Production and Technical Performance of Scrimber Composite Manufactured from Industrial Low-Value Wood for Structural Applications

Mehdi Arefkhani,[a,*] Mostafa Mohammadabadi,[b] Hamid Zarea Hosseinabadi,[a,*] Maliheh Akhtari,[c] and Islam Elsayed [b]

Development of scrimber composites and other engineered wood products from low-value wood and wood waste provides an effective opportunity to preserve natural resources, minimize waste, and innovate the production of higher-performance, environment-friendly construction materials. In this study, peeler cores, which are the center of poplar logs remaining after the peeling process in the veneer production, were utilized to develop scrimber composites. This study investigated the effects of different resins, including phenol-formaldehyde (PF) and urea formaldehyde (UF), as well as hydrothermal treatments at various temperatures (60 °C and 130 °C), on the physical and mechanical properties of the scrimber composites. Chemical changes in wood components and morphological changes in wood cell walls resulting from hydrothermal treatment were analyzed using Fourier transform infrared spectroscopy and scanning electron microscopy. To clarify how resin type and hydrothermal treatment affect structural performance, several physical and mechanical properties of scrimber composites, including thickness swelling, water absorption, internal bond strength, bending modulus of elasticity, and modulus of rupture, were measured. The test results revealed that hydrothermally treated wood scrims at 130 °C, when bonded with PF resin, produced scrimber composites with superior structural performance.

DOI: 10.15376/biores.19.4.8052-8067

Keywords: Scrimber composite; Poplar; Low-value wood; Hydrothermal treatment; Physical and mechanical properties

*Contact information: a: Department of Wood and Paper Science and Technology, Faculty of Natural Resources, University of Tehran, Karaj, Iran; b: Department of Sustainable Bioproducts, Forest and Wildlife Research Center (FWRC), College of Forest Resources (CFR), Mississippi State University, MS, USA; c: Department of Wood Science and Technology, Bojnourd Branch, Islamic Azad University, Bojnourd, Iran; *Corresponding author: mehdiarefkhani@ut.ac.ir; hzareah@ut.ac.ir*

INTRODUCTION

Scrimber boards are a type of new engineered wood product that is gaining popularity in the construction, building, and furniture industries (Li *et al*. 2022). Scrimber is a reclaimed wood product made from integrated parallel strips with a relatively higher proportion of raw material utilization, *i.e.*, high wood fiber utilization (Moya *et al*. 2013). Wood scrimber takes advantage of the directional arrangement of wood fibers and, at the same time, maintains the original pattern and other good qualities of wood (Zhang *et al*. 2018). This approach can be used to convert high-yielding and fast-growing wood with relatively lower mechanical properties into high-quality wood-based products with high structural performance (He *et al*. 2022).

Wood has several advantages that make it suitable for construction, including its high strength-to-weight ratio, renewability, and its low embodied energy. The environmental impact of wood construction compared to other materials has been widely investigated, with numerous individual buildings serving as case studies (Ruschi *et al*. 2020). However, with the global decline in both the quantity and quality of forest resources, it has become increasingly essential to explore opportunities for new engineered wood products to replace the forms of wood that have been traditionally used (Sharma *et al*. 2015).

For thousands of years, wood has been used as a building material and energy source, as well as in the production of furniture, textile fabrics, organic chemicals, and paper products. Several favorable factors, such as simplicity in construction, thermal insulation, and environmental compatibility, have made wood one of the most popular building materials. However, due to stricter environmental regulations and the decline in natural forests, fast-growing wood is expected to be used in building structures. The extensive use of wood across various industries generates a significant amount of wood waste (He *et al*. 2016). For instance, 20% to 30% of the logs used in wood veneer production become waste or residues (Syafii and Novari 2021). Through processing these wood wastes, value-added composites with improved physical and mechanical properties can be developed.

One of the main problems with wood and wood-based products is their hygroscopicity when exposed to moisture. Hygroscopicity negatively affects the performance of wood products from load-bearing capacity and dimensional stability to durability and appearance. Therefore, controlling the level of moisture absorption using various methods is one of the topics of ongoing interest. Physical and chemical modifications, such as heat treatment, are one of the well-known methods to improve the water resistance of wood and wood-based products (Dwianto *et al*. 2022). Treating wood with heat and water, known as hygro-thermal treatment, is an effective method to increase the water repellency of wood (Navi and Sandberg 2011). There are several types of heat treatment, which vary depending on factors such as the temperature applied, treatment duration, treatment atmosphere (inert gas, air, vacuum), system type (closed or open), wood species (softwoods and hardwoods), and whether the system is wet or dry (Hill *et al*. 2021). The presence of water vapor or water in the heat treatment process significantly affects the heat transfer and chemical reactions carried out in the wood (Cermak *et al*. 2021).

This study aimed to upcycle wood waste and low-value wood from veneer production facilities into scrimber composites. Utilizing long wood fibers enhances the structural performance of the final product, making it suitable for the building industry. The study evaluates the effects of UF and PF resins, along with hydrothermal treatment, on the dimensional stability and the physical and mechanical properties of scrimber composites.

EXPERIMENTAL

Materials

As shown in Fig. 1, the raw materials included peeler cores of poplar logs from a veneer and plywood production line at ChoobSang Co., Ltd., in Razavi Khorasan province, Iran. The average density of this low-value poplar wood was 450 kg/m^3. The phenol formaldehyde (PF) resin, with a solid content of 75.79%, and the urea-formaldehyde (UF) resin, with a solid content of 62.66%, were obtained from Samed Manufacturing and Industrial Company, Iran.

Fig. 1. Pith (log-core) poplar wood used in this study

Preparation of Poplar Scrimber

To produce scrimber composite, wood wastes needed to be processed into strips, which are bundles of fibers. Therefore, wood materials were plasticized and thermally treated using two different hydrothermal treatments. The first batch of poplar wood was soaked in the water at 60 °C for 6 h, while the second batch was subjected to water vapor pressure in a cylinder at 130 °C and 0.28 MPa pressure for 30 min. During the scrimming process, hydrothermally treated wood materials were pressed and cut into scrims, as shown in Fig. 2.

Fig. 2. Scrim strands produced from hydrothermally treated wood

Manufacturing Process of Scrimber Composite

Regardless of the resin type, whether UF or PF, a resin content of 12% based on the dry weight of the wood scrims was used for the fabrication of scrimber composites. According to the specifications, UF resin was mixed with ammonium chloride (NH_4Cl) as a hardener to a target content of 2% of the dry weight of UF resin. The wood scrims mixed with resin inside a rotary drum were used to create a 0.4 m × 0.4 m mat of five perpendicular layers. Wood scrims in each layer were hand-formed parallel to each other, uniaxially. The mat, placed between two thick aluminum caul sheets, was hot-pressed to the target thickness of 12 mm and target density of 750 kg/m^3, as shown in Fig. 3.

The resinated scrimbers were hot-pressed for 6 min to consolidate under heat and pressure. The average pressure applied on the mat to reach the target thickness was about 3.5 MPa. The press temperature was set at 120 °C for UF resin and 150 °C for PF resin. Boards made with UF resin were removed after 6 min, while those made with PF resin were left in the hot press for 12 h until the temperature was reduced to room temperature. All boards were conditioned in a chamber at a relative humidity of 65% and a temperature of 23 °C for two weeks before testing. Considering both UF and PF resins and two types of hydrothermal treatments, four groups were developed, with three replicates manufactured per group.

Fig. 3. A general view of manufactured scrimber composites before and after trimming

Measurement of Physical and Mechanical Properties of the Scrimber Boards

Dimensional stability and water resistance of the specimens were evaluated by measuring thickness swelling (TS) and water absorption (WA) after 24 h and 48 h immersion in water. The mechanical properties of scrimber composites, including bending strength (MOR), bending modulus of elasticity (MOE), and internal bond (IB) of the samples, were evaluated following the ASTM D1037-12 (2020) standard. To determine MOR and MOE, specimens were submitted to a three-point bending test with a span length of 240 mm and a deflection rate of 1 mm/min.

Scanning Electron Microscopy

The morphology of cell walls for the hydrothermal-treated specimens was investigated using the Zeiss Model LEO-1450VP scanning electron microscopy (SEM) (Carl Zeiss AG, Oberkochen, Germany) instrument. The acceleration voltage was 15 kV. To improve the conductivity of the samples and the quality of the SEM images, the samples were coated with a very thin layer (18 nm ± 0.2 nm) of aluminum on a specimen stub. Additionally, the sides were painted silver, and the surface was coated with a thin layer of gold using a covering SEM device (Denton Vacuum, LLC, Moorestown, NJ, USA).

Measurement of FTIR Spectra

A Thermo Nicolet Avatar 370 Fourier transform infrared (FTIR) spectrometer (Thermo Fisher Scientific, Waltham, MA, USA) was used to identify compounds qualitatively and quantitatively and ascertain functional groups and bonds in the heat and moisture-treated specimens compared to control specimens.

Statistical Analysis

Univariate analysis of variance was conducted using the IBM SPSS Statistics, version 25.0 software package (SPSS Inc., IBM Corp., Armonk, NY, USA) with a significance level of $p < 0.05$ to evaluate the effect of resins and treatment temperatures on the mechanical properties of scrimber boards made from wood waste. Significant differences among the average values of the treated and untreated specimens were determined using Duncan's multiple range test (DMRT).

RESULTS AND DISCUSSION

FTIR Spectroscopy

FTIR spectroscopy was used to investigate the chemical changes of cell wall components during heat and moisture treatments. The FTIR spectrum of hydrothermally treated poplar wood at 60 and 130 °C were compared to that of untreated poplar wood as a control, as shown in Fig. 4.

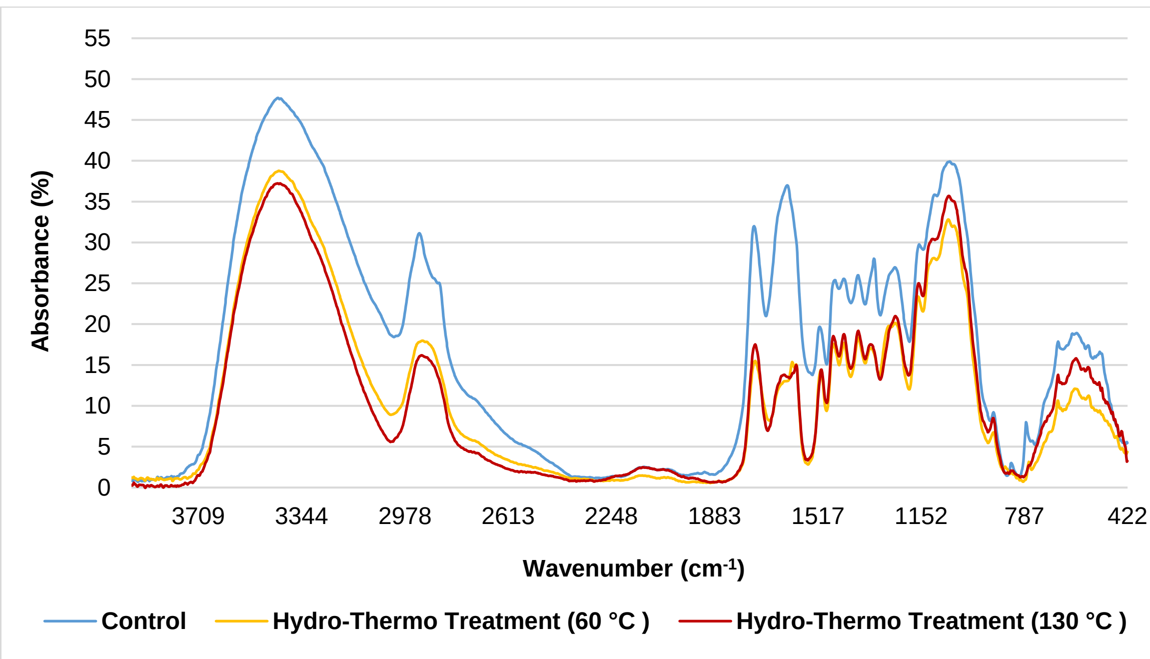

Fig. 4. FTIR spectroscopy of untreated and hydrothermal treated samples at 60 and 130 °C

In untreated specimens, a broad peak developed in the 3300 to 3500 cm^{-1} regions related to the stretching vibration of hydroxyl (O-H) groups (He *et al.* 2022). The symmetric and asymmetric vibration peaks assigned to the C-H bond in methyl ($-CH_3$) and methylene groups ($-CH_2-$) were observed at 2920 and 2850 cm^{-1}. Many well-defined peaks were observed in the fingerprint region of 1800 to 600 cm^{-1} (Mastouri *et al.* 2021). The assigned peaks in the range 1740 to 1730 cm^{-1} were attributed to the unconjugated -C=O group stretching vibrations of acetyl and carboxyl groups in hemicellulose (xylans) and probably lignin. The stretching vibration peaks at 1590 and 1510 cm^{-1} indicate the -C=C bond of the aromatic skeletal in lignin. The peak at 1457 cm^{-1} was assigned to $^{-}$C–H deformation (methyl and methylene) in lignin and xylan. Furthermore, the vibration peaks at around 1425, 1056, and 897 cm^{-1} were attributed to C-O bonds in carbohydrates, mainly cellulose, and 1030 cm^{-1} for the stretching vibration of C-O in hemicellulose (Yue *et al*. 2023). The vibration peaks at 1244 cm^{-1} were related to the syringyl ring and C–O stretching in lignin and xylan, and the peak at 1159 cm^{-1} corresponds to C–O–C vibration in cellulose and hemicellulose (Akhtari *et al*. 2013).

Significant changes can be seen in the spectrum of hydrothermally treated scrims at 60 and 130 °C compared to untreated scrims. A comparison of the spectra of these scrims in Fig. 4 shows some distinct differences. The broad strong O–H stretching band at 3500 to 3300 cm^{-1} was reduced in intensity due to the destruction of hemicelluloses. In addition, there was a reduction in the intensity of peaks at 2920 cm^{-1}, within the range of 1740 to 1730 cm^{-1}, 1590 cm^{-1}, 1510 cm^{-1}, 1425 to 1000 cm^{-1}, and 1030 cm^{-1} (Akhtari *et al*. 2013). The tendency of the peaks for scrims treated at 60 and 130 °C was similar, but the intensity of the peaks decreased more significantly for those treated at 130 °C. A notable reduction in peak height within the range of 1700 to 1500 cm^{-1} was observed in heat-treated scrims, indicating the degradation of hemicellulose compounds (Haseli *et al*. 2024). This suggests that hemicellulose compounds are more sensitive to heat treatment compared to cellulose and lignin compounds (Liu *et al*. 2004). In other words, lignin is more resistant to degradation than polysaccharides (Yang *et al*. 2007). Esteves *et al.* (2011) and Brito *et al.* (2008) conducted studies supporting this claim and found that the relative increase in lignin content in thermally treated wood specimens was partly due to the loss of polysaccharides.

Thermal treatment results in several changes, such as the decomposition of hemicelluloses (Tuong and Li 2011), branching of lignin (Windeisen *et al*. 2007), crystallization of cellulose (Bhuiyan *et al*. 2000), as well as the evaporation of water and volatile organic components with low molecular weight (Melkior *et al*. 2012). As a result, water resistance and dimensional stability of such treated wood should be improved. In the heat treatment of bamboo scrimber at temperatures ranging from 50 to 230 °C, moisture absorption decreased slightly for temperatures under 170 °C but increased thereafter (Shangguan *et al*. 2016).

Scanning Electron Microscopy

Figure 5 illustrates the SEM photographs of the untreated (control) wood compared to hydrothermally treated wood at 60 and 130 °C. It was observed that the middle lamella layers were fractured, and wood cell walls were broken on the cross-section after thermal treatment. Such damage was significant for scrims treated at the higher temperature of 130 °C. It should be highlighted that it was easier to make scrims and an even mat with thermally treated wood at 130 °C compared to that at 60 °C.

Based on previous studies, the changes in the cell wall that occur during hydrothermal treatment can lead to thermal expansion stresses in wood. Typically, changes in the free water content of wood will not affect the structure of the cell wall when the water content exceeds the fiber saturation point (Saito *et al*. 2016).

However, the hydrothermal process in an autoclave takes place in a restricted and confined area, where steam pressure and humidity jointly affect the wood cell walls. As the temperature increases, some amorphous polymers such as lignin and hemicellulose are likely to break down. It is widely recognized that these polymers are relatively concentrated in the compound middle lamella (Rosu *et al*. 2010). Shi *et al.* (2018) found that the matrix materials of lignin and hemicellulose served as a connection point between two wood cells. As a result, the stress concentration led to the breakdown of the cell walls, causing permanent fractures. However, no fractures or damage were observed in the inter-vessel pits or fiber cell wall pits, which are the primary water transport pathways.

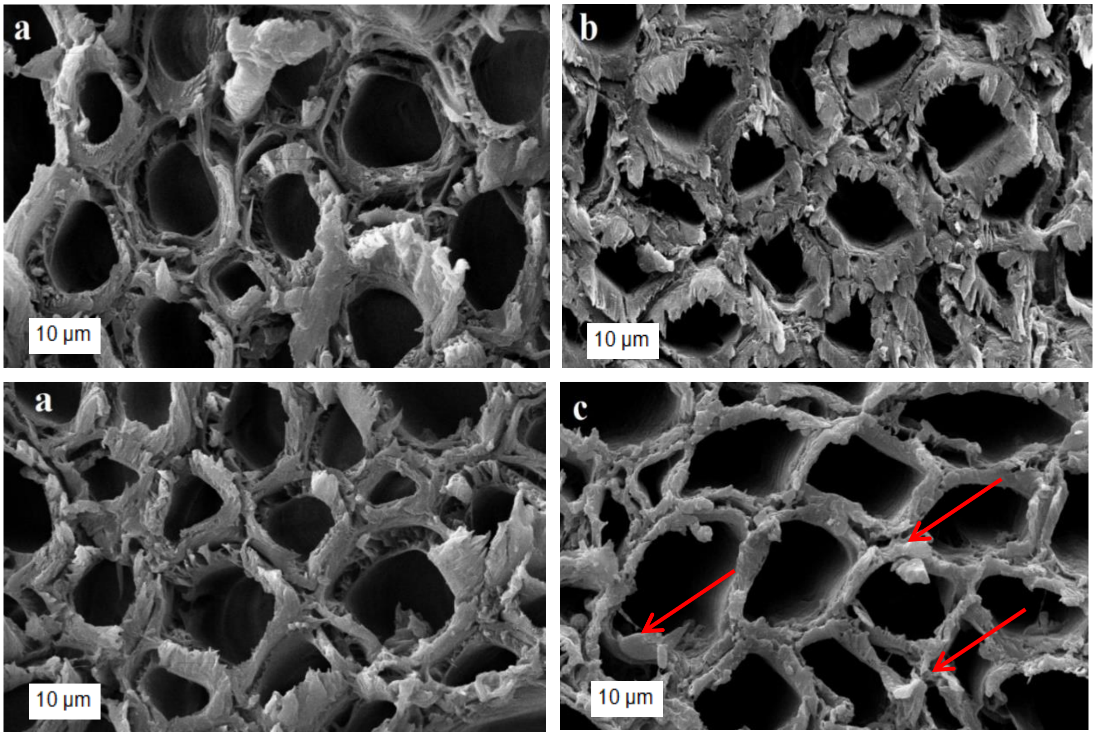

Fig. 5. Scanning electron micrograph of the wood cross-section of control (a), hydrothermal treatment on 60 °C (b), and 130 °C (c) (5000X), Red arrows show cracks on the compound middle lamella.

Physical Properties of Scrimber Composites

A large variation was observed in the density of fabricated poplar wood scrimbers, as shown in Fig. 6. This can be related to the long length of the scrimber, the different thicknesses along its length, and the impossibility of uniform dispersion in perpendicular layers. This leads to the creation of empty spaces between the scrimbers and causes density variation in scrimber panels. Kitchens *et al.* (2016) stated that in the construction of composite scrimber lumber from crushed southern yellow pine wood, X-ray examination of the timber revealed points with lower density. The density standard deviation in scrimber boards made of hydrothermally treated scrims at 130 °C was less than that of scrimber boards made from scrims treated at 60 °C. As SEM images revealed, this can be attributed to the damage in the middle lamella, resulting in higher quality and consistent scrims made from poplar wood treated at higher temperatures. Such scrims made it possible to make a more even scrim mat.

According to statistical analysis, the individual and interaction effect between the type of resin and heat treatment temperature had a significant effect within the 95% confidence level range on water absorption (WA) of scrimber composites. Results indicated that the lowest WA after 24 h (41.98%) and 48 h (57.24%) were obtained in the wood specimens made from scrims hydrothermal treated at 130 °C and bonded with PF resin. In contrast, specimens fabricated from treated scrims at 60 °C and UF resin showed the highest WA after 24 h (52.64%) and 48 h (69.93%), as shown in Fig. 7. In Duncan's multiple range test, the 24-h water absorption of scrimber composites made from PF resin treated at 60 and 130 °C were found to belong to the same statistical group.

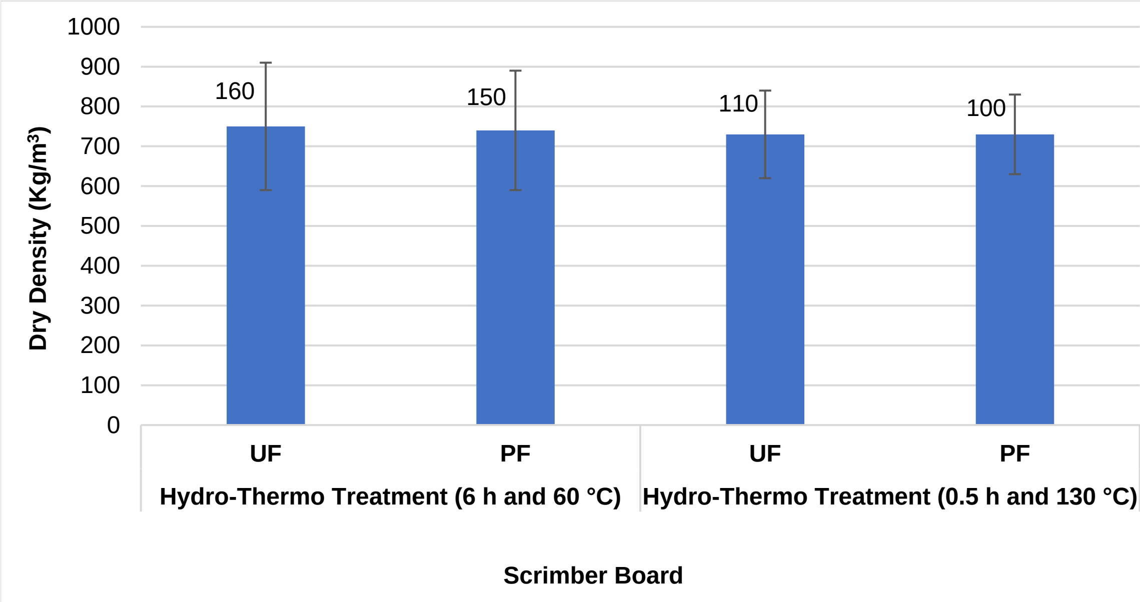

Fig. 6. Mean values ± standard deviation of the dry density of the scrimber board

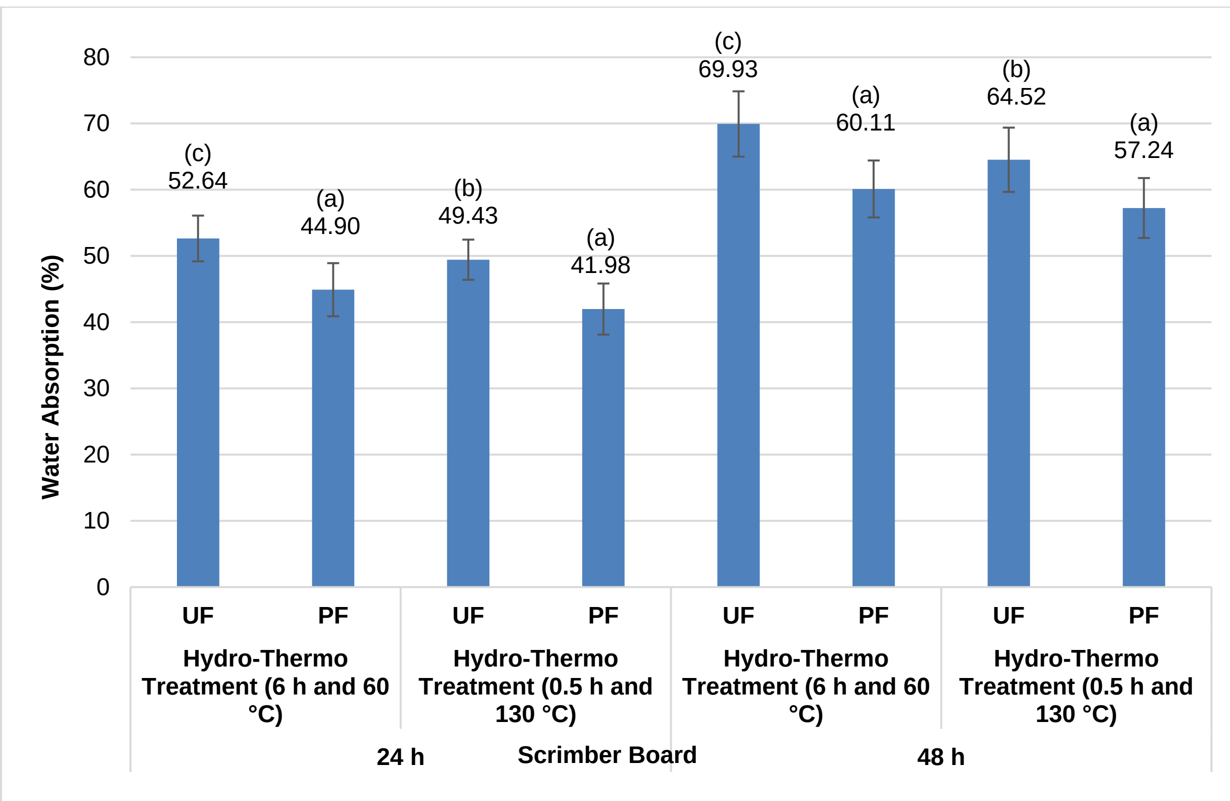

Fig. 7. Mean values ± standard deviation of the water absorption after 24 h and 48 h of scrimber board. Different letters in each column indicate a statistical difference ($p < 0.05$) among the treatment groups.

Wood is primarily composed of cellulose, hemicellulose, and lignin. Applying thermal and chemical modification treatments results in the development of hydrophobic hemicellulose and lignin, which act as protective layers for cellulose. Thermal modification processes break down wood into chemically bonded components in a polymeric structure (Homan *et al*. 2000).

These results indicated an inverse correlation between the average WA values of scrimber boards after 24 and 48 h with the density of the boards. This occurred due to the increased density resulting from higher compressibility and reduced porosity of the scrimbers, leading to a decrease in WA%. Moreover, in crushed wood, the increased specific surface area of the scrims and enhanced resin penetration into the wood pores contributed to reduced water penetration and absorption in these boards. Boards made with PF resin have less WA than boards made with UF resin (Yu *et al*. 2017).

Manafi-Dastjerdi *et al.* (2023) found that oriented strand boards made with PF resin have less water absorption and shrinkage than boards made with UF resin.

Additionally, Shangguan *et al*. (2016) found that when the samples were subjected to heat treatment at temperatures ranging from 50 to 230 °C for 2 h, a minor reduction in moisture absorption was observed for specimens treated at temperatures up to 150 °C, followed by an increase as the treatment temperature increased. This phenomenon was likely due to changes in crystallinity and chemical structure.

The effect of resins, time, and treatment temperatures on thickness swelling of scrimber composites after 24 and 48 h immersions in water is illustrated in Fig. 8. It was shown that the individual and interaction effects between the type of resin and treatment temperatures on thickness swelling (TS) after 24 h and 48 h were statistically significant at the 95% confidence level. The results demonstrated that the scrimber composite manufactured with PF resin at 130 °C exhibited the lowest TS values, measuring 7.22% and 8.40% after 24 and 48 h, respectively.

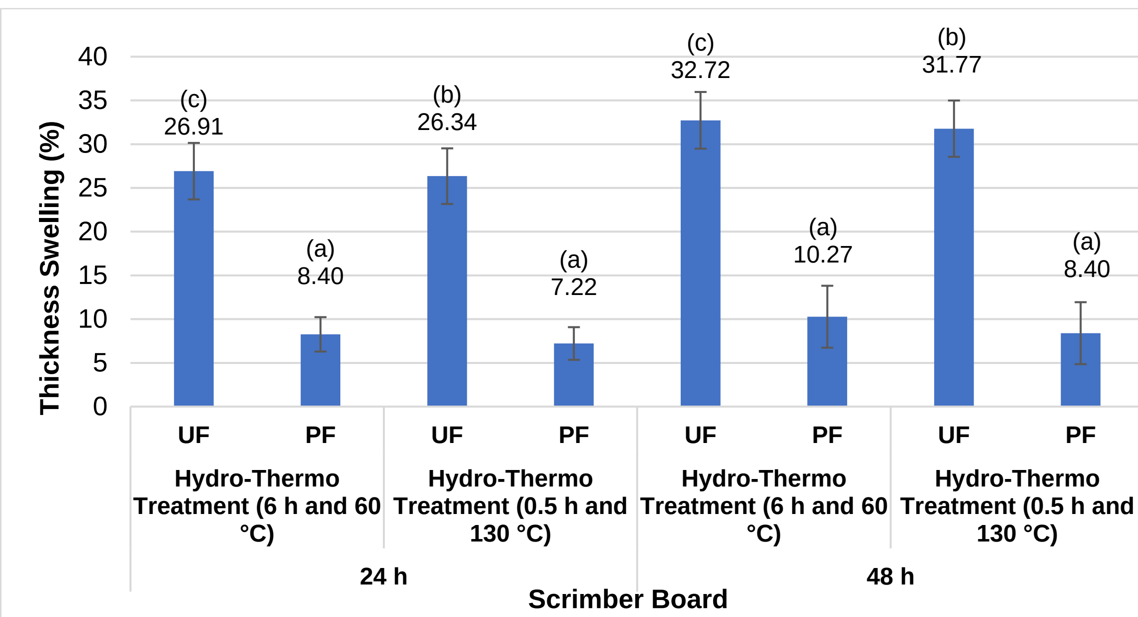

Fig. 8. Mean values ± standard deviation of the thickness swelling after 24 h and 48 h of scrimber board. Different letters in each column indicate a statistical difference ($p < 0.05$) among the treatment groups.

In contrast, the scrimber composite produced with UF resin at 60 °C showed the highest TS values, measuring 26.9% and 32.7% after 24 and 48 h, respectively, as illustrated in Fig. 8. Boards manufactured from wood treated at 130 °C exhibited increased resin absorption due to the increased specific surface area of the scrimbers, resulting in reduced water penetration into the wood pores and consequently minimizing thickness swelling. Istek *et al*. (2018) studied the effect of chip size on the particleboard properties and found a similar result: the specific surface area of the particles influenced the TS values. Additionally, the boards made with PF resin had less TS than the boards made with UF. Phenol–formaldehyde resins tend to be more chemically stable and less susceptible to hydrolysis than UF resins (Chrobak *et al*. 2022). Heat treatment at 130 °C compared to 60 °C had a greater effect on dimensional stability, especially when PF resin was used as a binder. Heat treatment of the bamboo fiber significantly improved the dimensional stability of the bamboo scrimber composites, making them highly suitable for outdoor flooring, construction, and building applications (Li *et al*. 2022). Hydrothermal treatment improves the dimensional stability of wood by reducing its equilibrium moisture content, which decreases the wood's tendency to swell and shrink with changes in humidity (Esteves and Pereira 2009).

Mechanical Properties of Scrimber Composites

The effect of resin types and heat treatment temperatures on the modulus of rupture (MOR) and the modulus of elasticity (MOE) of scrimber composites is presented in Figs. 9 and 10. Statistically, it was shown that the individual and interaction effect between the type of resin and temperatures of heat treatment and MOR samples had a significant effect within the range of 95% confidence level.

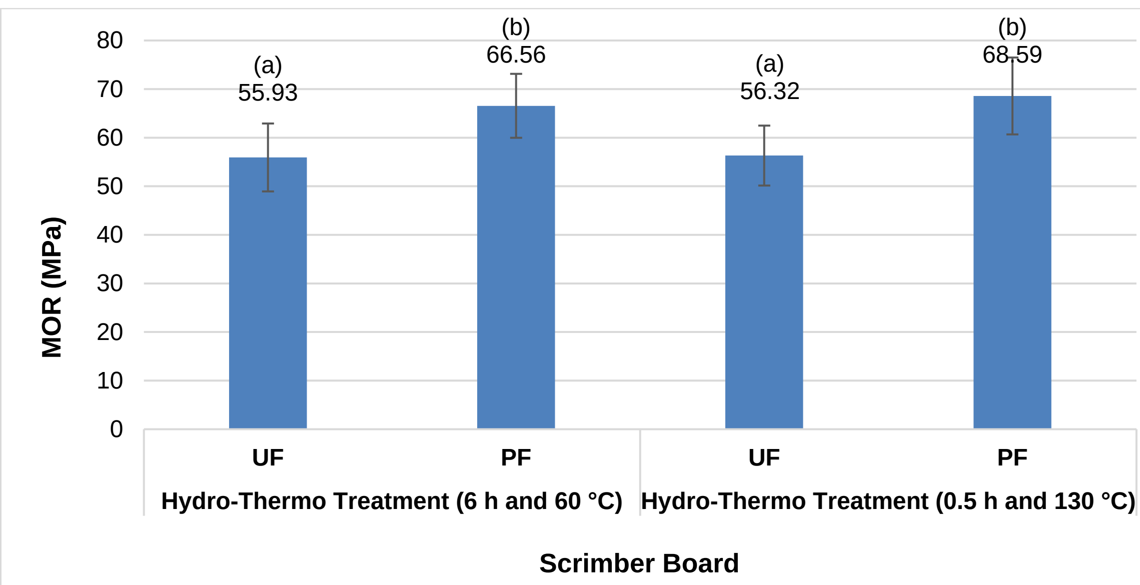

Fig. 9. Mean values ± standard deviation of the MOR of the scrimber board. Different letters in each column indicate a statistical difference ($p < 0.05$) among the treatment groups.

The results indicated that the scrimber composite made with UF resin and scrims hydrothermally treated at 60 °C exhibited the lowest bending strength (MOR) of 55.9 MPa, whereas the highest MOR of 68.6 MPa was observed in the scrimber composite made with PF resin and scrims hydrothermally treated at 130 °C, as shown in Fig. 9. Higher treatment temperature resulted in better separation of wood fibers during the scrimming process, facilitating improved resin penetration among the fibers and resulting in stronger fiber-to-fiber bonding and higher MOR. According to Duncan's grouping, the scrimber composites made from UF resin were grouped together, while those made with PF resin were classified into another distinct group. The results showed that the boards made with PF resin had higher bending strength (MOR). The main reason for this improvement is attributed to the higher formaldehyde content and the creation of a transverse bonding in the board (Kurt and Cavus 2011).

Shangguan *et al.* (2016) found that after hydrothermal treatment at temperatures up to 150 °C, there was a minor decrease in bending strength. However, as the treatment temperature increased to 200 °C, a significant reduction in bending strength occurred. This process is due to damage to the cell wall. Additionally, by reducing the amount of hemicellulose during the heat and moisture treatment process, the transverse bonding of the fibers was decreased, leading to a subsequent decrease in bending strength.

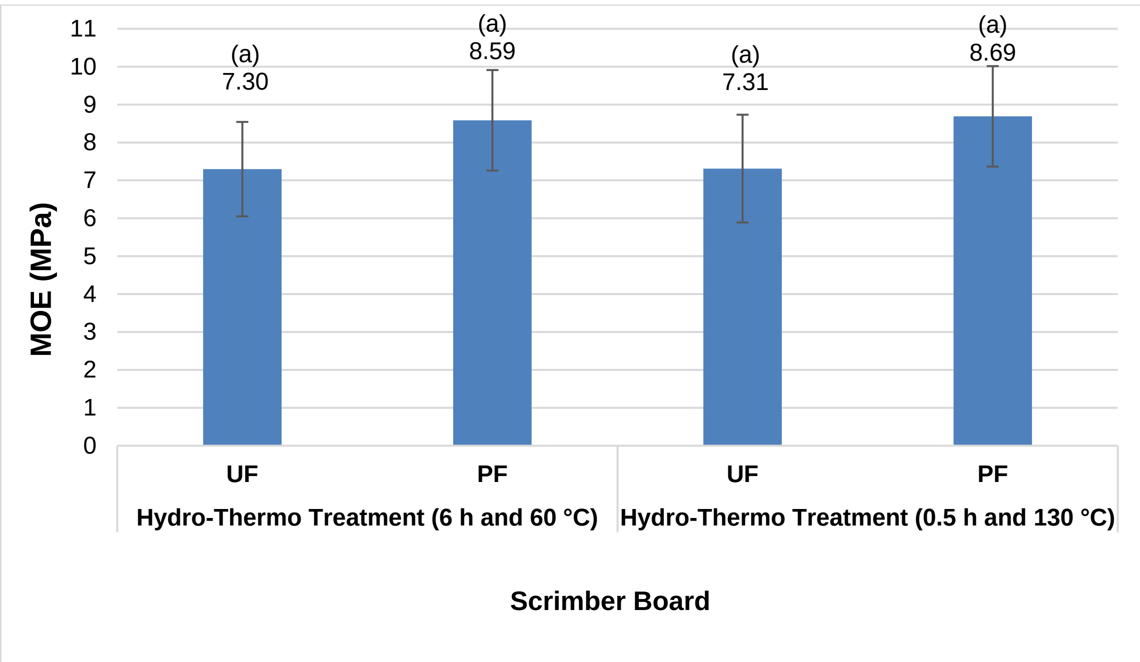

Fig. 10. Mean values ± standard deviation of the MOE of scrimber board; Letters in each column indicate a statistical difference ($p < 0.05$) among the treatment groups.

Mean values of the MOE of scrimber boards made from pith (log-core) poplar wood with different resins and treatment temperatures are shown in Fig. 10. Statistically, it was shown that the resin types had a significant effect at a 95% confidence level, while the treatment temperatures had no significant effect on MOE values of scrimber boards. The boards made with UF resin and hydrothermally treated at 60 °C exhibited the lowest MOE value of 7300 MPa, whereas those manufactured with PF resin and treated at 130 °C had the highest MOE value of 8690 MPa. According to Duncan's grouping, the scrimber composites made from UF resin were grouped together, and boards made with PF resin were classified into another group. The results showed that the boards made with PF resin had higher bending strength. The MOE of the boards manufactured from scrimbers heat-treated at 130 °C showed a slight increase compared to those hydrothermally treated at 60

°C. Homan *et al.* (2000) found that increasing the heat treatment temperature of spruce wood in the range of 130 to 170 °C leads to an increase in the MOE values. Savov *et al.* (2021) used a mixture of UF and PF resins in different proportions to fabricate high-density fiberboard (HDF). They found that the MOE showed an increasing trend with higher concentrations of PF resin in the mixture. The highest MOE was observed when only PF resin was used, while the lowest value was recorded with UF resin.

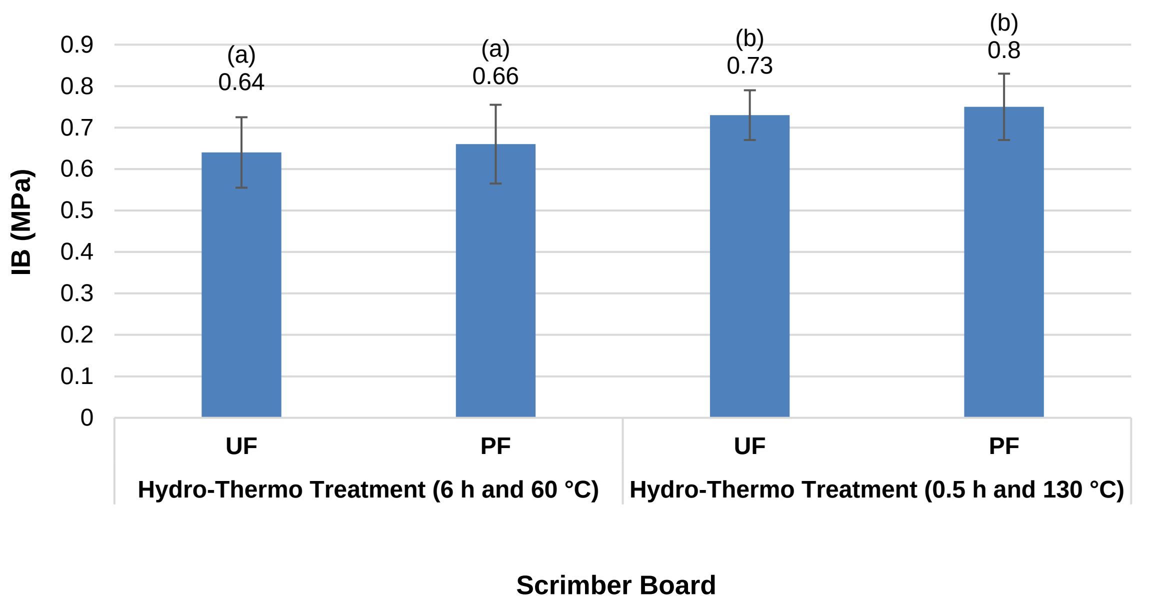

Fig. 11. Mean values ± standard deviation of the IB of the scrimber board; Different letters in each column indicate a statistical difference ($p < 0.05$) among the treatment groups.

According to statistical analysis, resin types and treatment temperatures had a significant effect on the Internal Bonding (IB), as shown in Fig. 11. Replacing UF resin with PF resin in hydrothermally treated scrimber at 130 °C led to higher IB values, ranging from 0.73 to 0.75 MPa. Results indicated that the scrimber boards manufactured from scrims treated at 130 °C had a higher internal bond than those treated at 60 °C. Based on SEM images given in Fig. 5, the middle lamella was observed to be broken because of hydrothermal treatment, particularly at 130 °C. This facilitated resin penetration into these areas, enhancing bonding compared to the natural bond of wood cell walls (Shangguan *et al*. 2016). Shi *et al.* (2018), Savov *et al.* (2021), and Mihailova *et al.* (2012) showcased superior performances of wood-based panels produced with PF resins in comparison to those made with UF resin. The scrimber composite can offer excellent mechanical properties that are equal to or better than those of other typical engineered wood or bamboo products used in construction and building applications (Sun *et al*. 2021).

CONCLUSIONS

1. Scrimber boards manufactured from scrims hydrothermally treated at 130 °C, regardless of the resin types, exhibited lower density standard deviation compared to

those made from hydrothermally treated scrims at 60 °C. This difference is attributed to the enhanced compression of wood during the scrimming process, influenced by factors such as length and thickness variations along the scrimber, which prevent uniform dispersion in perpendicular layers.

2. The scrimming process on wood hydrothermally treated at 130 °C resulted in better crushing, reduced thickness variations along the scrims' length, and improved uniform dispersion in perpendicular layers of panels.
3. The scanning electron microscopy (SEM) images reveal damage in the middle lamella, indicating higher quality and consistent scrims made from poplar wood treated at higher temperatures. These scrims facilitate the creation of a more uniform scrim mat. Additionally, crushing at a higher temperature enhances glue penetration into the bundle of fibers.
4. The highest values of 68.6 MPa for MOR and 8690 MPa for MOE were observed in the scrimber composite made from hydrothermally treated scrims at 130 °C and PF resin. Conversely, the highest TS and WA values after 24 h and 48 h were found in the scrimber composite made from hydrothermally treated scrims at 60 °C and UF resin. Scrimber boards produced hydrothermally treated scrims at 130 °C exhibited superior internal adhesion compared to those hydrothermally treated scrims at 60°C.

ACKNOWLEDGMENTS

This work was partially supported by the Vice Chancellor for Research, University of Tehran, I. R. Iran. Some parts of this research were also undertaken with the invaluable support and assistance provided by "ChoobSang Co., Ltd" (ID: 10380496937). In light of their valuable contributions, we would like to extend our sincerest gratitude and appreciation.

REFERENCES CITED

Akhtari, M., Taghiyari, H. R., and Ghorbani Kokandeh, M. (2013). "Effect of some metal nanoparticles on the spectroscopy analysis of Paulownia wood exposed to white-rot fungus," *European Journal of Wood and Wood Products* 71, 283-285. DOI: 10.1007/s00107-013-0676-5

ASTM D1037-12 (2020). "Standard test methods for evaluating properties of wood-base fiber and particle panel materials," ASTM International, West Conshohocken, PA, USA.

Bhuiyan, M. T. R., Hirai, N., and Sobue, N. (2000). "Changes of crystallinity in wood cellulose by heat treatment under dried and moist conditions," *J. Wood. Sci.* 46, 431-436. DOI: 10.1007/BF00765800

Brito, J., Silva, F., Leao, M., and Almeida, G. (2008). "Chemical composition changes in eucalyptus and pinus woods submitted to heat treatment," *Bioresource Technol.* 99(18), 8545-8548. DOI: 10.1016/j.biortech.2008.03.069

Cermak, P., Hess, D., and Suchomelová, P. (2021). "Mass loss kinetics of thermally modified wood species as a time-temperature function," *European Journal of Wood and Wood Products* 79, 547-555. DOI: 10.1007/s00107-020-01634-6

Chrobak, J., Iłowska J., and Chrobak, A. (2022). "Formaldehyde-free resins for the wood-based panel industry: Alternatives to formaldehyde and novel hardeners, *Molecules* 27(15), article 4862. DOI: 10.3390/molecules27154862

Dwianto, W., Tanaka, F., Inoue, M., and Norimoto, M. (1996). "Crystallinity changes of wood by heat or steam treatment," in: *46th Annual Meeting of the Japan Wood Research Society*, Nara, Japan, pp. 47-49.

Esteves, B., and Pereira, H. (2009). "Wood modification by heat treatment: A review," *BioResources* 4(1), 370-404. DOI:10.15376/biores.4.1.370-404

Esteves, B., Videira, R., and Pereira, H. (2011). "Chemistry and ecotoxicity of heat-treated pine wood extractives," *Wood. Sci. Technol*. 45, 661-676. DOI: 10.1007/s00226-010-0356-0

Haseli, M., Efhamisisi, D., Abdulkhani, A., Oladi, R., Ungerer, B., Al-musawi, H., Halmschlager, E., and Muller, U. (2024). "Effects of oil heat treatment on poplar wood properties: A pilot scale study," *Construction and Building Materials* 430, article ID 136353. DOI: 10.1016/j.conbuildmat.2024.136353

He, L., Zhang, T., Zhao, Y., Gao, J., Zhang, Y., Yang, Y., He, Z., and Yi, S. (2022) "Effect of natural tung oil on wood shrinkage during the thermal modification process," *J. Clean. Prod*. 379(Part 1), article ID 134450. DOI: 10.1016/j.jclepro.2022.134450

He, M., Zhang, J., Li, Z., and Lin, M. (2016). "Production and mechanical performance of scrimber composite manufactured from poplar wood for structural applications," *Journal of Wood Science* 62, 429-440. DOI: 10.1007/s10086-016-1568-1

Hill, C., Altgen, M., and Rautkari, L. (2021). "Thermal modification of wood – A review: Chemical changes and hygroscopicity," *Journal of Materials Science* 56, 6581-6614. DOI: 10.1007/s10853-020-05722-z

Homan, W., Tjeerdsma, B., Beckers, E., and Jorissen, A. (2000). "Structural and other properties of modified wood," in: *World Conference on Timber Engineering (WCTE)*, Vienna, Austria, pp. 1-9.

Istek, A., Aydin, U., and Ozlusoylu, I. (2018). "The effect of chip size on the particleboard properties," *International Congress on Engineering and Life Science*, Kastamonu, Turkey. pp. 439-444.

Kitchens, S., Amburgey, T. L., Barnes, H. M., and Seale, R. D. (2016). "Mechanical and durability properties of steam-pressed scrim lumber," *BioResources* 11(2), 5343-5357. DOI: 10.15376/biores.11.2.5343-5357

Kurt, R., and Cavus, V. (2011). "Manufacturing of parallel strand lumber (PSL) from rotary peeled hybrid poplar 1-214 veneers with phenol formaldehyde and urea formaldehyde adhesives," *Wood Res. J.* 56, 137-144.

Li, X., Li, L., Li, N., Bao, M., Bao, Y., Wu, Z., Wang, J., Rao, F., and Chen, Y. (2022). "Sustainable production of engineered bamboo scrimber composites for construction and flooring applications," *Construction and Building Materials* 347, article ID 128615. DOI: 10.1016/j.conbuildmat.128615

Liu, Y. X., and Zhao, G. J. (2004). *Wood Materials Science*, Chinese Forestry Press, Beijing, China.

Manafi-Dastjerdi, M., Rohani, M., Zarea Hosseinabadi, H., and Ebrahimi-Nik, M. (2023). "Transforming tree topping waste into flooring: A study on the production and evaluation of oriented strand board finish using urban and garden residues," *Environ. Sci. Pollut. Res. Int*. 30, 103743-103759. DOI: 10.1007/s11356-023-29759-0

Mastouri, A., Efhamisisi, D., Shirmohammadli, Y., and Oladi, R. (2021). Physicochemical properties of thermally treated poplar wood in silicone and rapeseed oils: A comparative study," *J. Build. Eng*. 43, article ID 102511. DOI: 10.1016/j.jobe.2021.102511

Melkior, T., Jacob, S., Gerbaud, G., Hediger, S., Le Pape, L., Bonnefois, L., and Bardet, M. (2012). "NMR analysis of the transformation of wood constituents by torrefaction," *Fuel* 92(1), 271-280. DOI: 10.1016/j.fuel.2011.06.042

Mihailova, J., Savov, V., and Petrov, K. (2012). "Effect of phenol–formaldehyde resin content and density on performance characteristics of MDF," in: *Conference Proceedings of COST Action FP 0904*, University de Lorraine, Lorraine, France, pp. 154-155.

Moya, R., Tenorio, C., Carranza, M., Camacho, D., and Quesada-Pineda, H. (2013). "Structural performance of I-beam fabricated from a fast-growing tree, *Gmelina arborea*," *J. Trop. For. Sci.* 25(2), 206-212.

Navi, P., and Sandberg, D. (2011). *Thermo-hydro-Mechanical Processing of Wood*, 1st Ed., EPFL Press, Lausanne, Switzerland.

Rosu, D., Teaca, C. A., Bodirlau, R., and Rosu, L. (2010). "FTIR and color change of the modified wood as a result of artificial light irradiation," *J. Photochem. Photobiol. B: Biol*. 99(3), 144-149. DOI: 10.1016/j.jphotobiol.2010.03.010

Ruschi Mendes Saade, M., Guest, G., and Amor, B. (2020). "Comparative whole building LCAs: How far are our expectations from the documented evidence," *Built Environ.* 167, article ID 106449. DOI: 10.1016/j.buildenv.2019.106449

Saito, K., Horikawa, Y., Sugiyama, J., Watanabe, T., Kobayashi, Y., and Takabe, K. (2016). "Effect of thermochemical pretreatment on lignin alteration and cell wall microstructural degradation in *Eucalyptus globulus*: Comparison of acid, alkali, and water pretreatments," *J. Wood Sci.* 62, 276-284. DOI: 10.1007/s10086-016-1543-x

Savov, V., Antov, P., and Trichkov, N. (2021). "Properties of high-density fiberboard bonded with urea–formaldehyde resin and ammonium lignosulfonate as a bio-based adhesive," *Polymer* 13(16), article 2775. DOI: 10.3390/polym13162775

Shangguan, W., Gong, Y., Zhao, R., and Ren, H. (2016). "Effects of heat treatment on the properties of bamboo scrimber," *J. Wood. Sci*. 62, 383-395. DOI: 10.1007/s10086-016-1574-3

Sharma, B., Gatoo, A., Bock, M., and Ramage, M. (2015). "Engineered bamboo for structural applications," *Constr. Build. Mater.* 81, 66-73. DOI: 10.1016/j.conbuildmat.2015.01.077

Shi, J., Lu, Y., Zhang, Y., Cai, L., and Shi, S. (2018). "Effect of thermal treatment with water, H_2SO_4 and NaOH aqueous solution on color, cell wall and chemical structure of poplar wood," *Mater. Sci. Envir. Sci.* 8, article ID 17735. DOI: 10.1038/s41598-018-36086-9

Sun, X., He, M., Liang, F., Li, Z., Wu, L., and Sun, Y. (2021). "Experimental investigation into the mechanical properties of scrimber composite for structural applications," *Constr. Build. Mater.* 276, article ID 122234. DOI: 10.1016/j.conbuildmat.2020.122234

Syafii, S., and Novari, F. (2021). "Study of veneer yield and amount of waste in veneer stripping with spindle-less type rotary lathe machine," *Buletin Poltanesa* 22(1), 95-100. DOI: 10.51967/tanesa. v 22i1.334

Tuong, V. M., and Li, J. (2011). "Changes caused by heat treatment in chemical composition and some physical properties of acacia hybrid sapwood," *Holzforschung* 65(1), 67-72. DOI: 10.1515/hf.2010.118

Windeisen, E., Strobel, C., and Wegener, G. (2007). "Chemical changes during the production of thermo-treated beech wood," *Wood. Sci. Technol.* 41, 523-536. DOI: 10.1007/s00226-007-0146-5

Yang, H., Yan, R., Chen, H., Lee, D. H., and Zheng, C. (2007). "Characteristics of hemicellulose, cellulose and lignin pyrolysis," *Fuel* 86(12-13), 1781-1788. DOI: 10.1016/j.fuel.2006.12.013

Yu, Y., Liu, R., Huang, Y., Meng, F., and Yu, W. (2017). "Preparation, physical, mechanical, and interfacial morphological properties of engineered bamboo scrimber," *Constr. Build. Mater.* 157, 1032-1039. DOI: 10.1016/j.conbuildmat.2017.09.185

Yue, K., Qian, J., Wu, P., Jiao, X., and Lu, D., and Song, X. (2023). "Experimental analysis of thermally-treated Chinese poplar wood with focus on structural application," *Ind. Crop. Prod.* 197, article ID 116612. DOI: 10.1016/j.indcrop.2023.116612

Zhang, Y., Huang, Y., Qi, Y., and Yu, W. (2018). "Novel engineered scrimber with outstanding dimensional stability from finely fluffed poplar veneers," *Measurement* 124, 318-321. DOI: 10.1016/j.measurement.2018.04.051

Article submitted: July 21, 2024; Peer review completed: August 18, 2024; Revised version received and accepted: August 19, 2024; Published: September 9, 2024.
DOI: 10.15376/biores.19.4.8052-8067