Comparison of Stiffness and Strength Properties of Untreated and Heat-Treated Wood of Douglas Fir and Alder

Vlastimil Borůvka, Aleš Zeidler,* and Tomáš Holeček

This paper investigates the effect of heat treatment temperature on the stiffness and strength properties of Douglas fir *(Pseudotsuga menziesii* Franco) and common alder (*Alnus glutinosa* Gaertn.) woods. Two temperatures of heat treatment were used: 165 and 210 °C. The effects of dynamic elasticity modulus, static elasticity modulus, impact toughness, bending strength, and density were evaluated. It is already understood that the mechanical properties, primarily the bending strength, decreases with increasing temperature. In contrast to the favorable stability in shape and dimension that was achieved, the changes in the woods' properties with temperature were mostly negative. Higher heat treatment temperatures corresponded with lower stiffness and strength properties. For higher temperature treatments, above 200 °C, deterioration of the tested properties was noticable as a result of the significant changes in the wood chemical structure. Even the positive effect of the equilibrium moisture decrease was not able to counterbalance the unfavorable changes. Moreover, it was observed that as the hemicellulose content is higher in alder wood, density, static bending strength, and toughness all decreased steadily at high temperatures, compared to Douglas fir wood.

Keywords: Heat treatment; Thermowood properties; Dynamic and static elasticity moduli; Impact toughness; Bending strength; Density

*Contact information: Department of Wood Processing, Czech University of Life Sciences in Prague, Kamýcká 1176, Praha 6 - Suchdol, 16521 Czech Republic; *Corresponding author: zeidler@fld.czu.cz*

INTRODUCTION

Heat-treated wood is a well known material that is commonly utilized in industry. The heat treatment method changes, by means of appropriate action of the heat, some of the wood's properties that are important from the view of its specific utilisation. The process does not use any chemicals, which is one of its many advantages. This aids in retaining the natural character of the wood. Thermowood has been utilized for several years, primarily in Western Europe. The most extensive and complete study of the wood heat treatment process took place in Finland. Heat-treated wood typically has a longer lifetime; therefore, it is a material suitable for outdoor exposure with no ground contact (ITA 2003; Barcík *et al*. 2014).

The influencing factors that affect the chemical reactions of the wood components during the heat treatment process (Fig. 1, Kačíková and Kačík 2011) include the wood species, ambient pressure, heat supply intensity, oxygen access to wood, and the wood's initial moisture content (Reinprecht and Vidholdová 2008, 2011). The heat treatment process (for Thermowood production), utilizing only wood and steam, changes the wood's internal structure (Gaff and Gašparík 2013; Gašparík and Gaff 2013). This causes a significant reduction in the hygroscopicity (up to 50%). Wood treated with this method achieves high structural and dimensional stability (Bekhta and Niemz 2003; ITA 2003; Calonego *et al*. 2012; Kvietková *et al*. 2015). On the other hand, the mechanical properties tested in these studies mostly reveal the negative impacts of increasing temperature during the heat treatment process (Borrega and Kärenlampi 2007; Shi *et al*. 2007; Sonderegger *et al*. 2007; Johansson 2008; Barcík and Gašparík 2014; Schneid *et al*. 2014). The changing in mechanical properties of wood mainly depends on the species and treatment degree. In the above-listed literature it is pointed out that at highest degrees of heat treatment, decreases of bending strength of conifer wood by approximately 20% (or by 40% in the case of decidious wood) is observed. The decrease in strength for the dynamic type of such load, which means toughness, can be even more significant. The decrease of static elasticity moduli can be 5%. A partial increase in most of the property values at lower heat treatment degree (160 - 170 ºC), or their preservation at the level of untreated wood cause the less significant chemical changes in wood, which lead only to the limitation of wood ability to bind the water.

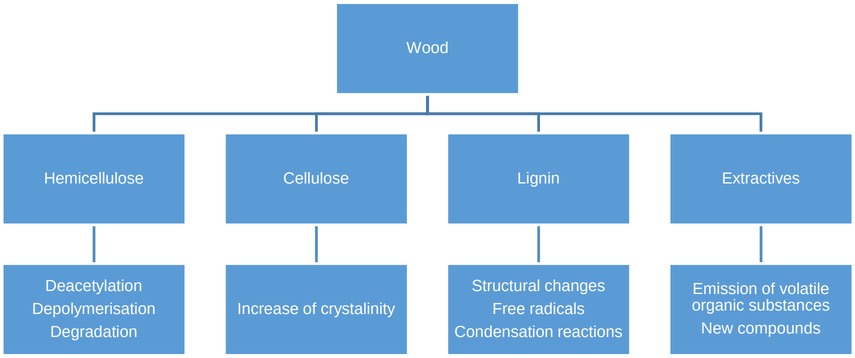

Fig. 1. Chemical changes of the main components in wood during the heat treatment

The aim of this study was to extend the database of stiffness and strength characteristics for the thermally modified wood of Douglas fir and common alder, and their mutual comparison. From the view of wood utilisation, these characteristics are essential to set limiting conditions for proper usage and protection of individual timbers, including the proper degree of heat treatment to ensure required properties.

EXPERIMENTAL

Materials

The testing material originated from tree trunks from the Školní Lesní Podnik (Forest Establishment) of the Czech University of Life Sciences in Kostelec nad Černými Lesy. Douglas fir (*Pseudotsuga menziesii*) and common alder (*Alnus glutinosa* Gaertn.) wood were processed into rectangular solids with dimensions of 25 mm × 50 mm × 1000 mm (R×T×L). Six test pieces with dimensions of 20 mm × 20 mm × 300 mm were cut from each piece to determine the longitudinal parallelism of the test samples with the samples chosen for two degrees of the heat treatment.

Transversal parallelism for two sets of tests (always a sample designed for the determination of density and toughness, underneath a sample on dynamic elasticity

Bořvka *et al*. (2015). “Heat-treated wood,” ***BioResources*** 10(4), 8281-8294. 8282

modulus, static elasticity modulus, and bending strength) enables mutual comparison. See the cutting diagram in Fig. 2.

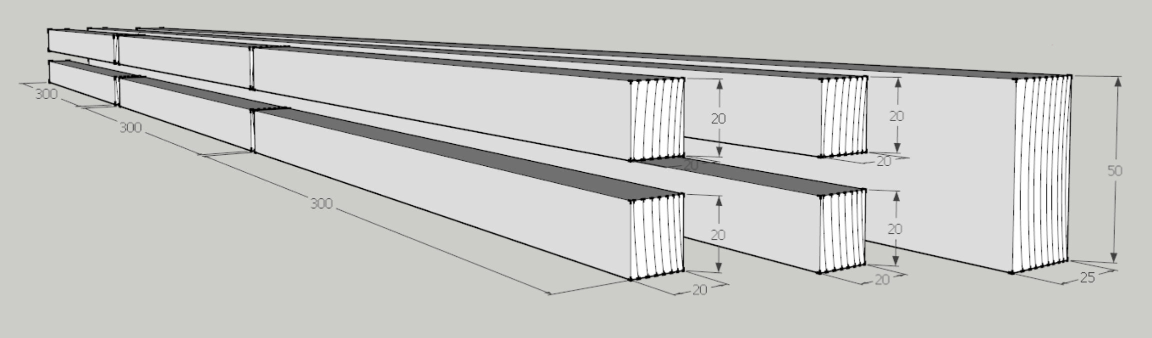

Fig. 2. Cutting diagram for testing sample preparation

A total of 180 test sections of the samples were divided into sets of 30 (two treatment temperature degrees and two wood species). The physical requirements for the samples were as follows: no knots, cracks, or reaction wood, as well as minimum angle of fiber declination in the bending plane (< 5°).

Subsequently, the samples were conditioned, to stabilize the equilibrium moisture content, inside of a Climacell 707 conditioning chamber (BMT Medical Technology Ltd., Czech Republic) at 20 ± 2 °C and a relative humidity of 65 ± 5%.

Afterwards, one third of the test samples was subjected to the first degree of heat treatment, in an air atmosphere at 165 °C, and the second third of the samples were heat-treated at 210 °C, in accordance with the Finnish technology for the wood heat treatment (Pat. EP-0759137 in Viitaniemi *et al.* 1998). The preparation of the testing samples took place inside a lab high-temperature chamber A type KHT (Katres Ltd., Czech Republic) (Fig. 3).

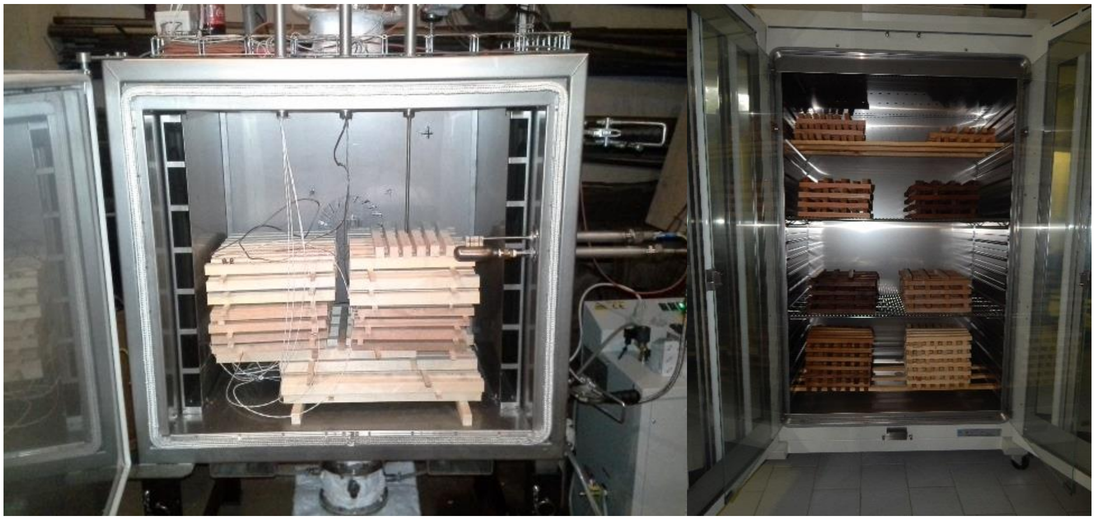

Fig. 3. Samples in position before the treatment in the chamber (left) and their conditioning after heat treatment (right)

A detailed preparation procedure is shown in Fig. 4. Subsequently, the test samples were conditioned again, to stabilize the equilibrium moisture content at 20 ± 2 °C and a relative humidity of 65 ± 5% (Fig. 3).

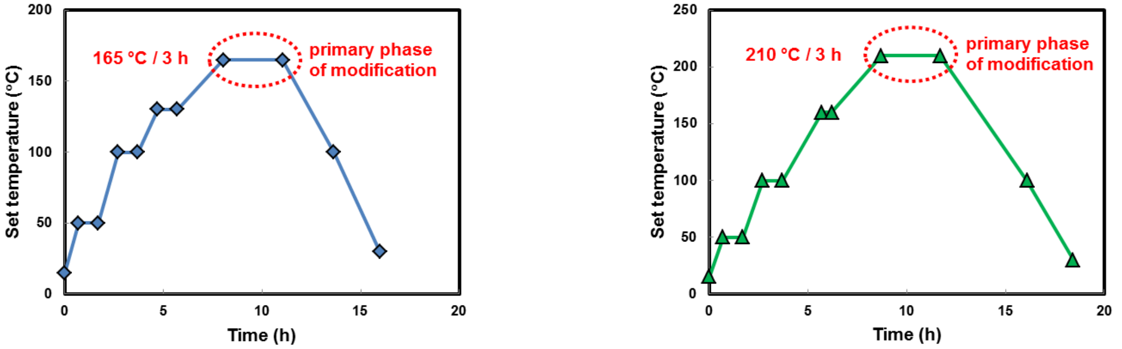

Fig. 4. Diagram representation of the heat treatment procedure at 165 °C (left) and at 210 °C (right)

Douglas fir and alder woods were chosen intentionally for the scope of this research. These species are relevant representatives of conifer and deciduous wood species with similar densities (Table 1) (Podrázský *et al.* 2013).

Table 1. Properties of Douglas Fir and Alder Woods

	Wood species[1]			
	Douglas fir		Alder	
	Min.	Max.	Min.	Max.
Density (g/cm^3)	0.350	0.750	0.490	0.640
Toughness - impact bending strength (J/cm^2)	3.8	6.0	2.5	10.8
Static modulus of elasticity (MPa)	11200	13500	7700	11700
Modulus of rupture – bending strength (MPa)	68	89	44	172

[1] Moisture content was between 12% and 15% (Wagenführ 2000)

Methods

The impact toughness (breaking power) is defined as the ability of wood to absorb the power of impact bending. The aim of this test was to determine the power consumed for the wood rupture (breaking point) under controlled conditions. Charpy's hammer (CULS, Czech Republic) was used for this determination. The hammer impact direction was tangential.

The following formula was used to calculate the impact toughness,

$$A_w = \frac{W}{b\,h} \tag{1}$$

where A_w is the impact toughness at the moisture content during the test time in J.cm^{-2}, W is the power consumed for the wood rupture in J, and b and h are the wood transversal dimensions in cm.

The wood bending strength is the stress corresponding to the test sample rupture caused by the combined forces with momentum at the plane perpendicular to the cross section. For the action of a single force in the center of the supports, the bending strength was calculated according to the following formula,

$$\sigma_{pohw} = \frac{3 \cdot F_{max} \cdot l_0}{2 \cdot b \cdot h^2} \tag{2}$$

where σ_{pohw} is the bending strength at the moisture content during the test time in MPa, F_{max} is the force corresponding to the breaking strength in N, l_0 is the distance between supports in mm, and b and h are the width and height dimensions, respectively, in mm.

A theoretical basis for the determination of the bend elasticity modulus is the differential equation of the bending curve, as follows (Požgaj *et al.* 1997),

$$\frac{\mathrm{d}^2 y}{\mathrm{d}x^2} = \frac{M}{E \cdot I} \tag{3}$$

where M is the bending momentum, E is the elasticity modulus, and I is the inertia moment.

For the action of a single force in the center of the supports, the static elasticity modulus was calculated according to the following formula,

$$E_{ohw} = \frac{1}{4} \cdot \frac{\Delta F \cdot l_0^3}{b \cdot h^3 \cdot \Delta y} \tag{4}$$

where E_{ohw} is the elasticity modulus at the moisture content during the test time in MPa, ΔF is the difference between the forces at maximum and minimum load limits in N, l_0 is the distance between the supports in mm, b and h are the width and height dimensions, respectively, in mm, and Δy is the test sample deflection in the area of pure bending, equal to the difference between the bending values corresponding to maximum and minimum load limits, in mm.

The static bending tests were carried out on a Tira 50 kN testing machine (Tira GmbH, Germany) (Fig. 5) with support distances of 240 mm, *i.e.*, 12-fold greater than the sample height.

Fig. 5. TIRA 50 kN testing machine (left), a rupture of heat-treated wood under the bending load (top right), and Fakopp Ultrasonic Timer instrument (bottom right)

The dynamic elasticity modulus was calculated as follows (Požgaj *et al.* 1997),

$$E_d = c^2 \cdot \rho \tag{5}$$

where E_d is the dynamic elasticity modulus in MPa, c is the speed of sound in m.s^{-1}, and ρ is the wood density in kg.m^{-3}. We used a Fakopp Ultrasonic Timer instrument (Fakopp Enterprise Bt., Hungary) (Fig. 5).

A reading for the wood density determination was taken from each test sample after the experiment. The density was calculated as follows,

$$\rho_w = \frac{m_w}{V_w} \tag{6}$$

where ρ_w is the wood density at the moisture content during the testing time in g.cm^{-3}, m_w is the wood mass at the moisture content during the testing time in g, and V_w is the wood volume at the moisture content during the testing time in cm^3.

After the samples were dried to zero percent moisture in a Binder FD 115 lab kiln (Binder Inc., Germany) at 103 ± 2 °C, the wood moisture content was calculated according to the following formula,

$$w_a = \frac{m_w - m_0}{m_0} \cdot 100 \tag{7}$$

where w_a is the sample's moisture content in %, m_w is the sample's mass at a certain moisture content in g, and m_0 is the sample's dry mass in g.

All of the test samples were conditioned under standardized conditions in a conditioning chamber with a relative humidity of 65 ± 5% and a temperature of 20 ± 2 °C to obtain 12% equilibrium moisture content for the solid, untreated wood. The heat-treated wood exhibited a lower moisture content under these conditions depending on the degree of the heat treatment. All tests were carried out completely in accordance with the testing standards (ČSN 49 0103 (1979), ČSN 49 0108 (1993), ČSN 49 0115 (1979), ČSN 49 0116 (1982), and ČSN 49 0117 (1980)), and the determination of the dynamic elasticity modulus was based on the methodology specified in the Fakopp instrumentation manual.

For statistical analysis ANOVA (two-factors) was used to evaluate the significance of individual factors. Linear regression model was used to set the degree of correlation of selected factors. For all analysis the same significance level $\alpha = 0.01$ (alternatively $\alpha = 0.05$) was employed.

RESULTS AND DISCUSSION

Tables 2 and 3 summarize the statistical data for the physical and mechanical properties of both wood species after the heat treatment. It is also evident from Table 1 that the evaluated properties of native wood corresponded to those presented in literature for the tested properties. The data obtained from this study were subjected to the statistical analysis (Tables 4 to 8; Figs. 6A to 6E). The end of this section contains more detailed analysis; however, it is worth mentioning that a drastic decrease in the bending strength was observed at higher treatment temperatures for alder wood, while an insignificant impact of the heat treatment temperature was observed for the static eleasticity modulus. This paper includes the results of a two-factor analysis; however, the wood species impact was obvious, *i.e.*, the results of a single-factor (heat treatment) analysis would be sufficient. At the same time, the existence of correlation between static and dynamic elasticity moduli has been confirmed (Dinwoodie 2000), taking into account the relation of all samples (both the reference and the heat-treated samples); see Fig. 6F.

Table 2. Basic Statistical Analyses of the Mechanical Properties for Untreated and Heat-Treated Douglas Fir Wood

	Heat treatment degree	Number of measurements	Mean	Median	Minimum	Maximum	Standard deviation	Coefficient of variation (%)
Density (g/cm^3)	1	60	0.596	0.599	0.536	0.633	0.025	4.2
	2	60	0.589	0.591	0.533	0.636	0.025	4.3
	3	60	0.575	0.578	0.507	0.619	0.026	4.5
Toughness - impact bending strength (J/cm^2)	1	30	8.9	8.7	6.8	11.6	1.4	15.7
	2	30	8.7	8.5	4.9	12.5	1.8	20.2
	3	30	5.8	5.7	3.9	7.9	1.1	18.5
Dynamic modulus of elasticity (MPa)	1	30	16696	16616	12092	21454	2558	15.3
	2	30	23683	24300	15290	31311	4240	17.9
	3	30	19140	18771	14808	22441	2147	11.2
Static modulus of elasticity (MPa)	1	30	12625	12335	10269	15628	1777	14.1
	2	30	13259	13329	11288	15490	1174	8.9
	3	30	13309	13176	10122	16576	1695	12.7
Modulus of rupture - bending strength (MPa)	1	30	92.1	86.3	70.0	130.0	17.8	19.4
	2	30	95.3	90.4	68.3	143.2	17.5	18.4
	3	30	84.9	73.8	59.5	134.5	22.9	26.9
Moisture content (%)	1	60	11.5	11.5	11.2	12.3	0.3	3.0
	2	60	7.7	7.7	5.4	8.6	0.5	6.0
	3	60	6.2	6.2	5.6	7.0	0.3	5.2

Heat treatment degree: 1 = reference, with no treatment, 2 = heat treatment at 165 °C, 3 = heat treatment at 210 °C

Generally a more significant influence of heat treatment was shown with respect to the properties of alder wood than for Douglas fir wood (Table 9). The most significant changes by using heat treatment were achieved for toughness by using a higher temperature of heat treatment.

A decrease in the case of Douglas fir wood by 34% and for alder wood by 63% was observed in comparison to untreated wood. Further significant changes were achieved at bending strength while using higher heat treatment degree, specifically the decrease by 45% was observed for alder wood and only by 8% for Douglas fir wood in comparison to untreated wood. The general trend corresponds with the results specified for example in ITA 2003 and Johansson 2008. Factors explaining the difference between the two tree species are described below.

Table 3. Basic Statistical Analyses of the Mechanical Properties for Untreated and Heat-Treated Alder Wood

	Heat treatment degree	Number of measurements	Mean	Median	Minimum	Maximum	Standard deviation	Coefficient of variation (%)
Density (g/cm^3)	1	60	0.570	0.568	0.507	0.642	0.032	5.6
	2	60	0.557	0.549	0.498	0.654	0.037	6.6
	3	60	0.511	0.513	0.423	0.580	0.031	6.0
Toughness - impact bending strength (J/cm^2)	1	30	3.7	3.9	0.7	6.5	1.5	39.7
	2	30	3.5	3.5	1.0	6.8	1.1	31.0
	3	30	1.4	1.3	0.3	2.8	0.5	39.7
Dynamic modulus of elasticity (MPa)	1	30	8290	8017	5490	11524	1670	20.1
	2	30	10879	10819	4906	14909	2353	21.6
	3	30	9485	9966	5743	13318	1886	19.9
Static modulus of elasticity (MPa)	1	30	8034	7959	5222	10158	1233	15.3
	2	30	8207	8221	4115	10024	1113	13.6
	3	30	7664	7846	5275	10119	1156	15.1
Modulus of rupture - bending strength (MPa)	1	30	78.2	77.9	34.9	107.6	15.0	19.2
	2	30	77.7	79.6	36.4	99.8	13.0	16.7
	3	30	43.0	44.2	24.4	76.8	11.7	27.3
Moisture content (%)	1	60	11.6	11.6	11.2	12.5	0.3	2.6
	2	60	9.5	9.5	9.0	10.0	0.3	2.9
	3	60	6.4	6.4	5.9	6.8	0.2	3.1

Heat treatment degree: 1 = reference, with no treatment, 2 = heat treatment at 165 °C, 3 = heat treatment at 210 °C

Table 4. Analysis of Variance for Wood Density

Monitored factor	Sum of Squares	Degree of Freedom	Variance	Fisher´s F-test	Significance Level
Intercept	119.0299	1	119.0299	136321.1	$P < 0.01$
1 - Wood species	0.1529	1	0.1529	175.1	$P < 0.01$
2 - Heat treatment degree	0.1080	2	0.0540	61.8	$P < 0.01$
1*2	0.0260	2	0.0130	14.9	$P < 0.01$
Error	0.3196	360	0.0009		

Significance was accepted at $P < 0.01$

Table 5. Analysis of Variance for Impact Toughness

Monitored factor	Sum of Squares	Degree of Freedom	Variance	Fisher´s F-test	Significance Level
Intercept	5264.227	1	5264.227	3195.261	*P* < 0.01
1 - Wood species	1136.122	1	1136.122	689.599	*P* < 0.01
2 - Heat treatment degree	277.620	2	138.810	84.254	*P* < 0.01
1*2	5.457	2	2.728	1.656	*P* = 0.19
Error	296.552	180	1.648		

Significance was accepted at P < 0.01

Table 6. Analysis of Variance for Dynamic Elasticity Modulus

Monitored factor	Sum of Squares	Degree of Freedom	Variance	Fisher´s F-test	Significance Level
Intercept	4.013E+10	1	4.013E+10	5789.125	*P* < 0.01
1 - Wood species	4.917E+09	1	4.917E+09	709.376	*P* < 0.01
2 - Heat treatment degree	7.235E+08	2	3.618E+08	52.192	*P* < 0.01
1*2	1.592E+08	2	7.958E+07	11.481	*P* < 0.01
Error	1.248E+09	180	6.931E+06		

Significance was accepted at P < 0.01

Table 7. Analysis of Variance for Static Elasticity Modulus

Monitored factor	Sum of Squares	Degree of Freedom	Variance	Fisher´s F-test	Significance Level
Intercept	2.055E+10	1	2.055E+10	10616.86	*P* < 0.01
1 - Wood species	1.206E+09	1	1.206E+09	623.26	*P* < 0.01
2 - Heat treatment degree	5.127E+06	2	2.564E+06	1.32	*P* = 0.27
1*2	8.625E+06	2	4.312E+06	2.23	*P* = 0.11
Error	3.484E+08	180	1.936E+06		

Significance was accepted at P < 0.01

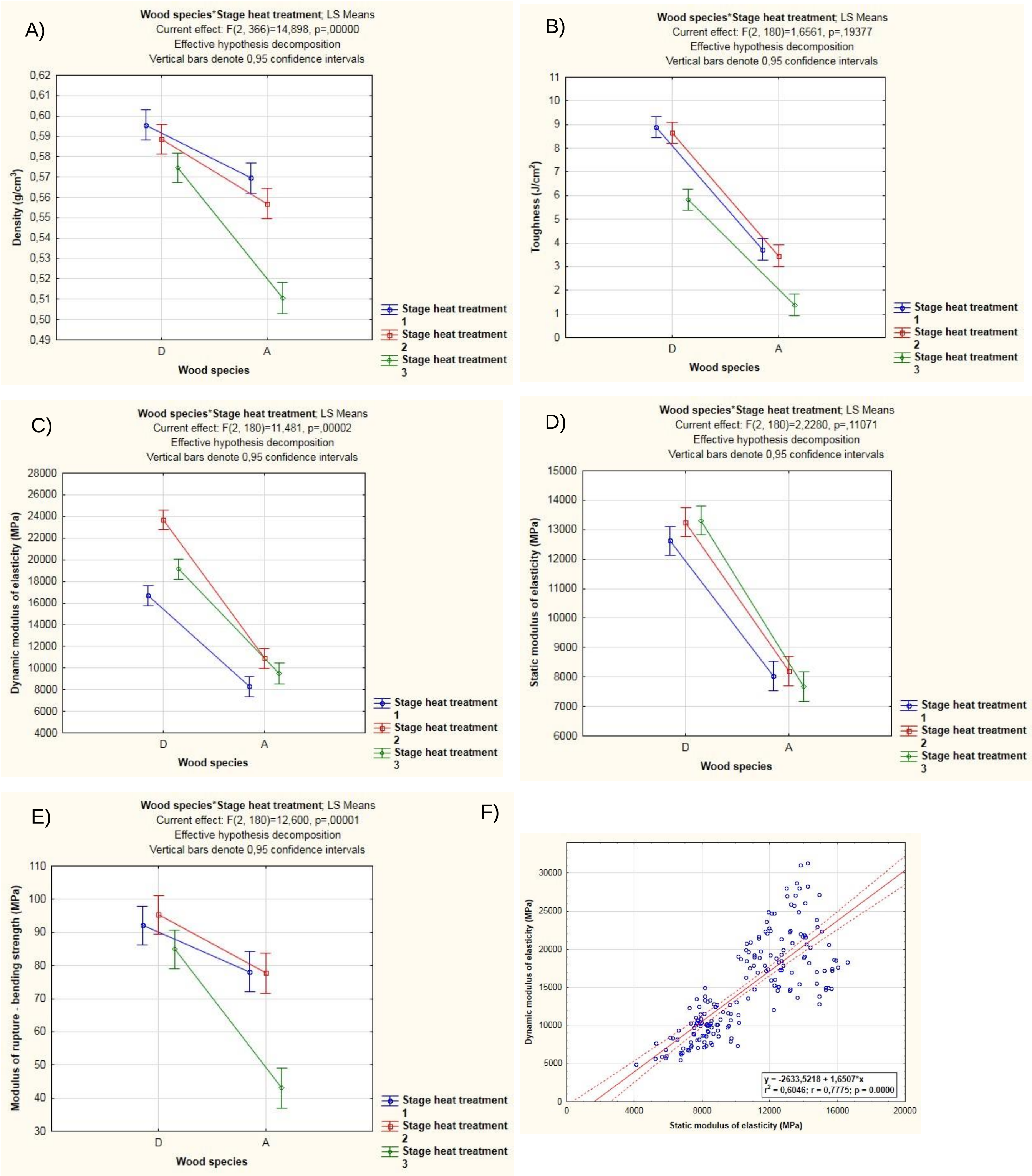

Fig. 6. Graphic visualization of the effect of wood species and heat treatment temperature on A) wood density, B) impact toughness, C) dynamic elasticity modulus, D) static elasticity modulus, and E) bending strength, at a 95% significance level. The relationship between static and dynamic elasticity moduli is shown in F. X-axis: D = Douglas fir and A = alder

Bořůvka *et al*. (2015). "Heat-treated wood," ***BioResources*** 10(4), 8281-8294. 8290

Table 8. Analysis of Variance for Bending Strength

Monitored factor	Sum of Squares	Degree of Freedom	Variance	Fisher´s F-test	Significance Level p
Intercept	1146107	1	1146107	4040.415	*P* < 0.01
1 - Wood species	27845	1	27845	98.163	*P* < 0.01
2 - Heat treatment degree	19796	2	9898	34.893	*P* < 0.01
1*2	7149	2	3574	12.600	*P* < 0.01
Error	51059	180	284		

Significance was accepted at P < 0.01

Table 9. Changes in Wood Property of Heat-treated Wood in Comparison to the Reference (untreated) Wood in %

	Heat treatment degree	Douglas Fir	Alder
Density	2/1	-1	-2
	3/1	-4	-10
Toughness - impact bending strength	2/1	-3	-7
	3/1	-34	-63
Dynamic modulus of elasticity	2/1	42	31
	3/1	15	14
Static modulus of elasticity	2/1	5	2
	3/1	5	-5
Modulus of rupture - bending strength	2/1	3	-1
	3/1	-8	-45

2/1 = heat treatment at 165 °C vs. reference, with no treatment
3/1 = heat treatment at 210 °C vs. reference, with no treatment

It is crucial, with respect to the heat treatment impact on the wood properties, to know that hemicelluloses are the most affected chemical components within this process (ITA 2003). Hemicelluloses consist of mostly pyranose structures. Coniferous species consist mostly of glucomannans, and deciduous species contain mostly xylans. Coniferous species, according to Požgaj *et al.* (1997), contain less hemicelluloses (approximately 23% to 25%) than deciduous species (approximately 26% to 35%). Mannan fractions, which are prevailing in softwood, behave more like a skeleton than filling material of wood. Moreover they have stronger bonds with cellulose than xylans in hardwoods. From the higher content of hemicelluloses in alder wood in comparison to Douglas fir wood, as well as their generally lower strength, the more significant decrease in density, static bending strength, and toughness at alder wood relative to Douglas fir wood was obvious at higher degrees of heat treatment (Figs. 6A and 6E). The differences in trend of these properties between two species at lower heat treatment degree, as well as elasticity moduli at higher treatment degree was not shown.

The disagreement between the static and dynamic moduli, not from the perspective of correlation, which was pretty high (r = 0.78), but from the perspective of increasing rate of parameters‘ values of measured dynamic moduli and static moduli at heat-treated wood was observed. It was shown that there was a greater increase of parameters for dynamic moduli than for static moduli, which can be explained by the differences in wood moisture content, while measuring the dynamic moduli and the static moduli. The passage rate of ultrasonic waves through wood in longitudinal direction is about 5000 m/s and through the water, bound water in this case, is about 1500 m/s (Kollmann and Côte 1968; Bucur 2006). Thus, in case of linear conversion of moduli values on uniform moisture, different conversion moisture coefficients should be applied for these two methods. The verification of this point needs further experiments and investigation. Another factor, influencing the difference in property values between the dynamic and static moduli, is the existence of shear stress in static three-point bending, which is irrelevant for the dynamic modulus set on base of the speed rate passage of ultrasonic waves. The combination of these two factors have a synergistic effect at thermowood.

Overall, it is generally understood that especially the strength properties of wood decrease with increasing heat treatment temperature. Increase of values, mostly insignificant, of majority of the properties at lower temperature degree of the treatment is related to the fact that the chemical changes are not yet so important and thus causing only a reduction of the ability of wood to bind water (Reinprecht and Vidholdová 2008, 2011). A decreased water content in wood in the same environmental conditions is the reason of the above-mentioned finding. This was, obviously, least evident for the dynamic impact test. For higher treatment temperatures, above 200 °C, a reduction in equilibrium moisture did not have a notable influence on the structural properties of wood because the greatest changes occurred in the wood's chemical structure and therefore affected the mechanical properties of wood.

CONCLUSIONS

1. Partial increase in the wood properties at lower temperatures were similar to those of untreated wood. This was related to the fact that the chemical changes have not yet occurred to a significant degree, thus causing only a reduction of the ability of wood to bind water.
2. Higher heat treatment temperatures resulted in lower stiffness and strength properties of heat-treated wood. For heat-treatement temperatures above 200 °C, the decrease of the tested properties was noticable as a result of the significant changes in the wood chemical structure and even positive effect of the moisture content decrease was not able to counterbalance this changes.
3. Apparently, wood with a higher hemicellulose content, *i.e*. a lower overall resistance, exhibits less density, static bending strength, and toughness. Therefore, a more significant decrease was observed for the common alder than for the Douglas fir at higher treatment temperatures. The decrease of toughness by about 63% at alder wood with treated temperatures of 210 ºC was observed in comparison to untreated wood. Bending strength at heat treated alder wood decreased by 45%.
4. Higher strength resistance was observed in Douglas fir than for alder wood with an increasing temperature treatment.
5. There was a significant correlation between static and dynamic elasticity moduli, which accounted for both sets of samples (untreated and heat-treated samples).
6. From the view of wood utilisation, the knowledge of above mentioned facts is important for determination of limiting values to ensure proper and save application of

individual timbers, including the appropriate degree of heat treatment to ensure required properties. From the achieved results it is clearly seen that usage of wood, treated with high temperatures, especially wood of decidious species, is not suitable for construction purposes, because of significant decrease at bending strength and toughness.

ACKNOWLEDGMENTS

The authors are grateful for the grant provided by the National Agency for Agricultural Research project No. QJ1520299. The authors are also grateful for the support of the Internal Grant Agency of the Faculty of Forestry and Wood Sciences, Czech University of Life Sciences, Prague, Project No. 20143127.

REFERENCES CITED

Barcík, Š., and Gašparík, M. (2014). "Effect of tool and milling parameters on the size distribution of splinters of planed native and thermally modified beech wood," *BioResources* 9(1), 1346-1360. DOI: 10.15376/biores.9.1.1346-1360

Barcík, Š., Gašparík, M., and Horejš, P. (2014). "Influence of thermal modification on nail withdrawal strength of spruce wood," *BioResources* 9(4), 5963-5975. DOI: 10.15376/biores.9.4.5963-5975

Bekhta, P., and 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. DOI: 10.1515/HF.2003.080

Bucur, V. (2006). *Acoustics of Wood*, Springer Series in Wood Science.

Borrega, M., and Kärenlampi, P. P. (2007). "Mechanical behavior of heat-treated spruce (Picea abies) wood at constant moisture content and ambient humidity," *Holz als Roh- und Werkstoff* 66(1), 63-69. DOI: 10.1007/s00107-007-0207-3

Calonego, F., Severo, E., and Ballarin, A. (2012). "Physical and mechanical properties of thermally modified wood from *E. grandis*," *European Journal of Wood and Wood Products* 70(4), 453-460. DOI: 10.1007/s00107-011-0568-5

ČSN 49 0103 (1979). "Drevo. Zisťovanie vlhkosti pri fyzikálnych a mechanických skúškach [Wood. Determination of moisture content at physical and mechanical testing]," Vydavatelství Úřadu pro normalizaci a měření, Praha, Česká Republika.

ČSN 49 0108 (1993). "Drevo. Zisťovanie hustoty [Wood. Determination of the density]," Český normalizační institut, Praha, Česká Republika.

ČSN 49 0115 (1979). "Drevo. Zisťovanie medze pevnosti v statickom ohybe [Wood. Determination of ultimate strength in flexure tests]," Vydavatelství Úřadu pro normalizaci a měření, Praha, Česká Republika.

ČSN 49 0116 (1982). "Drevo. Metóda zisťovania modulu pružnosti pri statickom ohybe [Wood. Determination of the modulus of elasticity in static bending]," Vydavatelství Úřadu pro normalizaci a měření, Praha, Česká Republika.

ČSN 49 0117 (1980). "Drevo. Rázová húževnatosť v ohybe [Wood. Impact strength in flexure]," Vydavatelství Úřadu pro normalizaci a měření, Praha, Česká Republika.

Dinwoodie, J. M. (2000). *Timber: Its Nature and Behavior*, Taylor & Francis, New York.

Fakopp Ultrasonic Timer user's guide (https://www.fakopp.com/site/downloads/Ultrasonic_Timer.pdf).

Gaff, M., and Gašparík, M. (2013). "Shrinkage and stability of thermo-mechanically modified aspen wood," *BioResources* 8(1), 1136-1146. DOI: 10.15376/biores.8.1.1136-1146

Gašparík, M., and Gaff, M. (2013). "Changes in temperature and moisture content in beech wood plasticized by microwave heating," *BioResources* 8(3), 3372-3384. DOI: 10.15376/biores.8.3.3372-3384

ITA (2003). *Thermowood Handbook*, International Thermowood Association, Helsinki, Finland.

Johansson, D. (2008). *Heat Treatment of Solid Wood (Effects on Absorption, Strength and Colour)*, Ph.D. dissertation, Luleå University of Technology, Luleå, Sweden.

Kačíková, D., and Kačík, F. (2011). *Chemické a Mechanické Zmeny Dreva pri Termickej Úprave [Chemical and Mechanical Changes of Wood due to the Thermal Modification]*, Technická Univerzita vo Zvolene, Zvolen, Slovakia.

Kvietková, M., Gašparík, M., and Gaff, M. (2015). "Effect of thermal treatment on surface quality of beech wood after plane milling," *BioResources* 10(3) 4226-4238. DOI: 10.15376/biores.10.3.4226-4238

Kollmann, F. F. P., and Côte, W. A. Jr. (1968). *Principles of Wood Science and Technology, I Solid Wood*, Springer – Verlag, Berlín – Heidelberg – New York.

Podrázský, V., Čermák, R., Zahradník, D., and Kouba, J. (2013). "Production of Douglas-fir in the Czech Republic based on national forest inventory data," *Journal of Forest Science* 59(10), 398-404.

Požgaj, A., Chovanec, D., Kurjatko, S., and Babiak, M. (1997). *Štruktúra a Vlastnosti Dreva [Structure and Properties of Wood]*, Príroda AS, Bratislava, Slovakia.

Reinprecht, L., and Vidholdová, Z. (2008). *Termodrevo – Príprava, Vlastnosti a Aplikácie* [*ThermoWood – Preparation, Properties and Applications*], TU Zvolen, Zvolen, Slovakia.

Reinprecht, L., and Vidholdová, Z. (2011). *Termodrevo* [*ThermoWood*], ŠMÍRA-PRINT, Česká Republika.

Shi, J. L., Kocaefe, D., and Zhang, J. (2007). "Mechanical behaviour of Québec wood species heat-treated using ThermoWood process," *Holz als Roh- und Werkstoff* 65(4), 255-259. DOI: 10.1007/s00107-007-0173-9.

Schneid, E., Cademartori, P. H. G. D., and Gatto, D. (2014). "The effect of thermal treatment on physical and mechanical properties of *Luehea divaricata* hardwood," *Maderas, Ciencia y Tecnología* 16(4), 413-422. DOI: 10.4067/S0718-221X2014005000033

Sonderegger, W., Mandallaz, D., and Niemz, P. (2007). "An investigation of the influence of selected factors on the properties of spruce wood," *Wood Science and Technology* 42(4), 281-298. DOI: 10.1007/s00226-007-0173-2

Viitaniemi, P., Ranta-Maunus, A., Jämsä, S., and Ek, P. (1998). "Method for processing of wood at elevated temperatures," *Pat. EP-0759137* VTT, Appl. EP95918005, 11.5.1995. Publ.4.2.1998. 10 pp.

Wagenführ, R. (2000). *Holzatlas*, Fachbuchverlag, Leipzig.

Article submitted: August 13, 2015; Peer review completed: October 5, 2015; Revised version received and accepted: October 12, 20115; Published: October 28, 2015.
DOI: 10.15376/biores.10.4.8281-8294