DENSIFICATION OF WOOD VENEERS COMBINED WITH OIL-HEAT TREATMENT. PART II: HYGROSCOPICITY AND MECHANICAL PROPERTIES

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In an effort to achieve high mechanical performance and improved dimensional stability, densification combined with oil-heat treatment (OHT) was performed. In our previous study, OHT was successfully applied to densified veneer, which resulted in improved dimensional stability. In the present study, the impact of OHT on densified wood veneer hygroscopicity and mechanical properties was determined. OHT at 180, 200, and 220ºC for 1, 2, and 3 hours was applied to densified Aspen (*Populus tremuloides*) veneers. OHT was found to be an efficient treatment to reduce the hygroscopicity of densified aspen veneers, although OHT had a negative impact on Brinell hardness. However, due to the contribution of densification, the hardness of oil-heat treated veneers was still two to three times higher than that of non-densified veneers. Similar results were found for tensile strength. Bending strength increased slightly at low OHT temperature, and then decreased at high temperature. Bending strength of oil-heat treated densified veneer samples was higher than that of non-densified ones. No significant effect of OHT was found on tensile MOE, but bending MOE increased after OHT. Compared to OHT duration, OHT temperature had a larger impact on densified wood hygroscopicity and mechanical properties.

Keywords: Wood densification; Oil-heat treatment; Hygroscopicity; Mechanical properties; Aspen

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INTRODUCTION

Wood densification by compression due to physical and mechanical means is well known to improve wood's mechanical strength while maintaining its natural character (Fang et al. 2012; Kamke 2006; Navi and Heger 2004; Seborg et al. 1945). However, the dimensional stability of compressed wood is often a problem and limits industrial applications. Various treatments have been attempted to improve the dimensional stability of compressed wood (Gabrielli and Kamke 2010; Inoue et al. 1993a; 1993b; 2008; Navi and Heger 2004). Thermal treatment of wood is known to improve dimensional stability and enhance its resistance against biological attack by reducing hygroscopicity and generating molecules toxic to fungi (Burmeste 1973; Giebeler 1983; Stamm 1964; Wang and Cooper 2005). However, thermal treatments usually reduce most of the mechanical properties of wood (Boonstra et al. 2007; Poncsak et al. 2006; Shi et al. 2007).

In our previous study (Fang et al. 2011), oil-heat treatment (OHT) was successfully applied to thermo-hygro-mechanically densified veneer, and an improved dimensional stability was achieved. The objective of the present study was to determine the effects of OHT temperature and duration on hygroscopicity and mechanical properties of densified wood veneers. Aspen (*Populus tremuloides*) was used in this study. It is an important fast-growing tree with low density wood and has good potential to be modified into high performance and high value products.

MATERIALS AND METHODS

Materials

Rotary-peeled aspen wood veneers were obtained from Temlam Inc., a laminated veneer lumber plant in Amos, which is located in the northwest of the province of Quebec, Canada. The nominal thickness of the aspen veneers was 3.2 mm. Veneers were conditioned at 20°C and 60% relative humidity (RH) before densification. Veneers of 700 mm × 700 mm were densified using pressure, heat, and steam as described in a previous work (Fang et al. 2012). The theoretical compression was set at 50%. Veneers densified at 160, 180, and 200°C were used for OHT. Before OHT, densified veneers were conditioned at 20°C and 60% RH until their weight became stable. Twelve specimens were prepared for each treatment. Forty control specimens were prepared for non-densified wood veneer measurements. Mean values of the replicated measurements were used for analysis.

Oil-Heat Treatment

Samples were cut from the densified veneers with a laser cutter. Depending on the tests conducted after OHT, different sample sizes were prepared. They were treated in a hot oil vessel at 180, 200, and 220ºC for 1, 2, and 3 hours, respectively. Canola oil (specific gravity 0.91, viscosity 78.2 cSt, smoke point 220-230 ºC) was used in this study. The samples were immersed in pre-heated canola oil as temperature was maintained at the target temperature. As all the samples were thin and small, their internal temperature could reach the target temperature quickly and uniformly. The samples were then taken out from the hot oil vessel, and the oil remaining on the sample surface was removed with a paper cloth. After, the samples were conditioned at 20°C and 60% RH until their weight became stable.

Hygroscopicity Determination

Equilibrium moisture content (EMC) at 20°C and 60% relative humidity, and saturated moisture content (SMC) after room temperature water soaking until reaching stable specimen weight were measured to determine the effect of densification treatment and OHT on wood hygroscopicity. Specimens of 70 mm × 70 mm were used. Measurements were performed on non-densified (control) and densified specimens with and without OHT.

Mechanical Properties Determination

Brinell hardness tests were conducted on specimens of 70 mm × 70 mm according to European standard EN 1534 (2000). The longitudinal tensile modulus of elasticity (MOE) and maximum tensile strength were obtained according to the ASTM D 1037-96a standard (1997). Tensile specimen shape and dimensions were reported in our previous study (Fang et al. 2012). Tensile strain was measured with a displacement sensor installed in the middle section of the specimen. Three-point static bending tests were also performed according to ASTM D 1037-96a standard (1997) to obtain the MOE and maximum strength in bending. Specimen size varied depending on thickness according to the ASTM standard.

RESULTS AND DISCUSSION

Hygroscopicity

The equilibrium moisture content (EMC) at 20°C and 60% relative humidity and saturated moisture content (SMC) at room temperature after water soaking until stable weight were measured to characterize the effect of OHT on wood hygroscopicity. Figure 1 shows the results obtained for EMC. After densification, EMC decreased significantly. For the specimens without OHT, EMC decreased with the increase in densification temperature (Fang et al. 2012). After OHT, EMC decreased further. The EMC of densified specimens was reduced to about 4% after OHT at 220°C. The reduced EMC after OHT could be explained by chemical changes in the wood's cell wall components, including a decrease of hydroxyl groups. These changes could be explained by the decomposition of hemicelluloses, the most hygroscopic of the three major cell wall components (Berry and Roderick 2005; Christensen and Kelsey 1959; Diouf et al. 2011; Fang et al. 2008; Wang and Cooper 2005).

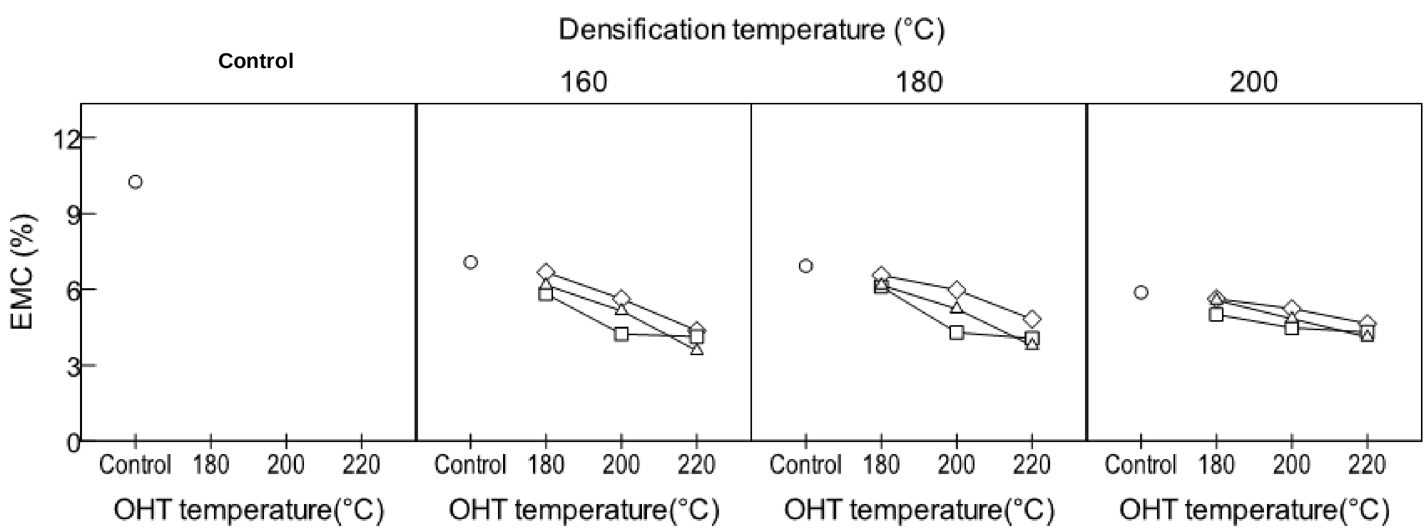

Fig. 1. Equilibrium moisture content (EMC) of densified veneers with and without OHT and non-densified veneers at 20°C and 60% relative humidity. Each data point is the average value of replicated measurements. Circles: without OHT; diamonds: OHT for 1h; squares: OHT for 2h; and triangles: OHT for 3h.

Enhanced inaccessibility of hydroxyl groups to water molecules due to increased cellulose crystallinity after heat treatment has also been suggested to explain the reduced EMC (Bhuiyan and Hirai 2005; Boonstra and Tjeerdsma 2006; Wikberg and Maunu 2004). For the densified specimens with OHT at the same densification temperature, a marked tendency was found, i.e. the higher the OHT temperature, the lower the EMC. This might indicate that the extent of hydroxyl groups degradation and/or cellulose crystallinity elevation were positively related to treatment temperature. Analysis of variance shows that OHT temperature had a significant impact on EMC. The effect of OHT duration on EMC did not show a clear trend. However, only one-hour-OHT showed higher EMC for all cases at the same densification and OHT temperatures.

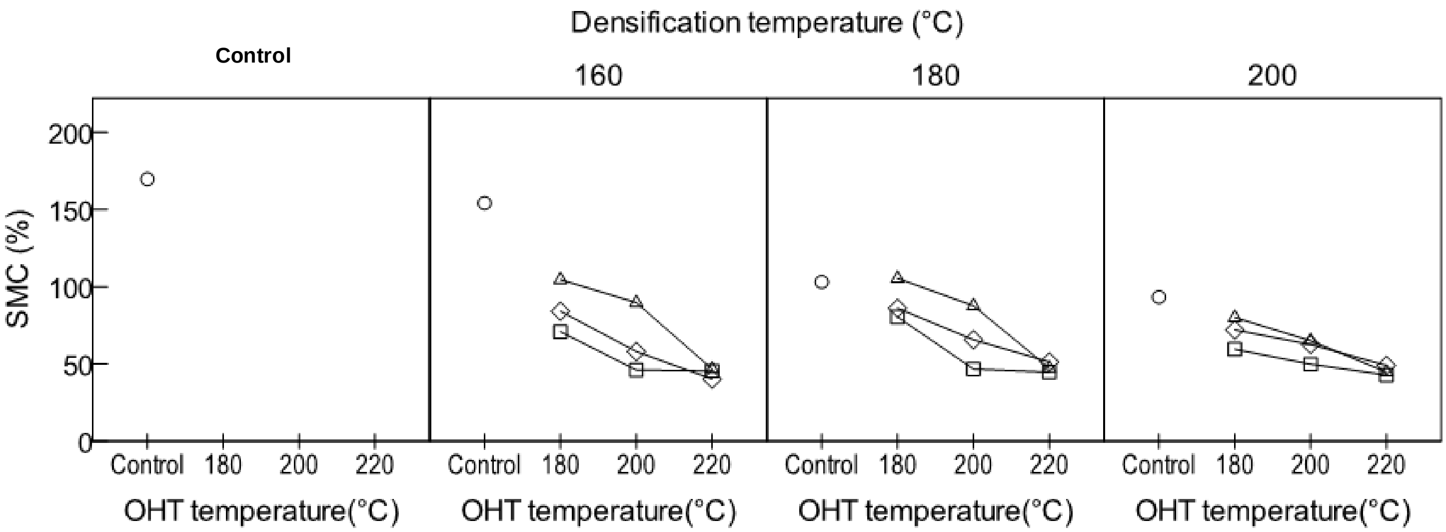

Fig. 2. Saturated moisture content (SMC) of densified veneers with and without OHT and non-densified veneers at room temperature after water soaking until specimens weight became stable. Each data point is the average value of replicated measurements. Circles: without OHT; diamonds: OHT for 1h; squares: OHT for 2h; and triangles: OHT for 3h

Similar results were found for SMC (Fig. 2). For the specimens without OHT, the reduced SMC after densification has been reported and discussed in our previous study (Fang et al. 2012). The effect of OHT on SMC is focused on in the present study. The reduced cell wall hygroscopicity could explain, to some extent, the reduced SMC, as discussed above. However, SMC depends mainly on capillary water present in the lumens, therefore, wood porosity determines SMC. As previously reported (Fang et al. 2011), after water soaking some compression set recovery occurred and less recovery was found at higher OHT temperature. This indicates that the specimens that had been oil-heat treated at higher temperature had lower porosity because recovery was mainly caused by the re-opening of cell lumens (Fang et al. 2012). Therefore, with the increase of OHT temperature, SMC decreased. Furthermore, no significant difference of SMC was found for specimens oil-heat treated at 220°C for all cases (Fig. 2). This could be explained by the fact that almost no recovery occurred in the specimens oil-heat treated at 220°C for all cases (Fang et al. 2011). As shown in Fig. 2, it was also found that for the specimens densified at 160°C, compared to 180°C and 200°C, SMC decreased markedly after OHT. This might be due to the greater reduction of recovery after OHT for the specimens densified at 160°C, compared to 180°C and 200°C (Fang et al. 2011). Both OHT temperature and duration had a significant impact on SMC, but the effect of OHT duration on SMC was not clear.

Mechanical Properties

Mechanical properties of control (non-densified), control densified (without OHT), and densified veneers with OHT at different temperatures and durations are shown in Figs. 3 through 7.

The impact of OHT duration on Brinell hardness was not significant according to the analysis of variance, while the impact of OHT temperature was significant at the 0.01 probability level. After densification without OHT, Brinell hardness was improved significantly (Fig. 3), as previously discussed (Fang et al. 2012). After OHT at 180°C, Brinell hardness did not show notable change, but with the increase of OHT temperature, Brinell hardness decreased significantly. There have been few reports on hardness of oil-heat treated wood. Boonstra et al. (2007) reported an increase in hardness after a “two-stage heat treatment” of Scots pine non densified wood. The variation in the results obtained might be due to the different methods of heat treatment and species of wood used. In the current study, the mechanical properties of specimens treated at different OHT temperature and duration were measured at different EMCs. Equilibrium moisture content decreased with increasing OHT temperature (Fig. 1). In general, wood mechanical strength increases with decreasing moisture content (Kretschmann and Green 1996). However, decrease in hardness with the increase of OHT temperature was found in this study. This might be due to the more advanced degradation of the hemicelluloses and lignin from the use of higher OHT temperature. Therefore, the influence of moisture content on hardness, as well as tensile and bending strengths (Figs. 4 and 5) was minor. However, due to the contribution of densification, the hardness of oil-heat treated veneers was 2 to 3 times higher than that of non-densified ones, although high temperature OHT had a negative impact on hardness. OHT treated wood showed great potential for appearance products as hardness is a critical property of the surface for this type of product.

Similar results were found for maximum tensile strength (Fig. 4). After densification without OHT, tensile strength was improved significantly (Fig. 4), as discussed in our previous study (Fang et al. 2012). After OHT, tensile strength decreased. This is in agreement with the results reported by Boonstra et al. (2007), who found a marked decrease in tensile strength after a “two-stage heat treatment” in Scots pine. Furthermore, it was found in the current study that the higher the OHT temperature, the lower the tensile strength. The impact of OHT temperature on tensile strength was significant at the 0.01 probability level, while the differences among different OHT durations at the same OHT temperatures were not significant.

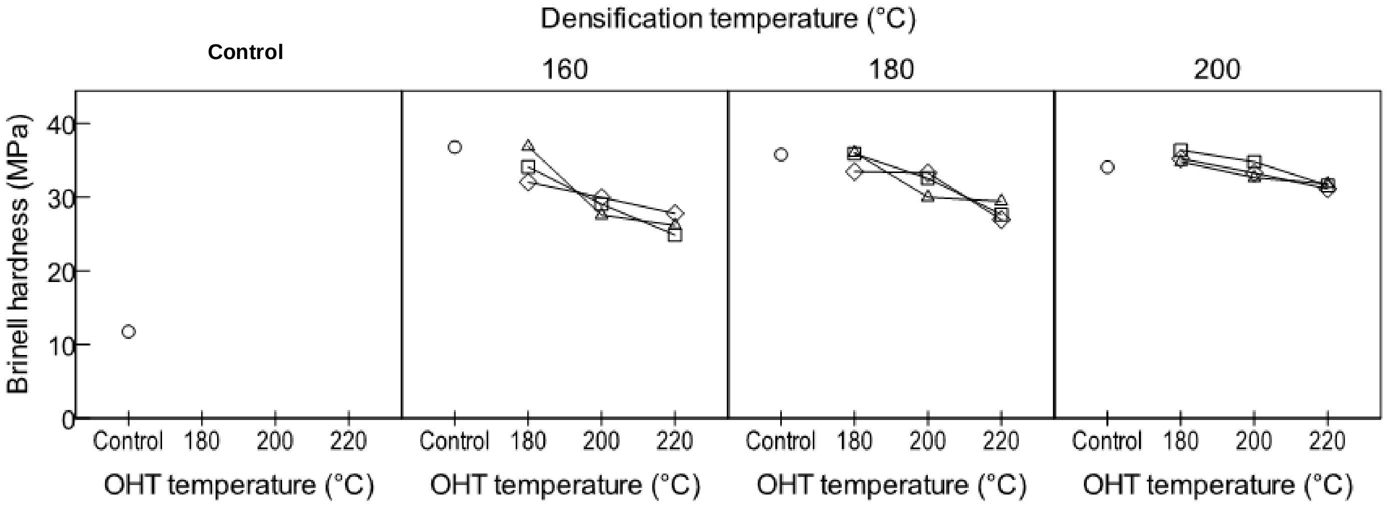

Fig. 3. Brinell hardness of densified veneers with and without OHT and non-densified veneers. Each data point is the average value of replicated measurements. Circles: without OHT; diamonds: OHT for 1h; squares: OHT for 2h; and triangles: OHT for 3h

The tensile strength losses might be mainly caused by the degradation of cellulose polymer and reduced degree of polymerization during heat treatment (Boonstra and Tjeerdsma 2006; Ifju 1964; Mark 1967; Winandy and Rowell 1984), because cellulose might be primarily responsible for tensile strength (Stamm 1964). Degradation of hemicelluloses during heat treatment might also contribute to the decrease of tensile strength (Boonstra et al. 2007). However, due to the contribution of densification, the tensile strength of oil-heat treated veneers was still higher than that of non-densified veneers except for a few ones treated at 220°C.

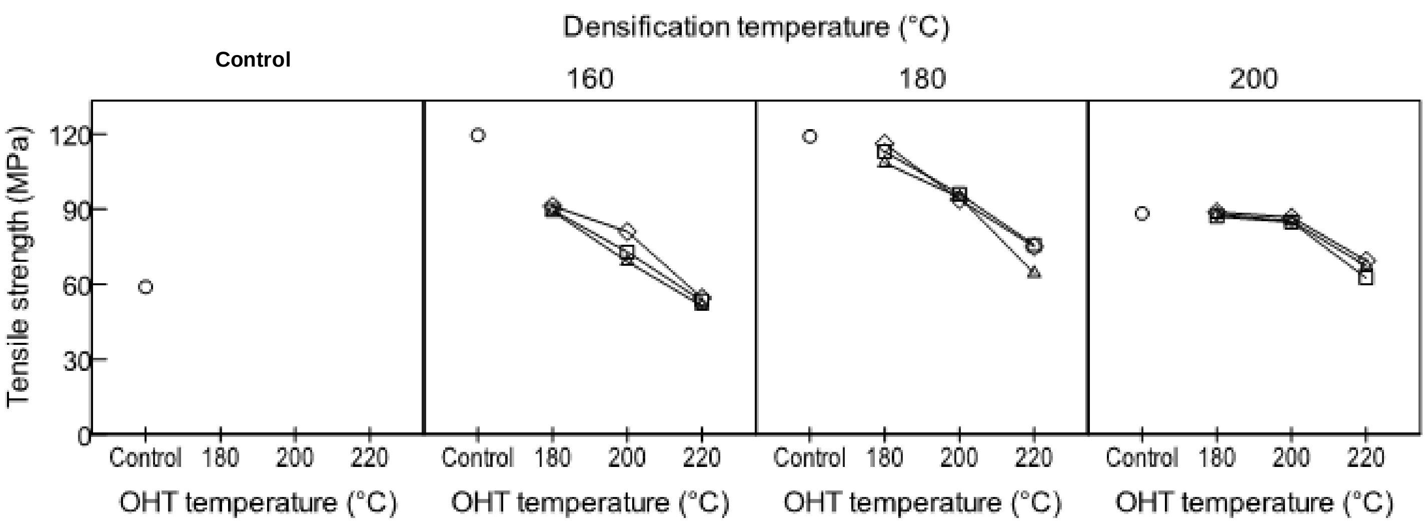

Fig. 4. Maximum tensile strength of densified veneers with and without OHT and non-densified veneers. Each data point is the average value of replicated measurements. Circles: without OHT; diamonds: OHT for 1h; squares: OHT for 2h; and triangles: OHT for 3h

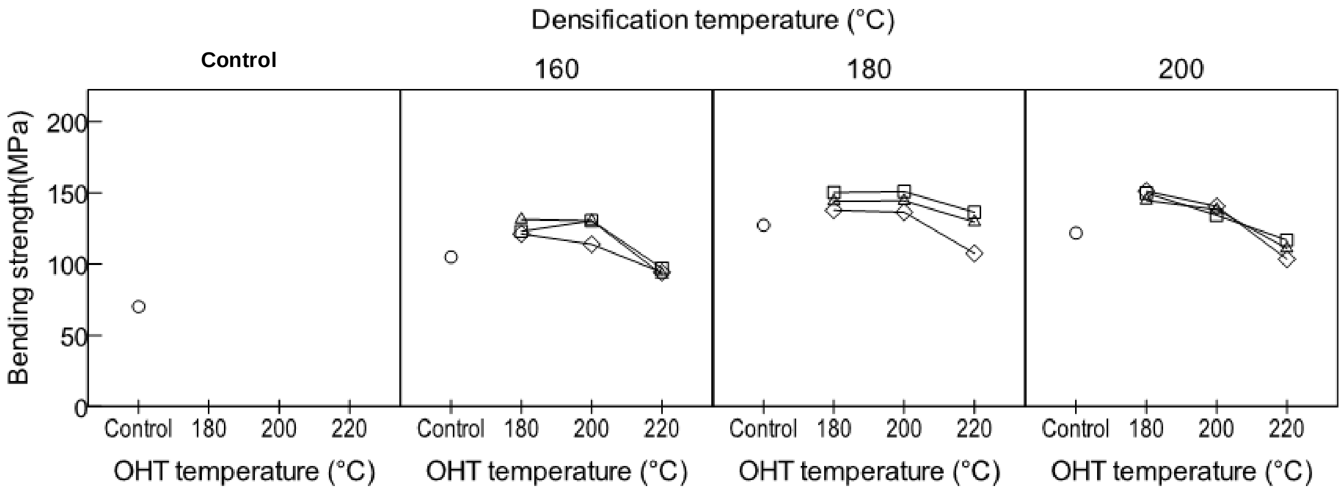

Fig. 5. Maximum bending strength of densified veneers with and without OHT and non-densified veneers. Each data point is the average value of replicated measurements. Circles: without OHT; diamonds: OHT for 1h; squares: OHT for 2h; and triangles: OHT for 3h

Figure 5 shows the results of maximum bending strength. As discussed in a previous report (Fang et al. 2012), bending strength increased after densification without OHT. Heat treatment has been reported to reduce bending strength (Boonstra et al. 2007; Poncsak et al. 2006; Shi et al. 2007; Stamm et al. 1946), which depends on wood species and treatment conditions. Kubojima et al. (2000), who found opposite results, reported that bending strength increased during the initial hours of heat treatment. Shi et al. (2007), who also had contrary findings, reported an increased modulus of rupture in heat-treated birch. In our study, bending strength increased slightly at low OHT temperature after OHT on densified aspen, and then decreased at high temperature. These results indicate that the higher the OHT temperature, the lower the bending strength. The changes in hemicelluloses content and structure might be primarily responsible for the loss of bending strength (Sweet and Winandy 1999; Winandy and Lebow 2001). However, due to the effect of densification, bending strength of oil-heat treated veneers was still higher than that of non-densified samples. The impact of OHT duration on bending strength did not show a clear trend. A similar result was reported by Poncsak et al. (2006), who found that the impact of treatment duration was not significant.

Tensile MOE and bending MOE are shown in Figs. 6 and 7, respectively. MOE increased significantly after densification. The impact of heat treatment on MOE has been reported extensively (Boonstra et al. 2007; Esteves and Pereira 2009; Kubojima et al. 2000; Poncsak et al. 2006). In this study, no significant change of tensile MOE was found after OHT. Furthermore, neither OHT temperature nor duration showed significant impact on tensile MOE. Bending MOE increased after OHT. Degradation of hemicelluloses, disruption of the load-sharing capacity of the lignin-hemicelluloses matrix, and increase in the relative amount of crystalline cellulose could contribute to the increase in MOE (Boonstra et al. 2007). The increased MOE indicates that wood stiffness increased and compliance decreased after OHT. However, OHT temperature did not show a significant impact on wood stiffness and the influence of OHT duration was not clear.

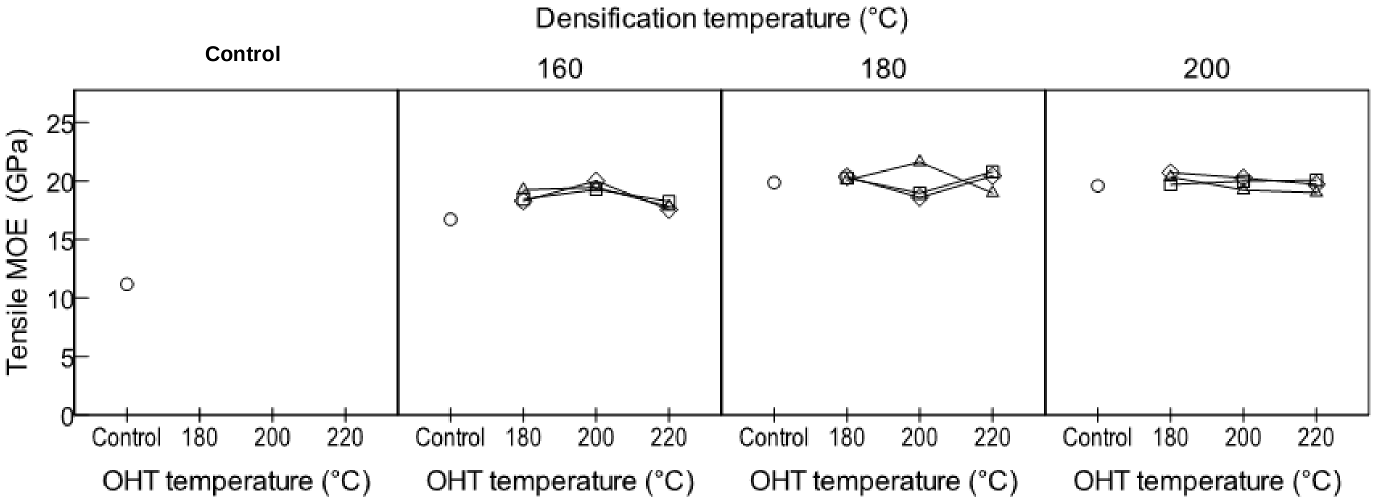

Fig. 6. Tensile MOE of densified veneers with and without OHT and non-densified veneers. Each data point is the average value of replicated measurements. Circles: without OHT; diamonds: OHT for 1h; squares: OHT for 2h; and triangles: OHT for 3h

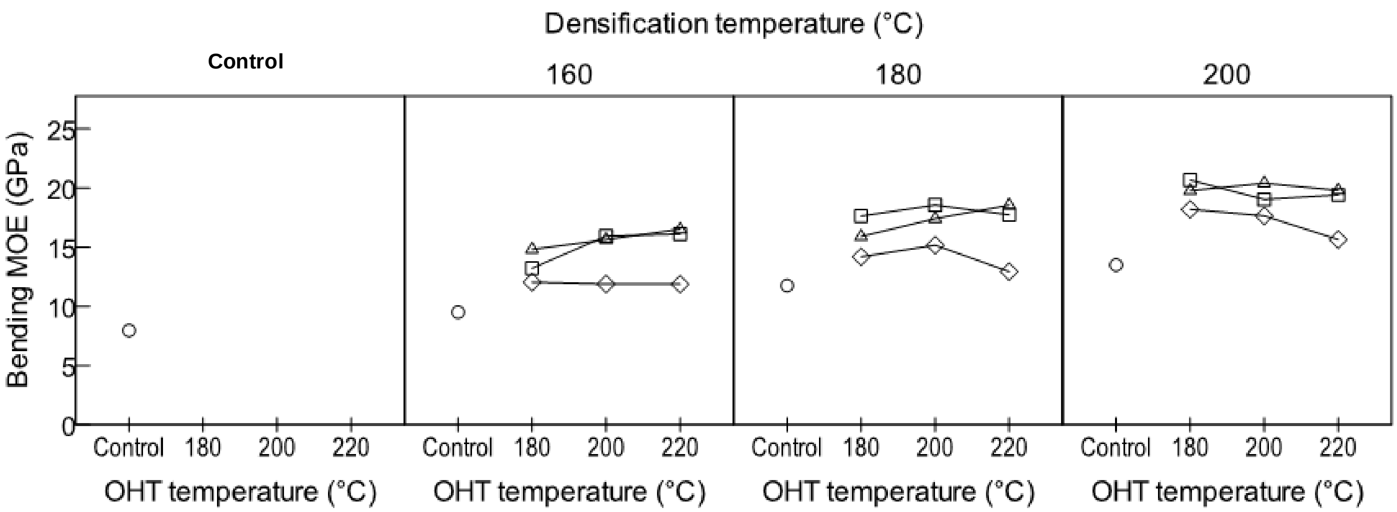

Fig. 7. Bending MOE of densified veneers with and without OHT and non-densified veneers. Each data point is the average value of replicated measurements. Circles: without OHT; diamonds: OHT for 1h; squares: OHT for 2h; and triangles: OHT for 3h

CONCLUSIONS

1. Oil-heat treatment (OHT) was found to be an efficient way to reduce the hygroscopicity of densified aspen veneers. The OHT temperature showed significant impact on equilibrium moisture content (EMC) and saturated moisture content (SMC). The higher was the OHT temperature, the lower was the EMC and the SMC. Equilibrium moisture content decreased to less than 6% under most OHT conditions.

2. Oil-heat treatment had a negative impact on Brinell hardness, which decreased with the increase of OHT temperature. However, due to the contribution of densification, the hardness of oil-heat treated veneers was still two to three times higher than that of non-densified veneers.
3. The OHT showed negative effect on tensile strength. Higher OHT temperature led to lower tensile strength, except for samples densified at 160°C and oil-heat treated at 220°C. The tensile strength of densified veneers after OHT was still higher than that of non-densified veneers due to the contribution of densification.
4. After OHT on densified aspen veneers, bending strength increased slightly at low OHT temperature, and then decreased at a high temperature. Bending strength of oil-heat treated densified veneer samples was higher than that of non-densified ones.
5. No significant effect of OHT was found on tensile MOE, but bending MOE increased after OHT.
6. Compared to OHT duration, OHT temperature had a larger impact on densified wood hygroscopicity, and mechanical properties.
7. Combined with results obtained in our previous study (Fang et al. 2011), densification combined with OHT showed good potential to overcome the drawbacks of densification and heat treatment. After OHT on densified wood, dimensional stability was improved and relatively high mechanical properties were maintained.

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