesia. Based on the fire investigation, this category has the highest resistance due to the lowest charring depth.

Second, 40-50 mm depth of charring. Major falls into this category along with Meranti, Spruce, Oak, and Bilinga wood. This type is also included in wood for construction purposes. Spruce and Oak are woods from sub-tropical regions, which have comparable fire resistance properties as Bajur because they have a similar charcoal depth when being heated in 1-hour intervals. This category is for wood that has moderate resistance to fire.

Third, over 40 mm depth of charring. Rajumas falls into this category along with Fir. Fir is wood from sub-tropical regions and is classified as a softwood [21]. This category is for wood that has the lowest resistance to fire according to the depth of char classified in this research.



Source : This research

Figure 7. Comparison Depth of Char

4.4. Mechanical Properties of Wood Post-Fire

Evaluation of the mechanical properties of wood residual capacity after exposure to high temperatures is conducted to the shear strength parallel to the fibers. The specimens are prepared from the beams after 60 minutes of burning time. Shear strength testing is based on national standards for wood testing [19].

The result of investigating the post-fire mechanical properties shows that there is an increase in shear strength in the core of the wood after the fire. The increase is found around 10-30% compared to pre-heated properties. This increase is due to the increasing in density and due to more hydrated water content. Wood can still sustain the load during a fire because a char layer prevents the core section from directly exposed to the fire. The core is the remaining part of the wood cross-section, which still has the strength after the fire.

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5. Conclusion

Jati Putih provides a limited char layer and pyrolysis due to fire. At intervals of 30 and 45 minutes of fire, Jati Putih and Bajur do not show char layers. After 60 minutes, a new charcoal layer occurs in Bajur, but Jati Putih is still in sound condition. Char has formed when burning 45 minutes on Rajumas, and the condition is getting severe with the increasing of fire intervals. Furthermore, according to post-fire shear strength observation, Jati Putih shows better resistance to fire among the local woods. Wood can still sustain the load during a fire because a char layer prevents the core section from directly exposed to the fire.

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