WOOD RESEARCH
64 (1): 2019
25-34

PREDICTION OF THE MECHANICAL PROPERTIES OF THERMALLY-MODIFIED RUBBER WOOD ON THE BASIC OF ITS SURFACE CHARACTERISTIC

Xiangyu Zhao, Dengyun Tu, Chuanfu Chen, Qiangfang Zhou
South China Agricultural University, College of Materials and Energy
Guangzhou, China

(Received April 2018)

ABSTRACT

The goal of this research was to investigate the effect of thermal treatment on mechanical properties and surface characteristic of rubberwood (*Hevea brasiliensis*) and find the mathematical model to predict the mechanical properties used by its surface characteristic. Rubberwood specimens were treated by steaming at five different temperature levels of 170, 185, 200, 215, and 230°C for two different durations of 1.5 and 3 h. Based on the results, the values of bending strength, modulus of elasticity, compression strength and impact bending decreased, and the glossiness and chromatic aberration (ΔE) increased with increasing temperature and enlarging duration further. This study revealed that chromaticity parameters b*, ΔE and the gloss of perpendicular to grain (GZT) could evaluate the mechanical properties of thermally-modified wood to achieve the mechanical properties detection without destruction.

KEYWORDS: Heat treatment, rubberwood, mechanical properties, surface characteristic, mathematical model.

INTRODUCTION

Heat treatment modification has developed in the world over the last quarter century since the first heat treatment plant was established in Finland in the early 1990s leading to the popular and commercialization of heat treatment products named thermally-modified wood (Esteves and Pereira 2009, Sarni et al. 1990). And the market share of heat treatment products has risen with a growing number of industrial treatment factories in the whole world like ThermoWood in Finland, PlatoWood in the Netherlands due to the increasing interest of consumers about eco-friendly products with non-preservatives (Kesik et al. 2014, Sivonen et al. 2002, Vernois 2007, Xie et al. 2002).

Heat treatment is an effective method to enhance hydrophobic performance, dimensional stability and biological durability without the use of chemtrails to improve applied value of low nature wood to meet the requires of floor, furniture, outdoor material etc. (Kesik et al. 2014, Cademartori et al. 2015, Joma et al. 2017). Furthermore, numerous researchers have investigated the influence of heat treatment to surface characteristic and found heat treatment could improve surface quality and change color closed to rosewood (Kačíková et al. 2013, Priadi and Hiziroglu 2013, Tomak et al. 2014, Yildiz et al. 2013).

However, heat treatment reduces the values of mechanical properties, while wood becomes more rigid and fragile after heat treatment. And the temperature and duration are the main influencing factors. mechanical properties significantly decrease with the higher temperature and longer duration (Joma et al. 2017, Hao et al. 2018). In the case, it is very necessary to detect mechanical properties in production.

At the present, the detective method of mechanical properties are destructive tests with the corresponding size and suitable moisture content, which include bending strength test, modulus of elasticity test, compression strength test and impact bending test etc. (Cademartori et al. 2015, Korkut 2008, Yildiz et al. 2006). A lot of researchers focused on the method for nondestructive determination, such as ultrasonic technology, microwave technology, radiographic inspection, vibration technology, and fast Fourier transform (He and Di 2015, Michaloudaki et al. 2005, Yu et al. 2012). A few studies have attempted to find relationships between mechanical properties and others to achieve the prediction of mechanical properties at a lower cost. Bekhta and Niemz (2003) investigated the relationship between bending strength and the chromatic aberration.

Many researchers explored the mechanism in the heat treatment and pointed out decomposition of cellulose, hemicelluloses, lignin, and extractives resulting in the decreasing of mechanical properties (Chen et al. 2012). On the other hand, the formation of aldehydes and phenols and the degradation of lignin in heat treatment resulting in the change of surface characteristic (Kačíková et al. 2013, Chen et al. 2012, Esteves et al. 2008, Yang et al. 2018). For this reason, it is feasible to put surface characteristic as a prediction of mechanical properties.

This paper further study the relationships between different mechanical properties and surface characteristic according to the research of Bekhta and Niemz (2003). This research was to find a most suitable parameter to achieve prediction of each mechanical properties of thermally-modified wood with convenient, fast, and nondestructive detection.

MATERIALS AND METHODS

Materials

Rubberwood (*Hevea brasiliensis*) boards (width 105 mm, thickness 26 mm, and length 1000 mm) were supplied from Thailand, which were collected from wood market with the moisture content at 14%. Plain sawn clear wood specimens for heart treatment were prepared with dimensions of 300 mm long (grain direction) by 105 mm wide (tangential direction) by 20 mm thick (radial direction). Eleven groups of specimens (ten for heat treatment and one for control) were prepared, and each group had 20 specimens.

Heat treatment

Heat treatment applications were applied at five different temperatures (170°C, 185°C, 200°C, 215°C and 230°C) and two durations (1.5 h or 3 h) in a small heating chamber (0.3 m^3) controlled to within ±0.5°C with a steaming injection system under atmospheric pressure. After heat treatment, all treated and untreated specimens were put in the laboratory at room temperature over four weeks.

Mechanical properties

As shown in Tab. 1, four wood physical and mechanical properties were conducted, based on their respective Chinese standards. All heat-treated and control specimens were prepared for bending strength, modulus of elasticity, compression strength and impact bending. Each group including 20 samples, and all the samples were conditioned at 20°C and 65% relative moisture content until moisture content stabilization before tests.

Tab. 1: Mechanical properties and their corresponding Chinese standards.

Properties test	Chinese standard	Specimen size (mm)
Bending strength	GB/T1936.1-2009	300×20×20
Modulus of elasticity	GB/T1936.2-2009	300×20×20
Compression strength (parallel the grain)	GB/T1935-2009	30×20×20
Impact bending	GB/T1940-2009	300×20×20

Surface characteristics

The surface characteristic tests have finished before the mechanical properties tests with the same samples. The changes in surfaces color due to heat treatment were measured by color measuring system (chromameter SC-80C, Zhuhai Tian Chuang, China) according to CIE L* a* b* color system. The measurements were made using D65 illuminant and a 10°standard observer. L*, a* and b* were measured for samples at five different locations on each. And ΔE was calculated used by Eq. 1, and the average value was calculated.

$$\Delta E = (\Delta L^2 + \Delta a^2 + \Delta b^2)^{1/2} \quad (1)$$

Where ΔL, Δa, Δb are the total changes of initial and final values of L*, a*, b* during heat treatment, respectively. L* represents lightness, the increase in L* value means the color of the sample becomes lightening. The a* and b* are the chromaticity parameters. A positive Δa is for the red shift, and a negative Δa is for the green shift. And a positive Δb is for the red yellow shift, and a negative Δb is for the blue shift.

Surface glossiness of species was measured by a gloss meter (KGZ-IC, Tianjin, China). The test angle was 60° according to ASTM standard D 2457-03. The glossiness results were measured for samples at five different positions on each species. The values of GZL and GZT were recorded. The GZL means the gloss of parallel to the grain, and The GZT means the gloss of perpendicular to grain. The unit is GU.

Linear regression analysis

The linear regression analysis was used by MATLAB based on the data from experimental results to find the most suitable surface characteristic factor for prediction of each mechanical properties of thermally-modified rubberwood.

RESULTS AND DISCUSSION

The effect of thermal treatment on properties of rubberwood

Tab. 2 presents the bending strength, modulus of elasticity, compression strength parallel to grain, and impact bending strength by heat treatment at different treatment temperatures and duration time for all groups. According to the averages, all the mechanical properties decreased with the increase of heat temperature and duration time overall. And the lowest values of the bending strength, modulus of elasticity, compression strength parallel to grain, and impact bending strength were reduced by 63.74% (32.16 MPa), 41.22% (4188 MPa), 26.16% (33.88 MPa), and 57.07% (34.09 MPa) at 230°C for 3 h, compared with control groups, respectively. The values of bending strength and impact bending strength decreased dramatically and constantly in the temperature range from 185°C to 215°C and long duration from 1.5 h to 3 h. But the different results of modulus of elasticity and compression strength parallel to grain were obtained. The modulus of elasticity value slightly increased when treated at the temperature of 170°C and 185°C for 1.5 h, as the same time, compression strength parallel to grain was increased similarly above the temperature of 170°C. As the treating time prolonged or the temperature increased, the modulus of elasticity and compression strength reduced immediately.

Tab. 2: The effect of heat treatment on the mechanical properties of rubberwood.

Temperature (°C)	Duration (h)	Bending strength (MPa)	Modulus of elasticity (MPa)	Compression strength parallel to the grain (MPa)	Impact bending ($kJ·m^{-2}$)
-	0	88.7±11.08	7125±1091	45.88±5.23	79.4±14.11
170	1.5	78.36±13.13	7425±946	47.68±5.95	53.25±6.74
	3	68.91±12.72	6801±881	46.17±5.36	50.12±4.64
185	1.5	77.33±12.86	7193±1873	45.43±3.88	49.45±8.63
	3	64.66±18.81	6707±1167	44.29±4.72	45.50±3.59
200	1.5	62.02±15.86	6500±1213	43.16±3.30	44.62±1.07
	3	60.22±7.72	6499±538	41.83±1.90	43.53±2.96
215	1.5	51.24±13.52	5491±886	37.57±2.90	41.50±2.17
	3	48.30±10.68	5340±378	35.97±3.62	40.91±1.33
230	1.5	34.25±4.92	5376±190	34.72±1.45	38.45±1.02
	3	32.16±5.7	4188±1474	33.88±1.27	34.09±2.41

Data represent mean value ± standard deviations.

The major factor for the reduction of the mechanical properties was the degradation of hemicelluloses and the crystallization of amorphous cellulose (Korkut and Aytin 2015). And the lower moisture content might affect positively the mechanical properties below the fiber saturation point (Borrega 2011). That might be the reason for the increasing slightly of the modulus of elasticity and compression strength parallel to grain at the heating temperature of 170°C or 185°C. But the effect is replaced by the degradation resulted in the sharp losses of bending strength, modulus of elasticity, compression strength parallel to grain, and impact bending strength.

The effect of heat treatment on color changes and surface glossiness of rubber wood was shown in Tab. 3. With the increase of temperature and duration, the surface glossiness was decreased slightly, while the GZL was about twice stronger than GZT. A similar result on color change was observed. The constant rise of value ΔE and decline of value L* suggested that the surface of rubber wood became darker and the color change became larger with the higher temperature and longer duration. And it changed towards a red color and then back towards a green color, the turning point was 200°C. the yellow-blue chromaticity parameters b* had a similar change that it changes towards a yellow color initially and then back towards a blue color, but the turning point was 185°C. In conclusion, heat treatment affected the color significantly and the major influence factor is temperature. Kučerová et al. (2016) also found the similar color change, but his turning point was 200°C in yellow-blue chromaticity. The color change might be correlated with the disintegration of lignin and the formation of carbonyl groups in the process of heat treatment.

Tab. 3: The effect of heat treatment on the surface characteristic of rubberwood.

Temperature (°C)	Duration (h)	Color				Surface glossiness (GU)	
		L*	a*	b*	ΔE	GZL	GZT
-	0	76.16±2.45	7.69±1.14	20.36±1.79	/	4.38±0.60	2.83±0.25
170	1.5	63.30±2.61	10.47±3.67	21.38±1.84	13.74±2.53	3.62±0.25	2.03±0.09
	3	62.27±1.40	10.76±0.87	22.39±1.44	14.46±1.76	3.59±0.34	1.93±0.25
185	1.5	61.10±1.85	11.53±0.52	21.62±1.08	15.64±1.76	3.57±0.46	1.77±0.15
	3	60.46±2.44	11.79±0.38	22.65±0.41	16.41±2.34	3.25±0.26	1.65±0.12
200	1.5	45.20±0.81	12.92±12.92	16.77±1.00	31.64±1.10	3.17±0.22	1.55±0.43
	3	45.14±0.77	13.34±0.96	17.32±0.75	31.70±0.59	3.03±0.37	1.45±0.33
215	1.5	41.90±1.47	12.94±0.96	15.66±0.61	34.99±1.56	2.90±0.30	1.43±0.23
	3	40.55±0.77	12.79±1.00	13.94±1.90	36.58±3.70	2.83±0.50	1.42±0.34
230	1.5	34.18±2.92	6.85±2.70	11.79±2.66	42.96±3.49	2.70±0.66	1.28±0.32
	3	32.94±2.79	7.89±1.31	10.24±2.39	44.44±3.22	2.57±0.20	0.88±0.12

Date represent mean value ± standard deviations.

The relationships between bending strength and surface characteristics

The mathematic relationship between bending strength and ΔE for spruce wood have been studied by Bekhta and Niemz (2003). He found their strong negative linear correlation with the value of coefficient of determination (r2) about 0.99.

In this study, the relationships between bending strength and the surface characteristic (lightness, the chromaticity parameters a*, b*, ΔE, GZL and GZT) were delved deeply, and the results shown in Fig. 1. The bending strength had a strong correlation with the surface characteristic, except the chromaticity parameters a* with the low value of coefficient of determination (r2=0.025392). A good linear correlation was found between bending strength and the other factors such as lightness, the chromaticity parameters b*, ΔE, GZL, and GZT. The value of their coefficient of determination was 0.90217, 0.78506, 0.90407, 0.892141, 0.88064, respectively. And ΔE is the most suitable characteristic to estimate bending strength and the coefficient of determination was 0.90407 shown in Fig. 1, and Eq. 2.

$$\textit{Bending strength} = 1.193 \times \Delta E + 91.2051 \ (r^2=0.90407) \text{ MPa} \quad (2)$$

The relationships between modulus of elasticity and surface characteristics

The surface characteristic and modulus of elasticity of rubberwood were disposed by Linear Regression Analyze of MATLAB, and the results were shown in Fig. 2. The surface characteristic was positively correlated with modulus of elasticity except for ΔE. The value of modulus of elasticity decreased with the trend of the darker and greener and bluer color changes.

According to these results, the chromaticity parameters b* can describe modulus of elasticity, and the value of coefficient of determination was 0.83979. Their relationship was shown in Eq. 3.

$$Modulus\ of\ elasticity = 209.9185 \times b^* + 2535.9153\ (r^2=0.83979)\ \text{MPa} \quad (3)$$

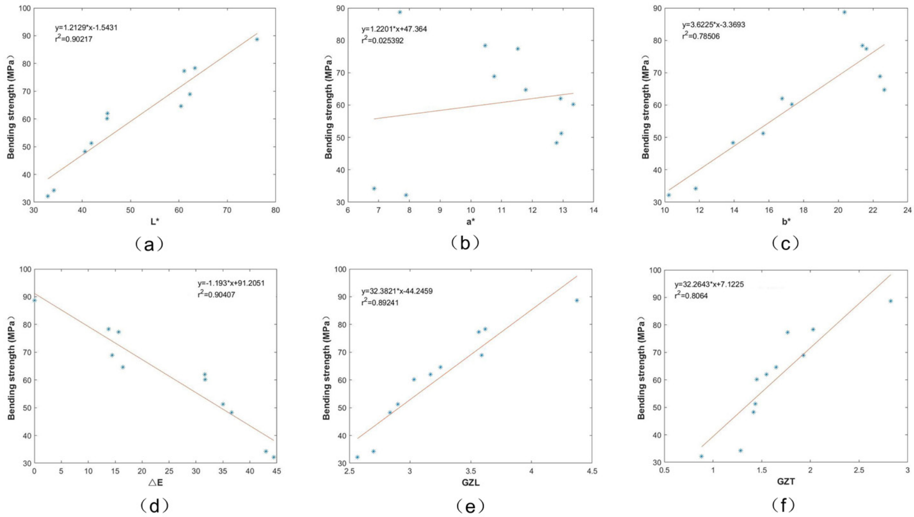

Fig. 1: Relationships between bending strength and surface characteristics of heat-treated Rubber: (a) L (b) a* (c) b* (d) ΔE (e) GZL and (f) GZT.*

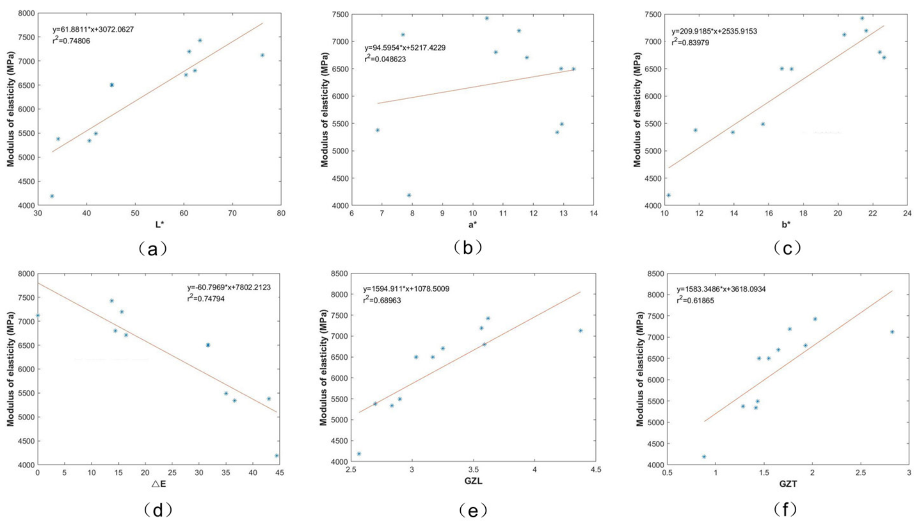

Fig. 2: Relationships between modulus of elasticity and surface characteristics of heat-treated Rubber: (a) L, (b) a*, (c) b*, (d) ΔE, (e) GZL, and (f) GZT.*

The relationships between compression strength parallel to grain and surface characteristics

After analyzing the data from Tabs. 1 and 2 by regression statistics, A linear regression equation was established and correlations were examined as well. The results can be seen in Fig. 3.

The values of coefficient of determination between compression strength parallel to grain and the factors which including lightness, the chromaticity parameters a*, b*, ΔE, GZL, and GZT was 0.80998, 0.03988, 0.89408, 0.80774, 0.72168, and 0.59795, respectively. The chromaticity parameters b* can also evaluate well compression strength parallel to grain used by Eq. 4.

$$\textit{Compression Strength parallel to grain} = 1.0895 \times b^* + 22.2805 \ (r^2 = 0.89408) \text{ MPa} \quad (4)$$

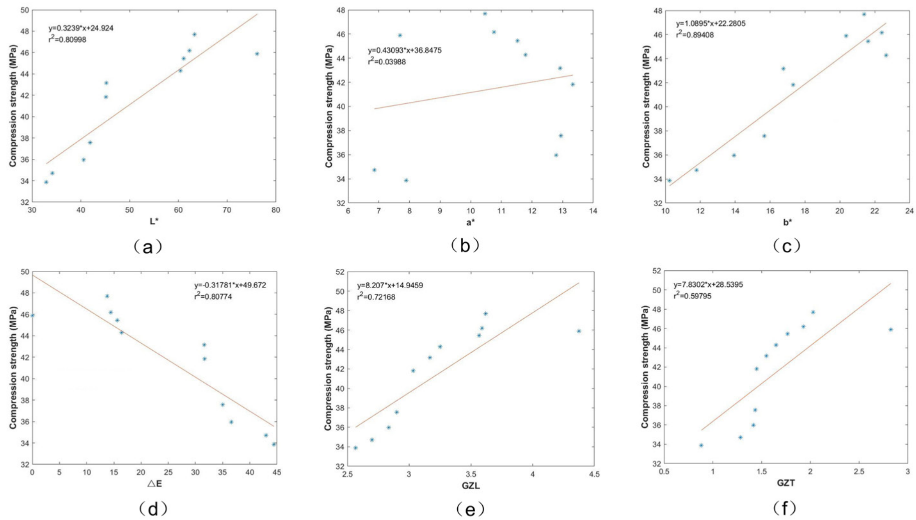

Fig. 3: Relationships between compression strength parallel to grain and surface characteristics of heat-treated Rubber: (a) L, (b) a*, (c) b*, (d) ΔE, (e) GZL, and (f) GZT.*

The relationships between impact bending and surface characteristics

There was a difference for the prediction model of impact bending compared with other mechanical properties shown as Fig. 4.

$$\textit{Impact Bending} = 23.3546 \times GZT + 8.6672 \ (r^2=0.94963) \text{ kJ·m}^{-2} \quad (5)$$

The lower correlations were observed between the chromaticity parameters b* and impact bending, and the value of coefficient of determination was only 0.35077. But the surface glossiness has stronger relevancy with impact bending compared with the other surface characteristic and the values of coefficient of determination were over 0.90 ($r^2>0.9$). The GZT was fitter to predict the impact bending compared with GZL. Eq. 5 was used to predict the impact bending.

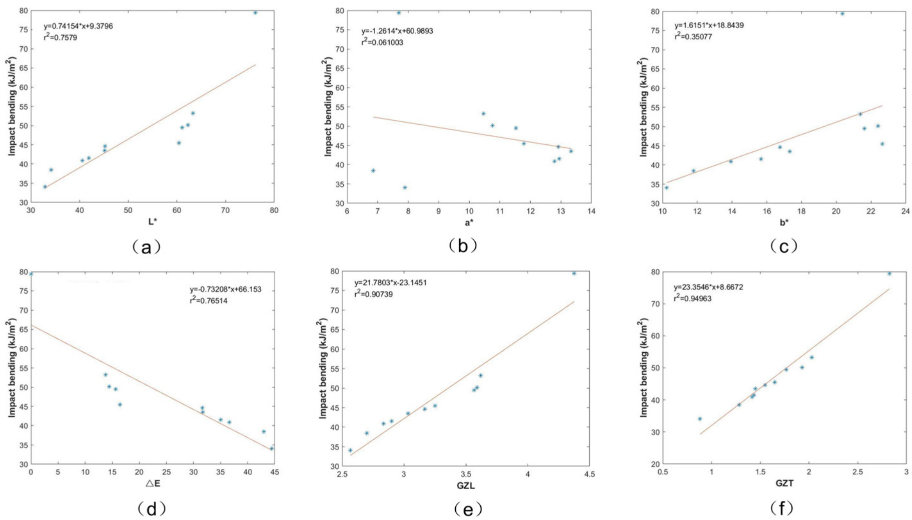

Fig. 4: Relationships between impact bending and surface characteristics of heat-treated Rubber: (a) L, (b) a*, (c) b*, (d) ΔE, (e) GZL, and (f) GZT.*

CONCLUSIONS

This study investigated the influences of thermally-modified treatment on physical and mechanical properties of rubberwood. According to this research, the values of all mechanical properties were reduced and the color of wood changed darker with the higher temperature and longer duration.

And this study provided a new idea to achieve the mechanical properties detection without destruction through establishing mathematical relations between the mechanical properties and surface characteristic. It was found that the ΔE can predict the bending strength, and the chromaticity parameters b* was more suitable to evaluate modulus of elasticity and compression strength, and the GZT was fitter to estimate impact bending.

To improve this research and gain more comprehensive applied ranges, the dimensional stability and surface wettability should be evaluated using by surface characteristic. And the precision of mathematical model must be considered.

ACKNOWLEDGEMENT

The authors are very grateful that this research was financially supported by the Guangdong government science and technology project of “Integration and demonstration of the key technology of comprehensive processing and utilization of Thailand’s rubberwood” (2017A050501030).

REFERENCES

1. Bekhta, P., Niemz, P., 2003: Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood, Holzforschung 57(5): 539-546.
2. Borrega, M., 2011: Mechanisms affecting the structure and properties of heat-treated and high-temperature dried Norway spruce (*Picea abies*) wood, Science 295(3): 170-177.
3. Cademartori, P.H., Missio, A.L., Mattos, B.D., Gatto, D.A., 2015: Effect of thermal treatments on technological properties of wood from two Eucalyptus species, Anais Da Academia Brasileira De Ciências 87(1): 471.
4. Chen, Y., Fan, Y., Gao, J., Stark, N.M., 2012: The effect of heat treatment on the chemical and color change of black locust (*Robinia pseudoacacia*) wood flour. Bioresources 7(1): 1157-1170.
5. Esteves, B., Velez, M.A., Domingos, I., Pereira, H., 2008: Heat-induced color changes of pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood, Wood Science & Technology 42(5): 369-384.
6. Esteves, B.M., Pereira, H.M., 2009: Wood modification by heat treatment: a review, Bioresources 4(1): 370-404.
7. GB/T 1935-2009, 2009: Method of testing in compressive strength parallel to grain of wood.
8. GB/T 1936.1-2009, 2009: Method of testing in bending strength of wood.
9. GB/T1936.2-2009, 2009: Method for determination of the modulus of elasticity in static bending of wood.
10. GB/T 1940-2009,2009: Method of testing in toughness of wood.
11. Hao, Y., Pan, Y., Du, R., Wang, Y., Chen, Z., Zhang, X., Wang, X., 2018: The influence of a thermal treatment on the decay resistance of wood via FTIR analysis, Advances in Materials Science & Engineering 2018(1): 1-7.
12. He, M., Di, M., 2015: Using non-destructive testing to determine the correlation between dynamic mechanical properties and bonding strength of wood-plastic composite adhesive joints, Bioresources 10(3).
13. Joma, E., Schmidt, G., Gonçalves Cremonez, V., Venson, I.; Simetti, R., 2017: The effect of heat treatment on wood-water relationship and mechanical properties of commercial uruguayan plantation timber *Eucalyptus grandis*, Social Science Electronic Publishing 10(1): 704-708.
14. Kačíková, D., Kačík, F., Čabalová, I., Ďurkovič, J., 2013: Effects of thermal treatment on chemical, mechanical and colour traits in Norway spruce wood, Bioresource Technology 144(4): 669-674.
15. Kesik, H.I., Korkut, S., Hiziroglu, S., Sevik, H.,2014: An evaluation of properties of four heat treated wood species, Industrial Crops & Products 60(1): 60-65.
16. Korkut, S., 2008: The effects of heat treatment on some technological properties in Uludağ fir (*Abies bornmuellerinana* Mattf.) wood, Building & Environment 43(4): 422-428.
17. Korkut, S., Aytin, A., 2015: Evaluation of physical and mechanical properties of wild cherry wood heat-treated using the thermowood process, Maderas Ciencia Y Tecnología 17: 171-178.
18. Kučerová, V., Lagaňa, R., Výbohová, E., Hýrošová, T., 2016: The effect of chemical changes during heat treatment on the color and mechanical properties of fir wood, bioresources 11(4): 9079-9094.

19. Michaloudaki, M., Lehmann, E., Kosteas, D., 2005: Neutron imaging as a tool for the non-destructive evaluation of adhesive joints in aluminium, International Journal of Adhesion & Adhesives 25(3): 257-267.
20. Priadi, T., Hiziroglu, S., 2013: Characterization of heat treated wood species, Materials & Design 49: 575-582.
21. Sarni, F., Moutounet, M., Puech, J.L., Rabier, P., 1990: Effect of heat treatment of oak wood extractable compounds, Holzforschung - International Journal of the Biology, Chemistry, Physics and Technology of Wood 44(6): 461-466.
22. Sivonen, H., Maunu, S.L., undholm, F., ämsä, S.,Viitaniemi, P., 2002: Magnetic resonance studies of thermally modified wood. Holzforschung 56(6): 648-654.
23. Tomak, E.D., Ustaomer, D., Yildiz, S., Pesman, E., 2014: Changes in surface and mechanical properties of heat treated wood during natural weathering, Measurement 53(7): 30-39.
24. Vernois, M., 2007: Heat treatment of wood in france –state of the art, Ww2. eventrebels. com.
25. Xie, Y.J., Liu, Y.X., Sun, Y.X., 2002: Heat-treated wood and its development in Europe, Journal of Forestry Research 13(3): 224-230.
26. Yang, Y., Dong, C., Luo, B., Chen, T., Lu, J., 2018: Characterization of wood surface elemental compositions after thermo-vacuum treatment and superheated-steam heat treatment, Bioresources 13(1): 1895-1908.
27. Yildiz, S., Gezer, E.D., Yildiz, U.C., 2006: Mechanical and chemical behavior of spruce wood modified by heat, Building & Environment 41(12): 1762-1766.
28. Yildiz, S., Tomak, E.D., Yildiz, U.C., Ustaomer, D., 2013: Effect of artificial weathering on the properties of heat treated wood, Polymer Degradation & Stability 98(8): 1419-1427.
29. Yu, G., Hu, Y., Gu, J., Wang, Q., 2012: Reliability analysis of wood-plastic planks based on predicted modulus of rupture, Bioresources 7(4): 5710-5718.

Xiangyu Zhao, *Dengyun Tu, Chuanfu Chen, Qiangfang Zhou Xiangyu Zhao
South China Agricultural University
College of Materials and Energy
Guangzhou
China
*Corresponding author: tudengyun@scau.edu.cn
Phone: +86-138-0242-6446