ORIENTED STRAND BOARD WITH IMPROVED DIMENSIONAL STABILITY BY EXTRACTION OF HEMICELLULOSES

Marina Natalia Hornus
Graduate Research Assistant
E-mail: mnh0022@auburn.edu

George Cheng
Research Fellow
E-mail: qzc0007@auburn.edu

*Iris Vega Erramuspe**
Research Scholar
E-mail: ibv0002@auburn.edu

Maria Soledad Peresin
Assistant Professor
Forest Product Development Center
School of Forestry and Wildlife Sciences
Auburn University
Auburn, AL 36849-5418
E-mail: soledad.peresin@auburn.edu

Tom Gallagher
Regions Professor of Forest Operations
School of Forestry and Wildlife Sciences
Auburn University
Auburn, AL 36849-5418
E-mail: gallatv@auburn.edu

Brian Via†*
Professor and Director
Forest Product Development Center
School of Forestry and Wildlife Sciences
Auburn University
Auburn, AL 36849-5418
E-mail: brianvia@auburn.edu

(Received June 2019)

Abstract. Oriented strand board (OSB) panels are commonly used for wooden building structures such as walls, floors, ceilings, and furniture. These wood composites are manufactured with small wooden strands held together in specific orientations by adhesives. Other additives such as wax might be added to reduce water absorption. One of the limitations of the panels produced today is their poor performance under high humidity conditions. The goal of the present work was 1) to extract hemicelluloses from pine wood strands before the fabrication of OSB panels and 2) to test the impact of the pretreatment on the dimensional stability of these panels. For that purpose, pressure-assisted hydrothermal processes at three different temperatures (120, 140, and 160°C) were performed for 45 min of extraction time in each case. Hemicelluloses in treated

* Corresponding author
† SWST member

Wood and Fiber Science, 52(3), 2020, pp. 257-265
https://doi.org/10.22382/wfs-2020-024

wood strands were quantified using high-performance liquid chromatography. Water absorption, thickness swell, MOE, MOR, and internal bond strength were measured to assess the influence of the pretreatment on OSB properties. According to the results, a hydrothermal pretreatment is beneficial for the performance of OSB panels at high humidity levels. The pretreatment of pine strands at 160°C allowed for the maximum removal of hemicelluloses, without a significant degradation of cellulose or lignin, and the OSB panels pretreated with these pinewood strands displayed the best performance in dimensional stability under wet conditions.

Keywords: OSB, dimensional stability, water adsorption, hydrothermal treatment, hemicellulose extraction, hemicelluloses.

INTRODUCTION

Oriented strand boards (OSBs) are engineered wood products used for furniture and as construction materials. The use of OSB panels as a low-cost alternative to plywood is rapidly increasing (Lippke and Edmonds 2006; Cheng et al 2018). One of the main disadvantages of the OSB produced today is the absorption of moisture, which can significantly affect their mechanical properties and lower their resistance to fungal decay. Thus, it is necessary to introduce modifications in the fabrication of the panels to avoid undesirable thickness swell and to improve the dimensional stability of panels exposed to high RH conditions (Barnes et al 2018). To achieve this, for example, Okino and collaborators have performed a postthermal treatment on OSBs made from cypress wood strands (Okino et al 2007). Improvement in the mechanical properties and lower thickness swell observed after the posttreatment were primarily attributed to the removal of hemicelluloses. On the other hand, hydrothermal pretreatment was performed to remove hemicelluloses such as xylan and mannan, resulting in a more dimensionally stable OSB (Guimarães et al 2018). Paredes and collaborators have also prepared OSBs using pretreated red maple (*Acer rubrum* L.) wood strands (Paredes et al 2008).

Because the hydrothermal treatments mentioned earlier did not require any additional chemicals other than water, they are considered an environmentally friendly step (Garrote et al 1999). During the hydrothermal treatment, acidic hydronium ions in hot water aid in the cleavage of acetyl groups present in hemicelluloses. Subsequently, the released ions generate acetic acid, which catalyzes depolymerization of hemicelluloses (Nabarlatz et al 2004). Under mild conditions (temperatures below 160°C, less than 1 h treatment), the autocatalytic process is favorable for the hydrolysis of hemicelluloses, the structure of which is less crystalline than cellulose, thus preserving the structure of wood almost intact thanks to the minimal degradation of cellulose and lignin ((Sattler et al 2008). Also, the hydrothermal pretreatment will reduce the amount of volatile organic compounds (VOCs), which is otherwise released during the manufacturing of OSBs (Paredes 2009). A reduction in the level of VOCs during the manufacturing process is also desirable because of the adverse health effects of VOCs.

The selective removal of hemicelluloses from wood strands using hydrothermal treatment has been studied thoroughly as a strategy to reduce the absorption of moisture. Thanks to the presence of carboxylic functional groups in the polysaccharide chains and to the amorphous structure which facilitates the hydrogen bonding with water molecules; these heteropolymers are the most hydrophilic polymers in wood (Simpson 1980; Weiland and Guyonnet 2003; Hosseinaei et al 2011). As the chemical composition and distribution of hemicelluloses vary dramatically, depending on the raw material, the optimal extraction conditions will significantly depend on the wood source and may play a decisive role in the properties of the resulting OSB (Mirabile and Zink-Sharp 2017; Paredes et al 2017). For example, Paredes et al (2008) found a decrease in strength and internal bond relative to the control sample after hemicellulose removal, whereas Hosseinaei et al (2011) found improvements in MOR, MOE, and internal bond. As wood strands made of southern pine (*Pinus* spp.) are typically used in the production of OSBs in the Southern United States, more research should be performed using this raw material. Also, the different production conditions

introduce new variables and need to be studied separately. For example, in a study by Hosseinaei, phenol formaldehyde thermosetting resins were used as a binder of wood strands and the material was pressed for 5 min at 200°C, while most of the processes used in the southern mills in the United States use polymeric diphenylmethane diisocyanate (pMDI) and have reduced the time in the press.

Implementation of a hydrothermal pretreatment does not only benefit the properties of the OSB panels but also help create value and has a positive impact on the economy of the OSB industry, as the hemicelluloses extracted in the hydrolysate are valuable polymers, which can be further used to produce new chemicals, fuels, and materials (Mosier et al 2005). For example, biofuels such as ethanol, butanol, and butanediol can be produced from hemicelluloses, as well as other compounds such as furfural, lactic acid, xylitol, or polylactic acid, with application in the chemical, pharmaceutical, and cosmetic industry. The strategy of producing new chemicals and materials from hemicelluloses is aligned with the biorefinery concept, which aims to produce new materials and energy from underused renewable materials (Il et al 2017; Mihiretu et al 2017).

The goal of the present study was to separate hemicelluloses from southern pine wood strands using a pressurized hot water treatment. The extracted strands were further used in the fabrication of OSB panels using a typical recipe and average hot-press time. The effect of the pretreatment on the thickness swell and dimensional stability of the panels under high humidity environmental conditions was tested using standard methods such as ASTM D1037 (ASTM 2012). We also studied the composition of the extracted liquor (hydrolysate) collected after the pretreatment—the quantification of the hemicelluloses in the hydrolysate that was assessed by high-performance liquid chromatography (HPLC).

MATERIALS AND METHODS

Materials

Mainly, southern yellow pine strands (*Pinus* spp.) with a 9% mean MC and with maximum thickness, length, and width of 0.095 cm, 12 cm, and 3.0 cm, respectively, were donated from a local Louisiana-Pacific OSB plant. Commercial polymeric resins with diphenylmethane diisocyanate (pMDI) (Mondur® 541, Covestro LLC, Pittsburgh, PA) and wax emulsion (Hexion Inc., Columbus, OH) were donated from Huber Engineered Woods R&D (Commerce, GA). Unless otherwise specified, all the values showed from now on this article are expressed on a dry weight basis.

Methods

Hemicellulose extraction. Hemicelluloses were extracted from 575 g of wood strands using a pressurized hot water extraction method in a 6.5-l Parr reactor (reaction time: 45 min; liquor-to-wood ratio: 1:10). The reactor was controlled with a Parr model 4842 controller (Parr Instrument Company, Moline, IL). Pretreatments were performed at temperatures 120, 140, and 160°C. The heating temperature ramp was 3°C/min, and the cooling temperature ramp was 8°C/min. The initial pH of the water was 7.8. Cooling was performed by circulating water through a cooling jacket inside the reactor. The reactor was opened when the temperature was 60°C, and the wood strands were separated from the hydrolysate liquid. After cooling, the pH of the hydrolysate was measured, and wood strands were washed with 2 L of tap water to remove deposited compounds. Then, the washed strands were dried in a ventilated room until an MC of approximately 9%. Strand samples were randomly selected for chemical characterization in an HPLC.

The percentage of the extracted material was calculated by the difference of dry weight before and after extraction, according to Eq 1,

$$\%\ \text{of Weight loss} = \frac{m_{\text{BE}} - m_{\text{AE}}}{m_{\text{BE}}} \times 100 \quad (1)$$

where m_{BE} the dry mass of strands before extraction and m_{AE} the dry mass of strands after extraction.

Quantification of extractives in wood strands. The solvent-soluble nonvolatile material

in wood strands, commonly referred to as wood extractives, was quantified following solvent extractives of wood and pulp TAPPI standard method (Proposed revision of T204 cm-97 standard) using reagent-grade acetone as a solvent.

HPLC analysis. Extracted free wood strand samples were randomly selected for chemical characterization, grained, and sieved through a 40-mesh test sieve. The sugar composition of the selected samples was analyzed by HPLC using the NREL/TP-510-42618 standard method for the determination of structural carbohydrates and lignin in biomass. In brief, 0.5 g of sample was grained and sieved through a 40-mesh sieve and hydrolyzed in a closed glass container placed into a water bath set at 30°C, with 5 mL 72% w/w sulfuric acid solution under stirring each 15 min for 1 h. Afterward, 140 mL of distilled water was added, and the containers with the samples were placed in an autoclave set at 121°C for 1 h. The hydrolysates were neutralized to pH 5-6 with calcium carbonate, centrifuged at 12,000 rpm for 12 min, and filtered through a 0.2-μm nylon 25-mm syringe filter into an HPLC vial. The samples (50 μL) were analyzed by means of an HPLC system (Shimadzu Corporation, Kyoto, Japan) equipped with a AMINEX-HPX87P column (BIO-RAD, Hercules, CA), a dual pump, and a refractive index detector with an aqueous mobile phase at a flow rate of 0.6 mL/min and at a temperature of 85°C. The collected data were analyzed with LC Lab solutions software (Shimadzu version 1.23, Japan).

EMC. The EMC was determined by equilibrating strands for 28 days in a closed vessel at 20 ± 2°C. Each vessel contained different saturated salt solutions to create a different RH environments (Wexler and Hasegawa 1954) (Greenspan 1976). Lithium chloride (11.3% RH), potassium hydroxide (16.7% RH), magnesium chloride (33.1% RH), potassium carbonate (43.2% RH), magnesium nitrate (54.4% RH), sodium nitrate (75.4% RH), potassium chloride (85.1% RH), and potassium sulfate (97.6% RH) were used in this work. The EMC was calculated according to Eq 2.

$$\text{Equilibrium moisture content} = \frac{\text{ME} - \text{MOD}}{\text{MOD}} \times 100, \quad (2)$$

where ME is the mass of the sample in equilibrium at the conditioning chamber and MOD is the oven-dry mass of the sample. In addition, vapor sorption isotherms were obtained by dynamic vapor sorption (DVS) measurements at 20°C using a DVS dual vapor gravimetric sorption analyzer (SMS Ltd., London, United Kingdom).

OSB manufacturing. OSB samples with dimensions of 45 × 45 cm were manufactured using the extracted strands as described earlier, whereas no extracted strands were used for preparing the control sample. In total, eight panels were produced, with two panels for each pretreatment and two panels for the control samples. The resin pMDI loading was 2% w/w (mass of resin/mass of the entire board), and the emulsified wax was 1% w/w (mass or wax/mass of total board). Enough strands to produce a single OSB were placed in a concrete mixer and covered with a vinyl covering to reduce spray drift. The pMDI and emulsified wax were sprayed using a gravity feed HVLP spray gun (HUSKY model #H4840GHVSG) while the strands were tumbled in the concrete mixer. Panels were hand formed, transferring strands to a forming box placed on a metal sheet and distributed uniformly in the box. The forming box was removed, and another metal plate was then placed on the strands mat. Because pMDI reacts with the metal of the press, aluminum foil was placed underneath the formed wood strands. The formed mat was then pressed with a Wabash hydraulic press (model 50-24-2TM) under the following conditions: a press time of 3 min, a temperature of 220°C, and a pressure of 1.6 MPa. Two press stops of 1.1 cm were used on either side of the pressed strands as guides to control the targeted thickness of the panel.

OSB mechanical and physical properties testing. For testing the physical and mechanical properties of each type of wood strands (ie

pretreated at 120, 140, and 160°C, and control sample), two OSB panels (size 45 × 45 cm) were prepared. From each panel, two rectangular samples (size 26.7 × 7.6 cm) and six square samples (size 5.1 × 5.1 cm) were obtained from each panel. Half of the rectangular samples were used to measure the MOE and MOR in dry conditions (MOE-d and MOR-d, respectively), while the other half was used to measure water absorption capacity, thickness swell, and MOE and MOR after 24 h underwater submersion (MOE-w and MOR-w, respectively). The square samples were used to measure the internal bond strength. Tests were measured according to the American Society for Testing and Materials (ASTM 2012).

The samples were immersed in tap water for 24 h to measure water absorption, thickness swell, MOE-w, and MOR-wh, and it was taken special care to prevent the samples from floating to the top by using a wire netting and weights. For each sample, thickness was measured in four premarked and equally spaced points, at the midpoint of each side and 2 cm from the edge. The thickness and weight measurements were taken before and after soaking. From the measurements, thickness swell and water absorption were calculated. The percentage of thickness swell was determined according to Eq 3,

$$\%\ \text{of Thickness swell} = \frac{t_2}{t_1} \times 100 - 100, \tag{3}$$

where t_2 is the average thickness of the 4-point measurement after 24 h of soaking, and t_1 is the average thickness of the 4-point measurement before 24 h of soaking.

Water absorption percentage was determined according to Eq 4,

$$\%\ \text{of Water absorption} = \frac{W_f - W_i}{W_i} \times 100, \tag{4}$$

where W_f is the final weight and W_i is the initial weight. Panel density was determined through the mean density of specimens of all the tests previously mentioned. MTS universal testing machine Zwick/Roell Z010 (Germany) was used for measuring the mechanical properties of OSBs.

Statistical analysis. Analysis of variance ($p < 0.05$) and least significant differences were conducted with Statistical Analysis System software (SAS software 9.2, Raleigh, NC). The correlation between OSB mechanical properties and density was investigated and found to be significant. Therefore, an adjustment using the analysis of covariance (ANCOVA) was carried out to correct for variation in density that occurred between samples because of mat-forming variation.

RESULTS AND DISCUSSION

Influence of the Pretreatment on the Wood Strands and Hydrolysate

The influence of temperature treatment on the percentage of the extracted material and the final pH of the hydrolyzed liquid phase is displayed in Table 1. According to the results, the quantity of the extracted material increased as the temperature of the reaction increased, whereas the pH of the liquid decreased because of the greater extent of the acid released during the autocatalytic process. These results are in agreement with earlier findings, which showed that the hydrolysis of softwood hemicelluloses is the main reason for the weight loss in wood during pressurized hot water extraction treatments at mild conditions (temperature below 170°C, extraction time shorter than 1 h, initial neutral pH). At severer conditions, lignin starts to dissolve at temperatures above 170°C and cellulose starts to degrade at temperatures above 240°C (Leppännen et al 2011 and also hemicelluloses become more easily

Table 1. Temperature pretreatments and their effect in the amount of extracted material and pH.

Temperature of pretreatment	Weight loss (% w/w)	pH of hydrolysate
120°C	1.8 (1.1)	4.6 (0.0)
140°C	5.5 (0.0)	4.2 (0.0)
160°C	14.1 (1.2)	3.8 (0.1)

Values within parentheses correspond to the deviation standard value.

depolymerized at elevated temperatures (Tjeerdsma and Militz 2005). It is also possible for extractives to be a significant contributor to weight loss if they are present in large quantities, which is not the case of the material used in this research. The amount of extractive in the material used in this study was only 3.3%.

Many studies have also found that there is a relationship between the temperature treatment and the pH of the hydrolyzed liquid phases (Tjeerdsma and Militz 2005; Grenman et al 2011). Hot water cleaves the O-acetyl bond and generates low–molecular weight acids such as acetic acid, which not only decreases the pH of the medium but also catalyzes the breakage of ether linkages in biomass (Mosier et al 2005). Table 2 shows the remaining percentage of hemicelluloses and cellulose in the control strands and treated strands. At a higher temperature, lower hemicellulose and higher cellulose percent were present as expected.

EMC

The EMC was higher for the control sample than for the pretreated strands at 160°C for each different point of the percentage of RH tested (Fig 1). The decrease in the equilibrium moisture agrees with the hypothesis that the removal of hemicelluloses, during the pretreatment, leads to a less hydrophilic material. The decrease in MC observed in Fig 1 is also in concordance with the improved dimensional stability that was reported shortly thereafter and the change in mass during the water sorption stage observed with DVS measurements (see supplemental file with additional information).

Table 2. Percent of cellulose and hemicelluloses in control strands and pretreated strands.

Temperature of pretreatment	Cellulose content (% w/w)	Hemicellulose content (% w/w)
N/A [a]	40.4	17.9
120°C	43.9	17.7
140°C	45.5	17.6
160°C	47.6	14.5

[a] Control sample

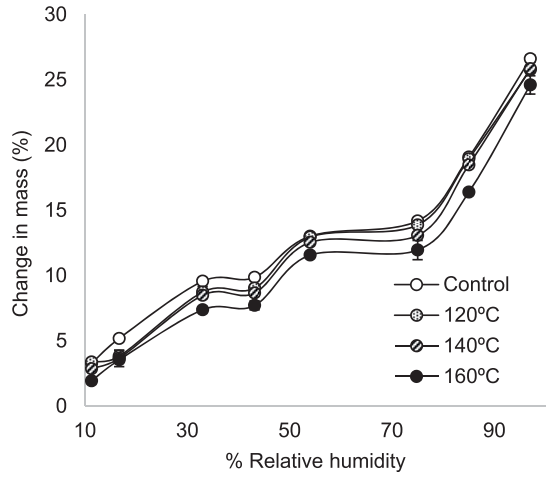

Figure 1. Absorption isotherm at 25°C of strands treated at 120, 140, and 160°C and untreated strands.

Mechanical and Physical Properties on OSBs

According to the results, the density of the prepared OSBs ranged from 0.62 to 0.8 g/cm^3, and the average thickness was in the range of 12.1-13.4 cm. Evidently, an increment in the temperature of the pretreatment leads to a reduction in the thickness of the panels, while contributing to the increase in their density. The results agree with earlier findings summarized by Pelaez and collaborators (Pelaez-Samaniego et al 2013), who provided a succinct while comprehensive review on the benefits of a thermal pretreatment in the fabrication of wood composites from different sources. According to the authors, the thermal pretreatment at elevated temperatures is responsible for an increased crystallinity of cellulose and the migration of lignin to the surface of the treated material. These changes might positively affect the wood structure and be the reason why the OSB panels prepared with pretreated wood strands are more compact, after the hot-press.

The physical and mechanical properties of the prepared OSBs were assessed using the ASTM standard. The data were analyzed using the ANCOVA test ($p < 0.05$) in which density was the covariate. The summary of the results in Table 3 shows that MOE-d, MOR-d, and internal bond strength mean values did not display a

Table 3. Oriented strand board properties measured under dry conditions.

Temperature of pretreatment	MOE-d (MPa)	MOR-d (MPa)	Internal bond strength (N/mm^2)
N/A[a]	3818 ± 485	25.2 ± 4.6	0.44 ± 0.06
120°C	3766 ± 439	27.4 ± 4.2	0.46 ± 0.04
140°C	3278 ± 434	23.4 ± 4.1	0.45 ± 0.06
160°C	3864 ± 637	26.9 ± 6.1	0.51 ± 0.09

[a] Control sample

significant difference between treatments, while the result summary in Table 4 demonstrates that thickness swell, water absorption, MOE-w, and MOR-w mean values had a significant difference between treatments. Also, a significant decrease in thickness swell and reduction of water absorption capacity were observed for the OSBs pretreated at the highest temperatures, under wet conditions. Therefore, there was not a significant difference in the performance of the OSBs under dry conditions, but the behavior of the OSBs is drastically affected under wet conditions, having the pretreatment with pressurized hot water a beneficial impact on the performance of the OSBs under high moisture conditions. Clearly, the OSBs prepared after the pretreatment of wood strands at 160°C showed the best performance under high moisture conditions, with an improvement of around 50% in all tested properties in comparison with the control sample under the same conditions.

The positive impact on the dimensional stability of the wood composite can be attributed not only to the selective removal of hemicelluloses during the hydrothermal treatment but possibly also to the redeposition of lignin onto the surface after the hydrothermal extraction (Donohoe et al. 2008, Hosseinaei et al. 2011) which yields wood strands with a more hydrophobic surface (Axelsson et al. 2012). Also, the hydrothermal treatment allowed for the production of OSBs with higher density, which, according to Pelaez-Samaniego et al (2013), is not a critical variable in the case of OSBs. However, the tendency of moisture migration into the wood is reduced during short-term exposures (Ayrilmiş et al. 2017). Furthermore, the removal of these heteropolysaccharides reduced the available carboxyl and hydroxyl groups, which are responsible for water uptake, making the matrix less hydrophilic (Weiland & Guyonnet 2003). As mentioned before, the pretreatments were carried out at relatively mild conditions (ie temperatures below 170°C, short extraction times, and no addition of acid or alkali) to avoid the degradation of cellulose and lignin, thus preserving the structure of wood (Hosseinaei et al 2011).

CONCLUSIONS

The wood strands pretreated with pressurized hot water improved the dimensional stability of OSBs prepared with wood pine strands. This was mainly attributed to the selective removal of hemicelluloses, which are the most hydrophilic polymers in wood. At 120°C, the percent of hemicelluloses extracted was meager and the impact of the pretreatment on the final mechanical and physical properties of the OSB panels

Table 4. Oriented strand board properties after soaking the samples.

Temperature of pretreatment	Thickness swell (% w/w)	Water absorption (% w/w)	MOE-w (MPa)	MOR-w (MPa)
N/A[a]	28.3 ± 2.3 a	63.1 ± 4.3 a	894 ± 323 c	8.4 ± 5.0 c
120°C	22.2 ± 2.3 b	42.7 ± 4.3 b	1139 ± 246 b-c	11.1 ± 3.8 b-c
140°C	18.4 ± 2.3 c	39.0 ± 4.3 b-c	1407 ± 246 b-a	14.8 ± 3.8 b-a
160°C	14.6 ± 2.3 d	34.1 ± 4.4 c	1751 ± 281 a	18.4 ± 4.3 a

The same letter in a column indicates that there is no statistical difference ($p < 0.05$) between the specimens according to t tests (LSD).
[a] Control sample

was insignificant. Conversely, at 160°C, the large volumes of hemicelluloses were extracted, while still reducing thickness swell and improving dimensional stability. The OSB panels prepared with the wood strands after the pretreatment at 160°C showed the best dimensional stability but also showed a higher percentage of weight loss. For that reason, higher temperatures and longer extraction times of pretreatment were avoided to prevent not only degradation of the wood structural components, which may be detrimental to the mechanical properties, but also reduction of the yield of OSB panels to unacceptable levels.

ACKNOWLEDGMENTS

The authors would like to acknowledge Louisiana-Pacific Corp. for providing the wood strands, Huber Engineered Materials for suppling pMDI and wax, and the Forest Products Society for the recognition given to Marina Hornus during the 72nd International Convention—2018 International Convention (1st place [winner award] in the student poster competition). We also thank Dr. Charles Essien and M.Sc. Qichen Wang for the support during the experiments described in the present research work.

REFERENCES

ASTM (2012) D1037 standard test methods for evaluating properties of wood-base fiber and particle panel materials. American Society for Testing and Materials, West Conshohocken, PA.

Barnes HM, Aro MD, Rowlen A (2018) Decay of thermally modified engineered wood products. Forest Prod J 68: 99-104.

Cheng Q, Zhou C, Jiang W, Zhao X, Via B, Wan H (2018) Mechanical and physical properties of oriented strand board exposed to high temperature and relative humidity and coupled with near-infrared reflectance modeling. Forest Prod J 68:78-85.

Garrote G, Domínguez H, Parajó JC (1999) Mild autohydrolysis: An environmentally friendly technology for xylooligosaccharide production from wood. J Chem Technol Biotechnol 74:1101-1109.

Greenspan L (1976) Humidity fixed points of binary saturated aqueous solutions. J Res Nat Bur Stand 81A:1-89.

Grenman H, Eranen K, Krogell J, Willfor S, Salmi T, Murzin DY (2011) Kinetics of aqueous extraction of hemicelluloses from spruce in an intensified reactor system. Ind Eng Chem Res 50:3818-3828.

Guimarães A, Vital B, De Cássia Oliveira Carneiro A, Vinha Zanuncio AJ (2018) Hydrothermal treatment of strand particles of pine for the improvement of OSB panels. Eur J Wood Wood Prod 76:155-162.

Hosseinaei O, Wang S, Rials TG, Xing C, Zhang Y (2011) Effects of decreasing carbohydrate content on properties of wood strands. Cellulose 18:841-850.

Il W, Jin H, Ju S, Keun K (2017) Thermo-mechanical fractionation of yellow poplar sawdust with a low reaction severity using continuous twin screw-driven reactor for high hemicellulosic sugar recovery. Biores Technol 241:63-69.

Leppännen K, Spetz P, Pranovich A, Hartonen K, Kitunen V, Ilvesniemi H (2011) Pressurized hot water extraction of Norway spruce hemicelluloses using a flow-through system. Wood Sci Technol 45:223-236.

Lippke BR, Edmonds L (2006) The environmental performance improvement in residential construction: The impact of products, biofuels, and processes. Forest Prod J 56: 58-63.

Mihiretu GT, Brodin M, Chimphango AF, Øyaas K, Hoff BH, Görgens JF (2017) Single-step microwave-assisted hot water extraction of hemicelluloses from selected lignocellulosic materials—A biorefinery approach. Biores Technol 241:669-680.

Mirabile, KV, Zink-Sharp A (2017) Fundamental bonding properties of douglas-fir and southern yellow pine wood. Forest Prod J 67:435-447.

Mosier N, Wyman C, Dale B, Elander R, Lee YY, Holtzapple M, Ladisch M (2005) Features of promising technologies for pretreatment of lignocellulosic biomass. Biores Technol 96:673-686.

Nabarlatz D, Farriol X, Montané D (2004) Kinetic modeling of the autohydrolysis of lignocellulosic biomass for the production of hemicellulose-derived oligosaccharides. Ind Eng Chem Res 43:4124-4131.

Okino EY, Teixeira DE, Del Menezzi CHS (2007) Post-thermal treatment of oriented strandboard (OSB) made from cypress (*Cupressus glauca* Lam.). Maderas Cienc Tecnol 9:199-210

Paredes JJ (2009) Influence of hot water extraction on the physical and mechanical behavior of OSB. MS thesis, University of Maine, Orono, ME.

Paredes JJ, Jara R, Shaler SM (2008) Influence of hot water extraction on the physical and mechanical behavior of OSB. Forest Prod J 58:56-62.

Paredes JJ, Shaler S, Howell C, Jakes J (2017) Influence of hot water extraction on cell wall and OSB strand mechanics. Wood Sci Technol 51:1307-1319.

Pelaez-Samaniego MR, Yadama V, Lowell E, Espinoza-Herrera R (2013) A review of wood thermal pretreatments to improve wood composite properties. Wood Sci Technol 47:1285-1319.

Sattler C, Labbé N, Harper D, Elder T, Rials T (2008) Effects of hot water extraction on physical and chemical

characteristics of oriented strand board (OSB) wood flakes. Clean (Weinh) 36:674-681.

Simpson W (1980) Sortpion theories applied to wood. Wood Fiber 12:183-195.

Tjeerdsma BF, Militz H (2005) Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood. Holz Roh Werkst 63:102-111.

Weiland JJ, Guyonnet R (2003) Study of chemical modifications and fungi degradation of thermally modified wood using DRIFT spectroscopy. Holz Roh Werkst 61: 216-220.

Wexler A, Hasegawa S (1954) Relative humidity-temperature relationships of some saturated salt solutions in the temperature range 0° to 50 °C. J Res Nat Bur Stand 53: 19.