

## Effect of high temperature treatment on the mechanical properties of birch (*Betula papyrifera*)

Sándor Poncsák · Duygu Kocaefe ·  
Mohamed Bouazara · Andre Pichette

Received: 21 October 2005  
© Springer-Verlag 2006

**Abstract** The thermal treatment of wood is an alternative to the chemical treatment for preservation purposes. The heat treatment process improves wood's resistance to decay and its dimensional stability. However, mechanical strength decreases as a result of heat treatment. Therefore, the treatment parameters have to be optimized to keep this loss at a minimum while improving other properties. Thermal treatment is new in North America, and its parameters are not yet adjusted for the Canadian species. Carrying out the parameter adjustment in an industrial furnace requires many trials which are costly in terms of material and man-power. A laboratory study was carried out to determine the effect of different parameters of the heat treatment on the mechanical properties of birch in order to optimize this process. A thermogravimetric analyzer was built to carry out the laboratory tests. The impact of the process parameters—such as maximum treatment temperature, holding time at this temperature, heating rate, and gas humidity—on the mechanical properties of birch was investigated. Temperature distributions in wood and in gas as well as the weight loss of wood were measured during the experiments. Afterwards, hardness, modulus of elasticity, modulus of rupture, and resistance to screw withdrawal of the samples were measured. The relation between the process parameters and the resulting mechanical properties was examined.

---

S. Poncsák (✉) · D. Kocaefe · M. Bouazara  
Department of Applied Sciences, University of Quebec at Chicoutimi,  
555, boul. de l'Université, Chicoutimi, QC, Canada G7H 2B1  
e-mail: sponcsak@uqac.ca

A. Pichette  
Department of Fundamental Sciences, University of Quebec at Chicoutimi,  
555, boul. de l'Université, Chicoutimi, QC, Canada G7H 2B1

**List of symbols**

$b$	width of the sample (mm)
$d$	thickness of the sample (mm)
$d_B$	diameter of the penetrating ball (mm)
$h$	penetration depth
$L$	plate separation (mm)
$m$	mass of wood sample (g)
$m_0$	initial mass of wood sample (g)
MOE	modulus of elasticity (N/mm <sup>2</sup> )
MOR	modulus of rupture (N/mm <sup>2</sup> )
$P$	maximum load before rupture (N)
$P_1$	load at the limit of the range of elasticity (N)
$P_p$	maximum load applied during the penetration of steel ball into the wood sample (N)
$t$	time (min)
$t_{\max}$	duration of the heat treatment (min)
$t_{\text{ref}}$	duration of the base case of the heat treatment (Table 1) [min]
$y_1$	displacement of the sample center at the limit of the range of elasticity (mm)
$W$	relative weight loss (non-dimensional)

**Introduction**

The most commonly used method of wood preservation is chemical treatment which involves the impregnation of chemical substances such as traditional oil (creosote, pentachloro-phenol) and chromated copper arsenate into the wood. Different preservation methods are sought in order to avoid the toxic effects of these chemicals. Wood treatment at high temperature (thermo-transformation) is a very promising alternative to the chemical treatment. This method is different than conventional drying as explained below.

During conventional drying, wood is heated to approximately 120°C with externally supplied superheated steam. During drying no structural change takes place in the wood, and water is only removed by evaporation. A minimum temperature of 140°C and prolonged drying times are required to remove the total moisture content (Amy 1961). The absence of moisture in wood prevents the undesirable biochemical reactions and microbiological attacks. Full descriptions of the moist air and superheated steam drying models are given in various papers (Pang et al. 1994; Fhyr and Rasmuson 1997; Johanson et al. 1997; Pang 1998).

During the high temperature treatment, the wood species are heated slowly up to 200–230°C in humid inert gas. This treatment reduces the hydrophilic behavior of the wood by modifying the chemical structure of some of its components (Raimo et al. 1996; Gailliot 1998). This modification prevents the re-absorption of water which promotes wood decay. When wood absorbs humidity from its surroundings, water molecules are inserted between and within the wood polymers (lignin, cellulose, and hemicelluloses), and hydrogen bonds are formed. This phenomenon makes the wood swell. During the heat treatment, the number of hydrophilic OH groups is decreased and replaced by hydrophobic *O*-acetyl groups

(Hinterstoisser et al. 2003). The latter creates cross-links between wood fibers and thus it significantly reduces the ability of the water to penetrate into the wood (Homan et al. 2000). The wood becomes dimensionally more stable compared to the untreated wood. Elimination of hydroxyl groups also reduces the number of potential anchor-points for fungi.

During the heat treatment process, many volatile organic compounds—such as alcohols, resins, terpenes etc.—are produced and released from the wood (Manninen et al. 2002; Graf et al. 2003). Significant decrease of hemicellulose content is also reported in the literature (Pavlo and Niemz 2003). The hemicelluloses degrade first (between 160 and 260°C) since their low molecular weight and their branching structure facilitate a faster degradation compared to the other components present in wood (Fengel and Wegener 1984). Hemicelluloses are nutrients to various kinds of fungi; therefore, they are one of the key components effecting wood decay (Fengel and Wegener 1984). The removal of the branched hemicelluloses increases the crystallinity index of the cellulose between 160 and 220°C as reported in the literature (Fengel and Wegener 1984; Weiland and Guyonnet 2001). However, at temperatures higher than 220°C, it decreases again. Cellulose is composed of linear chains which can crystallize, and hemicelluloses have an amorphous branched structure. As the hemicelluloses are eliminated, the crystallinity of wood increases temporarily around 160–200°C. The exact temperature depends on the type of wood species. At the end of the thermal treatment, the wood is abruptly cooled down with a spray of water. During this period, the extractives and other water soluble secondary substances with low molecular weights which come from the decomposition of various wood components are partially captured by water. Their quantity depends on the wood species, temperature, and time of the heat treatment as well as on the moisture content of wood.

Thermal treatment improves durability, prevents swelling and shrinking (Stamm et al. 1946; Stamm 1956), and gives a valuable dark color to the wood. It also modifies the mechanical properties. Wood becomes more rigid and fragile, and the mechanical resistance decreases. Depending on the treatment parameters such as the maximum treatment temperature, the heating rate, the holding time at the maximum temperature or the gas humidity, cracks can appear and the cell structure can be partially degraded as well. Individual optimization of these parameters must be carried out separately for each wood species. Even the same wood species coming from places with different climates can have significant differences in their cellular structures; therefore, they may require different treatment conditions.

There are many technologies used for wood heat treatment in Europe: the PLATO process (Holland), the Retification process (France), Bois Perdure process (France), OHT process (Germany), and the Thermo Wood process (Finland). The differences between these technologies are due to the design of the furnaces, gas composition, and the process parameters used (Militz 2002). These processes have to be adapted to the Canadian wood species.

This paper focuses on the influence of thermal treatment parameters on the mechanical properties of Canadian birch. The weight losses vs. time data measured during the experiments are analyzed, and the results are presented.

## Experimental set-up and experimental conditions

### Thermogravimetric system

A thermogravimetric analyzer was built to study the effect of the heat treatment parameters (maximum treatment temperature, heating rate, holding time, and gas humidity) on the birch quality (Fig. 1). The variation of the temperature distribution within the wood and the weight loss of the wood were recorded during the treatment. The analyzer consists of an electrical furnace, a temperature controller, and a balance. The wood sample was suspended from the balance into the furnace. In industry, wood is heated with hot combustion gases. In this study, a mixture of inert gases with a composition similar to that of the industrial furnace is used to heat the wood sample. A programmable temperature controller assured the desired evolution of temperature in the furnace.

The inert gas mixture (nitrogen, carbon dioxide, and water vapor) was used in order to prevent the oxidation reactions in the laboratory furnace. Nitrogen and carbon dioxide flow rates were controlled with flow meters. The gas humidity was adjusted using a second furnace which was placed directly under the main furnace. The latter was used to evaporate water and generate steam. Very fine water droplets were injected into this furnace via a valve. The high temperature maintained in this furnace assured the instantaneous vaporization of water and thus the creation of hot steam. A second valve was used to evacuate the excess vapor. The opening and closing of both valves were done with a controller. Then, the steam was injected into the main furnace in order to adjust the humidity of the gas which was in contact with the wood sample. The presence of water vapor in gas is particularly important. Without humidity, wood dries too fast which increases the risk of crack formation (McCabe et al. 1985).

The outlet gas is evacuated from the system with a suction pump. An ice bed, as shown in Fig. 1, was used to cool and collect condensable by-products, released from the wood. Parallel lines, equipped with timer controlled valves, were used to separate condensed by-products that were collected at different temperature intervals.

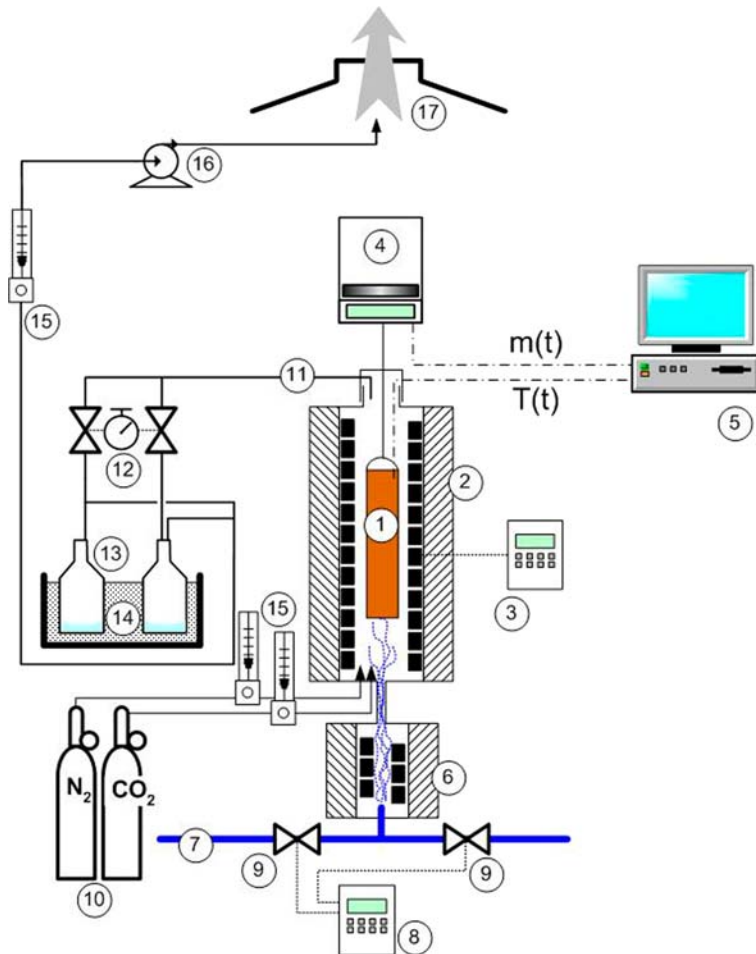
Mechanical properties such as MOR, MOE, hardness, and resistance against screw withdrawal (RASW) of the wood were measured after treatment in order to study the impact of the heat treatment parameters on the birch quality.

### Preparation of the wood samples

The birch (*Betula papyrifera*) samples treated during this study were obtained from a local sawmill of the Saguenay-Lac-Saint-Jean region of Quebec, Canada. The dimensions of the samples were  $0.035 \times 0.035 \times 0.2 \text{ m}^3$ . They were pre-dried in air, and their initial moisture contents were 5–12% before the heat treatment.

### Experimental procedure

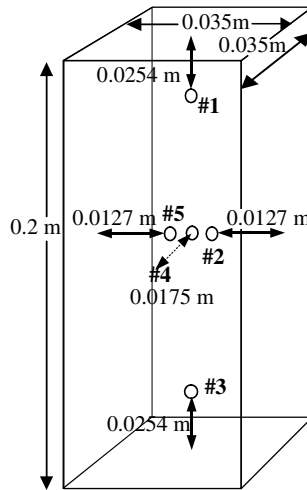
The experiments were conducted in a thermogravimetric analyzer. Two groups of experiments were carried out. During the first group of experiments, the weight loss of the sample was continuously measured. In the second group, the same experiments were repeated under the same condition as that used for the first group; however, this time, the evolution of temperature distribution within the sample was



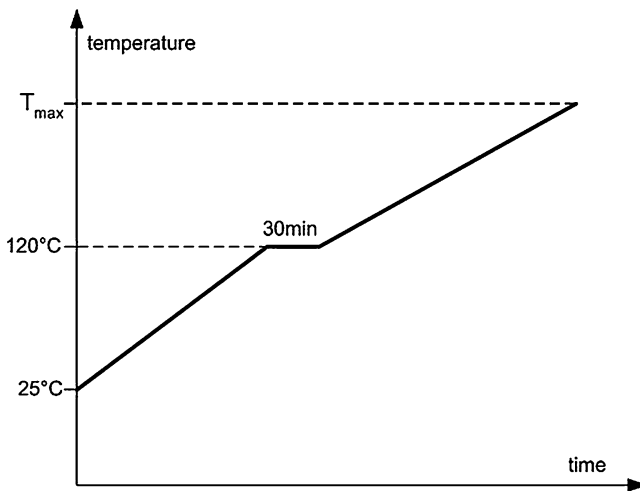
**Fig. 1** Schematic view of the thermogravimetric system: 1 sample, 2 main furnace, 3 temperature controller, 4 balance, 5 data acquisition system, 6 secondary furnace for steam generation, 7 water supply, 8 humidity controller, 9 valves, 10 gas, 11 gas and vapor evacuation line, 12 timer controlled valves, 13 Lixivia collection system, 14 cooling ice bed, 15 flow meters, 16 suction pump, 17 aeration system

measured. For the temperature measurement experiments, the samples were equipped with five thermocouples as shown in Fig. 2. An additional thermocouple was used to measure the gas temperature near the sample. The weight or temperature measurements were registered using a data acquisition system.

During the experiments, wood samples were first heated up to 120°C with a predetermined heating rate. The furnace temperature was kept constant at 120°C for half an hour to reduce the water content of wood before starting the thermochemical treatment which occurs at higher temperatures. Then, the samples were heated to a final desired temperature with the same heating rate. In order to study the effect of the holding time at the maximum treatment temperature, the temperature was kept constant for a known period of time at the end of the treatment. Afterwards, the wood samples were cooled down to 120°C with water spray. For the



**Fig. 2** Position of thermocouples in wood samples



**Fig. 3** Recipe of the base case of the heat treatment of the wood samples used in the thermogravimetric analyzer

base case, the heating rate was 20°C/h, the maximum treatment temperature was 220°C, the gas humidity was 100 g water/m<sup>3</sup> gas, and there was no holding time. Only one parameter at a time was changed during the following experiments, and the effects of this parameter on the weight loss and mechanical properties were studied. Figure 3 shows the heat treatment recipe used for the base case. Table 1 presents the heat treatment parameters used during the experiments.

### Measurement of mechanical properties

In order to determine the effect of the treatment parameters on the mechanical properties, the three point bending [modulus of elasticity (MOE) and modulus of

**Table 1** Summary of heat treatment parameters

Maximal temperature (°C)	Heating rate (°C/h)	Holding time (min)	Humidity (g water vapor/m <sup>3</sup> dry gas)
120	20	0	100
160	20	0	100
200	20	0	100
210	20	0	100
220 <sup>a</sup>	20	0	100
220	10	0	100
220	30	0	100
220	20	15	100
220	20	30	100
220	20	45	100
220	20	0	0
230	20	0	100

<sup>a</sup>Base case

rupture (MOR) measurements], the hardness, and screw withdrawal tests were carried out for the untreated and treated samples. Tests were carried out using the *MTS ALLIANCE RT 100* Universal Mechanical Test Machine and standard procedures were respected. The relationship between the treatment conditions and the mechanical properties was examined.

#### *Three point static bending test*

The ASTM D-143 standard was followed during these tests. Ten to twelve birch samples (dimensions  $1 \times 1 \times 20 \text{ cm}^3$ ) were tested for each set of parameters. The plate separation ( $L$ ) was 15.24 cm and the vertical speed of the mobile head was 1.3 mm/min. The force was applied to the middle of the upper face of the sample in a radial direction. The MOE and the MOR were determined from the measured load–deformation curves using the equations given below (ASTM 2004):

$$\text{MOE} = \frac{P_1 L^3}{4bd^3 y_1} \quad (1a)$$

$$\text{MOR} = \frac{3PL}{2bd^2}, \quad (1b)$$

where  $P$  is the maximum load before rupture,  $P_1$  and  $y_1$  denote the load and the displacement of the sample center at the limit of the range of elasticity, and  $b$  and  $d$  are the width and thickness of the samples, respectively (Fig. 4a). Tests were repeated ten times for every treatment parameter in both the radial and tangential directions.

#### *Penetration hardness test*

The ASTM D-1324-83 standard was followed during the test. Three samples (dimensions  $3.5 \text{ cm} \times 3.5 \text{ cm} \times 20 \text{ cm}$ ) were used for each set of parameters and the tests were repeated six times at both the radial and tangential faces for each sample. Figure 4b shows the hardness measurement and its parameters schematically. This method involves the measurement of the resistance of wood samples against the

penetration of a steel ball of 11.3 mm diameter ( $d_B$ ) at a constant penetration rate of 6 mm/min. The tests were stopped when 400 N ( $P_p$ ) was reached and the penetration depth ( $h$ ) was measured. During the tests, the displacement of the sample surfaces was also measured using a micrometer, and the results were corrected according to this measurement. Equation 2 shown below was used to determine the penetration hardness ( $H_m$ ) (ASTM 2004):

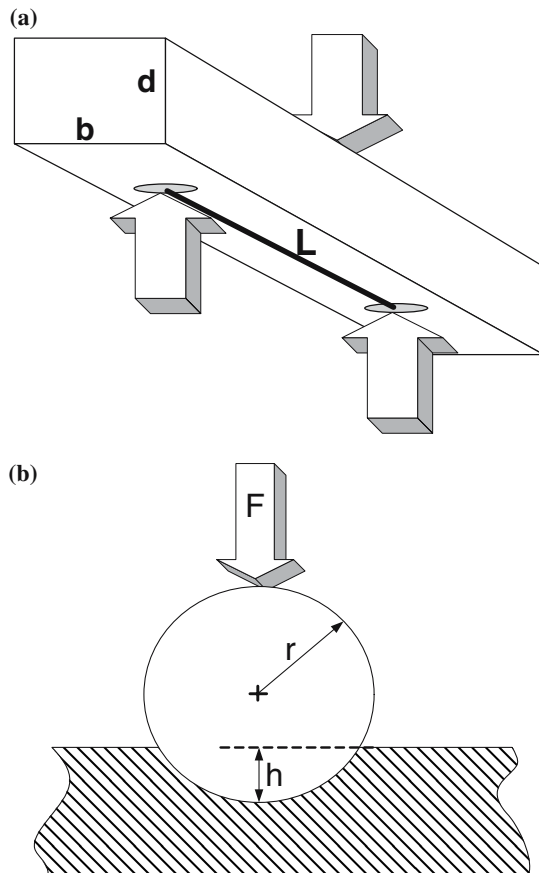
$$H_m = \frac{P_p}{\pi d_B h} \quad P_p = 400 \text{ N.} \quad (2)$$

The tests were repeated eight times for every treatment parameter.

#### *Screw withdrawal test*

This test, which was carried out according to the ASTM D-1761-88 standard, permits the evaluation of the screw (N° 10, 25 mm length) withdrawal resistance of wood. During such a test, the force required to pull out a screw from the wood sample is measured. This is another method to determine the mechanical

**Fig. 4** Schematic view of **a** the three point bending test, **b** the hardness test



strength of wood. The screws were inserted at the middle of the sample top to the depth of  $2/3$  samples width. The speed of withdrawal of the screw was constant (2.54 mm/min). The tests were repeated six times for every treatment parameter.

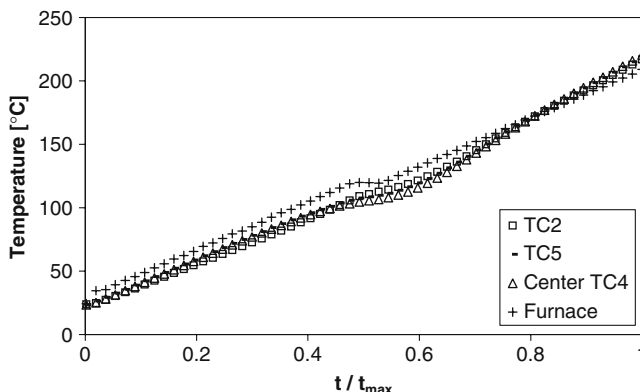
The size of the samples was smaller than that required by the ASTM standards since the samples that can be treated in the thermogravimetric analyzer were small ( $0.035 \text{ m} \times 0.035 \text{ m} \times 0.2 \text{ m}$ ). Using a small sample insures a more uniform temperature distribution during the treatment, and a uniformly treated product is obtained at the end of the treatment. Therefore, the standard tests were adjusted to the sample dimensions used in the experiments. The purpose here was to carry out only a comparative study in order to investigate and compare the effect of the treatment parameters on the mechanical properties.

## Results and discussion

### Temperature distribution in the wood sample during thermal treatment

Figure 5 shows the temperature distribution in the direction perpendicular to the sample length (horizontal direction). The figures showing the temperature effects are normalized using  $t_{\max}$  which is the total treatment time of a given experiment. It can be seen from this figure that the temperature of the birch sample follows the gas temperature with a small time-lag up to  $140\text{--}150^\circ\text{C}$ . During this part, which is also called “drying” period, the maximum temperature difference observed between the center of the wood and the gas is  $20^\circ\text{C}$ . The temperature at the center (TC4) of the sample is slightly lower than that close to the surface (TC2, TC5) as expected because the external surface of the wood is heated by hot gas.

Around  $150 \pm 5^\circ\text{C}$ , exothermic chemical reactions begin to take place within the wood. These reactions generate heat, and consequently, accelerate the rise of wood temperature which exceeds the gas temperature around  $170 \pm 5^\circ\text{C}$ . Due to the heat generated by the exothermic reactions above  $150^\circ\text{C}$ , the difference between the surface and the center temperatures disappears. The occurrence of these reactions at



**Fig. 5** Temperature versus time data for wood (thermocouples TC2, TC5, TC4) and for gas

the onset of thermo-transformation is also reported in the literature. Fengel isolated depolymerization products from wood treated at 150°C in a nitrogen atmosphere (Fengel and Wegener 1984). At higher temperatures, the wood temperature becomes higher than the gas temperature. A maximum temperature difference of 10°C is observed during the experiments. The wood temperatures recorded by the thermocouples TC2 and TC5 coincide perfectly showing that the temperature distribution in the sample is symmetrical.

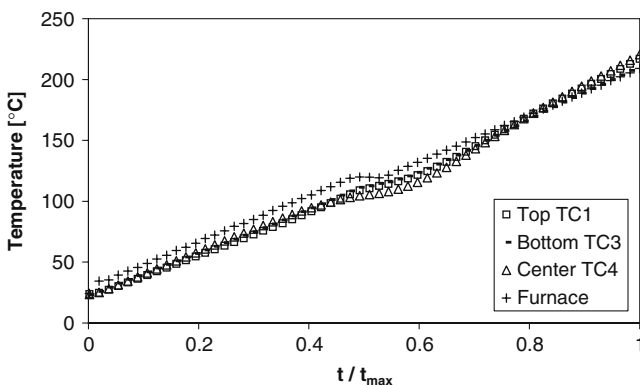
Figure 6 shows the temperature distribution parallel to the sample length (vertical direction), measured by the thermocouples TC1, TC3 (top and bottom), and TC4 (center). The center temperature is slightly lower compared to those of the top and bottom before the onset of chemical reactions. As soon as chemical transformation begins, the center temperature increases and catches up with the top and bottom temperatures resulting in a uniform temperature distribution within the sample.

#### Weight loss of the sample during thermal treatment

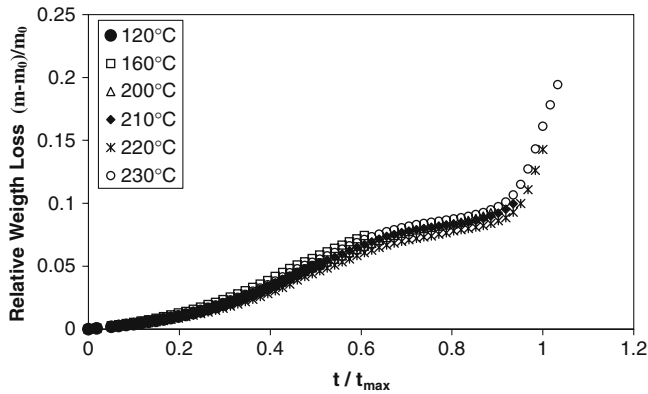
Figure 7 shows how the weight loss changes with time, measured with the thermogravimetric system for different final temperatures at a constant heating rate of 20°C/h. The relative weight loss ( $W$ ) is defined as the ratio of the actual weight loss ( $m - m_0$ ) to the initial sample weight ( $m_0$ ) as shown below:

$$W = \frac{m_0 - m}{m_0}. \quad (3)$$

The slight differences between the curves show the good repeatability of the tests. These differences are most likely the result of differences in initial humidity of the wood samples which varied between 5 and 12%. The presence of two inflection points at each curve can be seen in this figure. The first inflection point is observed at  $t/t_{\max} \approx 0.48$  and  $T_{\text{wood}} \approx 110 \pm 5^\circ\text{C}$ ; and it corresponds to the drying process. Water starts to evaporate even at lower temperatures, but this phenomenon becomes significant above 100°C. This can be explained by the fact that the molecular diffusivity



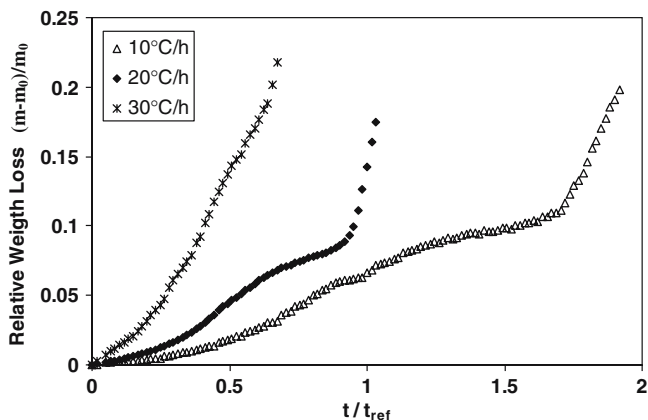
**Fig. 6** Temperature versus time data for wood (thermocouples TC1, TC3, TC4) and for gas



**Fig. 7** Effect of final temperature on the relative weight loss of the wood sample

of water in wood increases with increasing temperature. Also, at high temperatures, the physical bonds between water and the hydrophilic groups of the wood are broken which facilitate the movement of water. These phenomena accelerate the weight loss rate with increasing temperature in this region. However, the quantity of water in the wood is limited. After a maximum rate, the weight loss slows down as water is depleted. In the second inflection point at  $t/t_{\max} \approx 0.88$  and  $T_{\text{wood}} \approx 175 \pm 5^\circ\text{C}$ , acceleration of the weight loss observed is probably caused by the release of different by-products during the degradation of the wood components such as hemicelluloses (heat treatment or thermal transformation period).

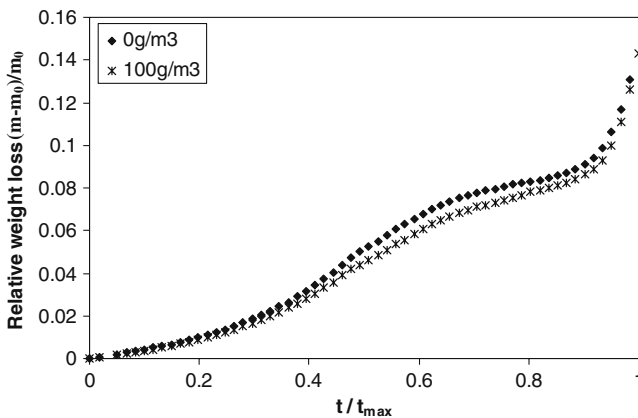
Figure 8 shows the effect of heating rate on the weight loss. Since the time of treatment changes with heating rate, the total treatment time ( $t_{\text{ref}}$ ) of the base case ( $20^\circ\text{C/h}$  heating rate) is chosen to calculate the relative time ( $t/t_{\text{ref}}$ ). Two inflection points described above are observed for the cases with 10 and  $20^\circ\text{C/h}$  heating rates. For the case with the highest heating rate ( $30^\circ\text{C/h}$ ), it is not possible to observe



**Fig. 8** Effect of heating rate on the relative weight loss of the wood sample ( $t_{\text{ref}}$  is the final treatment time of the base case at  $20^\circ\text{C/h}$  heating rate)

clearly separate drying and heat transformation regions on the weight loss curve. This might be due to the lack of sufficient time to eliminate the water, and the wood still contains a significant quantity of moisture when chemical transformation begins. The presence of water in wood during the heat treatment catalyses the chain splitting by acidic hydrolysis and thus promotes the degradation of wood polymers (Raimo et al. 1996; Kirk and Farrell 1987). On the other hand, the transformation of hemicelluloses by water catalyzed hydrolysis makes the wood more resistant to mold attack (Kirk and Farrell 1987).

The effect of gas humidity on the sample weight loss is shown in Fig. 9. In this figure, the weight loss data are presented for two experiments carried out with humid ( $100 \text{ g water vapor/m}^3$ ) and dry gases. The absence of gas humidity causes a slight increase in the weight loss rate. If the humidity of gas is low, the difference between the moisture contents of the gas and the initially humid wood (moisture concentration gradient) is high. This increases the moisture removal rate and might cause crack formation in the wood especially around the knots as shown in Fig. 10. In the absence of humidity in the heating gas, one to three cracks per samples were observed. No such failures were found in the samples treated in the presence of water vapor.



**Fig. 9** Effect of gas humidity on the relative weight loss of the wood sample



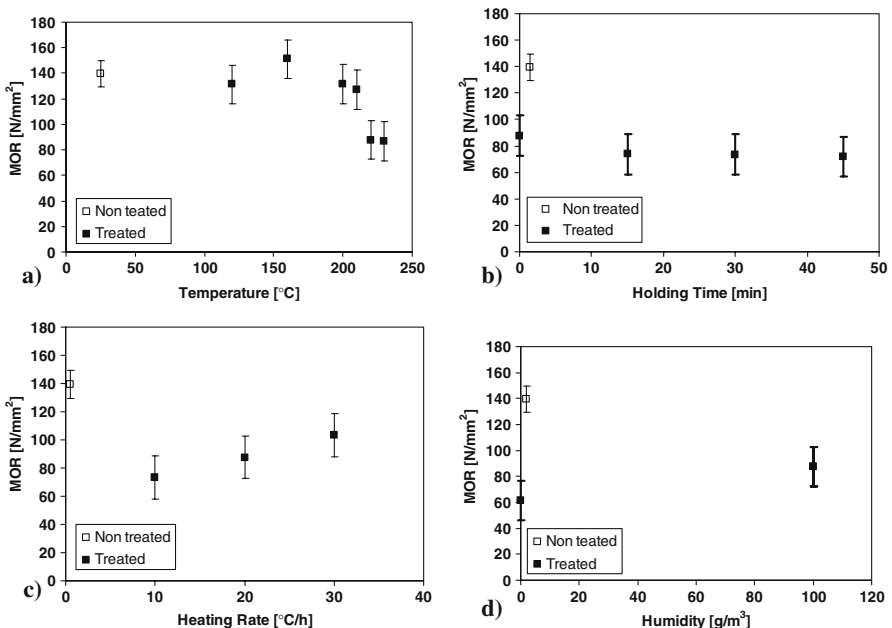
**Fig. 10** Crack formation on the wood sample heat treated with dry gas

## Mechanical properties

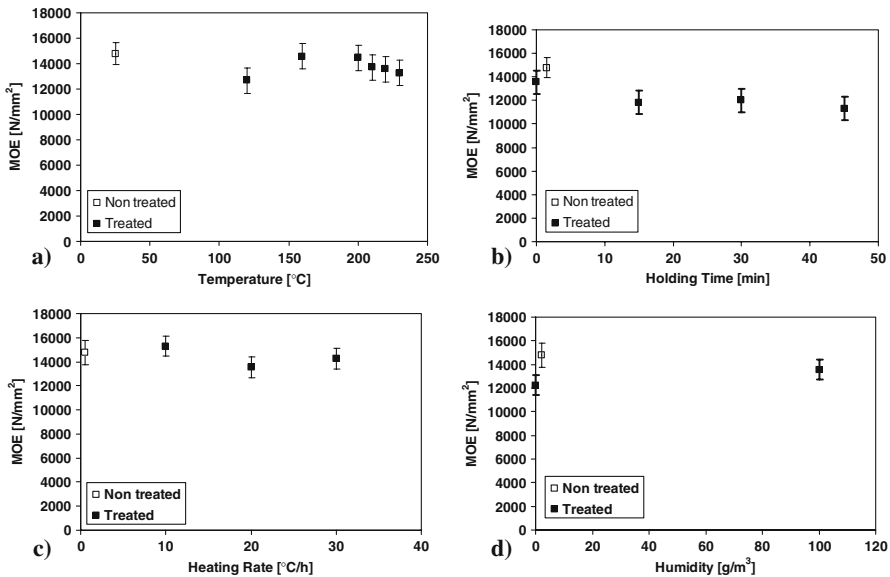
Wood is a non-homogenous material; consequently, its mechanical properties can differ from one sample to the other. Therefore, mechanical tests were repeated 6–12 times depending on the specific test in order to obtain statistically valid average values as explained below.

*Three point static bending test*

This test shows the maximum load-carrying capacity of the sample. Figure 11 shows the influence of the maximum treatment temperature, holding time, heating rate, and gas humidity on the MOR. The effects of the same operating conditions on the MOE are presented in Fig. 12. The results show that, the more the birch is subjected to heat (by using higher maximum temperatures or lower heating rates), the lower the MOR (Fig. 11). This is probably due to the break-up of the hemicelluloses and cellulose polymers. It can be seen from this figure that the failure rate increases significantly after 200°C, although the exothermal chemical reactions begin between 150 and 160°C. A faster heating rate or a shorter holding time decreases the contact time between the hot gas and wood. Thus, the mechanical property loss is smaller compared to the samples subjected to hot gas for longer times. However, the impact of the holding time is not significant; it is within the experimental error range. The elasticity of birch seems to be more or less constant under the experimental conditions used (Fig. 12). Pavlo et al. reported similar tendencies. They found that MOR decreases when the heat treatment temperature decreases while MOE does not seem to be affected significantly by the temperature (Pavlo and Niemz 2003).



**Fig. 11** Effects of **a** maximum treatment temperature, **b** holding time, **c** heating rate, and **d** gas humidity on the modulus of bending and modulus of rupture



**Fig. 12** Effects of **a** maximal temperature, **b** holding time, **c** heating rate, and **d** gas humidity on the modulus of elasticity

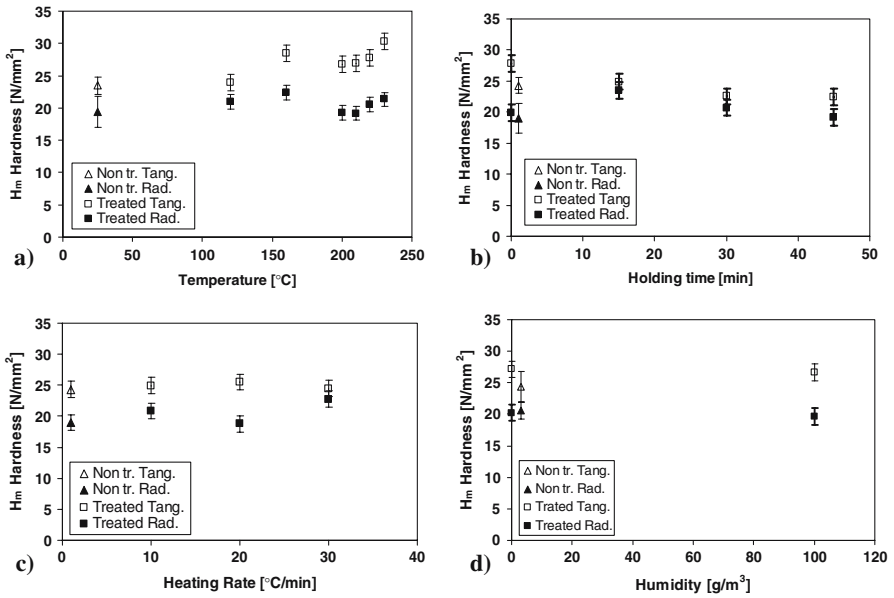
Figures 11d and 12d show the effect of gas humidity on the MOR and the MOE, respectively. The MOR increases clearly with increasing gas humidity while the MOE shows a slight increase. The relative error of the bending test was  $\pm 5$ –10%.

### Penetration hardness test

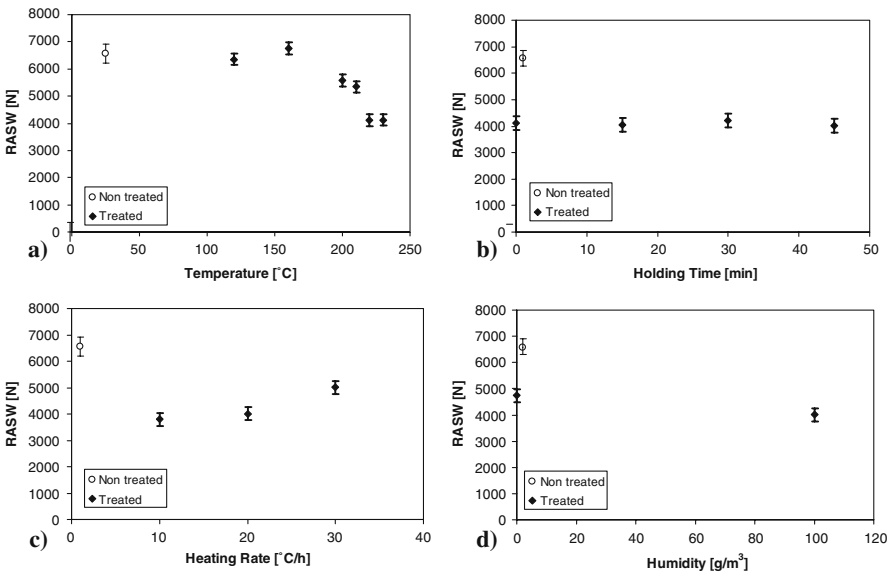
The hardness of birch in the tangential direction was found to be higher compared to that in the radial direction under various operating conditions as can be seen from Fig. 13. As it can be seen from this figure the hardness increases slightly with temperature, especially above 200°C. Around 160°C a local maximum of the hardness was observed, but the explanation of this phenomenon requires additional investigation. Those observations are in accordance with the literature (Pavlo and Niemz 2003). The hardness of birch decreases with increasing holding time at the maximum treatment temperature (220°C) probably due to further structural degradation. Gas humidity and the heating rate do not seem to have a significant effect on hardness (Fig. 13c, d). The relative error of the screw hardness test was  $\pm 2$ –8%.

### Screw withdrawal test

The results of the screw withdrawal tests are shown in Fig. 14. The RASW starts to decrease gradually above 200°C (Fig. 14a). On the other hand, the holding time (Table 1) at 220°C does not seem to affect this property of the birch significantly (Fig. 14b). RASW increases with increasing heating rate (lower degradation) and decreases with increasing humidity of the drying gas (Fig. 14c,



**Fig. 13** Effect of **a** maximal temperature, **b** holding time, **c** heating rate, and **d** gas humidity on hardness



**Fig. 14** Effects of **a** maximal temperature, **b** holding time, **c** heating rate, and **d** gas humidity on the resistance to screw withdrawal

d). It seems that changes in RASW and in MOR follow similar trends with respect to the treatment parameters. The relative error of the screw withdrawal test was  $\pm 3\text{--}5\%$ .

## Conclusions

The principal conclusions of this study are summarized below.

- When the heating rate is low, the drying and the thermal transformation periods can be clearly distinguished on the weight loss versus time diagrams of birch. At higher heating rates, these two phenomena can overlap. In this case, the wood moisture content cannot be eliminated during the drying period; therefore, wood still contains some moisture when the transformation starts at higher temperatures. This moisture might have some impact on the wood polymer degradation.
- The temperature versus time diagrams show that exothermic reactions start between 150 and 160°C for birch. Below this temperature, only moisture and some extractives are removed by evaporation. The heat generated by the exothermic reactions above these temperatures causes an additional increase in wood temperatures. Wood temperature starts to exceed the gas temperature around 170°C. The temperature distributions inside the birch samples were found to be symmetrical.
- Although the thermo-transformation (exothermic reactions) of wood begins around 150–160°C, it accelerates significantly only above 200°C as indicated by the sample weight loss. This phenomenon coincides perfectly with the decrease in mechanical strength.
- Mechanical properties such as the MOR and the RASW decrease with increasing treatment temperature, especially above 200°C. The hardness increases slightly with temperature above 200°C. Dry gas (0% humidity) can provoke crack formation which decreases the flexibility of birch. Slow heating rate has a similar impact on the mechanical properties as the higher treatment temperatures or the holding time at maximum treatment temperature. Due to a long contact time between hot gas and wood they cause deterioration in the mechanical strength of the birch. Fast heating rate can result in non-homogeneous and partially transformed wood especially for large samples.

**Acknowledgements** The authors would like to thank the administration of the University of Quebec at Chicoutimi (UQAC), especially Mr. Sylvain Cloutier; the Foundation of University (FUQAC); our partners, especially, Mr. Adam Lapointe and Mr. Denis Lapointe of PCI Industries; Mrs. Josette Ross, expert in wood chemistry at UQAC; our technicians, Mr. Patrice Paquette, Mr. Julien Tremblay, and Mr. Jacques Allaire for their support and contributions.

## References

- Amy L (1961) The physico-chemical bases of the combustion of cellulose and ligneous materials. *Cah du Centre Tech Du Bois* 45:30
- ASTM International (2004) Annual book of ASTM standards, Section 4 (construction), 4.10 (wood)
- Fengel D, Wegener G (1984) Wood, chemistry, ultrastructure, reactions. Walter de Gruyter & Co, Berlin
- Fhyr C, Rasmuson A (1997) Some aspects of the modelling of wood chips drying in superheated steam. *Int J Heat Mass Transfer* 40(12):2825–2842
- Gailliot FP (1998) Extraction and product capture in natural product isolation, Cannell. Humana Press, Totowa, pp 59–68
- Graf N, Haas W, Böchzelt H (2003) Characterization of gaseous emission from a small-size industrial plant for thermal wood modification by GC/MS, In: van Acker J, Hill C (eds) *The 1st European*

- conference on wood modification, proceeding of the first international conference of the European society for wood mechanics, April 2nd to 4th 2003, Ghent, Belgium, ISBN 9080656526, pp 55–58
- Hinterstoisser B, Schwanninger M, Stefke B, Stengl R, Patzelt M (2003) Surface analyses of chemically and thermally modified wood by FT-NIR. In: van Acker J, Hill C (eds) The 1st European conference on wood modification, proceeding of the first international conference of the European society for wood mechanics, April 2nd to 4th 2003, Ghent, Belgium, ISBN 9080656526, pp 65–70
- Homan W, Tjeerdsma B, Beckers E, Joossen A (2000) Structural and other properties of modified wood. Congress WCTE, Whistler, Canada, pp 3.5.1-1–3.5.1-8
- Johanson A, Fyhr C, Rasmuson A (1997) High temperature convective drying of wood chips with air and superheated steam. *Int J Heat Mass Transfer* 40(12):2843–2858
- Kirk TK, Farrell RL (1987) Enzymatic combustion: the microbial degradation of lignin. *Annu Rev Microbiol* 41:465–505
- Manninen AM, Pasanen P, Holopainen JK (2002) Comparing the VOC emission between air-dried and heat treated Scots pine wood. *Atmos Environ* 36:1763–1768
- McCabe WL, Smith JC, Harriot P (1985) Unit operations of chemical engineering, 4th edn. McGraw Hill Chemical Engineering Series, New York, p 707
- Militz H (2002) Heat treatment technologies in Europe: scientific background and technological state of art. In: Proceedings of conference—enhancing the durability of lumber and engineered wood products. Kissimmee, Orlando. Forest Product Society, Madison
- Pang S (1998) Relative importance of vapour diffusion and convective flow in modeling of softwood drying. *Drying Technol* 16(1–2):271–281
- Pang S, Langrish TAG, Keey RB (1994) Moisture movement in softwood timber at elevated temperatures. *Drying Technol* 12(8):1897–1914
- Pavlo B, Niemz P (2003) Effect of temperature on color and strength of spruce wood. *Holzforchung* 57:539–546
- Raimo A, Kuoppala E, Oesch P (1996) Formation of the main degradation compounds groups from wood and its components during pyrolysis. *J Anal Appl Pyrolysis* 36:137–148
- Stamm AJ (1956) Thermal degradation of cellulose. *Ind Eng Chem* 48(3):413–417
- Stamm AJ, Burr HK, Kline AA (1946) Heat-stabilized wood. *Ind Eng Chem* 38(6):630–634
- Weiland JJ, Guyonnet R (2001) Étude Physico-Chimique d'un traitement thermique du bois. *Récents Progrès en Génie des Procédés* 15(88):195–202