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Mechanical behaviour of Québec wood species heat-treated using ThermoWood process

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Abstract Finnish wood heat treatment technology, ThermoWood, was recently introduced to Québec, Canada by Ohlin Thermo Tech. Subsequently, a large number of initial trials were conducted on five commercially important Québec wood species, spruce (*Picea* spp.), pine (*Pinus* spp.), fir (*Abies* spp.), aspen (*Populus* spp.), and birch (*Betula* spp.). These species were thermally-modified in different batches at temperatures of 200 °C or higher. The static bending and hardness of the thermally-modified wood were examined. Decreases of 0% to 49% were observed in modulus of rupture of heat-treated spruce, pine, fir, and aspen depending on species and treatment schedules used; modulus of rupture of birch increased slightly after the heat treatment. The decrease in modulus of elasticity of heat-treated spruce and pine ranged from 4% to 28%; but the modulus of elasticity of heat-treated fir, aspen, and birch increased except one trial for fir. Hardness of the heat-treated wood increased or decreased depending on the species, test directions (radial, tangential, and longitudinal), and treatment schedules.

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Mechanische Eigenschaften von in Quebec vorkommenden Holzarten nach Behandlung mit dem ThermoWood-Verfahren

Zusammenfassung ThermoWood ist ein aus Finnland stammendes Verfahren zur Wärmebehandlung von Holz, das seit kurzem von Ohlin Thermo Tech in Quebec, Kanada angewendet wird. In diesem Zusammenhang wurden an fünf wirtschaftlich bedeutenden, in Quebec vorkommenden Holzarten, nämlich Fichte (*Picea* spp.), Kiefer (*Pinus* spp.), Tanne (*Abies* spp.), Pappel (*Populus* spp.) und Birke (*Betula* spp.), zahlreiche Versuche durchgeführt. Diese Holzarten wurden bei verschiedenen Temperaturstufen von 200 °C oder höher wärmebehandelt, daran anschließend wurden die Biegefestigkeit und Härte des wärmebehandelten Holzes untersucht. Die Biegefestigkeit von wärmebehandelter Fichte, Kiefer, Tanne und Pappel nahm je nach Holzart und Behandlung zwischen 0% und 49% ab; wohingegen die Biegefestigkeit von Birke nach der Behandlung geringfügig höher war. Der Elastizitätsmodul von Fichte und Kiefer nahm zwischen 4 und 28% ab, wohingegen der E-Modul von Tanne, Pappel und Birke mit Ausnahme eines Versuchs bei Tanne zunahm. Die Härte des wärmebehandelten Holzes nahm abhängig von Holzart, Orientierung (radial, tangential und longitudinal) und Behandlung zu oder ab.

1 Introduction

Heat treatment of wood at high temperature is one of the wood modification methods to improve the dimensional stability and bio-durability of timber. It has been studied for years in Europe (Chanrion and Schreiber 2002, Militz 2002, Rapp and Sailer 2000, Sailer et al. 2000, Syrjänen and Kangas 2000). In Europe, five processes were developed and are currently available at industrial scale including Plato-Process (The Netherlands), Retification Process (France), Bois Perdure (France), OHT-Process (Germany), and ThermoWood Process (Finland) (Militz 2002). The common ground of the five processes lies in modifying the chemical structure of lumber at temperatures ranging from 160 °C to 260 °C. The processes vary due to furnace design, type and condition of the heating gas, and treatment schedules.

ThermoWood process was developed at Finnish Research Center VTT in the early 90's. According to ThermoWood Handbook (Finnish ThermoWood Association 2003), the process consists of three phases: warming up, drying, and cooling and conditioning. The warming up phase is to heat and pre-dry lumber. The temperature in the kiln is raised rapidly and a large amount of steam is generated. At the beginning of the drying phase, the temperature is increased steadily and the timber is dried intensively. At a certain point of the drying phase when the moisture content of the lumber reaches nearly 0%, the temperature is raised rapidly to a range of 185 °C to 215 °C depending on the applications of the treated products. Wood is kept at this temperature for 2–3 h. In cooling and conditioning phase, the temperature of the wood is lowered to 80 °C to 90 °C using water spray system. Conditioning is carried out to moisten the heat-treated wood and bring its moisture content to 4%–7%.

After treatment at 180 °C or higher, chemical changes in lignin and hemicelluloses occur and the treated wood becomes less hydroscopic (Tjeerdsma et al. 1998b, Kotilainen 2000). As a result, the wood is more dimensionally stabilized when the relative humidity changes (Yildiz 2002). It turns the wood to be less prone to fungi degradation as well (Dirol and Guyonnet 1993, Troya and De Navarrete 1994, Viitanen et al. 1994, Tjeerdsma et al. 1998a). Some studies showed the reduction in bending strength of the treated wood (Bengtsson et al. 2002, Santos 2000, Yildiz et al. 2002). The degree of such decrease is very dependant on the wood species to be treated, the maximum temperature reached in the process, and the holding time at that temperature, etc (Vernois 2001).

In this study, five Québec wood species, spruce (*Picea* spp.), pine (*Pinus* spp.), fir (*Abies* spp.), aspen (*Populus* spp.), and birch (*Betula* spp.) were heat-treated using ThermoWood process at Ohlin Thermo Tech.'s lab (Jonquière, Canada). A large number of trials was carried out in setup period and the mechanical properties of the treated wood were characterized. The data can provide firsthand information to industry and academia with regard to the mechanical behaviour of Québec wood species treated by ThermoWood process.

2 Materials and methods

2.1 Materials and heat treatment

Spruce (*Pices* spp.), pine (*Pinus* spp.), fir (*Abies* spp.), aspen (*Populus* spp.), and birch (*Betula* spp.) were purchased from a local lumber store in Québec. Prior to heat treatment, the boards have already been kiln-dried. The boards were subject to ThermoWood heat treatment furnace using various schedules. The properties of the boards and key treatment parameters are presented in Table 1. After the heat treatment, the boards were visually evaluated for cracks, twists, and other deformations. Only those boards that were free of defects were selected for further mechanical property testing. The moisture content (MC) of the heat-treated boards was measured to be 2%–3%. The untreated wood of the same species was used as a control sample.

Table 1 Summary of the board properties and treatment conditions
Tabelle 1 Ausgangsfeuchte, Abmessungen und Rohdichte des Versuchsmaterials und Prozessparameter

Species	Trial no.	Initial average MC (%)	Board dimension (mm)	Board average density (kg/m^3)	Maximum temperature (°C)	Total processing time (h)	Duration at maximum temperature (h)
Spruce	1	19.2	39 × 140 × 2500	401	212	40.5	3
	4	16.4	39 × 140 × 2500	399	212	44	3
Pine	2	13.4	42 × 140 × 2500	411	212	61	3
	5	24.4	16 × 140 × 2500	402	212	24	3
	8	20.1	39 × 90 × 2500	418	202	39	3
	9	13.3	23 × 140 × 2500	389	202	25	3
	12	18.7	32 × 140 × 2500	400	200	34	3
Fir	11	19.0	45 × 145 × 2500	405	202	46	3
	13	15.5	32 × 140 × 2500	410	202	34	3
	14	18.2	32 × 140 × 2500	420	212	30	3
Aspen	7	19.1	44 × 140 × 2500	344	200	46	3
Birch	10	14.3	23 × 120 × 2500	409	200	31	3

Note: MC is moisture content.

2.2 Specimen preparation and property testing

The specimens for static bending and hardness measurements were cut from heat-treated and untreated boards. All specimens were then conditioned in a chamber at 22 °C and 65% relative humidity (RH) for four weeks before testing. Static bending was determined on the specimens with a dimension of $25 \times 25 \times 410\,\text{mm}^3$ (radial × tangential × longitudinal) using three-point bending test method (ASTM 2004) with the span of 360 mm, and twelve specimens were tested in each series. For those boards that were thinner than 25 mm, the original thickness was kept when preparing the specimens. A testing machine with the model MTS Alliance RT/100 was used. Loading speed was set at 25 mm/min.

The specimens for hardness test were 50 mm in width and 75 mm in length; the thickness was in accordance with the initial thickness of the boards. The procedures described in ASTM D-143-94 (2004) were followed for hardness test. The diameter of the ball used for penetration was 12.7 mm and the ball penetration depth into wood specimens was 2.54 mm for all specimens. Four tests on two radial surfaces, four tests on tangential surfaces, and one test on each end of the boards were carried out. The penetration positions were chosen far enough from the edges to prevent splitting or chipping. Load was applied to the specimens continuously at a rate of 6 mm/min which is equal to the rate of motion of the movable crosshead. Six specimens were tested for each species from each trial.

3 Results and discussion

3.1 Overall performance of the wood treated using ThermoWood process

The boards were visually checked after they were taken out of the furnace. The defects (e.g. internal or surface cracks, twists, and deformations, etc.) were found to be at minimum level. The overall performance of spruce, pine, fir, aspen, and birch was quite acceptable.

3.2 Properties of heat-treated spruce

The changes in static bending and hardness of heat-treated spruce, pine, fir, aspen, and birch compared to the properties of untreated wood of the same species are presented in Table 2. The changes were obtained by calculating the property difference between heat-treated wood and untreated same species as a percentage of untreated wood property. Modulus of rupture (MOR) of heat-treated spruce from trial no. 1 decreased 49% compared to the untreated same species (Table 2). Modulus of elasticity (MOE) of heat-treated spruce from the same trial decreased 14%. Spruce treated using the schedule of trial no. 4 reduced less in MOR and MOE (Table 2). The maximum temperature and duration at that temperature remained constant for the two trials as can be seen in Table 1. The thickness of the boards for the two treatments was the same. But initial moisture content of the boards was higher and total processing time was shorter for trial no. 1. This reflects that initial MC and total

Table 2 Changes in static bending and hardness of heat-treated spruce, pine, fir, aspen and brich compared to the properties of untreated wood (UT) of the same species

Tabelle 2 Änderungen der Biegefestigkeit und Härte von wärmebehandelter Fichte, Kiefer, Tanne, Pappel und Birke verglichen mit unbehandelten Proben derselben Holzarten

Species			Treatment				
			Static bending			Hardness	
			MOR	MOE	Radial	Tangential	Longitudinal
Spruce	UT	(MPa)	75.2	9.73×10^3	1.16×10^3	1.19×10^3	3.19×10^3
	Trial No.	1	−49%	−14%	+7%	+7%	+16%
		4	−34%	−7%	+3%	−6%	+8%
Pine	UT	(MPa)	66.4	1.03×10^4	1.25×10^3	1.06×10^3	2.95×10^3
(jack pine	Trial No.	2	−28%	−5%	+17%	+52%	+43%
and		5	−22%	−4%	+19%	+41%	+36%
white pine)		8	−26%	−4%	+12%	+45%	+37%
		9	−10%	−15%	−24%	−10%	0
		12	−32%	−28%	−13%	−5%	+11%
Fir	UT	(MPa)	61.0	7.41×10^3	936	997	2.83×10^3
	Trial No.	11	0	+25%	+4%	+2%	+13%
		13	0	+17%	+19%	+6%	+15%
		14	−37%	−6%	+7%	−25%	+6%
Aspen	UT	(MPa)	75.1	9.16×10^3	1.21×10^3	1.24×10^3	2.82×10^3
	Trial No.	7	−35%	+15%	−26%	−39%	−15%
Birch	UT	(MPa)	94.5	1.09×10^4	1.75×10^3	1.65×10^3	3.41×10^3
	Trial No.	10	+6%	+30%	+36%	+22%	+37%

processing time can possibly make a difference in bending properties of spruce.

Hardness of the treated spruce in radial direction for trials no. 1 and 4 increased 7% and 3% compared to untreated wood. The same tendency was observed for longitudinal hardness for trial no. 4 (16% and 8%, respectively). Tangential hardness of spruce treated using the schedule of trial no. 1 increased 7%, but decreased 6% for trial no. 4 compared to untreated wood.

3.3 Properties of heat-treated pine

The trials 2, 5 and 8 were carried out using jack pine as material whereas trials 9 and 12 were conducted on white pine. MOR of heat-treated jack pine from trials no. 2, 5, and 8 was reduced by 28%, 22%, and 26%, respectively, compared to that of the untreated same species (Table 2). Also MOE of the heat-treated jack pine decreased slightly (Table 2). MOR and MOE of the heat-treated white pine from trial no. 9 decreased 10% and 15%, respectively. From trial no. 12, MOR and MOE were reduced by 32% and 28%. In Table 1, we observed that in trial no. 12 the initial MC of the boards was higher, the boards were thicker, and the total processing time was longer when compared with trial no. 9. This indicates that the initial MC, board thickness, as well as the total processing time may cause the difference in MOR and MOE of jack pine.

Heat-treated jack pine from trials no. 2, 5, and 8 had higher radial, tangential, and longitudinal hardness compared to the untreated wood (Table 2). As seen that jack pine and white pine behaved differently in hardness, the structure changes due to the treatment in the two species may remain different; moreover, initial MC, board dimension, and total processing time can affect the hardness of heat-treated wood.

3.4 Properties of heat-treated fir

MOR of fir treated in trial no. 11 and 13 remained the same after heat treatment; but MOE increased by 25% and 17%, respectively (Table 2). The improvement in MOE indicates that the stiffness of fir after heat treatment is increased, which is in accordance with the results published by (Callister 1994). MOR and MOE of heat-treated fir from trial no. 14 decreased by 37% and 6% compared to its untreated control. The maximum temperature for trial no. 14 was higher than it was set in trials 11 and 13 (Table 1), which may result in a sharp decrease in MOR and MOE of heat-treated fir.

The hardness of treated fir from trial no. 11 and 13 was improved in radial, tangential, and longitudinal directions (Table 2). By applying the schedule of trial no. 14 to fir, the wood turned to be more rigid in radial and longitudinal directions, however, the wood was less rigid in tangential direction (Table 2).

3.5 Properties of heat-treated aspen

From trial no. 7, MOR was reduced compared to untreated aspen, but MOE increased by 15% (Table 2). Radial, tangential, and longitudinal hardness of heat-treated aspen were reduced after the heat treatment by 26%, 39%, and 15%, respectively (Table 2).

3.6 Properties of heat-treated birch

MOR and MOE of birch increased 6% and 30% after the heat treatment (Table 2). Radial, tangential, and longitudinal hardness of heat-treated birch from the same trial were improved from 22% to 37% as compared to the untreated wood (Table 1).

4 Conclusions and recommendations

Heat treatment of wood involves different phases and in each phase different operating parameters are exhibited. Each of these parameters can affect the final product properties and should be chosen carefully. The results of the initial tests carried out in this study show that the overall performance of the five species grown in Québec and treated by ThermoWood process is acceptable. Generally, the reduction in modulus of elasticity was smaller than that in modulus of rupture; in hardwood such as aspen and birch, modulus of elasticity increased by 15% and 30% compared with their untreated controls. In this preliminary study, the board size (especially thickness), initial wood moisture content, maximum treatment temperature, and total processing time varied but were believed to be essential for the determination of product mechanical properties. The effect of each variable on final product properties needs further investigation.

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