Tectona grandis Linn. and its Fire Characteristics Affected by the Thermal Modification of Wood

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After a long absence, tropical wood species are beginning to be applied in the production of interior elements and construction once again. Due to their positive reaction to thermal treatment, they are increasingly subjected to such processes. Tropical hard wood, in spite of some deficiencies of mechanical properties, are still better than softwoods. Another advantage of this wood is its higher durability in comparison with softwoods. However, there is a lack of knowledge about the properties of treated tropical wood species. Specifically, little is known about their reaction to fire, which is necessary in the application of this wood. This study investigated the effects of thermal treatment of Teak (*Tectona grandis* Linn) wood on selected burning characteristics. Results obtained from raw (untreated) wood test specimens were compared with results obtained from test specimens subjected to thermal treatment at 160 °C, 180 °C, and 210 °C. The monitored characteristics were weight loss and the burn rate. The thermal treatment of teak wood significantly increased its flammability and accelerated its combustion. In addition, its burn rate was higher than in untreated wood, reflecting that it is necessary to add fire retardants to thermally-treated teak wood.

Keywords: Building material reaction to fire; Burn rate; Teak; Thermal treatment of wood; Course of burning

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INTRODUCTION

Wood is deliberately exposed to elevated temperatures for different technological operations, most often during artificial drying, steaming, and boiling at temperatures of 50 °C to 140 °C. Relatively high temperatures, 110 °C to 130 °C, affect the wood even when it is chemically protected by creosote oil, and it is exposed to even higher temperatures during pressing in the manufacturing of wood composites (chipboard, fibreboard, plywood, and other materials). These high temperatures of up to or beyond 150 °C usually do not cause obvious changes in the chemical structure of the wood, and therefore do not lead to permanent changes in its properties. This situation changes when the wood is exposed to temperatures above 150 °C for longer periods of time (Bekhta and Niemz 2003).

Thermal modifications of solid wood create a material that meets specific criteria such as lower hygroscopicity, higher dimensional stability, resistance to biotic factors (wood-decay fungus, mold and wood-destroying insects), and improved aesthetic properties (such as color, minimum amount of cracks, and shine) (Bekhta and Niemz

2005; Yinodotlgör and Kartal 2010; Kacik *et al.* 2012; Barcík *et al.* 2015). All technological processes for producing thermally modified wood reduce its mechanical properties and a change its color (Yildiz *et al.* 2006; Phuong *et al.* 2007; Esteves and Pereira 2009). In general, however, the change in the properties of thermally modified wood depends on the specific conditions of its treatment. Basically, all thermal modifications of wood at temperatures above 100 °C, but especially above 150 to 170 °C, cause certain changes in its chemical structure. These changes are reflected in changes in its properties (Kacikova *et al.* 2013, Akkus *et al.* 2014, Zawadzki *et al.* 2016).

Thermally modified wood is professionally known as and commonly used under the name Thermowood®. Thermal modification, based on the Finnish patent, is carried out with air, and the entire internal environment is humidified with steam (Yildiz *et al.* 2006). No additional chemicals are used in this thermal treatment process, and the material is therefore harmless to the environment (Metsä-Kortelainen and Viitanen 2009). The properties of Thermowood, including its resistance to decay, are well known. Thus, the treated wood has a wide application in construction (Tjeerdsma *et al.* 1998; Welzbacher and Rapp 2005, 2007; Metsä-Kortelainen *et al.* 2011). However, information about the fire resistance of this material is still lacking, even though this knowledge is very important with regard to its use in wood construction. Although there are studies addressing the issue of burning Thermowood (Martinka *et al.* 2013, 2016), information about modifying Thermowood in terms of fire resistance and the effect of these modifications on its properties is lacking.

EXPERIMENTAL

Materials and Thermal Modification

The teak wood was harvested from Bhamo, Burma. Test specimens were radially cut to dimensions of 20 mm × 100 mm × 200 mm (h × w × l). There were two basic sets of test specimens (with 5 test specimens in each set): without thermal treatment (T - 20) and with thermal treatment (T - 160, T - 180, and T - 210) (Fig. 1).

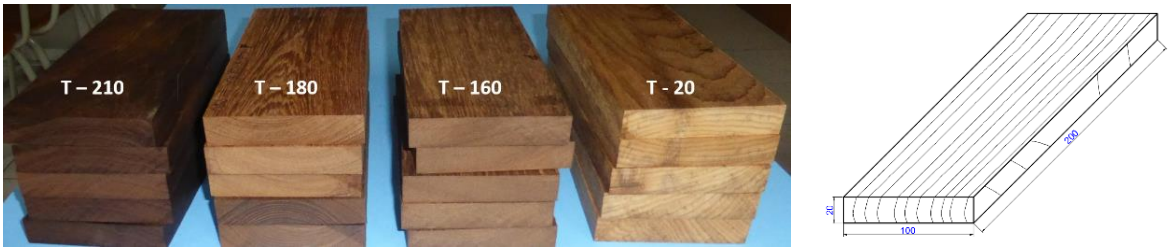

Fig. 1. Test specimens (T - 210, T - 180, T - 160, and T - 20)

To determine the effect of thermal treatment on the weight loss and burn rate, the results measured on the test specimens were compared with specimens that were not thermally-treated (Fig. 1). The thermal modification process was performed according to (Fig. 2), comprising the following steps:

1. Heating and drying – In this stage, the temperature increases rapidly in an oven at about 100 °C to support the action of steam. Then, the wood pitch decreases and

increases to the level of 130 °C. Drying medium is hot air or hot steam. Throughout this phase, the wood is dried to approximately to zero moisture.

2. Thermal modification– In the second stage the temperature is raised to the level of 185 to 230 °C for 2 to 3 h. The height of temperature and duration of action are determined by the requirements of the class of products THERMOWOOD (Thermo-S and Thermo-D).

3. Refrigeration and Air Conditioning – In the third phase, the thermally modified wood is gradually cooled to a temperature of 80 to 90 ° C and the humidity is stabilized so that the final moisture level was normal within the range 4 to 7%.

The technology used for the thermal treatment is shown in Fig. 2 and in Table 1. Temperatures in Fig. 2 were measured from the test specimens using an IR sensor. The modification time was time at target modification temperature. The sets of test specimens were subjected to thermal treatment, which was performed in three phases by the ThermoWood method in a Katres thermal chamber (Brno, Czech Republic). The average density and moisture values of the monitored sets of test specimens are shown in Table 2.

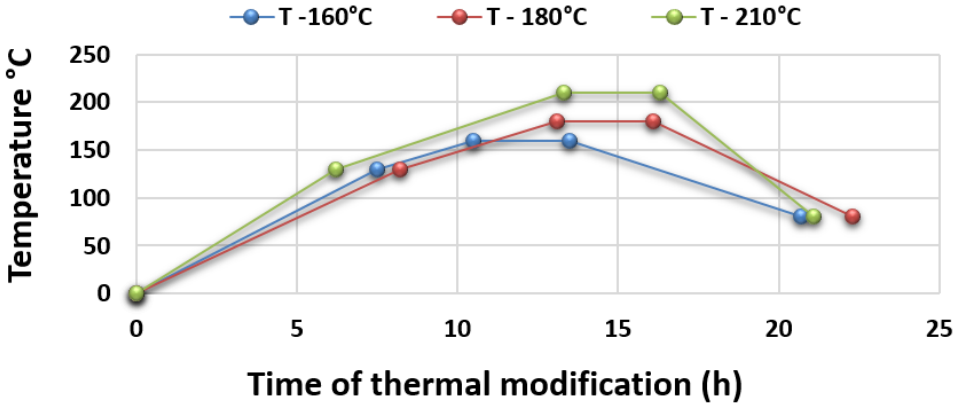

Fig. 2. The thermal modification process specimens (T - 210, T - 180, T - 160)

Table 1. Thermal Modification Process Parameters

Thermal modification process			
Parameters	**160 ° C**	**180° C**	**210° C**
Heating	7.5 Hours	8.2 Hours	6.2 Hours
Thermisation	13.5 Hours	13.1 Hours	13.3 Hours
Cooling	20.7 Hours	16.1 Hours	16.3 Hours
Total modification time	**20.7 Hours**	**22.3 Hours**	**21.1 Hours**

Table 2. Average Density and Moisture Values of Testing

At the time of testing				
Test samples	T - 20	T - 160	T - 180	T - 210
Density (kg m^{-3})	533	531	576	572
Moisture content (%)	9.3	9.4	8.7	8.7

Methods

This study tested a new method of evaluating the burning, which was divided into two phases. The first phase consisted of the direct exposure of the test specimen to a gas burner for 10 min. The test specimen was placed under the burner at a 45° horizontal angle. The size of the flame was 10 cm from the mouth of the burner, and it was placed at the center of the underside of the test specimen. The distance from the mouth of the burner to the center of the sample was 9 cm. In the second phase (after 10 min), the flame was removed from the sample, and the weight loss and burn rate was recorded for another 5 min. The goal of the second phase was to record the course of burning. Thermal degradation can continue to develop in the glowing layer of the wood, resulting in self-ignition, re-ignition, and sustained charring. This method of evaluation was meant to simulate the natural wood-burning process with a flame source, sustained air supply, and free flow of combustion gases. The experiment simulated real conditions of fire open fire at temperatures above the flame source. At 600 s the flame source was discontinued, and the system was observed until 900 s, which represented only spontaneous combustion.

The device consisted of a USBEC 1011/1 propane burner (DIN-DVGW- Reg. Mr. NG-2211AN0133, blasting, 1.7 kW, Dresden, Germany), propane tank, electric scales (MS 1602S/MO1, Mettler Toledo, Geneva, Switzerland), and BalanceLink 4.2.0.1 software (Mettler Toledo, Switzerland) to record the wood's weight. With continuous weighing during the flammability test, the weight loss of the test specimens was recorded at a regular interval of 10 sec. The average burn rate and weight loss were calculated from the measured values by Eqs. 1 and 2, respectively,

The obtained data was evaluated with Excel software (Microsoft, Redmond, WA, USA). The entire course of burning is described in graphs that capture the 15-min burning of the test specimen.

Evaluation and Calculation

The burn rate was calculated using Eq. 1,

$$v = \frac{m_t - m_t + 10}{m_{t0} * 10}.100 \quad (1)$$

where v is the burn rate (%/s), m_t is the weight (g) at time t, m_{t+10} is the weight (g) of the sample 10 s later, and m_{t0} is the weight (g) of the sample at time 0.

The weight loss was calculated according to Eq. 2,

$$\Delta m = \frac{m_1 - m_2}{m_1}.100 \quad (2)$$

where Δm is the weight loss (%), m_1 is the sample's weight before the test (g), and m_2 is the sample weight after the test (g).

An additional characteristic for the assessment of material properties relating to the fire is the ratio of the maximum speed of burning and the time at which the maximum speed is reached. If there is a higher ratio, the fire protection value is worse. The ratio of the maximum speed was calculated according to Eq. 3,

$$P = \frac{v_{max}}{T_{max}} \quad (3)$$

where P is the ratio of the maximum speed of burning (%), v_{max} is the maximum speed of burning (%.s^{-1}), and T_{max} is the max time to reach the maximum speed of burning (s).

The density and moisture content of the test samples were ancillary criteria that assisted in sorting the samples according to their quality. These physical parameters (density and moisture content) needed to be sorted so that they do not affect the values of the fundamental evaluation criterion.

The wood density was determined before and after testing according to ISO 13061-2 (2014) and Eq. 3,

$$\rho_w = \frac{m_w}{V_w} \quad (4)$$

where ρ_w is the density of the sample at moisture content w (kg/m^3), m_w is the mass (weight) of the sample at moisture content w (kg), and V_w the volume of the sample at moisture content w (m^3).

The moisture content of the samples were determined and verified before and after testing out according to ISO 13061-1 (2014) and Eq. 5,

$$w = \frac{m_w - m_0}{m_0} * 100 \quad (5)$$

where w is the moisture content of the samples (%), m_w is the mass (weight) of the sample at moisture content w (kg), and m_0 is the mass (weight) of the oven-dry sample (kg). Drying to an oven-dry state was also carried out according to ISO 13061-1 (2014).

RESULTS AND DISCUSSION

Natural teak exhibited a weight loss of 4.77% after a 10-min exposure to a direct flame. After thermal treatment at 160 °C, 180 °C, and 210 °C, the weight loss increased to 12.77%, 13.48%, and 11.22%, respectively. In untreated teak wood, there was a remarkable weight loss between 110 and 160 s, after which the weight loss increased evenly, as shown in Fig. 3.

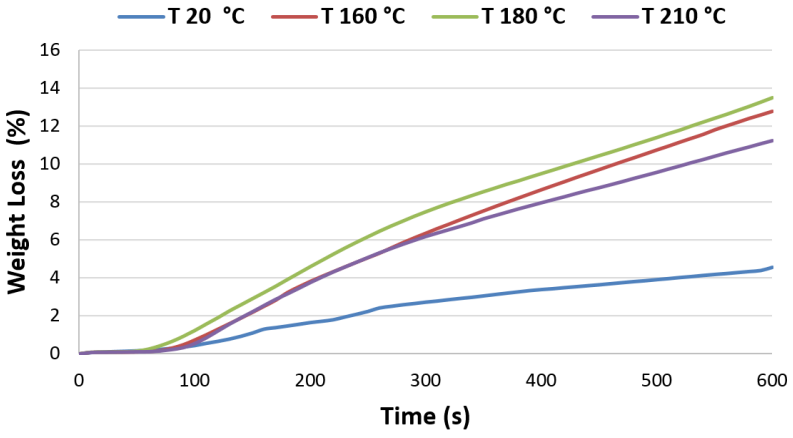

Fig. 3. Time versus average weight loss from 0 s to 600 s

In the thermally modified teak wood there was a substantial change in the weight loss between 100 and 130 s, and it also increased evenly. The values from 600 s to 900 s are are shown in Fig. 4.

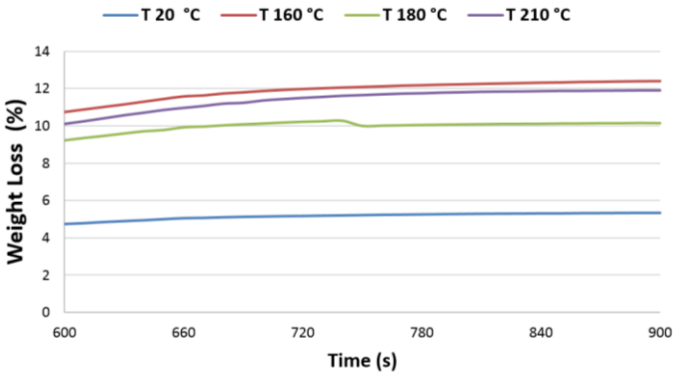

Fig. 4. Time versus average weight loss from 0 s to 600 s

Based on the course of combustion, there is reason to believe that thermal treatment had changed the wood structure and chemical composition of teakwood. As the experiment was conducted at the flame source under the conditions of a real fire (open fire with a machine by controlling the air supply and flue). In this experiment it was possible to observe quick ignition of the thermally-treated wood teak. Compared to other species, the signs of ignition began taking off from the surface of the wood with small twinklings. These observations were tentatively attributed to the release of small droplets of accompanying substances that had been concentrated at the surface of the wood. This release there was a combination of two physical phenomena: microcracks in the structure of wood and wood viscosity changes. Further treatment was a flame to evaporate such accompanying substances, which gave rise to intense flames. These phenomena have an impact on the chosen evaluation criteria.

The burn rate results indicated that teak wood began to burn indiscriminately after 10 s from the start of the test (seen in the first small peak of Fig. 5). Natural teak wood started burning after 110 s, reaching a second peak and the highest burn rate after 160 s. There was a remarkable decrease in the burn rate up until 200 s into the test. It then continued to burn faintly until the end of the test. Samples that were thermally-treated at 180 °C and 210 °C had a very similar course of burning, which is also reflected in the burn rate. Figure 4 shows the curves of the burn rate with a similar course.

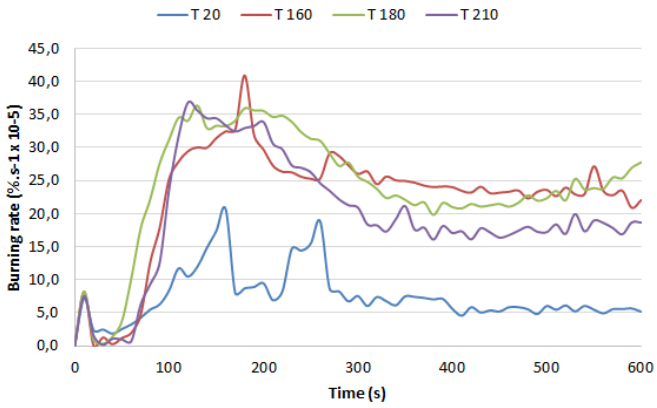

Fig. 5. Burn rate graph from 0 s to 600 s

Combustion occurred after 130 s (second peak). At 200 s the wood flared up again, and then the combustion and burn rate gradually declined. At 550 s there was a small flare in both samples. Teak wood thermally modified at 160 °C had a different course of burning and burn rate. The combustion and increasing burn rate occurred at 70 s; it reached the highest burn rate at 170 s, the highest of all the tested samples. The highest peak on the graph (Fig. 5). Another flare occurred at 280 s and then again at 540 s, which is shown by the smaller peaks. Figure 6 shows the development of the burn rate from 600 s to 900 s. The differences in the burning of untreated and thermally modified teak wood at different temperatures are shown in Figs. 7 and 8.

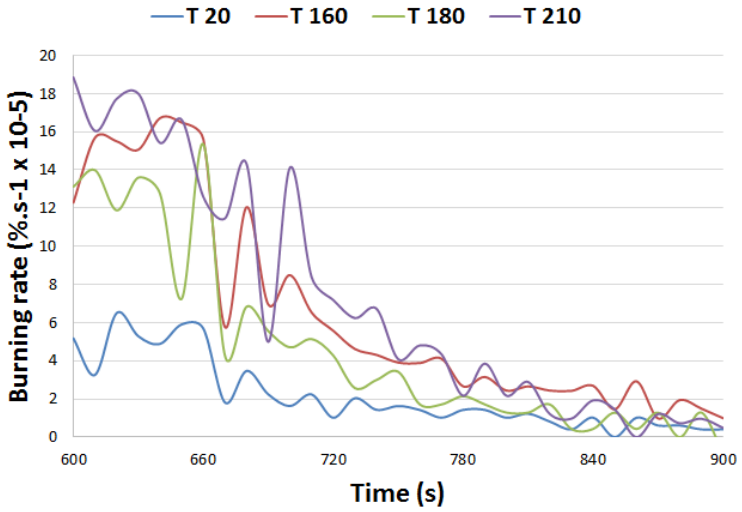

Fig. 6. Burn rate graph from 600 s to 900 s

(a) **(b)**

Fig. 7. Teak P (a) 20 °C after the test and (b) P 160 °C after the test

(a) **(b)**

Fig. 8. (a) Teak P 180 °C after the test and (b) teak 210 °C burn-through

Table 3 shows the results of ANOVA evaluating the effect of thermal modification of wood on the monitored characteristics. Based on the significance level "P", it can be concluded that the degree of thermal treatment of wood had demonstrated statistically significant effects only on the values of observed characteristics for "Weight Loss - 600 s" (%). In other cases, there was no significant influence of thermal treatment on the monitored characteristics.

Table 3. Basic Statistical Characteristics Evaluation the Effect of Thermal Treatment on the Values of the Monitored Characteristics

Effect	Sum of squares	Degrees of freedom	Variance	Fisher's F - Test	Significance level P
Weight Loss - 600 s (%)					
Free term	2207.355	1	2207.355	174.698	***
Thermal modification	249.606	3	83.202	6.585	***
Error	202.164	16	12.635		
Weight Loss 900 s (%)					
Free term	317.031	1	317.031	9.667	***
Thermal modification	24.858	3	8.286	0.253	NS
Error	524.743	16	32.796		
Burning rate - 600 s (%.s^{-1} x 10^{-5})					
Free term	6450.625	1	6450.625	28.356	***
Thermal modification	1223.323	3	407.774	1.793	NS
Error	3639.814	16	227.488		
Burning rate - 900 s (%.s^{-1} x 10^{-5})					
Free term	2.087	1	2.087	5.694	***
Thermal modification	0.178	3	0.059	0.162	NS
Error	5.865	16	0.367		
The maximum speed of burning (%.s^{-1})					
Free term	0.000	1	0.000	124.825	***
Thermal modification	0.000	3	0.000	0.315	NS
Error	0.000	16	0.000		
The time to reach the maximum speed of burning (s)					
Free term	459045.0	1	459045.0	169.546	***
Thermal modification	6535.0	3	2178.3	0.805	NS
Error	43320.0	16	2707.5		
Ratio of the maximum speed of burning (%)					
Free term	0.000	1	0.000	75.846	***
Thermal modification	0.000	3	0.000	0.907	NS
Error	0.000	16	0.000		

NS- not significant, ***- significant

Figures 9 through 15 show the results of thermal impact adjusted to the monitored characteristics. From the results it is clear that the values of "Weight Loss - 600 s (%)" were greatly increased for thermally modified wood (160 °C, 180 °C, and 210 °C) (Fig. 9) compared with the untreated wood. Thus, none of the other monitored performance characteristics were affected by the thermal treatment of wood.

Thermally modified teak wood has a greater ability to ignite and burn more intensely than untreated teak wood. This is due to the change in the chemical composition that occurs during the termination of the wood.

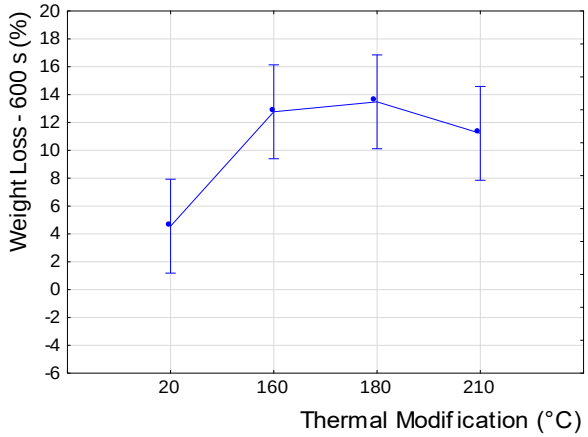

Fig. 9. The effect of the thermal modification on the weight loss in 600 s

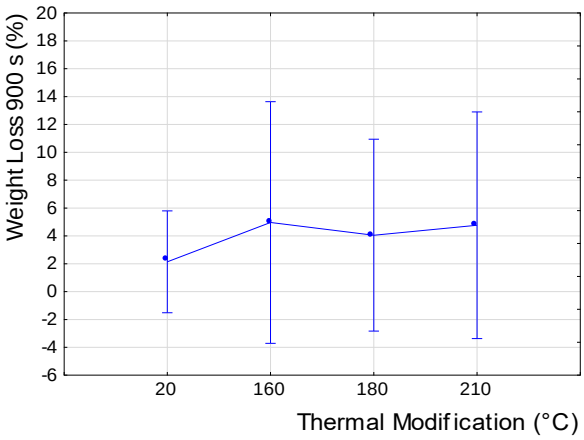

Fig. 10. The effect of the thermal modification on the weight loss in 900 s

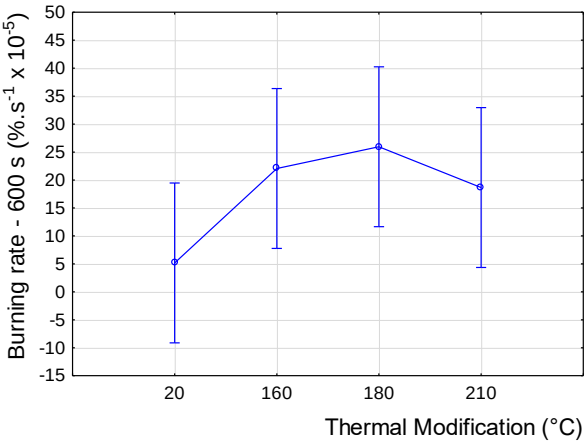

Fig. 11. The effect of the thermal modification on the burning rate in 600 s

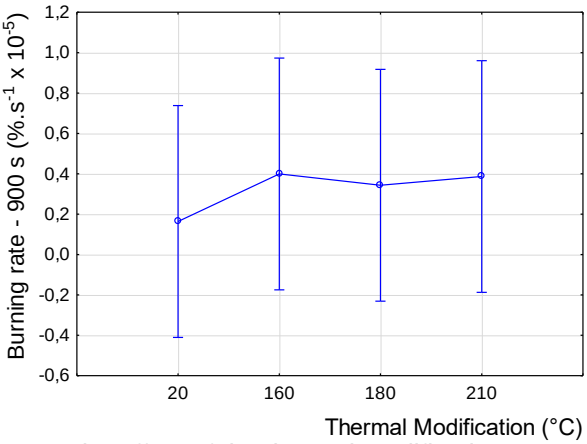

Fig. 12. The effect of the thermal modification on the burning rate in 900 s

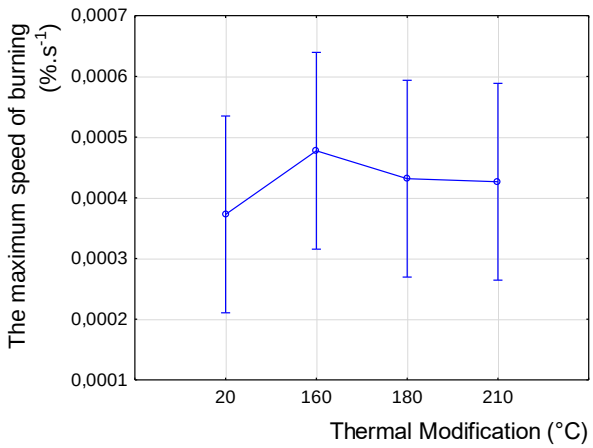

Fig. 13. The effect of the thermal modification on the maximum speed of burning (%.s^{-1})

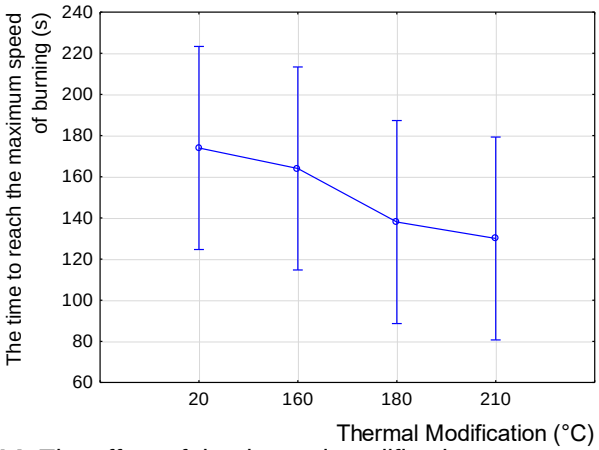

Fig. 14. The effect of the thermal modification on the time to reach the maximum speed of burning (s^{-1})

Table 4. Comparison of the Effects of individual Factors using Duncan Test on the Monitored Characteristics

Weight Loss - 600 s (%)		(1) 4.5528	(2) 12.769	(3) 13.481	(4) 11.220
1	20		0.003	0.002	0.009
2	160	0.003		0.756	0.501
3	180	0.002	0.756		0.355
4	210	0.009	0.501	0.355	
Weight Loss 900 s (%)		(1) 2.1418	(2) 4.9640	(3) 4.0530	(4) 4.7668
1	20		0.484	0.605	0.503
2	160	0.484		0.815	0.957
3	180	0.605	0.815		0.846
4	210	0.503	0.957	0.846	
Burning rate - 600 s (%.s-1 x 10-5)		(1) 5.1728	(2) 22.059	(3) 25.952	(4) 18.653
1	20		0.112	0.061	0.177
2	160	0.112		0.689	0.726
3	180	0.061	0.689		0.480
4	210	0.177	0.726	0.480	
Burning rate - 900 s (%.s-1 x 10-5)		(1) 0.16350	(2) 0.39908	(3) 0.34312	(4) 0.38646
1	20		0.112	0.061	0.177
2	160	0.112		0.689	0.726
3	180	0.061	0.689		0.480
4	210	0.177	0.726	0.480	
The maximum speed of burning (%.s^{-1})		(1) 0.00037	(2) 0.00048	(3) 0.00043	(4) 0.00043
1	20		0.112	0.061	0.177
2	160	0.112		0.689	0.726
3	180	0.061	0.689		0.480
4	210	0.177	0.726	0.480	
The time to reach the maximum speed of burning (s)		(1) 174.00	(2) 164.00	(3) 138.00	(4) 130.00
1	20		0.112	0.061	0.177
2	160	0.112		0.689	0.726
3	180	0.061	0.689		0.480
4	210	0.177	0.726	0.480	
Ratio of the maximum speed of burning (%)		(1) 0.00000	(2) 0.00000	(3) 0.00000	(4) 0.00000
1	20		0.253	0.181	0.257
2	160	0.253		0.793	0.940
3	180	0.181	0.793		0.750
4	210	0.257	0.940	0.750	

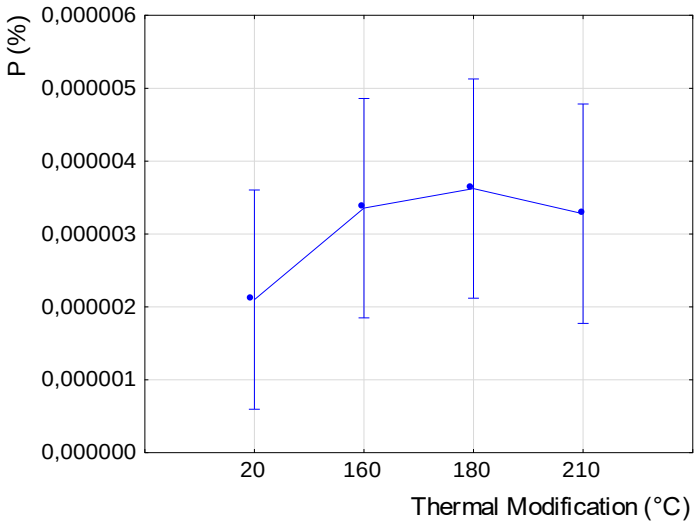

Fig. 15. The effect of the thermal modification on the ratio of the maximum speed of burning (%)

Oil substances that are contained in this wood species are released to the surface of the wood during thermal treatment at temperatures of 160 °C and 180 °C, based on the course of burning. The samples burned quite intensively with a homogeneous flame. At about 4 to 6 min from the start of the test, flaming droplets of the released oil were observed. This effect did not occur in wood thermally-treated at 210 °C, and the burning intensity of these samples was lower. This was also reflected in the final weight loss value at 600 s (Fig. 3), as well as the development from 600 to 900 s of the experiment (Fig. 4). Notably, combustion did not occur after the removal of the flame source at 600 s, although the weight loss slightly increased (below 1%) in untreated samples and by approximately 2% in thermally-treated samples.

Based on the results by Duncan's test (Table 4), it is clear that the thermal effect of the modifications reflected only the observed characteristic "Weight Loss - p 600 (%)". In this case, the thermal difference between untreated wood and other adjustments, was shown at a level of P = 0.003 (160 °C), P = 0.002 (180 °C), P = 0.009 (210 °C). With respect to the other monitored characteristics, thermal treatment effect was not affected.

CONCLUSIONS

1. Thermally-modified teak wood has a greater weight loss in open flame burning than wood that is untreated. Thermally-modified teak wood has a greater ability to ignite and burn more intensely than untreated teak wood.
2. It is clear from these results that thermally-treated teak wood at all temperatures have higher burn rates than untreated teak woods. Teak wood begins to burn after 10 s of exposure to the flame, and from 100 s to 130 s flares up significantly, resulting in a high burn rate. The highest burn rates occur within the first 200 s. The burn rate is highest in teak wood that is thermally modified at 160 °C. Thermally-treated teak wood showed a higher burn rate throughout the test even after it exceeded the highest burn rate of untreated samples. For these evaluation criterions, one can also determine the causes of these phenomena, as was done for the weight loss.

3. The results show that thermally-treated teak wood greatly increases its ability to ignite and combust, and increases its burning intensity. This was also confirmed by the selected evaluation criteria. The authors recommend the addition of fire retardants to the thermally modified wood, which is also the objective of future experiments.
4. The aim of this study was to determine the effects of thermal modification on the selected fire-resistant properties of teak wood. It was expected that thermal modification will result in changes in the wood chemical composition, which has a direct impact on its ignition and combustion; this will be the subject of further research.

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