Combined Hydro-Thermo-Mechanical Modification (CHTM) as an Innovation in Mechanical Wood Modification

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ABSTRACT

Current research is an innovation in the mechanical modification of wood. It was planned to modify wood in two steps of the hydrothermal and the mechanical treatments. Poplar wood blocks were prepared in sizes of 500 (l) × 55 (t) × 50 (r) mm, soaked in the water for 24 h and then treated at temperatures of 120, 150 and 180 °C for holding time of 0, 30 and 90 min. The treated blocks were immediately pressed at 160 and 180 °C for 20 min, then dried in an oven for 24 h at 100 °C. Density, radial swelling, spring back, moduli of elasticity and rapture, impact load resistance and hardness were determined in the test blocks. Results showed increase in all properties. The best treatment was determined as 150 °C. The density, MOE, MOR, impact load resistance, hardness were gained for 77%, 60%, 114%, 125% and 261% respectively. The spring back was decreased in the treated samples and it was determined about 15% as the lowest among the treatments. The lowest radial swelling was determined in the treated samples at 150 °C.

INTRODUCTION

The subject of the wood compression has been studied for 100 years, although most of the research on wood compression was in the years 1930-1960. Wood compression technologies were utilised by various industries, with various products appearing; such as Lignostone, Lignofol, Staypak and Compreg wood, *etc*. (Kollman *et al*. 1975). Earlier research did not pay much attention to the dimensional stability of the compressed wood. Due to its elastic behaviour, the wood tends to return to its previous dimensions after compression. This property is named "shape memory" and its magnitude is known as "set recovery" (Dwianto *et al*. 1997, 1999, Ito *et al*. 1988 a, 1988b, Kulticova 1999, Navi and Girardet 2000, Heger *et al*. 2004, Kamke 2006). In the earlier researches, the compression of the wood was combined with the heat (Ito *et al*. 1988 a, 1988b). In later works, the authors understood that it was necessary to compress the wood in the presence of heat and steam to ease the compression due to softening of the wood (Inoue *et al*. 1993, Navi and Girardet 2000). Regarding interesting results of the steaming in ceasing the springback of the compressed wood, no good results were still achieved for the dimensional stability and bioresistance of the compressed wood (Heger *et al*. 2004, Navi and Girardet 2000). The current research concerns results of the hydrothermal wood modification and the mechanical wood modification (wood compression) and the use of a combination of both modification techniques for wood compression.

According to the results of the hydrothermal wood modification, the wood becomes dimensionally stable (Mohebby and Sanaei 2005) and bioresistant against microorganisms (Tjeerdsma *et al*. 2000). Also, its strengths are increased due to the mechanical wood modification (Dwianto *et al*. 1997, 1999, Ito *et al*. 1988 a, 1988b, Kulticova 1999, Navi and Girardet 2000, Heger *et al*. 2004 Kamke, 2006). Here, the authors were optimistic to achieve good results for the wood properties if they combine two different techniques of the wood modification, the hydrothermal and the mechanical. The hydrothermal treatment of the wood, not only ease its softening and provides better compression; but also the wood achieves enhanced properties of the hydrothermal modification. For this reason, the current innovated work has been named as "combined-hydro-thermo-mechanical wood modification (CHTM)".

EXPERIMENTAL

Sample preparation-Test blocks were cut from fresh sawn poplar wood in sizes of 500 (length) × 55 (tangential) × 50 (radial) mm. The blocks were soaked in the water for 24 h prior to the treatment and they were then placed in a stainless steel cylinder containing preheated water (100 °C) and treated at temperatures of 120, 150 and 180 °C for holding time of 0, 30 and 90 min. The holding time indicates the time that the blocks were remained in the constant temperature after achieving the target treatment temperature. The hydrothermally treated blocks were immediately compressed in the radial direction at a compression set of 60% by a press at pressure of 80 bar and the temperatures of 160 and 180 °C for 20 min. Target thickness was 20 mm after compressing the blocks. Thickness was measured at three points on the blocks immediately after compressing and they were then dried in an oven at 103±2 °C for 24 h.

Springback - The thickness of the blocks was determined in the same measured points after 24 h of drying in an oven to calculate the springback based on Eq. 1. Ten blocks were prepared for each treatment.

$$Springback = \frac{T_2 - T_1}{T_1} \times 100 \qquad (1)$$

Where: T_1, thickness after compression (mm), T_2, thickness after drying

Density- Samples were prepared in sizes of 20×20×20 mm and oven dry density was determined according to ASTM D2395. Ten blocks were used as the replicates of each treatment.

Soaking-drying- Small blocks of 20×20×20 mm were prepared from the test samples and their dimensions as well as dry weights were determined prior to soaking in the water. Afterwards, the specimens were immersed in the water at room temperature for 24 h and they were then dried in an oven at 103±2 °C for 24 h. The samples were soaked again in the water and dried once again. The soaking and drying cycle was repeated for 5 steps. At last step, wet samples were weighed and their dimensions were determined to calculate the radial thickness swelling and anti-swelling-efficiency (ASE) based on Eqs. 2 and 3. Replicates of the current test were 10 specimens for each treatment.

$$S = \frac{R_w - R_0}{R_0} \times 100 \qquad (2)$$

Where: S is the radial swelling (%), R_0 and R_w, the radial thicknesses before and after immersion in the water (mm), respectively.

$$ASE = \frac{S_2 - S_1}{S_1} \times 100 \quad (3)$$

Where: ASE is the anti-swelling-efficiency (%), S_2 and S_1, volumetric coefficient of the treated and the untreated wood (%), respectively.

Set recovery- Recovered radial thickness of the dried specimens were determined after 5 steps of the soaking-drying to calculate the set recovery in the combined hydrothermally treated wood based on Eq. 4. Ten samples were used for each treatment.

$$S_R = \frac{R_s - R_0}{R_0} \times 100 \quad (4)$$

Where: S_R is set recovery in the radial direction (%), R_s, radial thickness after fifth soaking-drying (mm), R_0, radial thickness before soaking-drying (mm)

Static bending strength- Blocks of 20×20×300 mm were prepared from the combined hydrothermally treated woods to determine moduli of elasticity (MOE) and rupture (MOR) according to ASTM D-1324. The equations 5 and 6 were applied to determine the MOE and the MOR. The test replicate was 10 samples for each treatment.

$$MOE = \frac{L^3 (P_{40\%} - P_{10\%})}{4WB^3 (X_{40\%} - X_{10\%})} \quad (5)$$

Where: MOE is modulus of elasticity (N/mm^2), L,W and B are span, specimen's width and thickness (mm), $P_{10\%}$, $P_{40\%}$ load at 10 and 40% of maximum load (N), $X_{10\%}$,$X_{40\%}$, sample displacement at 10 and 40% of maximum load (mm),

$$MOR = \frac{3P_{\max} L}{2W.B^2} \quad (6)$$

Where: MOR is modulus of rupture (N/mm^2), P_{max}, load at maximum (N), L, W and B are span, specimen's width and thickness (mm)

Hardness- Samples of 20 × 51 × 152 mm were prepared from the treated blocks and the hardness was determined according to ASTM D 1324 and equation 7. Ten samples were used as the replicates of each treatment.

$$H_m = \frac{P}{2\pi r h} \quad (7)$$

Where: H_m is hardness (N/mm^2), P is load (N), r and h are radius of the metal bubble and its penetrated depth in the wood (mm)

Impact load resistance- Samples of 20 × 20 × 280 mm were prepared from the CHTM treated poplar wood blocks to determine the impact load resistance according to ASTM D-1324. Replicates of this test were ten samples for each treatment.

RESULTS

Oven dry density- The combined hydrothermal modification (CHTM) of the poplar wood increased the oven dry density. The highest density gain was determined mostly in the samples were treated at 150 °C. In those samples, the density gain was more than 75%.

Springback and set recovery- According to the results increase of the hydrothermal treatment temperature as well as the press temperature caused reduction in the springback (Fig. 1), however, in some higher treatment temperatures, the springback was negative.

Increase of the hydrothermal treatment and press temperatures caused significant loss in the set recovery. At treatment temperature above 150 °C, not only there was no set recovery in the radial thickness; but also there was a thickness loss in some treatments; especially in the treated samples at 180 °C. Compression of the samples at 180 °C of the press temperature was more effective than that of the 160 °C in loss of the set recovery.

Soaking-drying- Influence of five times of the soaking-drying on the radial swelling of the CHTM treated polar wood is shown in Fig. 2. According to the results, the treatment temperature reduced the radial swelling in the poplar wood. Among the treated samples, the lowest swelling was determined in the treated woods at 180 °C. However, higher radial swelling was determined in the treated samples at 120 °C for 30 min with a press temperature of 180°C. In general, the radial swelling of the treated samples was higher than that of the untreated one.

In spite of the radial swelling, determination of the anti-swelling-effect (ASE) of the CHTM treated wood showed that the treated samples at 180 °C gained higher amounts of the ASE among the treated samples (Fig. 3). It means that those samples achieved a dimensional stability. The treated samples at 150 °C showed lesser dimensional instability. According to the results increase of the treatment temperature as well as the press temperature increased the ASE in the CHTM treated poplar wood.

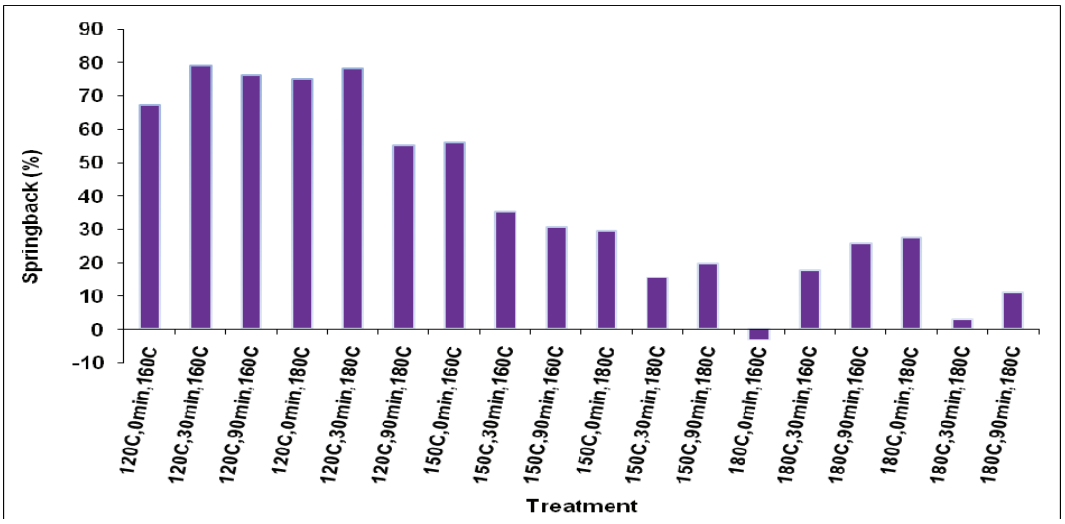

Figure 1: Spring back in CHTM treated wood

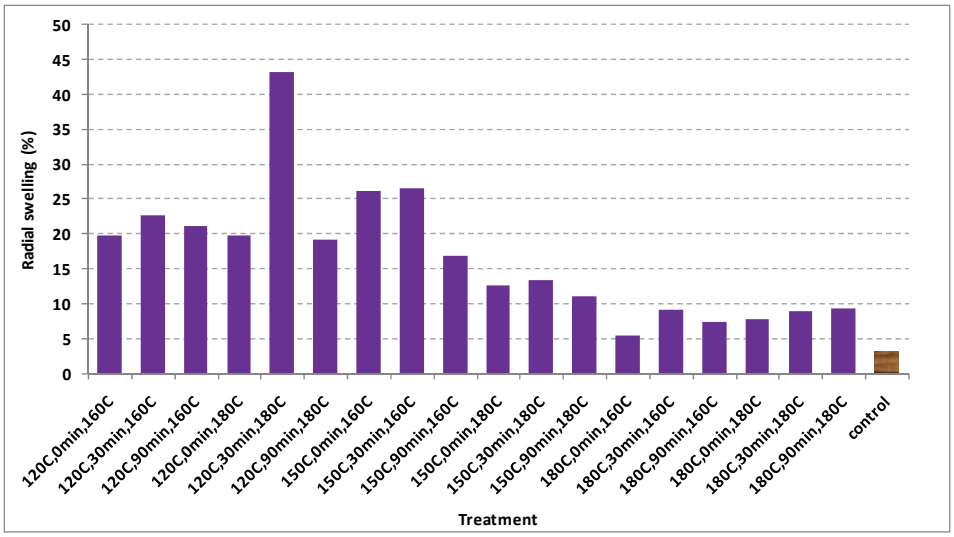

Figure 2: Radial swelling after 5 steps of soaking-drying cycle

Static bending- Figs. 4 and 5 represent moduli of the elasticity (MOE) and the rupture (MOR) in the CHTM treated poplar wood. According to the results, modulus of the elasticity of the treated wood was mostly increased due to the treatment (Fig. 4). However, there was reduction in the samples which were treated at 120 °C. The MOE in the treated samples at treatment temperature of 150 °C and press temperature of 180 °C was determined as the highest among the treatments.

Increase of the treatment temperature increased the MOR except for the treated samples at 180 °C (Fig. 5). The highest MOR was achieved in the treated samples at 150 °C, similar to the MOE.

Hardness- Treatment of the poplar wood by CHTM process increased mostly the hardness (Fig. 6). However, there was reduction in some treatments of the treatment temperature of 120 °C. The higher increase of the hardness was determined in the samples treated at 150 °C of the treatment temperature and 180 °C of the press temperature.

Impact load resistance- Effect of the CHTM process on the impact resistance of the compressed poplar wood was different (Fig. 7). However, the larger amounts of the impact load resistance were determined in the samples which were treated at 150 °C.

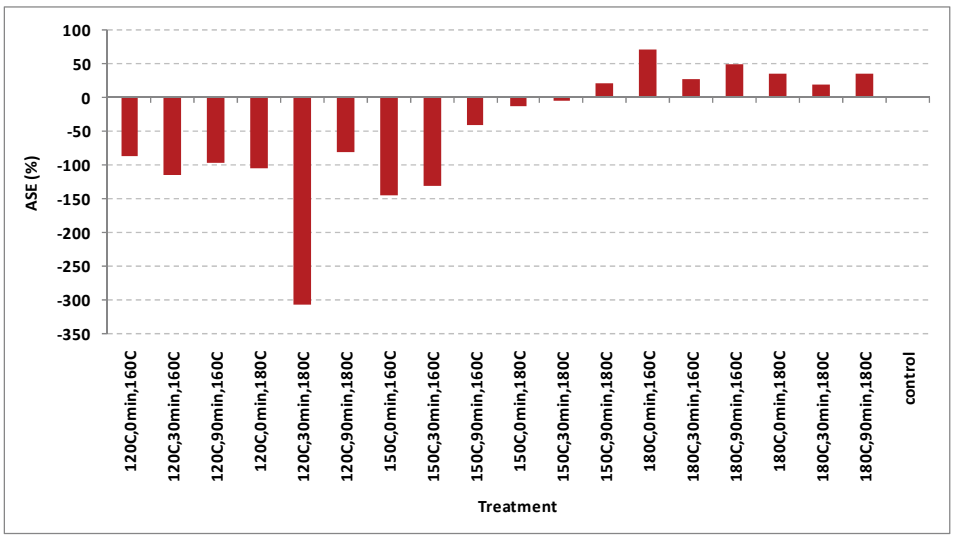

Figure 3: Anti-swelling effect in CHTM treated wood after 5 steps of soaking-drying cycle

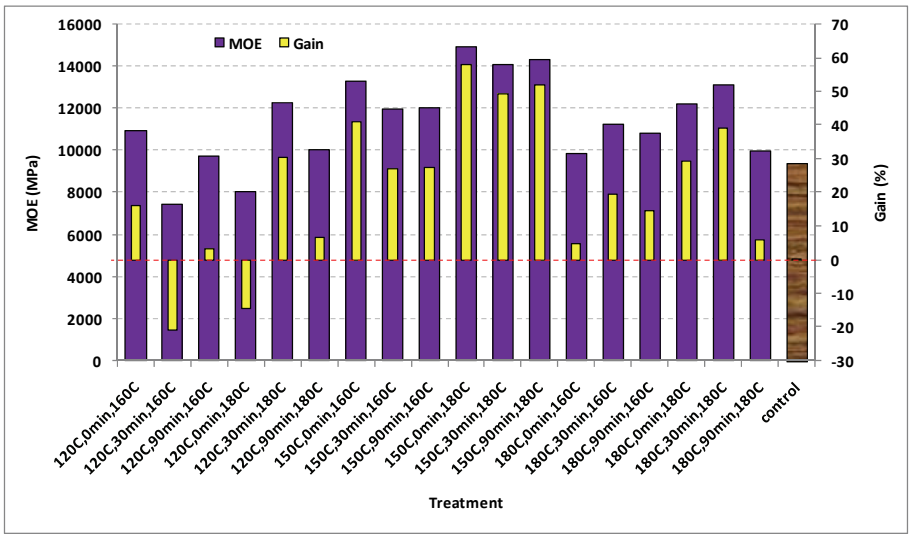

Figure 4: Modulus of elasticity of CHTM treated wood

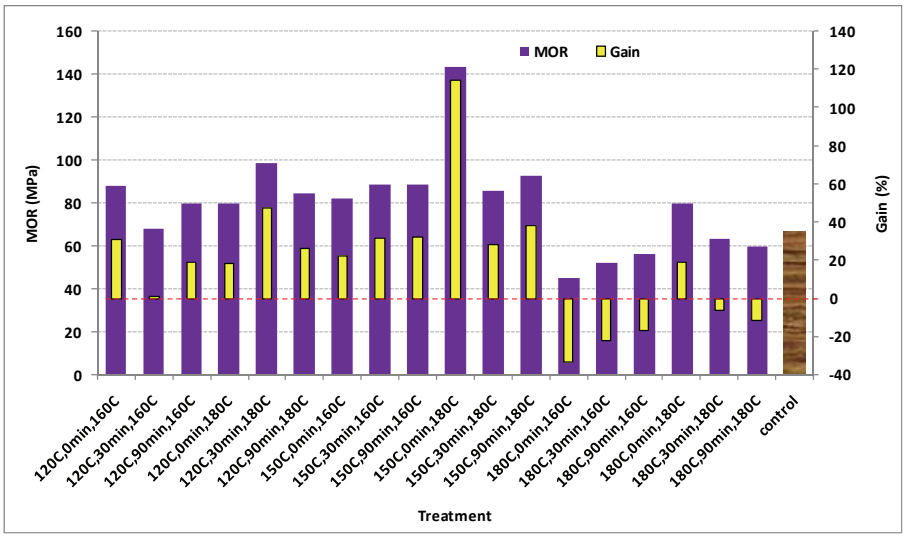

Figure 5: Modulus of rupture of CHTM treated wood

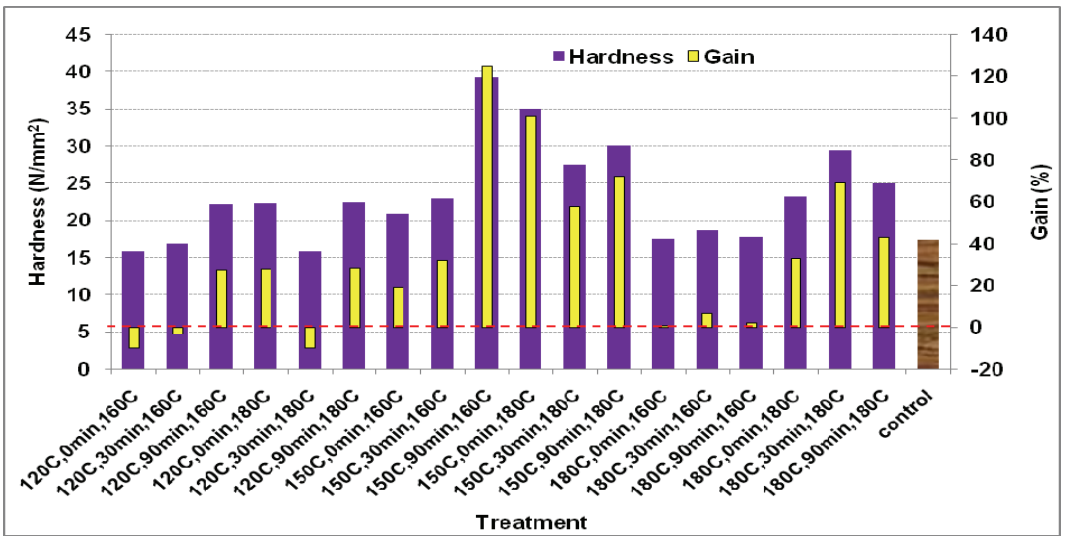

Figure 6: Hardness strength of CHTM treated wood

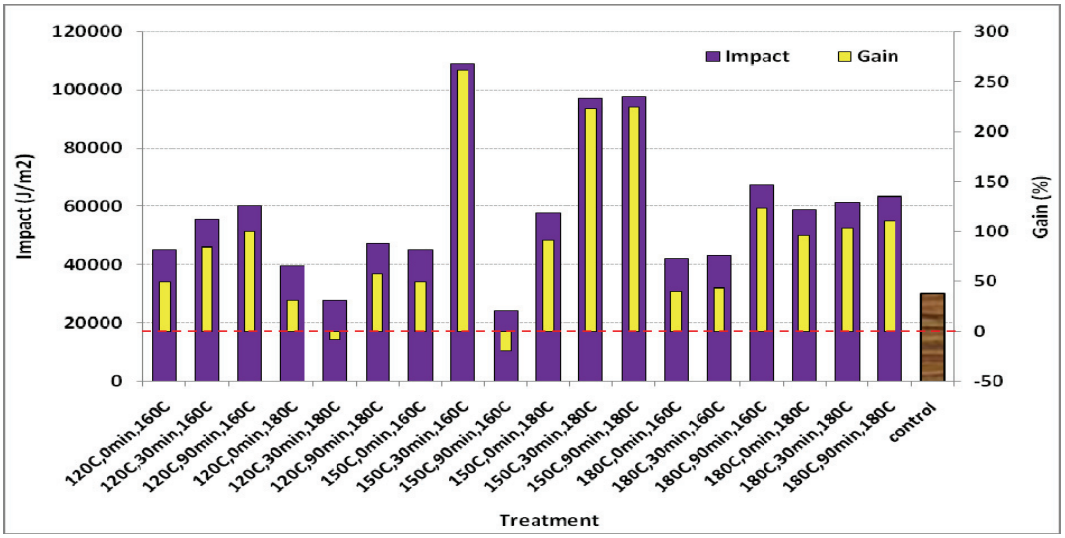

Figure 7: Impact load resistance of CHTM treated wood

DISCUSSION

According to the results, the oven dry density of the CHTM treated wood was increased due to the treatment. It can be expressed that the wood is a thermoplastic material. Therefore, it became more softened due to increase of the temperature during the hydrothermal treatment and also increase of the press temperature during the compression. Consequence of the compression was increase of the density. Heat increases plasticity of the wood and facilitates its compression (Morsing, 2000; Blomberg and Persson, 2004; Blomberg, 2006).

It was indicated that increase of the treatment temperature as well the press temperature reduced the springback of the poplar wood. It can be withdrawn from the results that the hydrothermal treatment temperature was more effective on reduction of the springback than the press temperature. As the reasons, the chemistry of the wood is altered during the hydrothermal modification (Tjeerdsma and Militz 2005, Garrote *et al*. 1999, 2001) and the wood is turned to a hydrophobic material (Mohebby and Sanaei 2005). Besides that, the hemicelluloses are degraded and removed during the treatment (Boonstra and Tjeerdsma 2006, Garrote *et al*. 2001, Sundqvist 2006a). Consequence of the chemical alteration of the wood is increase of the crystalline regions in the cellulose polymers (Yildiz and Gümüşkaya, 2007; Sundqvist, 2006b), cross linkings and condensation reactions in the lignin polymers (Boonstra and Tjeerdsma, 2006) as well as relaxation of the cellulose due to removal of the hemicelluloses (Dwianto *et al*. 1999). The springback is depended on the amount of stress relief in the wood (Navi and Heger 2004, Dwianto *et al*. 1999). Lesser stress relief is the consequence of the hemicelluloses' removal. The removal of the hemicelluloses provides reorientation of the cellulose during the wood compression (Navi and Heger, 2004) and it facilitates the stress relief. Besides that, cross linked structure of the lignin is provided a quite unique structure of the wood, which facilitates better release of the stresses during the compression. According to Norimoto *et al*. (1993), three mechanisms are involved in the springback and also set recovery of the compressed wood: 1. Cross linking of the microfibrils in the cellulose; 2. Stress relief in the microfibrils as well as the matrix polymers; 3. Isolation of the hydrophilic polymers; such as the hemicelluloses against the moisture.

Concerning Norimoto *et al*. (1993) and Dwianto *et al*. (1999), the hydrothermal treatment provides suitable condition for ceasing the springback and reducing the set recovery. Increase of the treatment temperature reduced the thickness swelling and also increased the ASE in the CHTM treated poplar wood. In this case, the hydroxyl groups in the hemicelluloses and the cellulose polymers are responsible for the moisture absorption and the swelling of the wood. Removal of the hemicelluloses and blocking of the hydroxyl groups in the cellulose are the main reasons for the swelling reduction and increase of the ASE. According to the reports, the hemicelluloses are removed, crystallinity of the cellulose is increased and the amorphous regions of the cellulose are decreased due to the hydrothermal treatment (Yildiz and Gümüşkaya, 2007). Also, the cellulose polymer cross linked with the lignin during the treatment (Wallenberger and Weston 2004, Garrote *et al*. 1999, Bhuiyan *et al*. 2000, Dwianto *et al*. 2000, Kubojima et al, 2004). Consequently, the hydroxyl groups reduced due to the hydrothermal treatment. Since the hydroxyl groups of the crystalline regions are not accessible; the water molecules can not link via the hydrogen bonds with the cellulose polymer. By this way, the hydrophobicity of the wood is increased because of the hydrothermal treatment (Pott *et al*. 2000; Tjeerdsma *et al*. 1998) and it resulted increase of the dimensional stability of the CHTM treated wood.

According to the results, mechanical strengths of the CHTM treated poplar wood was increased due to the treatment. The higher strengths were achieved at treatment temperature of 150 °C and reduction of the strengths was occurred at higher temperature. The main reason for the increased strengths is the increase of wood density in the compressed wood, because, they are directly depended to the density (Blomberg *et al*. 2005, Morsing, 2000, Navi and Girardet 2000, Heger *et al*. 2004, Brischke *et al*. 2005). Any reduction of the strengths at higher treatment temperature is related to brittleness of the lignin (Navi and Heger, 2004) and alteration of the long chained cellulose polymer to shorter oligomers that were occurred due to the hydrothermal treatment (Garrote *et al*. 1999). According to Winandy and Rowell (2005), shortening of the cellulose chain affects the mechanical strengths in the wood.

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