Improvement of Wood Densification Process *via* Enhancing Steam Diffusion, Distribution, and Evaporation

Chang-Hua Fang,[a,]* Alain Cloutier,[b] Ze-Hui Jiang,[a] Jia-Zhong He,[c] and Ben-Hua Fei [a,]*

Mechanical densification treatments make it possible to increase the density of low- or moderate-density woods, and thus a high mechanical strength of densified wood and high-value products can be obtained. The authors' previous treatments showed that the diffusion and distribution of steam and the release of vapor inside densified wood were prevented to some extent during thermo-hydro-mechanical (THM) densification, causing the occurrence of protrusions, carbonization, blisters, and blows. This study aimed to overcome these problems. Based on the authors' previous THM densification, different materials, such as fabric, metal mesh, metal foam, and sintered metal mesh laminate (SMML), were used to improve the process. Densification was tested on different wood species. The results showed that SMML was the preferable material for THM densification through enhancing diffusion and distribution of steam, and evaporation of moisture inside wood. No protrusion, carbonization, blisters, or blows were found after densification with SMMLs. The densified wood specimens showed uniform color and a neat surface.

Keywords: Wood densification; Heat treatment; Steam treatment; Thermo-hydro-mechanical densification; Wood compression

Contact information: a: State Forestry Administration (SFA) and Beijing Co-built Key Laboratory of Bamboo and Rattan Science & Technology, SFA, Department of Biomaterials, International Centre for Bamboo and Rattan, 8 Futong East Street, Chaoyang District 100102, Beijing, China; b: Renewable Materials Research Centre (CRMR), Université Laval, Quebec City, Canada; c: Zhejiang Jiazhong Wood Industry Co., Ltd., Huzhou City, Zhejiang, China;
** Corresponding authors: cfang@icbr.ac.cn; feibenhua@icbr.ac.cn*

INTRODUCTION

Generally, high-density wood species are preferable for many engineering structures and applications due to their high mechanical strength. However, high-density wood resources are limited and usually expensive. Densification treatments make it possible to increase the density of low- or moderate-density woods, as well as to obtain a specific strength of densified wood higher than that of most structural metals and alloys. These characteristics make it a low-cost, high performance, and lightweight alternative (Song *et al.* 2018). Many densification processes, including mechanical compression and chemical impregnation, have been attempted and developed (Inoue *et al.* 1993a,b, 2008; Higashihara *et al.* 2000; Kamke 2006; Boonstra and Blomberg 2007; Fukuta *et al.* 2008; Gabrielli and Kamke 2008; Rautkari *et al.* 2011; Belt *et al.* 2013; Laine *et al.* 2013; Li *et al.* 2013; Fu *et al*. 2017; Kariz *et al.* 2017). Compared to mechanical compression, chemical treatments affect the nature and sustainable character of wood and are usually more expensive (Navi and Heger 2004).

Different mechanical densification treatments have been reported for over a century (Kollmann *et al.* 1975; Fang *et al.* 2012c; Sandberg *et al.* 2013; Song *et al.* 2018). Many densification treatments have been performed through compression combined with heat. Such methods are also called thermo-mechanical (TM) densification. However, this type of densified wood is unstable with a high percentage of compression set recovery (Navi and Heger 2004; Laine *et al*. 2013, 2016; Kariz *et al.* 2017). Recently, Song *et al.* (2018) reported a two-step densification process involving the partial removal of lignin and hemicellulose from natural wood by boiling in a chemical solution followed by hot-pressing. They obtained densified wood with extremely high density (1300 kg/m^3). However, for a small-size sample (120 mm × 44 mm × 44 mm), their two-step process took a long time (more than 31 h). Compared to TM densification, compression combined with heat and steam treatment, also called thermo-hydro-mechanical (THM) densification, is a more efficient way to achieve more dimensionally stable densified wood. Many THM, or similar densification processes, in an open or sealed press system have been reported (Navi and Girardet 2000; Kamke 2006; Li *et al.* 2013; Popescu *et al.* 2014; Fu *et al.* 2016, 2017). Some of them still cannot solve the problem of dimensional stability. Other processes take a long time or are complex. Furthermore, most of them have dealt with small-size wood samples. All these problems and limitations could be due to the difficulty of distributing steam on large wood surfaces and vapor release from core-densified wood due to the high pressure of the hot press platens. Recently, the authors' team developed a relatively simple THM densification process (Fang *et al.* 2011, 2012a,b,c; Fu *et al.* 2016, 2017; Cruz *et al.* 2018) that can deal with large-size wood samples with high efficiency. Steam treatment showed a positive effect on wood softening, time saving, and dimensional stability for wood densification (Inoue *et al.* 1993a; Navi and Girardet 2000; Navi and Heger 2004; Gabrielli and Kamke 2008; Fang *et al.* 2012c). However, diffusion and distribution of steam, and the release of vapor inside densified wood were still prevented to some extent. The objective of this study is to improve the densification process by enhancing steam diffusion and distribution on the samples' surface and its release from the core of the densified wood samples.

EXPERIMENTAL

Materials

The THM densification treatment was tested on trembling aspen (*Populus tremuloides*), hybrid poplar clone 15303 (*Populus maximowiczii* × *Populus balsamifera*), sugar maple (*Acer saccharum*), red oak (*Quercus rubra*), black cherry (*Prunus serotina*), and yellow birch (*Betula alleghaniensis*) obtained from Quebec, Canada. For aspen and hybrid poplar, veneers of 700 mm × 700 mm were used for densification. The nominal thicknesses of aspen and hybrid poplar veneers were 3.2 mm and 4.3 mm, respectively. For the other species, thin-sawn strips were used for the tests. The nominal thickness of the strips varied from 3.4 mm to 6.0 mm. The length and width were 700 mm and 90 mm, respectively. They were conditioned at 20 °C and 60% relative humidity before treatment.

Methods

Densification treatments- Previous THM densification treatments

The general densification process was described in previous work (Fang *et al.* 2011, 2012a,b,c). A Dieffenbacher steam injection press (Dieffenbacher North America Inc., Windsor, Canada) with dimensions of 862 mm × 862 mm was used for THM densification (Fig. 1). Holes were distributed on both the upper and lower platens at 32-mm intervals. Holes with a diameter of 1.5 mm were used for steam injection and venting. The specimens were compressed, using the procedure shown in Fig. 2, from initial to target thickness at a maximum hydraulic pressure of 4.5 MPa to 9.0 MPa. Platens were then maintained at the same position during post-treatment. Steam was continuously injected at a line pressure of 550 kPa during the whole compression and maintaining process. At the end, steam injection was stopped and steam was vented through the holes in the platens. Tests were performed at 180 °C, 200 °C, and 220 °C, respectively. Four different total treatment durations were tested: 10 min, 15 min, 20 min, and 30 min.

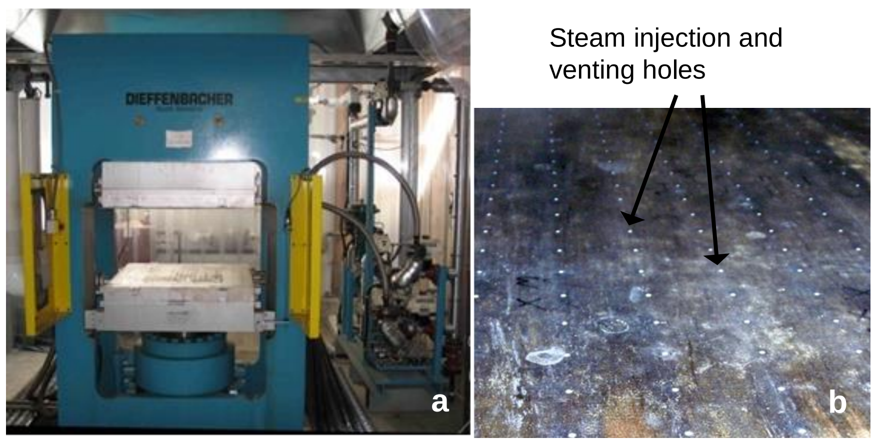

Fig. 1. Steam injection hot press used for the densification treatment: (a) 862 mm × 862 mm hot press, (b) steam injection and venting holes on both the upper and lower platens

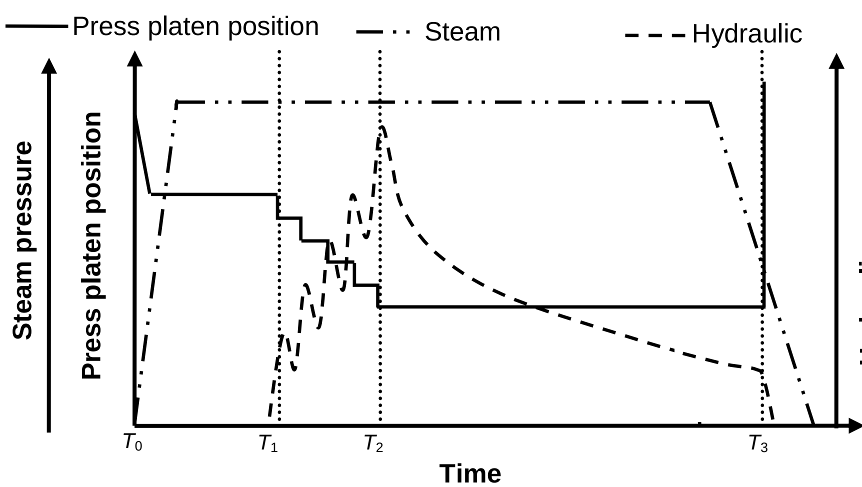

Fig. 2. Schematic diagram of the densification process: pre-treatment (T_0 to T_1), compression (T_1 to T_2), and post-treatment (T_2 to T_3)

THM densification treatment with fabric

The THM densification process was performed as described above in the previous treatment. Specimens were covered with a special fabric, on both the upper and lower sides (Fig. 3a) which is steam-permeable and heat-resistant. It is made of Nomex® III A and manufactured by Dupont™ (Chatham, Canada) with a fabric thickness of 0.5 mm. Densification was tested at 180 °C, 200 °C, and 220 °C, respectively.

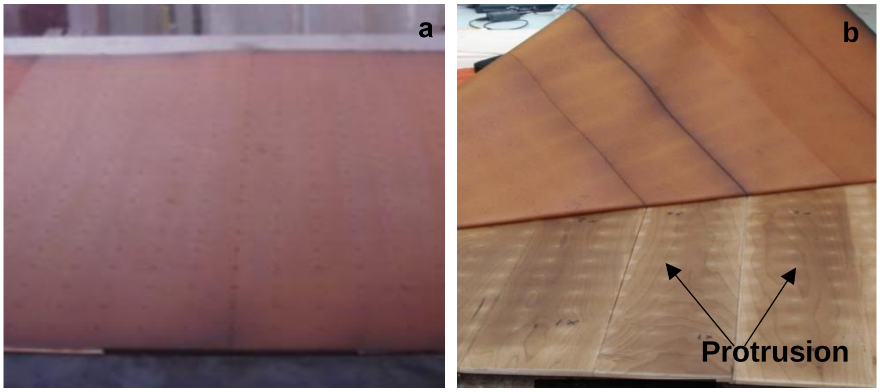

Fig. 3. Both sides of the sugar maple specimens were covered with steam-permeable and heat-resistant fabric before densification (a), and protrusions surrounded with dark color were found after densification (b)

Fig. 4. Both sides of red oak specimens were covered with copper wire mesh before densification (a), and the specimens' surface became rough after densification (b)

THM densification treatment with metal mesh

Instead of fabric, specimens were covered with a metal mesh on both sides and then densified using the same densification process. The mesh was made of copper wire as shown in Fig. 4a. The thickness of the mesh was approximately 2 mm. The tests were performed at 200 °C.

THM densification treatment with metal foam

The same THM densification process was used. Both sides of the specimens were covered with 2-mm-thick metal foam (MTI Corporation, Hefei, China) (Fig. 5a). A metal foam is a cellular structure consisting of a solid metal with pores comprising a large portion of the volume. The pores can be sealed (closed-cell foam) or interconnected (open-cell foam). Open-cell metal foam, also called metal sponge, can be used in heat exchangers, energy absorption, flow diffusion, and lightweight optics. In this study, open-cell metal foam was used due to its high porosity to ensure steam permeability. Two different metal foams were tested. One was made of nickel and the other one was made of steel. The tests were performed at 200 °C.

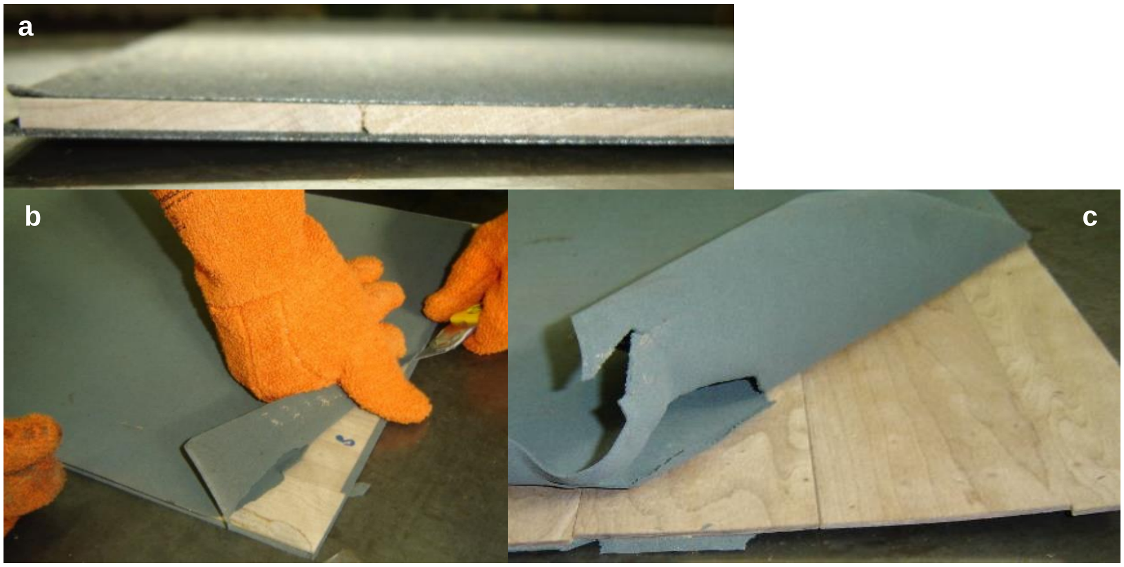

Fig. 5. Both sides of specimens were covered with open-celled metal foams with interconnected pores (a), specimens' surface became very rough and the metal foams stuck to wood after densification (b and c)

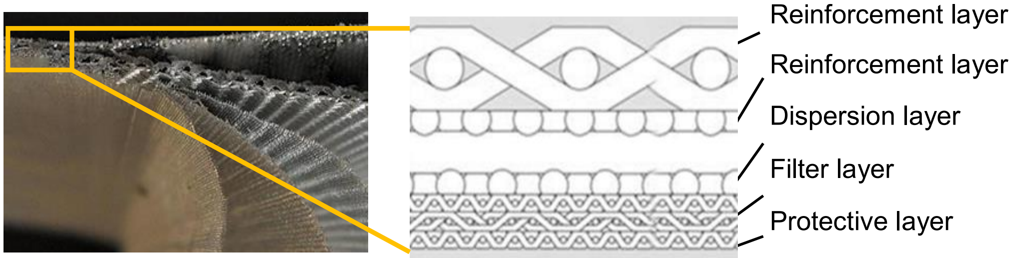

Fig. 6. Five-layer SMML used to cover wood specimens

THM densification treatment with sintered metal mesh laminate

Two pieces of special sintered metal mesh laminate (SMML; Beijia Filter Equipment Co., Ltd., Anping, China) were used to cover both sides of the specimens and the same densification process was performed. The SMML is a porous metal composite made from multilayer stainless steel wire mesh and sintered into one metal panel (Fig. 6). It is heat-resistant and anti-corrosive with high mechanical strength and wide filter rating ranges.

The SMML is a new, fine material usually used for purification and filtration of liquid and gas, separation and recovery of solid particles, control of airflow distribution, and enhancement of heat and mass transfer. It is easy to clean and reusable. In this study, SMMLs consisting of five layers of metal weave mesh, as shown in Fig. 6, were used and the thickness was 1.5 mm. The SMMLs were placed on the press with the rough reinforcing layer towards the platens and the fine smooth protective layer towards the wood specimens. The tests were performed at 200 °C and 220 °C. To test the reusability of SMML, hundreds of tests were performed.

RESULTS AND DISCUSSION

Previous THM Densification Treatments

After densification treatment, protrusions were found on all of the densified specimens at all the corresponding spots of steam injection holes (Fig. 7). The holes on the platens were also found plugged with wood particles. These phenomena were caused by the high mechanical pressure of the platens during the THM densification process. At a high temperature with steam treatment, the specimens were softened, which facilitated the protruding into the holes in the platens. The plugging of the holes might have blocked the injection and venting of steam to a great extent during densification. Furthermore, the protrusions on the densified specimens needed a further sanding or planing process to remove them. In addition, the spots with protrusions were not densified as elsewhere on the same specimens. Thus, the spots with protrusions could be weak points of densified wood.

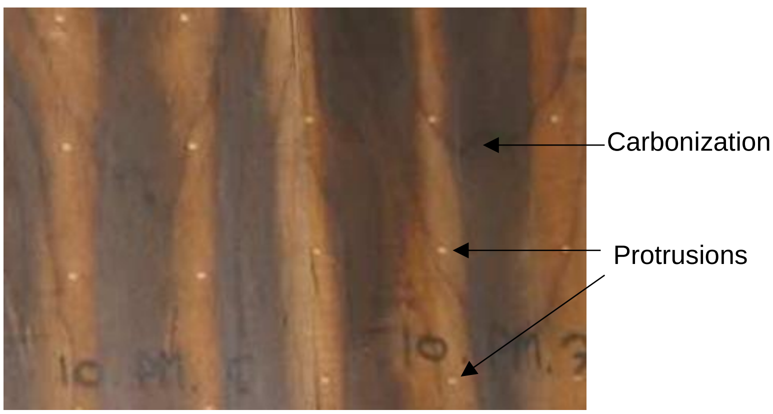

Fig. 7. Protrusions and carbonization on specimens after the previous THM densification treatment

Carbonization was also found on sugar maple specimens after densification at 200 °C (Fang *et al.* 2012a) (Fig. 7). In the longitudinal direction of the specimens, carbonization stripes were distributed between protrusions on the densified specimens. The stripes around the protrusions in the longitudinal direction of wood were not carbonized because water and steam was transported more easily in the longitudinal direction than the transverse direction in wood. Carbonization might have caused a severe decrease in the wood's mechanical strength. The carbonization stripes indicated that steam was not distributed well on these areas. This might have been caused by two factors: (1) steam was blocked due to the plugging of injection holes on platens and (2) during compression, especially at the end of the process, wood specimens contacted tightly with the hot press platens under high pressure. Therefore, there was no more space for steam to move on the wood surface. In addition, it is difficult for steam or water to move inside wood in the transverse direction.

Other defects (blisters and blows) were also found on some of the densified specimens, which were described in the authors' previous study (Ahmed *et al.* 2013). During compression, moisture inside wood becomes vapor at high temperatures. As specimens were compressed tightly by hot platens, it was impossible for vapor inside the wood to evaporate and release, as there was no space for the vapor to move, even during venting at the end of the densification process. Therefore, vapor inside the wood samples created high pressure. Once the platens were opened, blisters or blows developed immediately. Explosions even occurred for the specimens with high initial moisture content. These phenomena also happened during the densification process without steam treatment (Bao *et al*. 2017).

THM Densification Treatment with Fabric

Protrusions were still found on all of the densified specimens (Fig. 3b), but they were smaller than those with previous THM densification treatment without the diffuser. The fabric diminished the size of the protrusions, but it was not solid enough to completely prevent the occurrence of protrusions. However, the holes on the press platens were not plugged with wood specimens. No more carbonization was found on control specimens at the same densification temperature (200 °C). However, at all the locations of protrusions the color was lighter than the surrounding areas (Fig. 3b). These results indicated that the fabric improved the steam distribution on the specimens during densification, but the distribution was still not uniform. The protrusions still prevented to some extent the injection and venting of steam, and they can still be regarded as a defect for further application.

THM Densification Treatment with Metal Mesh

No more protrusions were found after densification with metal mesh, and the holes on the press platens were not blocked (Fig. 4b). The surface color also showed as uniform. These results indicated that steam was well distributed on the specimens. However, a critical defect was the rough surface on both sides of the densified specimens, which would cause a large amount of waste due to planing for further applications except for some special cases where a rough wood surface is not an issue.

THM Densification Treatment with Metal Foam

Specimens with a uniform color and without protrusion were obtained after densification with both open-cell nickel and steel foams (Figs. 5b and 5c). This indicated that the steam was well diffused and distributed on the specimens. However, after a couple of uses the nickel foams were compressed and could not recover to their initial thickness, which to a large extent prevented the diffusion of steam. In addition, the nickel foams were indented into the wood specimens and hard to separate (Figs. 5b and 5c). Steel foams had longer service life than nickel foams, but were also compressed and permanently deformed. Furthermore, the surface of densified specimens was rough due to the rough open-cell foam surface.

THM Densification Treatment with Sintered Metal Mesh Laminate

Good results were obtained after densification with SMML (Fig. 8). No protrusion occurred on the densified wood surface. No carbonization was found after densification, even at 200 °C for 30 min and 220 °C for 20 min (Fig. 8). The densified specimens showed uniform surface color. These results showed that the SMMLs used had good ability of steam diffusion and the steam was distributed quite uniformly on densified specimens under the high mechanical pressure applied by the press platens.

Blisters or blows were not found on the densified specimens, except for red oak with occasional blisters. This finding indicated that vapor created inside the wood specimens was released. This could have been explained by the fact that permeable porous SMML between densified specimens and press platen offered space for vapor to be transported and released from the densified specimens. The occasional blisters on densified red oak need further investigation with respect to its anatomical structure and chemical components.

As wood specimens' surface contacted with the fine, smooth protective layer during the densification process, densified specimens had a smooth surface.

After hundreds of tests, the SMMLs were not compressed. Rather, they maintained their initial thickness. Thus, the SMMLs used in this study were solid enough and could be reused. For improving efficiency, SMMLs can be installed and fixed on press platens.

It can be concluded that SMML was a preferable material for THM densification by enhancing injection, diffusion, and distribution of steam and evaporation of moisture inside the wood. The SMMLs might be also useful for thermo-mechanical densification process by enhancing a release of vapor created inside the wood to avoid blisters, blows, and explosions.

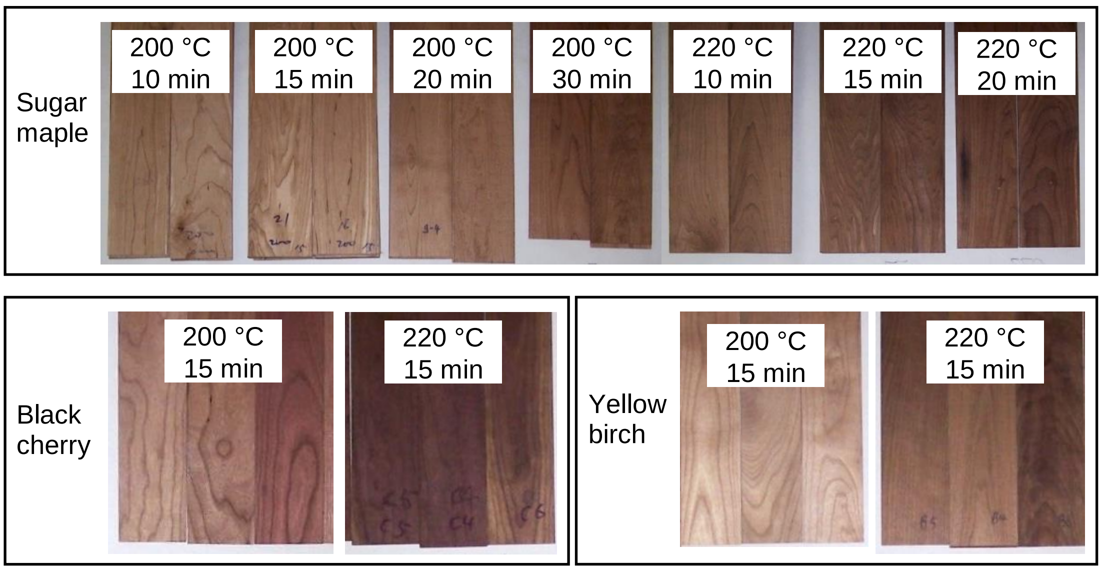

Fig. 8. Specimens after densification with SMMLs at different temperatures with different durations

CONCLUSIONS

1. The thermo-hydro-mechanical (THM) densification of wood with steam injection and without steam diffusion showed protrusions, carbonization, blisters, and blows caused by the prevention and blockage of steam injection and diffusion as well as vapor release.
2. Densification with heat-resistant fabric improved, to a limited extent, steam diffusion but small protrusions occurred, and the steam was not uniformly distributed on the specimens. The thin soft fabric could not completely prevent the steam injection holes from being blocked.
3. Metal mesh solved the problems abovementioned, but a rough specimen surface was another defect after densification.
4. The THM densification with open-cell nickel and steel foams showed good results but they were permanently deformed after compression and indented into the densified

specimens. Thus, metal foams could not be reused. In addition, the wood surface was also rough.

5. The sintered metal mesh laminates (SMMLs) showed good performance for THM densification. No protrusion, carbonization, blisters, or blows were found after densification with SMMLs. The densified wood specimens showed uniform color and a neat surface. The SMML was a preferable material for THM densification by enhancing diffusion, and distribution of steam and evaporation of moisture inside the wood.

ACKNOWLEDGMENTS

The authors acknowledge the financial support from the Foundation of International Centre for Bamboo and Rattan (1632019002 and 1632016015).

REFERENCES CITED

Ahmed, S. A., Morén, T., Hagman, O., Cloutier, A., Fang, C.-H., and Elustondo, D. (2013). "Anatomical properties and process parameters affecting blister/blow formation in densified European aspen and downy birch sapwood boards by thermo-hygro-mechanical compression," *J. Mater. Sci.* 48(24), 8571-8579. DOI: 10.1007/s10853-013-7679-9

Bao, M., Huang, X., Jiang, M., Yu, W., and Yu, Y. (2017). "Effect of thermo-hydro-mechanical densification on microstructure and properties of poplar wood (*Populus tomentosa*)," *J. Wood Sci.* 63(6), 591-605. DOI: 10.1007/s10086-017-1661-0

Belt, T., Rautkari, L., Laine, K., and Hill, C. A. (2013). "Cupping behaviour of surface densified Scots pine wood: The effect of process parameters and correlation with density profile characteristics," *J. Mater. Sci.* 48(18), 6426-6430. DOI: 10.1007/s10853-013-7443-1

Boonstra, M. J., and Blomberg, J. (2007). "Semi-isostatic densification of heat-treated radiata pine," *Wood Sci. Technol.* 41, 607-617. DOI: 10.1007/s00226-007-0140-y

Cruz, N., Bustos, C., Aguayo, M. G., Cloutier, A., and Castillo, R. (2018). "Impact of the chemical composition of *Pinus radiata* wood on its physical and mechanical properties following thermo-hygromechanical densification," *BioResources* 13(2), 2268-2282. DOI: 10.15376/biores.13.2.2268-2282

Fang, C.-H., Cloutier, A., Blanchet, P., Koubaa, A., and Mariotti, N. (2011). "Densification of wood veneers combined with oil-heat treatment. Part I: Dimensional stability," *BioResources* 6(1), 373-385. DOI: 10.15376/biores.6.1.373-385

Fang, C.-H., Blanchet, P., Cloutier, A., and Barbuta, C. (2012a). "Engineered wood flooring with a densified surface layer for heavy-duty use," *BioResources* 7(4), 5843-5854. DOI: 10.15376/biores.7.4.5843-5854

Fang, C.-H., Cloutier, A., Blanchet, P., and Koubaa, A. (2012b). "Densification of wood veneers combined with oil-heat treatment. Part II: Hygroscopicity and mechanical properties," *BioResources* 7(1), 925-935. DOI: 10.15376/biores.7.1.925-935

Fang, C.-H., Mariotti, N., Cloutier, A., Koubaa, A., and Blanchet, P. (2012c). "Densification of wood veneers by compression combined with heat and steam," *Eur. J. Wood Wood Prod.* 70(1-3), 155-163. DOI: 10.1007/s00107-011-0524-4

Fu, Q., Cloutier, A., and Laghdir, A. (2016). "Optimization of the thermo-hygromechanical (THM) process for sugar maple wood densification," *BioResources* 11(4), 8844-8859. DOI: 10.15376/biores.11.4.8844-8859

Fu, Q., Cloutier, A., and Laghdir, A. (2017). "Effects of heat and steam on the mechanical properties and dimensional stability of thermo-hygromechanically-densified sugar maple wood," *BioResources* 12(4), 9212-9226. DOI: 10.15376/biores.12.4.9212-9226

Fukuta, S., Asada, F., and Sasaki, Y. (2008). "Influence of drilled holes on bending properties of compressed wood manufactured by new process," *Forest Prod. J.* 58(10), 19-24.

Gabrielli, C., and Kamke, F. A. (2008). "Treatment of chemically modified wood with VTC process to improve dimensional stability (viscoelastic thermal compression)," *Forest Prod. J.* 58(12), 82-86.

Higashihara, T., Morooka, T., and Norimoto, M. (2000). "Permanent fixation of transversely compressed wood by steaming and its mechanism," *Mokuzai Gakkaishi* 46(4), 291-297.

Inoue, M., Norimoto, M., Tanahashi, M., and Rowell, R. M. (1993a). "Steam or heat fixation of compressed wood," *Wood Fiber Sci.* 25(3), 224-235.

Inoue, M., Ogata, S., Kawai, S., Rowell, R. M., and Norimoto, M. (1993b). "Fixation of compressed wood using melamine-formaldehyde resin," *Wood Fiber Sci.* 25(4), 404-410.

Inoue, M., Sekino, N., Morooka, T., Rowell, R. M., and Norimoto, M. (2008). "Fixation of compressive deformation in wood by pre-steaming," *J. Trop. Forest Sci.* 20(4), 273-281.

Kamke, F. A. (2006). "Densified radiate pine for structural composites," *Maderas- Cienc. Tecnol.* 8(2), 83-92. DOI: 10.4067/S0718-221X2006000200002

Kariz, M., Kuzman, M. K., Sernek, M., Hughes, M., Rautkari, L., Kamke, F. A., and Kutnar, A. (2017). "Influence of temperature of thermal treatment on surface densification of spruce," *Eur. J. Wood Wood Prod.* 75(1), 113-123. DOI: 10.1007/s00107-016-1052-z

Kollmann, F. P., Kuenzi, E. W., and Stamm, A. J. (1975). *Principles of Wood Science and Technology II, Wood Based Materials*, Springer, Berlin, Germany.

Laine, K., Belt, T., Rautkari, L., Ramsay, J., Hill, C. A., and Hughes, M. (2013). "Measuring the thickness swelling and set-recovery of densified and thermally modified Scots pine solid wood," *J. Mater. Sci.* 48(24), 8530-8538. DOI: 10.1007/s10853-013-7671-4

Laine, K., Segerholm, K., Wålinder, M., Rautkari, L., and Hughes, M. (2016). "Wood densification and thermal modification: Hardness, set-recovery and micromorphology," *Wood Sci. Technol.* 50(5), 883-894. DOI: 10.1007/s00226-016-0835-z

Li, L., Gong, M., Yuan, N., and Li, D. (2013). "An optimal thermo-hydro-mechanical densification (THM) process for densifying balsam fir wood," *BioResources* 8(3), 3967-3981. DOI: 10.15376/biores.8.3.3967-3981

Navi, P., and Girardet, F. (2000). “Effects of thermo-hydro-mechanical treatment on the structure and properties of wood,” *Holzforschung* 54(3), 287-293. DOI: 10.1515/HF.2000.048

Navi, P., and Heger, F. (2004). “Combined densification and thermo-hydro-mechanical processing of wood,” *MRS Bull.* 29(5), 332-336. DOI: 10.1557/mrs2004.100

Popescu, M.-C., Lisa, G., Froidevaux, J., Navi, P., and Popescu, C.-M. (2014). “Evaluation of the thermal stability and set recovery of thermo-hydro-mechanically treated lime (*Tilia cordata*) wood,” *Wood Sci. Technol.* 48(1), 85-97. DOI: 10.1007/s00226-013-0588-x

Rautkari, L., Laine, K., Laflin, N., and Hughes, M. (2011). “Surface modification of Scots pine: The effect of process parameters on the through thickness density profile,” *J. Mater. Sci.* 46(14), 4780-4786. DOI: 10.1007/s10853-011-5388-9

Sandberg, D., Haller, P., and Navi, P. (2013). “Thermo-hydro and thermo-hydro-mechanical wood processing: An opportunity for future environmentally friendly wood products,” *Wood Mater. Sci. Eng.* 8(1), 64-88. DOI: 10.1080/17480272.2012.751935

Song, J., Chen, C., Zhu, S., Zhu, M., Dai, J., Ray, U., Li, Y., Kuang, Y., Li, Y., Quispe, N., *et al*. (2018). “Processing bulk natural wood into a high-performance structural material,” *Nature* 554, 224-228. DOI: 10.1038/nature25476

Article submitted: November 12, 2018; Peer review completed: February 3, 2019; Revised version received: February 27, 2019; Accepted: February 28, 2019; Published: March 5, 2019.
DOI: 10.15376/biores.14.2.3278-3288