Properties of Plywood Boards Composed of Thermally Modified and Non-modified Poplar Veneer

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Possibilities for use of thermally modified poplar veneer were evaluated for the production of plywood boards in industrial conditions. Formats of poplar veneer were treated at temperatures of 190 °C, 200 °C, 210 °C, and 215 °C for 1 h. By combining the treated and non-treated formats of veneer, thirteen different types of board were made. Analyses showed that the examined physical and mechanical properties were influenced by both the type of construction and the applied thermal treatment. Boards composed only of thermally modified veneer achieved the best results regarding moisture absorption and dimensional stability, and boards composed of the combined veneers had better mechanical properties. Treatments at 200 °C and 210 °C proved to be optimal, while the treatment at 215 °C was too harsh and should not be used for the thermal modification of poplar veneer.

Keywords: Thermal modification; Poplar wood; Veneer; Plywood

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INTRODUCTION

Numerous scientific studies on the influence of the thermal modification on wood properties indicate that thermal modification leads to a decrease in the equilibrium moisture content (Borrega and Kärenlampi 2010; Ding *et al.* 2011), a decrease in surface hydrophilicity of the treated material (Kocaefe *et al.* 2008a), an increase in dimensional stability (Kocaefe *et al.* 2008b; Korkut and Bektas 2008; Cao *et al.* 2012; Icel *et al.* 2015), and a change of color (Schnabel *et al.* 2007; Gonzales-Pena and Hale 2009; Todorović *et al.* 2012; Lovrić *et al.* 2014), but also to a weakening of the mechanical properties of treated material (Kubojima *et al.* 2001; Shi *et al.* 2007; Poncsak *et al.* 2006). Apart from these changes, thermal modification also improves wood resistance against rot-causing fungi and xylophages insects (Estaves and Pereira 2009; Ohnesorge *et al.* 2009; Rowell *et al.* 2009), which makes it suitable for outdoor usage. Increased durability and resistance of thermally modified wood makes possible the substitution of deficient and expensive wood species with available plantation-grown and inexpensive species, such as poplar.

Studies of thermal treatments have been conducted in two directions. One is based on forming the boards out of thermally treated material and the other on the thermal treatment of already formed boards. Most of them follow the former direction. Boonstra *et al.* (2006) researched the potential use of thermally treated wood chips in the production of medium-density fiberboard (MDF). Paul *et al.* (2007) used thermally treated chips before the production of oriented strand board (OSB).

Garcia *et al.* (2006) employed thermally treated fibers before the production of MDF, while del Menezzi *et al.* (2009) treated OSB boards after production. These studies used chipped wood as the base material. Only a few studies had the goal of producing boards out of thermally treated wood of larger formats, such as Nazerian *et al.* (2011) with the production of laminated veneer lumber (LVL) and Goli *et al.* (2014) with the production of plywood.

The goal of this research is to produce, under industrial conditions, thermally modified poplar plywood board suitable for use in conditions of variable air humidity and temperature. Poplar plywood board was chosen based on its economical and ecological advantages because it is a cheap and fast-growing species, and it is commonly used for plywood production in Serbia, as substitution for traditionally used beech wood. In addition, plywood was chosen because it is a simple installation of this product, caused by larger dimensions of plywood compared to solid wood (*e.g.*, installing wall sidings).

Studies by Šernek *et al.* (2008) and Kariž (2011) indicate that it is possible to create a good quality adhesive bond between pieces of thermally modified wood when cold-setting melamine-urea-formaldehyde (MUF) adhesive is used. Considering that the use of cold-setting MUF in industrial production is neither technologically nor economically feasible (pressing would last too long), this experiment used hot-setting MUF adhesive, one of the most frequently used adhesives in the production of boards made for use in increased air humidity or exterior applications (Pizzi and Mittal 2003).

EXPERIMENTAL

Materials

This experiment used logs of poplar clone *Populus x euramericana* 'I-214' (Srbijasume, Belgrade, Serbia), peeled into veneer with a nominal thickness of 3.2 mm. After drying, sheets of 800 mm × 1000 mm × 3 mm were made and divided into five groups. One group was selected as the control, while the other four were thermally modified in a laboratory kiln (Baschild ATK (1 m^3, ± 1 °C sensitivity), Treviolo, Italy) in a protective atmosphere filled with water vapor. Four different treatments were applied: 190 °C, 200 °C, 210 °C, and 215 °C for 1 h (treatment schedules were chosen based on previous studies (Lovrić and Zdravković 2009). According to these studies, thermal modification of poplar veneer at a temperature of 180 °C and below had a low impact on veneer physical properties (in case of treatments shorter than 2 h). On the other hand, if the treatments were longer than 2 h at temperatures of 210 °C or higher, the loss of veneer mass was too high. By combining treated and non-treated sheets, five-ply boards of 800 mm × 800 mm × 15 mm were produced. In total, 78 boards were produced and their structures are shown in Table 1.

Hot-setting MUF adhesive, with a melamine content of 15%, was used in this experiment. According to a glue producer (Hadjilucas S.S., Athens, Greek), the specific gravity of this adhesive is 1.285-1.295 g/mL, pH value 8-10 and viscosity 200 to 400 cP at 25 °C. The glue spread rate was 200 g/m^2, and assembly time was approximately 10 min. Pressing was conducted with no pre-pressing in a nine-story press, (Pagnoni, Monza, Italy) (Fig. 1) at 100 °C and 1 MPa, for 15 min.

Table 1. Types and Amounts of Produced Boards

Board Type / Schedule	5N[a]	T3NT[b]	TNTNT[c]	5T[d]	Total
Control	6	-	-	-	6
190 °C	-	6	6	6	18
200 °C	-	6	6	6	18
210 °C	-	6	6	6	18
215 °C	-	6	6	6	18
Total	6	24	24	24	78

[a] Boards composed only of non-treated poplar veneer (control); [b] boards with outer sheets made of treated veneer and the middle made of non-treated veneer; [c] boards composed of alternating sheets of treated and non-treated veneer; [d] boards composed only of thermally treated veneer

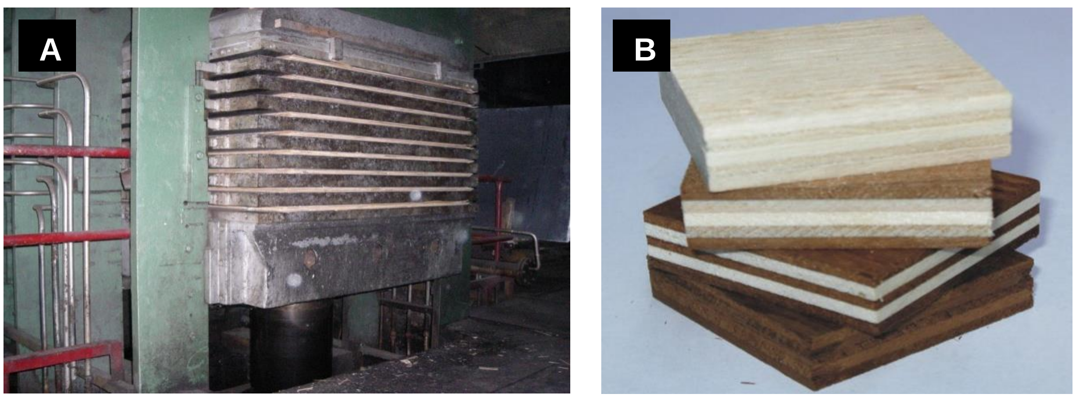

Fig. 1. Board pressing (A) and types of pressed boards (B)

Methods

Two groups of samples were cut from each board. One group was conditioned at 22 °C and 60% relative humidity (*φ*) to assess the differences in the boards' properties when used in an indoor climate. This first group of samples was used to determine equilibrium moisture content according to EN 322 (1993), density (EN 323 (1993)), bending strength and modulus of elasticity parallel (longitudinal samples) and perpendicular (cross-sectional samples) to the grain orientation of the top board layer (EN 310 (1993)), and shear strength (EN 314 (1993)). The second group of samples was used for analysis of sorption and swelling. These samples were oven-dried at 103 °C ± 2 °C, their mass and dimensions were measured, and they were placed in closed containers above distilled water. During the first week, the mass and thickness were measured each day, and afterwards this was done weekly until the measured values stabilized. The samples were then soaked in water for an additional two weeks to reach moisture content saturation. For every board type, the swelling and moisture content changes were calculated from oven-dry to saturated state.

Statistical analysis was conducted by using the one-way ANOVA (SPSS 20.0, IBM Corporation, Armonk, New York, USA) with a significance level of 95%. In cases where the samples had an equal variance, the Tukey post hoc test was used. In some cases, when the Levene test showed an unequal variance of samples, the Bonferroni post hoc test was used.

RESULTS AND DISCUSSION

Equilibrium Moisture Content of Conditioned Boards

A statistical analysis showed that there were significant differences in the achieved moisture content among most of the boards F (12,377) = 213,166, $p < 0.05$). With higher treatment temperatures and a higher share of thermally modified sheets of veneer in boards, values of absorption were lower (Table 2). Accordingly, the boards had different reactions to the same air humidity. The type of board construction and veneer treatment temperature both influenced the equilibrium moisture content of the boards. The decrease of hygroscopicity with the increase of treatment temperature was expected because the number of hydroxyl groups decreases during thermal treatment (Boonstra and Tjeerdsma 2006; Windeisen *et al.* 2007; Rowell *et al.* 2009). This is one of the reasons why the equilibrium moisture content was lower in boards with larger shares of thermally modified veneer.

Table 2. Moisture Content of Conditioned Boards

Board Type / Schedule	190 °C	200 °C	210 °C	215 °C
Control	9.01% (0.33)			
T3NT	8.82% (0.21)	8.37% (0.19)	8.31% (0.34)	8.12% (0.37)
TNTNT	8.16% (0.29)	7.79% (0.25)	8.05% (0.29)	7.41% (0.30)
5T	7.72% (0.22)	7.32% (0.32)	6.54% (0.30)	6.31% (0.30)
Note: Table shows mean values of moisture content, with standard deviations in parentheses				

With an increase of treatment temperature, the moisture content of boards made only of thermally modified veneer (5T) was lower than that of the control by 4.42%, 8.76%, 27.41%, and 29.97%, respectively. The great decrease of moisture content (almost 19%) between treatments at 200 °C and 210 °C potentially indicated a significant structural collapse of poplar veneer treated at 210 °C.

Density of Conditioned Boards

The average density of conditioned control boards (φ = 60% and T = 22 °C) was 436 kg/m^3 and was similar to the value of 441 kg/m^3 reported by Bal and Bektas (2014) for a five-ply poplar board of the same nominal thickness, bonded by 200 g/m^2 of MUF glue and conditioned in indoor air. Statistical analysis indicated that there were significant differences in board densities (F (12,377) = 13.564, $p < 0.05$). These differences were mostly related to the density decrease of boards made out of sheets treated above 200 °C as compared to the control boards. One possible explanation is that an increase in treatment temperature leads to a decrease in the density of poplar veneer (Lovrić and Zdravković 2009). The densities of other compared boards did not show distinct significant dependence on board construction nor the applied thermal treatment (Table 3).

Table 3. Density of Conditioned Boards (kg/m^3)

Board Type / Schedule	190 °C	200 °C	210 °C	215 °C
Control	436.36 (11.21)			
T3NT	414.22 (25.83)	419.65 (13.32)	420.87 (35.35)	393.13 (32.24)
TNTNT	424.55 (18.32)	424.21 (32.43)	400.26 (29.80)	393.84 (24.53)
5T	404.46 (13.64)	411.04 (13.69)	388.64 (27.79)	378.21 (10.52)
Note: Table shows mean values of density, with standard deviations in parentheses				

However, board density is influenced not only by veneer density, but also by denser pressing of thermally modified sheets (Fioravanti *et al.* 2013), as well as by the decreased elasticity of thermally modified wood (Shi *et al.* 2007; Kocaefe *et al.* 2008a), which can cause a smaller "spring back" effect. Therefore, the decrease in veneer sheet density during thermal modification contributed to a decrease in board density, while harder pressing and a decrease of reverse deformation increased board density. It was possible that these opposing forces prevented significant density changes across different schedules.

Moisture Content and Board Thickness Changes in Humid Air Conditions

During the first week of the experiment, both board moisture content and thickness increased rapidly. Moisture content stabilized after 5 weeks (Fig. 2) and the dimensions stabilized after approximately 9 weeks (Fig. 3).

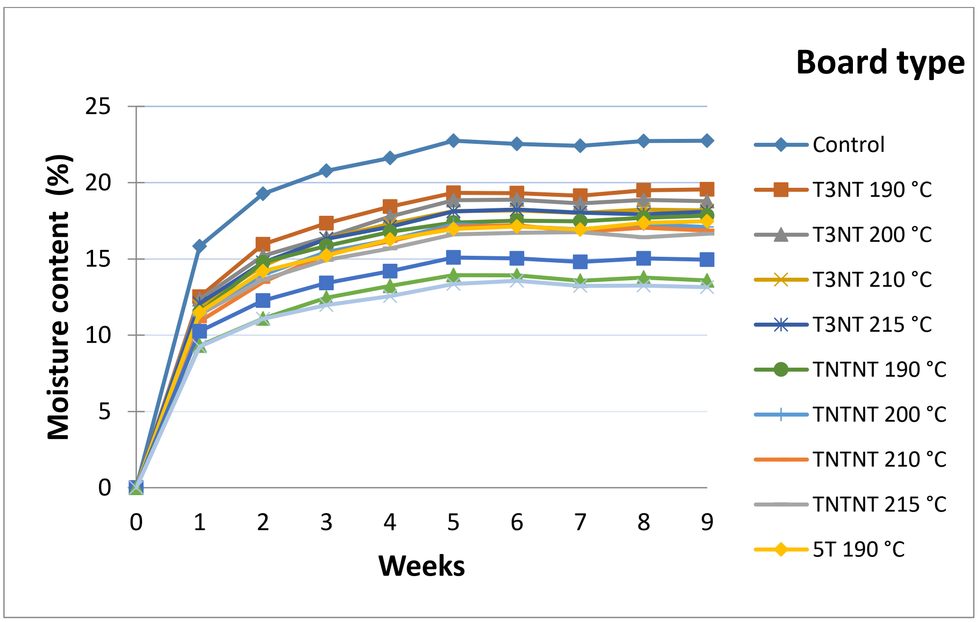

Fig. 2. Moisture content change curves of board samples above water

Values measured after 9 weeks into the experiment were used for statistical analysis. An analysis of moisture content showed significant differences in the moisture content of different boards (F (12,377) = 153.508, $p < 0.05$). Control boards (5N) had significantly higher moisture content than all other boards. Out of the other 66 pairs, significant differences occurred in 47 cases. Compared to the control boards, the final moisture content of boards made only of thermally treated veneer was lower 23.2%, 34.3%, 40.3%, and 42.2%, respectively, from the mildest to the harshest treatment.

It was noticeable (Fig. 2) that the results were influenced by both the schedules and the types of board construction. In each board type, the moisture content decreased with higher treatment temperatures, and boards with more thermally modified veneer had lower equilibrium moisture content. After 9 weeks, the control board (5N) had the highest equilibrium moisture content (22.74%), while the lowest moisture content was exhibited by the board made only from thermally modified veneer (5T) at 215 °C (13.14%).

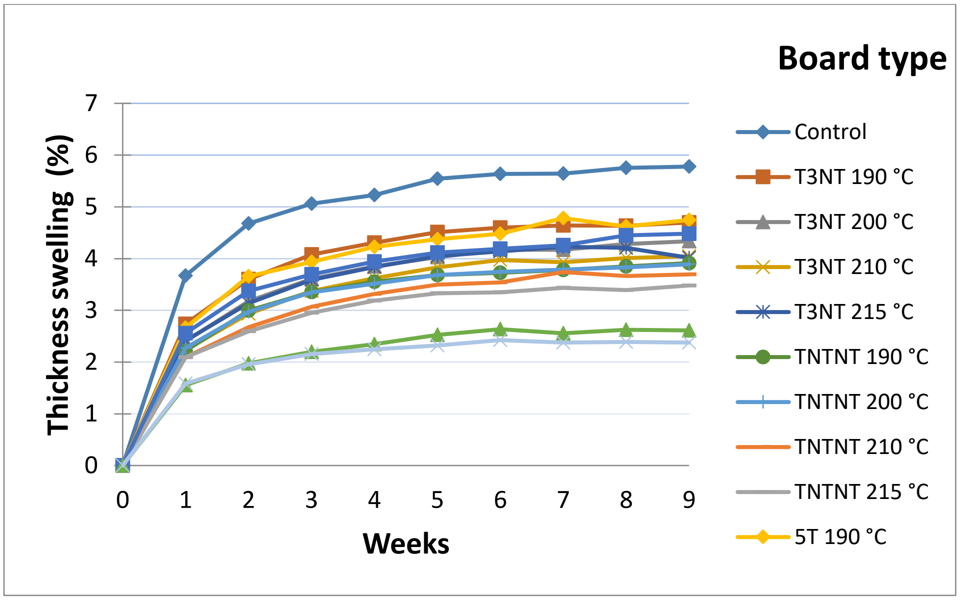

Fig. 3. Curves of thickness swelling of boards samples above water

The equilibrium moisture content was more influenced by board construction than by temperature of modification, except with 5T board at 190 °C (Fig. 4).

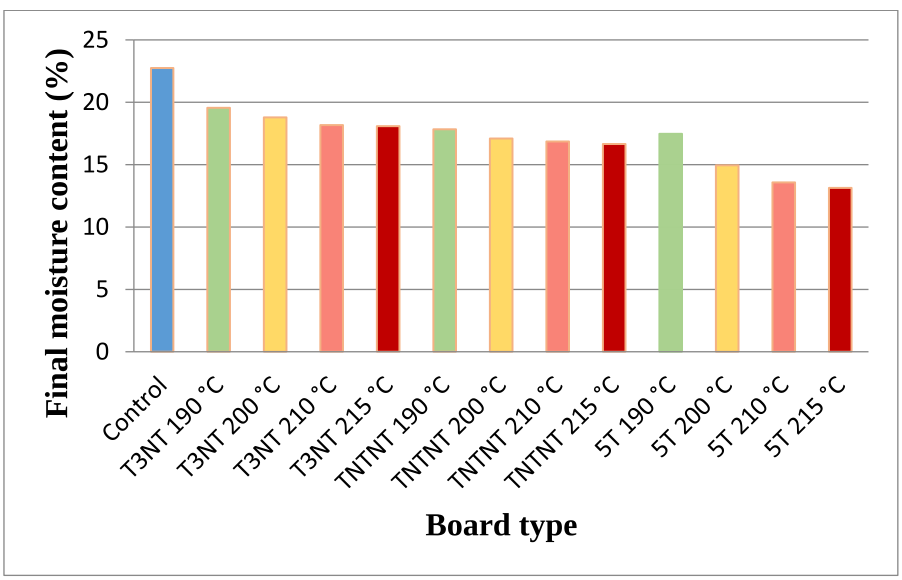

Fig. 4. Influence of board construction and treatment temperature on final moisture content

The T3NT board at 215 °C had a bigger change than *e.g.*, TNTNT at 190 °C or 5T at 200 °C. This observation could be important in considerations for the usage of these boards. Considering that the temperature increase leads to a decrease of most of the mechanical properties of treated material (Poncsak *et al.* 2006; Kocaefe *et al.* 2008b; Poncsak *et al.* 2011), it is important to note that positive effects can be achieved not only by applying lower temperatures but also with a change of construction.

Total swelling across thickness was also more influenced by board construction than by treatment temperature. The control board (5N) after 9 weeks, showed the highest thickness swelling (5.78%), while 5T at 215 °C showed the lowest swelling of 2.38%. A positive effect of thermal modification on the decrease of swelling across board thickness was also reported by Nazerian *et al.* (2011) on LVL made from thermally modified black poplar wood. The decrease in swelling across board thickness to 54.8% (5T at 210 °C) matched the reported value of 54% for thermally modified aspen wood (a species with similar properties to the one examined) after a 4 h long treatment at 220 °C (Kocaefe *et al.* 2008b). Although these were not the same species, this indicated the potential advantages of plywood constructed from thermally modified veneer as compared to thermally modified solid wood, because the same positive results occurred at lower temperatures and in shorter time.

Bending Strength and Modulus of Elasticity

The measured bending strength of the control samples (5N) matched the values reported by Bal and Bektas (2014) for poplar plywood. However, the values of the modulus of elasticity were significantly lower in both of the examined anatomical directions (Tables 4 and 5). In addition, for longitudinal samples, the values of standard deviations (SD) (both for bending strength and modulus of elasticity) were similar to those reported by Bal and Bektas (2014), but for cross-sectional samples they were higher. This was probably influenced by somewhat larger cracks (created on the tensile side of veneer during log peeling) because their influence was stronger on the cross-section than on the longitudinal samples. These cracks probably caused a high SD in most of the boards containing thermally modified sheets, especially those from harsher treatment schedules that additionally influenced the widening of cracks and the decrease of mechanical properties of the treated veneer.

In a study by Goli *et al.* (2014), the bending strength of boards constructed only from thermally modified poplar veneer (5T) at 180 °C was 38 MPa in the longitudinal direction, and 19 MPa in the cross-sectional direction. These values fall between the values for 5T board treated at 190 °C and 200 °C in this study. The difference was mostly caused by a longer thermal modification that lasted 23 h in the other study as compared to 1 h in this one. Testing the significance of differences in bending strength in longitudinal samples showed that a significant difference occurred when the control board was compared to all of the others ($F_{(12,143)} = 14.206$, $p < 0.05$). In comparing different schedules, a significant difference occurred only five times: three times when comparing the 5T board at 215 °C with other boards, and once each for the TNTNT board at 210 °C and at 215 °C. These results indicated that thermal modification caused a decrease of bending strength in the longitudinal samples, but also that the negative effect of the thermal treatment on bending strength was attenuated by inserting non-treated veneer into the board construction. The significantly lower bending strength in 5T board at 215 °C was a consequence of a massive structural collapse of poplar veneer at this temperature.

Table 4. Bending Strength and Modulus of Elasticity of Boards Constructed from Thermally Modified and Non-modified Poplar Veneer, in Longitudinal Direction

Board Type / Schedule		Bending Strength (MPa)	Modulus of Elasticity (MPa)
Control		58.07 (4.27)	6078 (329)
	T3NT	33.87 (6.03)	4652 (479)
	TNTNT	38.26 (5.71)	5295 (522)
	5T	34.77 (7.07)	4969 (502)
	T3NT	32.28 (8.46)	4409 (536)
	TNTNT	33.54 (5.76)	4566 (492)
	5T	41.89 (4.72)	5436 (843)
	T3NT	36.51 (9.45)	5233 (779)
	TNTNT	29.46 (7.36)	4560 (735)
	5T	33.31 (5.38)	4853 (741)
	T3NT	31.50 (12.5)	4505 (1298)
	TNTNT	29.50 (9.22)	4832 (888)
	5T	25.44 (5.19)	4284 (567)
Note: Table shows mean values, with standard deviations in parentheses			

In cross-sectional samples, the statistical analysis showed that the control boards had a significantly higher bending strength only when compared with 5T boards treated at 200 °C, 210 °C, and 215 °C, and with TNTNT boards at 215 °C ($F(12,143) = 15.203$, $p < .05$). These four board types exhibited the lowest values of bending strength (Table 5), so the comparisons among these board types with all other board types also showed significant differences.

Table 5. Bending Strength and Modulus of Elasticity of Boards Constructed from Thermally Modified and Non-modified Poplar Veneer, in Cross-section

Board Type / Schedule		Bending Strength (MPa)	Modulus of Elasticity (MPa)
Control		28.40 (5.60)	2027 (473)
	T3NT	26.38 (4.38)	1757 (264)
	TNTNT	27.92 (3.33)	1991 (171)
	5T	22.74 (3.55)	1604 (191)
	T3NT	26.96 (3.92)	1924 (273)
	TNTNT	29.46 (4.39)	2001 (274)
	5T	17.88 (3.15)	1485 (129)
	T3NT	24.37 (3.10)	1731 (217)
	TNTNT	24.62 (3.53)	1847 (332)
	5T	17.18 (5.24)	1547 (274)
	T3NT	24.59 (4.61)	1732 (254)
	TNTNT	21.23 (2.17)	1742 (280)
	5T	14.82 (4.87)	1425 (341)
Note: Table shows mean values, with standard deviations in parentheses.			

This indicated that thermal treatments caused a decrease in bending strength in cross-sectional samples, but almost only in 5T board types. These boards did not contain any non-treated veneer to prevent the negative effects of thermal modification. This is why this board type showed a noticeable decrease of bending strength at higher treatment temperatures which, when compared to control boards, was 19.0%, 37.0%, 39.5%, and 47.8%, respectively.

The statistical analysis of the modulus of elasticity in both the longitudinal and cross-sectional directions showed fewer significant differences than bending strength; however, the significant differences mostly occurred in the same samples as with the bending strength. This indicated that these differences were created by the same causes, but also that thermal modification affected bending strength more than the modulus of elasticity. These results conflicted with those reported by Goli *et al.* (2014), which showed no significant effect of thermal modification of veneer on the modulus of elasticity of plywood constructed from such treated material. Different conclusions are probably caused by different conditions in these two experiments.

Shear Strength

Table 6 shows the mean values of shear strength and the percentage of cohesive wood failure, along with an assessment of whether or not the criteria of the EN 314 standard were satisfied. Examinations were conducted for three types of water resistance: boards for dry conditions, boards for humid conditions, and boards for exterior conditions (classification according to EN 636 (2003)).

Table 6. Possibilities of Board Application in Dry, Humid, and Exterior Conditions (EN 314)

Test		Dry			Humid			Exterior		
Board Type / Schedule		σ (MPa)	W (%)	Pass	σ (MPa)	W (%)	Pass	σ (MPa)	W (%)	Pass
Control		1.603	67.92	✓	1.220	16.25	✓	1.095	5.42	✓
	T3NT	1.488	71.17	✓	1.016	2.50	✓	0.803	1.25	x
	TNTNT	1.228	39.36	✓	0.701	12.50	x	0.624	1.67	x
	5T	1.326	82.14	✓	0.770	6.67	x	0.675	8.33	x
	T3NT	1.417	66.94	✓	1.018	13.75	✓	0.843	15.83	x
	TNTNT	1.397	76.50	✓	0.905	9.17	x	0.763	9.47	x
	5T	1.141	76.50	✓	0.753	13.75	x	0.719	4.17	x
	T3NT	1.150	56.00	✓	0.947	33.91	x	0.970	23.64	x
	TNTNT	1.232	60.00	✓	0.741	14.82	x	0.735	19.17	x
	5T	0.883	49.09	✓	0.674	19.05	x	0.634	17.08	x
	T3NT	1.231	62.22	✓	0.876	24.50	x	0.825	20.23	x
	TNTNT	1.005	50.78	✓	0.724	25.45	x	0.720	24.91	x
	5T	0.837	52.22	✓	0.626	23.00	x	0.588	21.86	x
σ: Shearing strength in adhesive layer; W: Percentage of cohesive wood failure										

All boards passed the dry conditions test. Within this group (with small deviations), shear strength decreased with harsher schedules, as well as with a higher content of thermally modified veneer in board construction. Control boards had the highest values (1.60 MPa) while 5T boards at 215 °C had the lowest values (0.84 MPa). The percentage of cohesive wood failure for dry conditions was between 39.4% and 82.1%, and in most boards it was above 50%. This high percentage of cohesive wood failure indicated that the pre-treatment (24 h of soaking in water at 20 °C) did not overly reduce the quality of the adhesive bond, and that the differences in shear strength (in this water-resistance class) were mostly caused by the lower shear strength of the thermally modified veneer (Boonstra *et al.* 2007). The lowest shear strength was exhibited by 5T boards, which were the only ones with two treated veneer sheets exposed to tensile stress perpendicular to the grain.

Harsher pre-treatment (determination of suitability for use in humid and exterior conditions) led to a significant decrease in shear strength. Out of 13 different board types examined in this research, 12 types had significantly lower shear strength after the pre-treatment for humid conditions, and the same was true after the pre-treatment for exterior use. Only the T3NT board at 210 °C did not have a statistically significant decrease of shear strength, but this board also did not pass the EN 314 requirements after pre-treatments (Table 6). After comparing boards for use in humid conditions with those for exterior use, none of the 13 types showed a significant decrease in shear strength.

The observed decrease in shear strength was mostly caused by the weakening of the bond between glue and veneer, which was confirmed by the amounts of cohesive wood failure. This breakage was 62.4% for dry conditions, 16.6% for humid conditions, and 13.3% for exterior conditions. Had the problem been in the bond between the treated and non-treated veneer, that is, had the different dimensional changes of treated and non-treated veneer caused the decrease of bonding strength, then the 5T boards (made only of treated veneer) would have exhibited better values than the TNTNT and T3NT boards within the same schedule. Because this was not the case, and due to the control boards (which had a similar percentage of cohesive wood failure) requiring stronger force to cause breakage, it was logically concluded that the applied MUF adhesive was not adequate for gluing the thermally modified veneer. This was in accordance with the study by Goli *et al.* (2014), which indicated that shear strength (in boards constructed from thermally treated poplar veneer) was reduced after the second pre-treatment (boards for humid conditions) approximately 64%.

Šernek *et al.* (2008) and Kariž (2011) created an adhesive bond of high quality by using cold-setting MUF adhesive with thermally modified wood. An important difference was that pressing times in those experiments were 90 min and 180 min, while in this study pressing time was 15 min. The longer pressing time when using cold-setting MUF adhesive allows these adhesives to better spread out and to penetrate the wood structure. According to the theory of mechanical interlocking (Frihart 2005), deeper penetration of glue allows for stronger bond creation between glue and wood, that is, such a bond requires a stronger force to break up – especially with shearing. The correlation between the longer pressing time and higher shear strength in using cold-setting MUF adhesive (as compared to hot-setting MUF) can be extrapolated from results reported by Kariž (2011). He concluded that gluing of thermally modified wood exhibits better results when the recommended pressing times are prolonged.

CONCLUSIONS

1. The examined physical and mechanical properties of plywood were affected both by the schedules of thermal modification and plywood construction types. Boards made of veneer treated at higher temperatures, as well as boards that contained more thermally modified veneer, had lower equilibrium moisture content and lower swelling across their thickness, but also weaker mechanical properties in comparison with the control boards.
2. Treatment at 215 °C was too harsh because it overly decreased the mechanical properties of all board types. Plywood that contained poplar veneer treated at this temperature should only be used when the goal is to achieve a specific color, or when the board will not be exposed to high stresses.
3. In other treatments, the negative influence of thermal modification was attenuated by combining the treated and non-treated veneer. A choice between TNTNT and T3NT boards depends on the desired purpose. From the viewpoint of usage of these boards, it is important to note that a positive effect can be created by using lower temperatures but also by using a different construction – *e.g.*, TNTNT board (alternating modified and non-modified veneer) at 190 °C instead of T3NT board (modified on the outside, with the middle three sheets being non-modified veneer) at 215 °C.
4. The significant decrease of shear strength after harsher pre-treatment indicated that the hot-setting MUF adhesive was not adequate for construction of water resistant plywood from thermally modified poplar veneer.

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REFERENCES CITED

Bal, B. C., and Bektas, I. (2014). "Some mechanical properties of plywood produced from eucalyptus, beech, and poplar veneer," *Maderas. Ciencia y Tecnologia* 16(1), 99-108. DOI: 10.4067/S0718-221X2014005000009

Boonstra, M. J., Pizzi, A., Zomers, F., Ohlmeyer, M., and Paul, W. (2006). "The effects of a two stage heat treatment process on the properties of particleboard," *HolzalsRoh- und Werkstoff* 64(2), 157-164. DOI: 10.1007/s00107-005-0055-y

Boonstra, M. J., and Tjeerdsma, B. (2006). "Chemical analysis of heat treated softwoods," *HolzalsRoh- und Werkstoff* 64(3), 204-211. DOI: 10.1007/s00107-005-0078-4

Boonstra, M. J., Van Acker, J., Tjeerdsma, B., and Kegel, E. (2007). "Strength properties of thermally modified softwoods and its relation to polymeric structural wood constituents," *Annals of Forest Science* 64(7), 679-690. DOI: 10.1051/forest:2007048

Borrega, M., and Kärenlampi, P. P. (2010). "Hygroscopicity of heat-treated Norway spruce (*Picea abies*) wood," *European Journal of Wood and Wood Products* 68(2), 233-235. DOI: 10.1007/s00107-009-0371-8

Cao, Y., Lu, J., and Huang, R., and Jiang, J. (2012). "Increased dimensional stability of Chinese fir through steam-heat treatment," *European Journal of Wood and Wood Products* 70(4), 441–444. DOI: 10.1007/s00107-011-0570-y

del Menezzi, C. H. S., Tomaselli, I., Okino, E. Y. A., Teixeira, D. E., and Santana, M. A. E. (2009). "Thermal modification of consolidated oriented strand boards: Effects on dimensional stability, mechanical properties, chemical composition and surface color," *European Journal of Wood and Wood Products* 67(4), 383-396. DOI: 10.1007/s00107-009-0332-2

Ding, T., Gu, L., and Li, T. (2011). "Influence of steam pressure on physical and mechanical properties of heat-treated Mongolian pine lumber," *European Journal of Wood and Wood Products* 69(1), 121-126. DOI: 10.1007/s00107-009-0406-1

EN 310 (1993). "Wood-based panels: Determination of modulus of elasticity in bending and of bending strength," European Committee for Standardization, Brussels, Belgium.

EN 314 (1993). "Plywood – Bond quality," European Committee for Standardization, Brussels, Belgium.

EN 322 (1993). "Wood-based panels – Determination of moisture content," European Committee for Standardization, Brussels, Belgium.

EN 323 (1993). "Wood-based panels – Determination of density," European Committee for Standardization, Brussels, Belgium.

EN 636 (2003). "Plywood - Specifications," European Committee for Standardization, Brussels, Belgium.

Estaves, B., and Pereira, H. (2009). "Wood modification by heat treatment: A review," *BioResources* 4(1), 370-404. DOI: 10.15376/biores.4.1.370-404

Fioravanti, M., Goli, G., Negro, F., Cremonini, C., and Zanuttini, R. (2013): "Effect of heat treatment on mechanical properties and bonding quality of poplar plywood glued with MUF resin," in: *Proceedings of the 4th International Scientific Conference on Hardwood Processing*, Florence, Italy, pp. 227-232.

Frihart, C. R. (2005). "Adhesive bonding and performance testing of bonded wood products," *Journal of ASTM International* 2(7), 1-12. DOI: 10.1520/JAI12952

Garcia, R. A., Cloutier, A., and Riedl, B. (2006). "Dimensional stability of MDF panels produced from heat-treated fibres," *Holzforschung* 60(3), 278-284. DOI: 10.1515/HF.2006.045

Goli, G., Cremonini, C., Negro, F., Zanuttini, R., and Fioravanti, M. (2014). "Physical-mechanical properties and bonding quality of heat treated poplar (I-214 clone) and ceiba plywood," *iForest - Biogeosciences and Forestry* 8(1), 687-692. DOI: 10.3832/ifor1276-007

Gonzales-Pena, M., and Hale, M. (2009). "Color change in thermally-modified wood and its relationship with property changes," in: *Proceedings of 4th European Conference on Wood Modification*, Stockholm, Sweden, pp. 181-185.

Icel, B., Guler, G., Isleyen, O., Beram, A., and Mutlubas, M. (2015). "Effects of industrial heat treatment on the properties of spruce and pine woods," *BioResources* 10(3), 5159-5173. DOI: 10.15376/biores.10.3.5159-5173

Kariž, M. (2011). *Influence of Thermal Modification of Wood on Curing of Adhesives and Bond Performances*, Ph.D. Dissertation, Univerzitet v Ljubljani, Ljubljana, Slovenia.

Kocaefe, D., Poncsak, S., Dor´e, G., and Younsi, R. (2008a). "Effect of heat treatment on the wettability of white ash and soft maple by water," *Holz als Roh- und Werkstoff* 66(5), 355-361. DOI: 10.1007/s00107-008-0233-9

Kocaefe, D., Shi, J. L., Yang, D. Q., and Bouzara, M. (2008b). "Mechanical properties, dimensional stability, and mold resistance of heat-treated jack pine and aspen," *Forest Products Journal* 58(6), 88-93.

Korkut, S., and Bektas, I. (2008). "The effects of heat treatment on physical properties of Uludag fir (*Abies bornmuelleriana* Mattf.) and Scots pine (*Pinus sylvestris* L.) wood," *Forest Products Journal* 58(3), 95-99. DOI: 10.3390/ijms9091772

Kubojima, Y., Wada, M., Suzuki, Y., and Tonosaki, M. (2001) "Real-time measurement of vibration properties and fine structural properties of wood at high temperature," *Wood Science and Technology* 35(6), 503-515. DOI: 10.1007/s002260100113

Lovrić, A., and Zdravković, V. (2009). "Influence of the thermal treatments on density, swelling and mass loss of poplar veneer," *Prerada Drveta* 28(1), 35-43.

Lovrić, A., Zdravković, V., and Furtula, M. (2014). "Influence of thermal modification on colour of poplar (*Populus x euramericana*) rotary cut veneer," *Wood Research* 59(2), 661-670.

Nazerian, M., Ghalehno, M. D., and Kashkooli, A. B. (2011). "Effect of wood species, amount of juvenile wood and heat treatment on mechanical and physical properties of laminated veneer lumber," *Journal of Applied Sciences* 11(6), 980-987. DOI: 10.3923/jas.2011.980.987

Ohnesorge, D., Tausch, A., Krowas, I., Huber, C., Becker, G., and Fink, S. (2009). "Laboratory tests on the natural durability of six different wood species after hygrothermal treatment," in: *Proceedings of 4th European Conference on Wood Modification*, Stockholm, Sweden, pp. 159-164.

Paul, W., Ohlmeyer, M., and Leithoff, H. (2007). "Thermal modification of OSB-strands by a one-step heat pretreatment-Influence of temperature on weight loss, hygroscopicity and improved fungal resistance," *Holz als Roh- und Werkstoff* 65(1), 57-63. DOI: 10.1007/s00107-006-0146-4

Pizzi, A., and Mittal, K. L., (2003). "Melamine–Formaldehyde adhesives," in: *Handbook of Adhesive Technology*, Marcel Dekker, Inc., New York, NY. DOI: 10.1201/9780203912225.ch32

Poncsak, S., Kocaefe, D., Bouazara, M., and Pichette, A. (2006). "Effect of high temperature treatment on the mechanical properties of birch (*Betula papyrifera*)," *Wood Science and Technology* 40(8), 647-663. DOI: 10.1007/s00226-006-0082-9

Poncsak, S., Kocaefe, D., and Younsi, R. (2011). "Improvement of the heat treatment of Jack pine (*Pinus banksiana*) using ThermoWood technology," *European Journal of Wood and Wood Products* 69(2), 281-286. DOI: 10.1007/s00107-010-0426-x

Rowell, R. M., Ibach, R. E., McSweeny, J., and Nilsson, T. (2009). "Understanding decay resistance, dimensional stability and strength changes in heat treated and acetylated wood," in: *Proceedings of 4th European Conference on Wood Modification*, Stockholm, Sweden, pp. 489-502.

Schnabel, T., Zimmer, B., Petutschnigg, A. J., and Schonberger, S. (2007). "An approach to classify thermally modified hardwoods by color," *Forest Products Journal* 57(9), 105-110.

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

Šernek, M., Boonstra, M., Pizzi, A., Despres, A., and G´erardin, P. (2008). "Bonding performance of heat treated wood with structural adhesives," *Holz als Roh- und Werkstoff* 66(3), 173-180. DOI: 10.1007/s00107-007-0218-0

Todorović, N., Popović, Z., Milić, G., and Popadić, R. (2012). "Estimation of heat-treated beech wood properties by color change," *BioResources* 7(1), 799-815. DOI: 10.15376/biores.7.1.799-815

Windeisen, E., Strobel, C., and Wegener, G. (2007). "Chemical changes during the production of thermo-treated beech wood," *Wood Science and Technology* 41(6), 523-536. DOI: 10.1007/s00226-007-0146-5

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