Effect of Thermomechanical Densification Treatment on Abrasion Resistance of Five US Hardwoods

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Abstract

The effect of thermomechanical densification treatment on the abrasion resistance of five hardwood species were investigated in this study. The species tested include ash (*Fraxinus* sp.), hickory (*Carya* sp.), red oak (*Quercus* sp.), sweetgum (*Liquidambar styraciflua*), and white oak (*Quercus* sp.). The abrasion test was performed according to the American Society of Testing and Materials standards. Ten specimens from each species were initially tested for abrasion resistance, and those specimens were then put through a thermomechanical densification process. The densification process consisted of bringing the heated platen up to a temperature of 176°C (350°F) on one surface and pressing the specimens at 6.9 MPa (1,000 Psi) for a period of 5 minutes. The densified specimens were then subject to the same abrasion testing procedure. All data were statistically analyzed by two-way analysis of variance (ANOVA) with the procedure of general linear mixed models. The results of this study indicated that densified hickory had the highest abrasion resistance among the five hardwood species tested.

Wood is widely used for applications such as furniture, structures, interior panels, flooring, etc. Compared with other materials, wood has remarkable features such as excellent workability and great mechanical properties. Machinability, flexibility, and wear resistance are some of the exceptional properties of wood. In flooring and staircases, the wear resistance plays a very significant role (Ohtani et al. 2001, 2002, 2003; Liu et al. 2012; Brožek 2017). Commercial and industrial flooring has long been made of oak and hickory because of the species' abrasion resistance and resilience, that is, the ability to absorb and recover from impact or shock loading. The wear resistance of wood is affected by temperature, moisture content, and chemical additives such as preservative treatments. Different species vary in properties and perform differently in term of resistance to abrasives. In some cases, wood surfaces can be densified to improve wear resistance. Density is the single most important property of wood. Increasing the density of wood (densification) enhances its mechanical properties. Thermomechanical densification treatments improve physical and mechanical properties, biological resistance, and dimensional stability. They have been shown to improve surface smoothness as well as reduce surface wettability (Candan et al. 2021). Thermomechanical densification treatments change the resistance features of wooden materials by changing the structural characteristics of wood and reduce the empty spaces of the wood cells and compress it (Navi and Heger 2004); therefore, the density is enhanced (Coelho et al. 2017). Density and specific gravity are two main specific factors for a wood species to be chosen to use for flooring applications (Zhou et al. 2019, Tenorio et al. 2021). Thermomechanical densification treatments tend to densify material more toward the surface than the core of the material(Unsal and Candan 2008, Candan et al. 2013). Additionally, in applications that require high wear resistance, denser species are often specified. For example, historically, persimmon (*Diospyros* sp.) and maple (*Acer* sp.) were used for shaft bearings because these woods are dense, heat resistant, and demonstrate high abrasion

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resistance. However, some wood species commonly used for flooring and decking are listed as endangered or threatened. This has led to the search for new options and alternative for existing species to replace previous options and to satisfy the demand for truck decking and flooring. Thus, the objective of this research is to examine the effect of the thermomechanical densification treatment on the abrasion behavior of five US hardwoods including ash (*Fraxinus* sp.), hickory (*Carya* sp.), red oak (*Quercus* sp.), sweetgum (*Liquidambar styraciflua*), and white oak (*Quercus* sp.).

Materials and Methods

Specimen preparation

The five US hardwood species—ash, hickory, red oak, sweetgum, and white oak—were selected to evaluate the effect of thermomechanical densification treatment on the abrasion resistance. The preparation of the abrasion test specimens was performed according to the method describe by Khademibami et al. (2022). Thirty individual parent boards were then selected from each group of species. These boards then had a section of approximately 76 cm (30 in) cut off in order to have the necessary samples prepped from each one. The boards were first skim-planed and joined in order to make four clean faces. The samples were then ripped to a width of 5.08 cm (2 in). Prepped samples from a 5.08-cm (2-in) ripped strip were used for abrasion test samples. The strip was then planed to a thickness of inch (0.75 in =←1.90 cm). This resulted in a sample with dimensions of 1.90 by 5 by 10.16 cm^3 (0.75 by 2 by 4 in) according to the ASTM D2394-17 (2017). This piece then had a ½ shoulder cut on the ends to facilitate mounting on the abrasion tester, which left a 5 by 7.6 cm^2 (2 by 3 in^2) face to be abraded. The samples were then acclimated in a 12 percent humidity chamber with 158°C (70°F) and 65 percent relative humidity for a minimum of 2 weeks. The densities of all five hardwood species were 0.682 g/cm^3(0.025 lb/in^3) for ash, 0.801 g/cm^3 (0.029 lb/in^3) for hickory, 0.731 g/cm^3(0.026 lb/in^3) for red oak, 0.602 g/cm^3(0.022 lb/in^3) for sweet gum, and 0.760 g/cm^3(0.027 lb/in^3) for white oak (Khademibami et al. 2022).

Abrasion resistance test

The samples were tested using a Navy-Type Wear Tester according to ASTM D2394-17 (2017) after conditioning in a humidity chamber for 2 weeks. Whereby the sample is mounted on a plate that rotates at 32.5 revolutions per minute (RPM) with a 4.53-kg (10-lb) weight mounted above. This plate also raises 1/16th of an inch (0.158 cm) off the abrading plate twice per rotation. The abrading plate rotates in the same direction as the sample plate at a rate of 23.5 RPM. The abrading plate has a constant flow of 80-grit aluminum oxide media applied for the duration of the test. Samples were measured for thickness at five points—the four corners and the center—before testing and then after each 100 rotations of the machine. This process was repeated until the samples had achieved 500 rotations each (Fig. 1).

Thermomechanical densification process

Ten samples from this initial test were then used for thermomechanical densification treatment by the following process. The thermomechanical densification treatment process consisted of bringing the heated platen up to a temperature of 176°C (350°F) on one surface. The samples were pressed in a Carver hot press and two specimens were treated at a time with only the abrading surface receiving heat. The specimens were pressed at 6.9 MPa (1,000 Psi) for a period of 5 minutes. The pressing parameters generally were based on previous work by the United States Department of Agriculture, Forest Products Laboratory as reported in Seborg et al (1956). In this manner, densification occurred preferentially at the specimen surface that directly contacted the heated platen. The densified samples were then subjected to the same abrasion test process as before in order to evaluate whether the thermomechanical densification process affected the abrasion resistance.

The degree of densification (DD) varied among specimens and species. The change in thickness due to the heat and pressure was taken as the difference between the specimen's thickness as measured after the 500-revolution initial abrasion test minus the thickness as measured immediately before the postdensification abrasion test. The degree of densification (DD) was then calculated as follows:

$$\mathrm{DD} = \leftarrow \frac{\Delta \mathrm{T_{in}} \quad \Delta \mathrm{T_f}}{\Delta \mathrm{T_{in}}} \times 100$$

where, DD is degree of densification (%), ΔT_{in} means initial thickness loss (in or mm) before thermomechanical densification treatment. ΔT_f means final thickness loss (in or mm) after thermomechanical densification treatment. The degree of densification is presented in Table 1.

Statistical analysis

The experimental design was a completely randomized design, and the data for abrasion test (thickness loss) in undensified and densified treatments in five species were analyzed using two-way analysis of variance (ANOVA). The statistical analysis was performed with SAS 9.4 (SAS Institute 2013) to generate the linear mixed models (PROC GLIMMIX). The *P* values for all tests were calculated and differences were considered significant with a *P* value 0.05.

Results and Discussion

Summary statistics of thickness loss (abrasion resistance) for undensified (control) and densified treatments of five hardwood species are shown in Table 2. The results illustrate that there are significant differences in undensified (control) and densified treatments ($P < 0.0001$), as well as among all five US hardwood species ($P = 0.048$; Table 3). The two-way ANOVA results demonstrated that there are significant differences in interaction between

Table 1.—Degree of densification (DD; %) of five hardwood species after thermomechanical densification treatment.

	DD (%)				
	Ash	Hickory	Red oak	Sweet gum	White oak
Mean	46.09	72.21	28.47	45.35	16.35
Median	49.00	76.30	25.45	49.96	16.07
SD	15.38	10.56	14.98	17.10	12.62
Min.	20.00	51.11	10.71	25.00	1.75
Max.	65.18	81.18	52.13	65.12	34.48

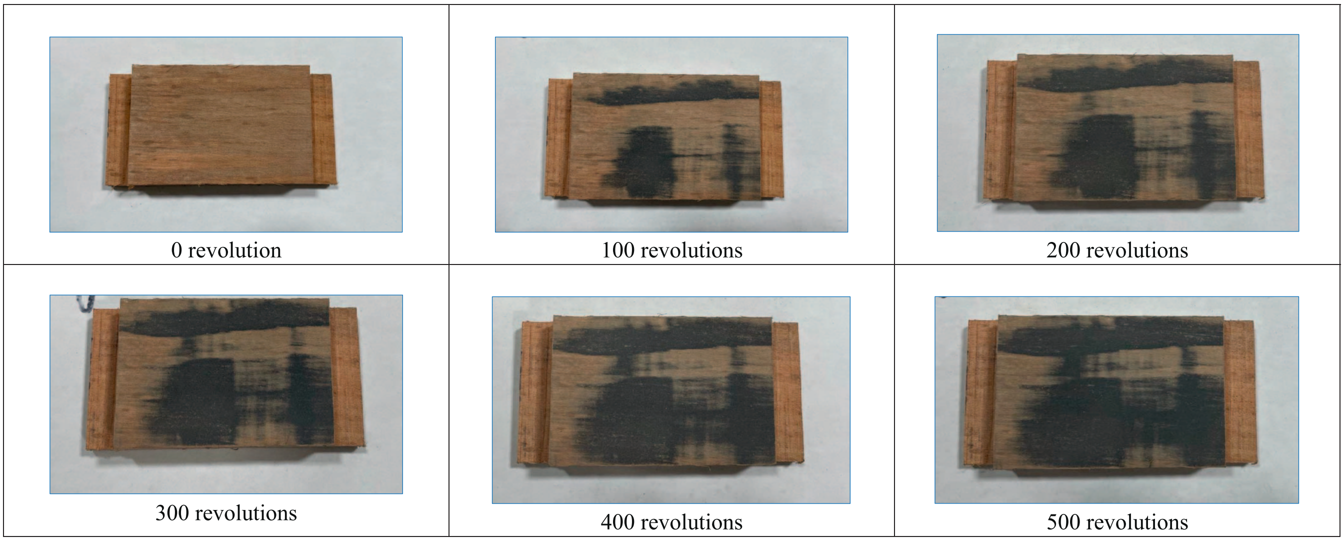
0 revolution
100 revolutions
200 revolutions
300 revolutions
400 revolutions
500 revolutions

Figure 1.—Sweetgum control (undensified) specimens after different revolutions by Navy-Type Wear Tester.

densification treatment and species (Table 3). As shown in Figure 2, species with the same letter were not statistically different from each other at the alpha = 0.05 level of significance. In all five hardwood species, the densified specimens had less thickness loss (more abrasion resistance) in comparison with the undensified specimens. Densified hickory had the smallest thickness loss (0.064 mm = 0.0025 in) among all undensified (control) and densified tested species, while undensified treated sweetgum had the largest thickness loss (0.233 mm = 0.0092 in). In white oak species, there was negligible difference in thickness loss in undensified and densified treated species (0.147 mm vs. 0.144 mm).

The relationship of abrasion resistance (thickness loss) appears to be associated to a large extent with the density of species. The less dense species, undensified sweetgum in this research, is abraded at a higher level because of the greater depth of penetration of the abrasive (Franz and Hinken 1954). Franz and Hinken (1954) also reported that the penetration of the grit particles into wood can be controlled by relative density. Thermomechanical densification treatment makes the porous wood denser. The evaluation of abrasion resistance in undensified and densified treated cherry species showed more abrasion resistance in densified samples in comparison with undensified treated ones, especially in tangential boards (Aytin et al. 2015). Greater wear index has been observed in densified wood (Arruda and Del Menezzi 2013, Tenorio et al. 2021). Thus, in applications where more abrasion resistance is needed, thermomechanical densification treatment would be a great option for the required performance.

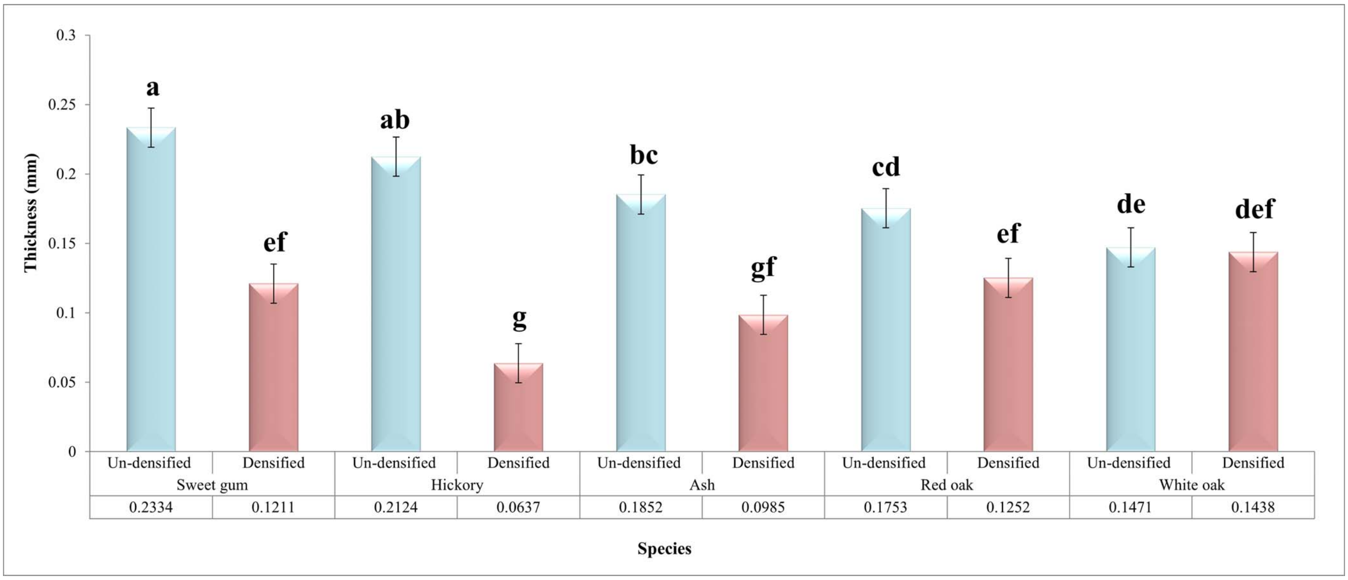

Figure 2.—Thickness loss of control (undensified) and densified of five hardwood species Materials with the same letter were not statistically different from each other at the alpha = 0.05 level of significance.

Table 2.—Summary statistics of thickness loss for control specimens (undensified) and densified specimens of five hardwood species.

	Δ Thickness loss in mm (in)									
	Control (Undensified) [a]					Densified[b]				
	Ash	Hickory	Red oak	Sweet gum	White oak	Ash	Hickory	Red oak	Sweet gum	White oak
Mean	0.185 (0.0073)	0.212 (0.0084)	0.175 (0.0069)	0.234 (0.0092)	0.147 (0.0058)	0.098 (0.0039)	0.064 (0.0025)	0.124 (0.0049)	0.119 (0.0047)	0.144 (0.0056)
Median	0.187 (0.0073)	0.208 (0.0082)	0.166 (0.0065)	0.226 (0.0089)	0.144 (0.0057)	0.098 (0.0039)	0.052 (0.0020)	0.127 (0.005)	0.118 (0.0046)	0.137 (0.0054)
SD	0.045 (0.0018)	0.056 (0.0022)	0.043 (0.0017)	0.1 (0.0039)	0.034 (0.0013)	0.026 (0.0010)	0.041 (0.0016)	0.021 (0.0008)	0.031 (0.0012)	0.031 (0.0012)
COV (%)	24.2	26.4	24.8	42.6	23.2	26.43	64.30	16.91	25.39	21.384
Min.	0.074 (0.0029)	0.098 (0.0039)	0.107 (0.0042)	0.114 (0.0045)	0.074 (0.0029)	0.071 (0.0028)	0.03 (0.0012)	0.076 (0.003)	0.076 (0.003)	0.109 (0.0043)
Max.	0.284 (0.0112)	0.343 (0.0135)	0.264 (0.0104)	0.678 (0.0267)	0.229 (0.0090)	0.163 (0.0064)	0.168 (0.0066)	0.155 (0.0061)	0.19 (0.0075)	0.208 (0.0082)

[a] The number of replicates for control (undensified) specimens for each species was 30.

[b] The number of replicates for densified specimens for each species was 10.

Table 3.—Wear test values in thickness loss of control (undensified) versus densified of 5 hardwood species along with P value levels of significance as well as mean separations. Materials with the same letter were not statistically different from each other at the alpha = 0.05 level of significance.

Species	Treatment	Δ Thickness in mm (in)	Δ Thickness mean separation
Sweet gum	Control (Undensified)	0.234 (0.0092)	A
Hickory	Control (Undensified)	0.212 (0.0084)	AB
Ash	Control (Undensified)	0.185 (0.0073)	BC
Red oak	Control (Undensified)	0.175 (0.0069)	DC
White oak	Control (Undensified)	0.147 (0.0058)	DE
White oak	Densified	0.144 (0.0056)	DEF
Red oak	Densified	0.124 (0.0049)	EF
Sweet gum	Densified	0.119 (0.0047)	EF
Ash	Densified	0.098 (0.039)	GF
Hickory	Densified	0.064 (0.0025)	GF
Pooled SEM		0.01409	
P value	Species	0.048	
	Densification	< 0.0001	
	Species × Densification	< 0.0001	

Conclusion

The effect of the thermomechanical densification treatment on the abrasion behavior of five US hardwoods was investigated in this study. It would appear from the results of this investigation that densified hickory species had the highest abrasion resistance among the five undensified and densified treated hardwood species tested. Consequently, densified hickory seems to be the best potential candidate for wood flooring applications. That said, red and white oak are used in industrial truck and trailer flooring and heat treating may provide enhanced serviceability for those species. In order to increase the reliability of current research, hardness tests for densified samples could also be performed as an additional study. Also, because dimensional stability was not measured herein, that property likely should be investigated as part of any commercialization path. To enhance dimensional stability and minimize the potential for cupping, likely both faces of the wood material should be heat-treated.

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Literature Cited

American Society of Testing and Materials (ASTM). 2017. Standard Test Methods for Simulated Service Testing of Wood and Wood-Based Finish Flooring. ASTM D2394-17. ASTM International, West Conshohocken, Pennsylvania. 11 pp.

Arruda, L. M. and C. H. S. Del Menezzi. 2013. Effect of thermomechanical treatment on physical properties of wood veneers. *Int. J. Wood Wood Prod*. 4(4):217–224.

Aytin, A., S. Korkut, N. As, Ö. Ünsal, and G. Günduz. 2015. Effect of heat treatment of wild cherry wood on abrasion resistance and withdrawal capacity of screws. *Drvna Ind*. 66(4):297–303.

Brožek, M. 2017. Abrasive wear resistance of selected woods. *Res. Agric. Eng*. 63(2):91–97. https://doi.org/10.17221/74/2015-RAE

Candan, Z., O. Gonultas, H. V. Gorgun, and O. Unsal. 2021. Examining parameters of surface quality performance of paulownia wood materials modified by thermal compression technique. *Drvna Ind*. 72(3):231–236

Candan, Z., S. Korkut, and O. Unsal. 2013. Thermally compressed poplar wood (TCW): Physical and mechanical properties. *Drvna Ind*. 64(2):107–211.

Coelho, M. U., C. D. Menezzi, and M. R. Souza. 2017. Abrasion resistance of Pinus wood subjected to thermomechanical treatments. *PRO LIGNO* 13(4):94–100.

Franz, N. C. and E. W. Hinken. 1954. Machining wood with coated abrasives. *J. Forest Prod. Res. Soc*. 4(5):251–254.

Khademibami, L., R. Shmulsky, D. Snow, A. Sherrington, I. Montague, R. J. Ross, and X. Wang. 2022. Wear resistance and hardness assessment of five U.S. hardwoods for bridge decking and truck flooring. *Forest Prod. J*. 72(S1):9–13. https://doi.org/10.13073/FPJ-D-21-00074

Liu, Z. D., W. B. Wang, L. Cai, D. J. Guo, and Z. D. Dai. 2012. Friction and wear properties of commercial solid wood floorings. *Mocaxue Xuebao (Tribology)* 32:557–562.

Ohtani, T., K. Kamasaki, and C. C.Tanaka, 2003. On abrasive wear property during three-body abrasion of wood. *Wear* 255:60–66.

Ohtani, T., T. Yakou, and S. Kitayama. 2001. Two-body and three-body abrasive wear properties of Katsura wood. *J. Wood Sci*. 47:87–93.

Ohtani, T., T. Yakou, and S. Kitayama. 2002. Effect of annual rings on abrasive wear property of wood. *J. Wood Sci*. 48:264–269.

Seborg, R. M., M. A. Millett, and A. J. Stamm. 1956. Heat-Stabilized Compressed Wood (Staypak). U.S. Department of Agriculture. Rept. No. 1580 (Revised), Forest Service, Forest Products Laboratory, Madison, Wisconsin. https://www.fpl.fs.fed.us/documnts/fplr/fplr1580.pdf. 21 pp. Accessed June 23, 2022.

Statistical Analysis System (SAS) Institute. 2013. User Guide: Statistics (Release 9.4). SAS Institute, Cary, North Carolina. 484 pp.

Tenorio, C., R. Moya, and A. Navarro-Mora. 2021. Flooring characteristics of thermo-mechanical densified wood from three hardwood tropical species in Costa Rica. *Maderas*. *Cienc. y Tecnol*. 23(16):1–12.

Navi, P. and F. Heger. 2004. Combined densification and thermo–hydro–mechanical processing of wood. *MRS Bull*. 29(5):332–336. https://doi.org/10.1557/mrs2004.100

Unsal, O. and Z. Candan. 2008. Moisture content, vertical density profile and janka hardness of thermally compressed pine wood panels as a function of press pressure and temperature. *Drying Technol*. 26(9):1165–1169.

Zhou, Q., C. Chen, D. Tu, Z. Zhu, and K. Li. 2019. Surface densification of poplar solid wood: Effects of the process parameters on the density profile and hardness. *BioResour*. 14(2):4814–4831.