Determination of Some Physical and Mechanical Properties of Parallel-strand Lumber Manufactured with Bamboo (*Phyllostachys bambusoides*)

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Parallel-strand lumber was manufactured with bamboo (*Phyllostachys bambusodies*). A polyol compound was added to modify the adhesive (pMDI). Bamboo culms were used to manufacture strands 3 mm thick, 19 mm wide, and 65 cm long. Adhesive was applied to the strands at 200 g/m^2 with pressing at 110 °C, 15 kg/cm^2, and 30 min. Panels were made with width 600 mm, length 600 mm, and thickness 20 mm. Some physical properties (oven-dry density, air-dry density, moisture content, thickness swelling, and water absorption percentage) and mechanical properties (bending resistance, modulus of elasticity, impact resistance, screw-holding capacity in tangential, radial, and transverse directions) of parallel-strand lumber for both adhesive types were determined. Both resin types improved some physical and mechanical properties of parallel-strand lumber. Additionally, the modulus of rupture and flexural modulus of elasticity of the test specimens using pMDI+5%MP adhesive were higher than those of the test specimens using pMDI. The average screw-holding capacity values of the test specimens were affected by the fiber aspect of the specimens rather than the adhesive type. Parallel-strand lumber produced from both pMDI and pMDI+5%MP adhesives can be used in structural applications, especially in places exposed to the disturbing effects of weather.

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INTRODUCTION

Rapidly increasing population, urbanization, industrialization, and changing consumption habits in the world have led to problems of unconscious use of natural resources in general and forest resources in particular. To meet the increasing need for wood raw materials, studies on fast-growing tree species are increasing in the forest industry. The increasing deficit of wood raw materials brings to the agenda the activation of some wood raw material resources in terms of quality and quantity. Bamboo is a hollow woody plant belonging to the plant family (Gramineae), subfamily Bambusoideae (Khalil *et al.* 2012). Bamboo is used worldwide in different fields, from food and medicine to furniture and scaffolding. It tends to grow in tropical, subtropical, and temperate climates around the world and in an area extending up to 3500 m in altitude. Bamboo can generally be divided into herbaceous and woody species. The herbaceous ones are small in diameter and resemble grasses, while the woody ones are larger in diameter and can be used for construction. The diameters of woody bamboo range from 10 to 200 mm, and wall thicknesses range from < 10% of the outer diameter to completely solid (Kaminski *et al.* 2016). There are about 1250 different bamboo species and 75 genera worldwide, of which about 1100 can be classified as woody bamboo. Bamboo grows naturally in many parts of the world, including Africa, North and South America, Asia, and Oceania. The chemical composition is of great importance as it affects the durability of materials produced with bamboo. The main organic components of bamboo cultures are similar to those of wood, mainly cellulose (± 55%), hemicellulose (± 20%), and lignin (± 25%), which account for more than 90% of the total mass. Different parts of the bamboo stem and different ages of the same bamboo stem have minor components such as resins, tannins, waxes, and inorganic salts. However, compared to wood, bamboo has higher alkaline extractives, ash, and silica content (Liese 1986). To be considered as an alternative to wood, bamboo must be able to significantly match the various mechanical properties exhibited by wood. Bamboo is a heterogeneous and anisotropic material that resembles wood. Therefore, its mechanical properties are highly unstable and, in some respects, they are more unstable than those of wood (Ogunwusi and Onwualu 2013). This can be explained by the irregular distribution of vascular bundles, their varying density in relation to different heights and positions, shrinkage, and strength reduction during drying. In general, the distribution of vascular bundles in the outer part of the stem wall is much closer than in the inner part, so the strength of the outer part is higher (Chand *et al.* 2008). Bamboo stem wall thickness increases in density from the bottom, so its strength increases in the same direction (Gerhards 1982). These disadvantages of bamboo can be eliminated by using it in the production of parallel-strand lumber, an engineered wood material. Bamboo can be considered the best alternative to lumber. Bamboo is used as a biomaterial in a wide range of engineering and civil construction applications, including scaffolding, fiber-reinforced composites, and bridges, as a biomaterial, in pulp and paper production, where it is used to form truss elements in construction, and is an important raw material for housing and bridge construction (Krause and Ghavami 2009; Tan *et al.* 2011; Xing *et al.* 2015; Tang *et al.* 2019; Yuan *et al.* 2019).

Parallel-strand lumber (PSL), commonly known as Parallam, is designed to replace large dimension lumber (beams, planks, and poles). Parallel-strand lumber was developed in Canada and introduced in the late 1980s. The PSL comes in many thicknesses and widths and is produced up to 20 m long (Fig. 1). The strands are mostly cut from peeled veneers. The veneers are dried to 11% moisture content and inspected for strength before being cut into strands. They are then set parallel to each other, coated with waterproof adhesive, and pressed. They are used as columns, beams, and headers in residential and commercial building construction and as structural elements in bridge construction (Fan *et al.* 1995; Yihai and Le 2003; Kurt and Cavus 2011; Andre and Iskandar 2013).

This study investigates some physical and mechanical properties of parallel-strand lumber manufactured with bamboo (*Phyllostachys bambusoides*). The effect of polyol presence in poly(methyldiphenyldiisocyanate) (pMDI) was also evaluated.

EXPERIMENTAL

Wood Material

Bamboo (*Phyllostachys bambusodies*) was obtained from the bamboo field in Erdemli district of Mersin province in Turkey. The selection of bamboos with smooth stems that were not exposed to insect attacks and fungi was preferred. Diameters of preferred bamboo were: the lowest 6 cm, the largest 13 cm, and an average of 9.5 cm in diameter. Bamboo was cut into 2-m-long pieces in the field (Figs. 1A and B). Bamboo was dried to 10 to 12% humidity in room conditions with a temperature of 18 to 20 °C and a humidity of 50 to 65%. The dried bamboos were then cut into strands with a width of 20 mm in the direction of the fiber with the help of a special mold on a circular saw machine. The process applied during strand making and bamboos cut to 65 cm in length are shown in Figs. 1C.

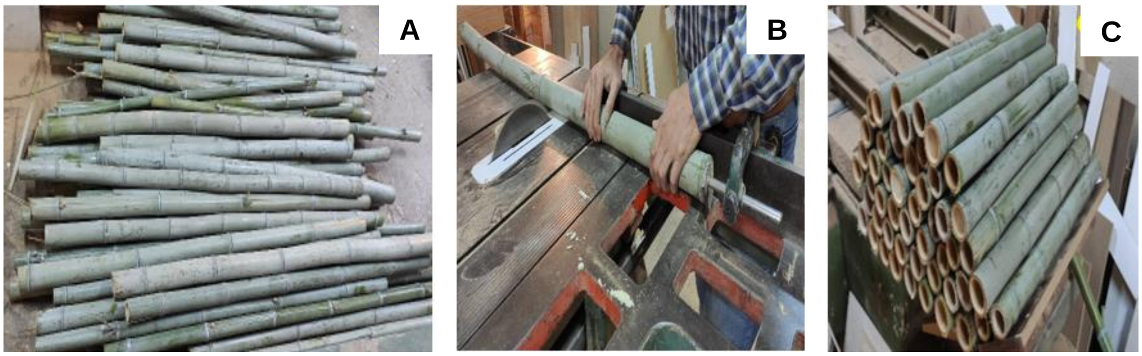

Fig. 1. Bamboo logs and length dimensioning of bamboo; A: Bamboo culms; B: Cutting length; C: Bamboo culms cut to length

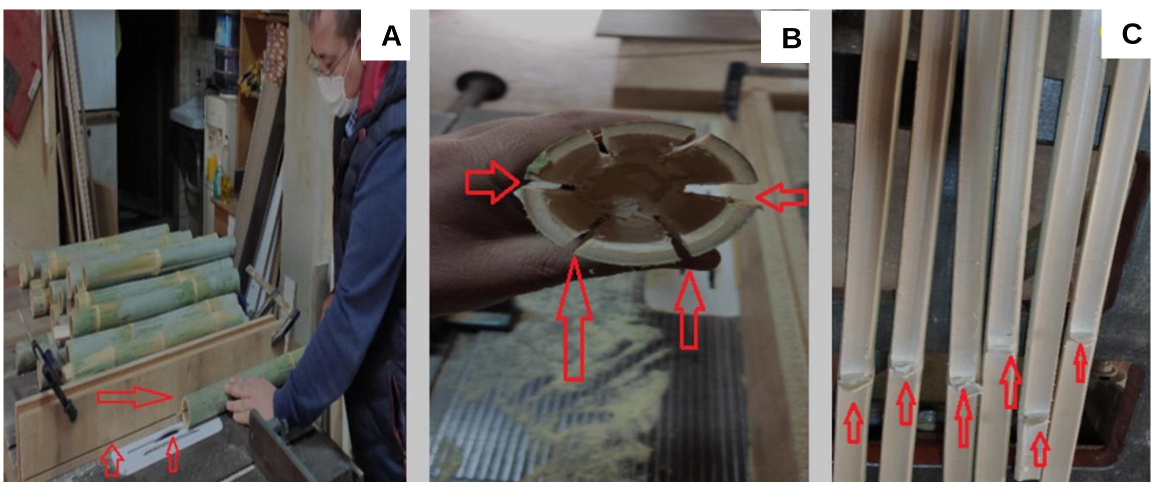

Fig. 2. The manufactured bamboo strands: A: Cutting culms for strips in the mold strands; B: Culms cutting into strands; C: node appearance in strands

The bamboo strands were cut into lengths of 60 cm on a circular saw machine. The bamboos, which were made into strands, were hand-selected visually, and the ones that did not have a fissure or crack were utilized. The wall thickness of the bamboos was measured, and it was determined that they were 5 to 7 mm thick on average. To ensure the smoothness of the surface and the desired thickness (3 mm) and width (19 mm) of the strands, the surfaces were made parallel to each other with the help of a special mold connected to the circular saw machine (Fig. 2A through C).

Adhesives

The pMDI adhesives are very effective since they can penetrate the wood cell wall forming 'chemical bridges' of urethane and biuret structures *via* covalent bonds with bound water and hydroxyl groups in wood and bamboo cell wall components (Nkeuwa *et al.* 2022). Commercial polymeric diphenylmethane diisocyanate (PMDI) adhesive and polymeric diphenylmethane diisocyanate adhesive modified with 5% polyol were preferred as the adhesive types used in this study. Arcol® Polyol PPG 2000 is a bi-functional, clear, colorless polyether polyol. It was used to modify the pMDI glue. This polyol is a bifunctional polyether polyol and it can be used in conjunction with isocyanates for the production of polyurethane products. Technical properties of this polyol are density at 20 °C approx. 1.01g/cm³; hydroxyl number 54.7 to 57.5 mg KOH/g; viscosity at 25 °C 325 to 365 mPa*s; acidity max. 0.020 mg KOH/g; water content max. 0.050% by wt; pH 4.5 to 7.5; Pour Point < -25 °C; Boiling Point > 300 °C, and Flash Point 168 °C. The pMDI adhesives are used in many sectors that do not need hardener and are used in polyurethane floor coverings, adhesive for wooden boards, panel applications for cold rooms, and spray in insulation applications. Depending on the production conditions, both polyol-added and polyol-free PMDI adhesives are applied only with hot processing. The storage period of these adhesives is 45 days at 20 °C. The properties of these adhesives are shown in Table 1.

Table 1. Some Properties of PMDI and PMDI+5%MP Adhesives

Features	PMDI	PMDI+%5 Polyol
	Dark brown liquid	Yellowish
Physical Form	Liquid, Viscous	Liquid, Viscous
Solids content by weight (%)	200 +/- 50 mPas	200 +/- 50 mPas
Viscosity (20 ºC, cPs)	> 300 °C	> 300 °C
pH (20 ºC)	10 to 4 mmHg @ 40 °C	10 to 4 mmHg @ 40 °C
Vapor pressure	> 204 °C	> 204 °C
Boiling point/Range	230 °C	230 °C

Parallel-strand Lumber Manufacturing and Testing

Bamboo (*Phyllostachys bambusodies*) strands were used to manufacture parallel-strand lumber with pMDI and polyol added at 5% by weight in pMDI adhesives. The strands were classified visually based on the surface and edge smoothness of the defects used to manufacture PSLs. Adhesive was applied to the strands (Fig. 3A) with the help of a spray gun (2.5-mm nozzle) attached to the compressor (Stanley/Fatmax/ New Britain, CT, USA) for 200 g/m^2. The amount of adhesive to be applied was calculated according to ASTM D899-00 (1994) standard. Adhesive-applied strands were drafted and pressed in a hydraulic hot press (Cemil USTA/SSP-180 T/, Turkey). The PSL was produced with pressing conditions of press temperature of 110 °C, a press pressure of 15 kg/cm^2, and a press time of 30 min (Fig. 3B and C).

The dimensions of the PSL coming out of the press were 600 mm long, 600 mm wide, and 20 mm thick. Parallel-strand lumbers were cut to the dimensions specified in the relevant standard using a circular sawing machine (Törk/AC 1500, Turkey). To avoid any edge-related effects on the properties, 50 mm of the edges of each PSL were trimmed. In this way, the final dimensions of the PSL were reduced to approximately 500 mm × 500 mm × 20 mm. The air-dried test specimens were kept in an air conditioning cabinet with a temperature of 20 ± 2 °C and a relative humidity of 65 ± 3% to reach a moisture content of 12% until they reached constant weight. The test samples were cut 1 mm larger in all directions than the dimensions specified in the relevant standards, and a contact sanding machine (Jet/JWDS-2244OSC-M) was used to bring them to a clear size and to ensure that their surfaces were smooth.

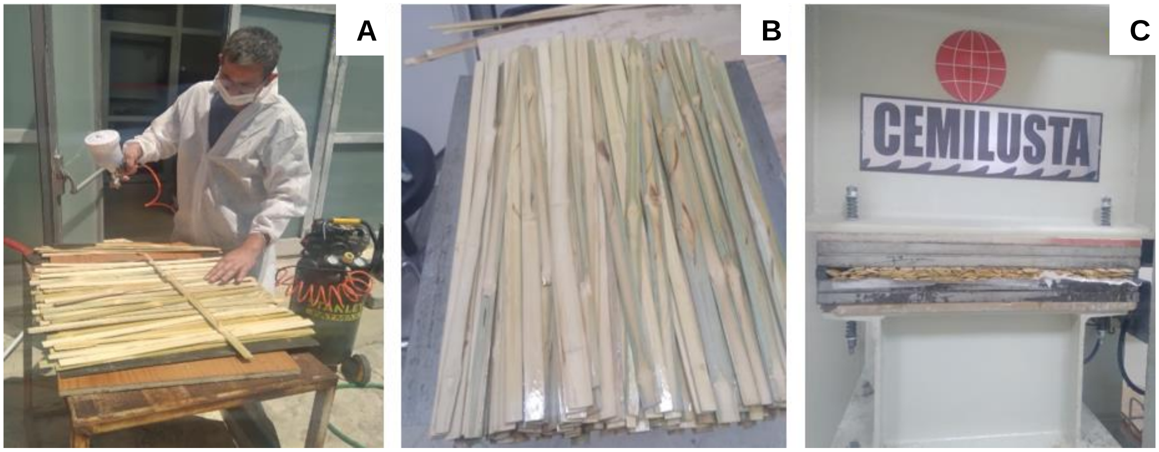

Fig. 3. A: Applying adhesive to the strands, B: drafting, and C: pressing

The test name, number of pieces, type of adhesive, and applied standards used to determine the physical and mechanical properties of the bamboo parallel-strand lumber produced are given in Table 2.

Table 2. Test Procedure for Specimens

Test Specimens Properties	Code	Dimensions (mm) (Radial, Tangential, and Axial)	Standards
Air-dry specific gravities	AD	20 x 20 x 30	TS ISO 13061-1 (2021)
Oven-dry specific gravities	OD	20 x 20 x 30	TS ISO 13061-2 (2021)
Thickness swelling	TS	15.2 x 15.2 x 2.54	ASTM D1037 (2006)
Water absorption	WA	15.2 x 15.2 x 2.54	ASTM D1037 (2006)
Modulus of rupture	MOR	20 x 20 x 360	TS ISO 13061-3 (2021)
Modulus of elasticity	MOE	20 x 20 x 360	TS ISO 13061-4 (2021)
Impact bending strength	IBS	20 x 20 x 300	TS ISO 13061-10 (2021)
Screw-holding capacity	SHC	50 x 50 x 50	TS EN 13446 (2005)

A total of 20 specimens were tested for each condition. For the modulus of rupture, modulus of elasticity, and impact bending strength tests, force was applied to the tangential surface. For modulus of rupture and modulus of elasticity tests, the distance between the centers of the cylindrical heads where the test specimen was placed was set to 13 times the thickness of the test specimen (20 mm × 13 = 260 mm). The load was fixed on the surface of the test specimen, which loaded rapidly, and the test speed was 1.5 ± 0.5 min after the test samples started loading. After determining the force at break (P_{max}) of the test specimens, σ_E was then calculated.

The distance between the centers of the supports where the test specimens were placed for impact bending strength was set at 240 mm. Screw-holding capacity was determined on three surfaces (tangential, radial, and longitudinal). Screws with a diameter of 4 mm and a length of 50 mm were preferred in the study. First, the center of the specimens was drilled with a 2.5-mm diameter drill bit for the pilot hole. Screws were screwed 20 mm from the pilot hole into the test specimens. The test rate was 5 mm/min, adjusted for speed. The screw-holding capacity, MOR, and MOE were determined using a universal testing machine (ALŞA, Istanbul, Turkey) (50 kN) at a speed of 2 mm/min. A pendulum impact tester (ALŞA, Istanbul, Turkey) was used to determine the impact bending strength (Fig. 4A through C). The results from the test samples were subjected to a Tukey *post-hoc* analysis test to determine the significant difference between the groups ($\alpha >$ 0.05) by applying analysis of variance (ANOVA) to the IBM SPPS 22.0 Program (IBM Corp., Armonk, NY, USA).

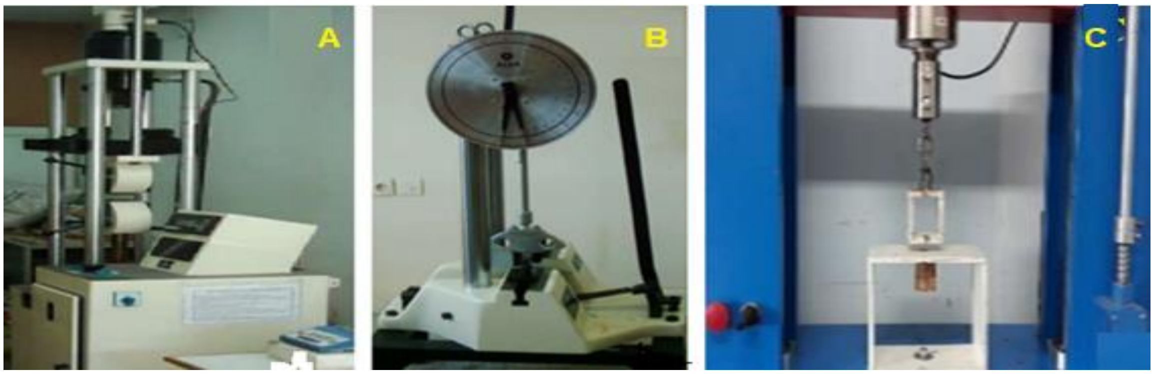

Fig. 4. Universal testing machine (A), pendulum impact tester (B), and screw-holding capacity test procedure (C)

RESULTS AND DISCUSSION

The physical and mechanical properties of test specimens are shown in Table 3. Density is a unit of measurement that has a relatively constant value and can be used for the evaluation of bamboo material. The mean air-dry density values of PSL with pMDI and pMDI+5%Polyol adhesives were 1.02 and 0.99 gr/cm^3, respectively, while the mean oven-dry density values were 0.99 and 0.94 gr/cm^3, respectively (P value > 0.05). The density value of the test sample produced with pMDI+5%Polyol was slightly lower than that produced with pMDI alone. This can be explained by the addition of polyol to the pMDI mixture, which expands and causes the formation of 90 to 92% closed and rigid foam (Akdoğan 2011).

Density is the best and simplest determinant of the strength of wood materials and, therefore, of bamboo. With increasing density, strength values also increase. However, the density of wood material varies according to its properties and the place where it is taken from the tree. This situation is valid for bamboo materials. In the literature, it has been reported that the basic density of bamboo material (whole stem weight/green bamboo volume) is in the range of 0.40 to 0.9 g/cm^3, and this density depends on the vascular bundles and their composition (Liese 1986; Razak *et al.* 2007; Kelemwork 2008). In previous studies on parallel-strand lumber, it was reported that the densities of the samples produced varied according to the material from which they were produced. It has been reported that an increase in density occurs, and this increase may be due to the use of high-density adhesives and the high pressure applied during production under high temperatures, or the anatomical properties of the wood material may contribute to this increase (Kurt 2010; Kurt and Cavus 2011; Kurt *et al.* 2012, 2013).

Table 3. Physical and Mechanical Properties of Test Specimens

Test		N	Adhesive	Min.	Max.	$\bar{x}$	σ
AD (gr/cm^3)			pMDI	0.98	1.04	1.02	0.18
			pMDI+5%MP	0.96	1.01	0.99	0.50
OD (gr/cm^3)			pMDI	0.96	1.01	0.99	0.43
			pMDI+5%MP	0.93	0.96	0.94	0.53
MC			pMDI	4.74	5.21	5.13	0.14
			pMDI+5%MP	4.69	5.01	4.92	0.11
TS (%)	2 Hour		pMDI	3.24	4.01	3.78	0.61
	22 Hour			11.96	12.66	12.41	0.41
	2 Hour		pMDI+5%MP	2.35	2.57	2.49	0.66
	22 Hour			8.65	1.00	9.66	1.71
WA (%)	2 Hour		pMDI	4.74	6.01	5.96	0.14
	22 Hour			17.09	18.99	18.72	0.13
	2 Hour		pMDI+5%MP	4.29	4.79	4.73	0.10
	22 Hour			15.65	17.02	16.76	0.31
MOR (N/mm^2)			pMDI	78.7	162.7	111.74	24.4
			pMDI+5%MP	101.2	239.9	187.21	43.8
MOE (N/mm^2)			pMDI	19523	25963	21210	2072
			pMDI+5%MP	18844	26777	22434	2482
IBS (N/mm^2)			pMDI	5.80	9.90	9.20	1.19
			pMDI+5%MP	5.00	8.85	7.03	1.93
SHC (N/mm^2)	Tangent		pMDI	42.16	45.41	43.61	0.22
	Radial			43.04	48.45	47.22	0.33
	Transverse			32.13	36.21	35.15	0.28
	Tangent		pMDI+5%MP	45.12	48.03	47.21	0.33
	Radial			46.07	49.25	48.61	0.09
	Transverse			30.54	34.09	32.47	0.22

σ: standard deviation; **AD**: air-dry density; **OD**: oven-dry density; **Mc**: moisture content; **TS**: thickness swelling; **WA**: water absorption; **MOR**: modulus of rupture; **MOE**: modulus of elasticity; **IBS**; impact bending strength; **SHC**: screw-holding capacity; **pMDI+5%MP:** pMDI modified with 5% polyol.

The mean average moisture content values of PSL with pMDI and pMDI+5%MP adhesives were 5.13% and 4.92%, respectively. To improve the dimensional stability of the wood material, it is recommended to make it in laminated sheets, to apply water-resistant adhesive to reduce moisture absorption, and to reduce the hygroscopicity of cellulose materials (Simpson and TenWolde 1999). The increase and decrease in the amount of moisture also affect the physical and mechanical properties of the wood material (Gerhards 1982). When the test specimens made with two adhesive types were compared with each other, the average dimensional stability values of the test specimens made with pMDI and pMDI+5%MP adhesive increased 3.78% and 2.49% at the end of 2 h, respectively, while this ratio was determined as 12.41% and 9.66% at the end of 24 h in the same order. According to the data obtained, it was determined that there was a statistically significant (P value <0.05) difference between the 2-h and 24-h expansion percentage values of the samples prepared with polyol-added adhesive. These values are in line with the values found in the literature (Ghavami 2005; Kurt and Cavus 2011; Kurt *et al.* 2012; De lima *et al.* 2023).

When the test specimens made with two adhesive types were compared with each other, the average water absorption percentage values of the test specimens made using pMDI and pMDI+5%MP adhesive increased 5.96% and 4.73% at the end of 2 h, respectively, while this ratio was determined as 18.72% and 16.76% at the end of 24 h.

pMDI + 5% polyol addition caused a decrease in the expansion percentage values of the test samples. According to the data obtained, it was determined that there was a statistically significant (P-value < 0.05) difference between the 2-h and 24-h water absorption percentage values of the samples prepared with polyol-added adhesive. The data obtained were in agreement with previous studies (Kurt and Cavus 2011; Kurt *et al.* 2012, 2013).

According to the data obtained, it was determined that the polyol additive made a statistically significant (P-value < 0.05) difference in the modulus of rupture of the prepared samples. The average modulus of rupture values of the test specimens made using pMDI and pMDI+5%MP adhesive were 111.74 and 187.21 N/mm², respectively. The modulus of rupture of the test specimens made using pMDI+5%MP adhesive was higher than the test specimens made using pMDI. It was determined that the average modulus of rupture values of the test specimens were affected by the type of adhesive. This increase in modulus of rupture may be due to the addition of 5% polyol as a modifier. Adhesives have a significant effect on the overall behavior of wood (Wu *et al.* 1998). Similar results were obtained in the bending resistance values of the specimens produced in previous studies on parallel-strand lumber produced with different adhesives. It has been reported that this increase, depending on the type of adhesive, may be due to the type of adhesive and the carbon-carbon bonds formed during polymerization (Marra 1992; Wu *et al.* 1998; Simpson *et al.* 1999; Sulastiningsih *et al.* 2005; Ahmad and Kamke 2011; Li *et al.* 2015; Gong *et al.* 2016; He *et al.* 2018; Sulastiningsih *et al.* 2021; Qiu *et al.* 2022).

The average values of the modulus of elasticity in bending of the test specimens using pMDI and pMDI+5%MP adhesive were 21210 and 22434 N/mm², respectively. The modulus of elasticity in bending of the test specimens using pMDI+5%MP adhesive was higher than the test specimens using pMDI. It was determined that the average flexural modulus of elasticity values of the test specimens were affected by the type of adhesive. This increase in the flexural modulus of elasticity may be due to the addition of 5% polyol as a modifier. According to the data obtained, it was determined that there was no statistically significant (P-value> 0.05) difference in the modulus of elasticity of the samples prepared with polyol-added adhesive (Kurt and Cavus 2011).

The average impact resistance values of the test specimens using pMDI and pMDI+5%MP adhesive were 9.2 and 7.03 kg/cm^3, respectively. The impact resistance of the test specimens using pMDI+5%MP adhesive was lower than that of the test specimens using pMDI. It was determined that the average impact resistance values of the test specimens were affected by the type of adhesive. According to the results of the statistical analysis of variance test of the impact test data depending on the adhesive type, it was determined that a significant difference (P-value <0.05) occurred between the groups at the 95% confidence level. Statistically, polyol-added adhesive has a decreasing effect on impact strength. The impact resistance of parallel-strand lumber produced with different wood species obtained in previous studies showed a better performance than the dynamic bending resistance of the lumber from which it was produced (Wu *et al.* 1998; Simpson *et al.* 1999; Sulastiningsih and Santoso 2005; Kurt and Cavus 2011; Ahmad and Kamke 2011; Kurt *et al.* 2012, 2013; Li *et al.* 2015; Gong *et al.* 2016; He *et al.* 2018; Zhang *et al.* 2018).

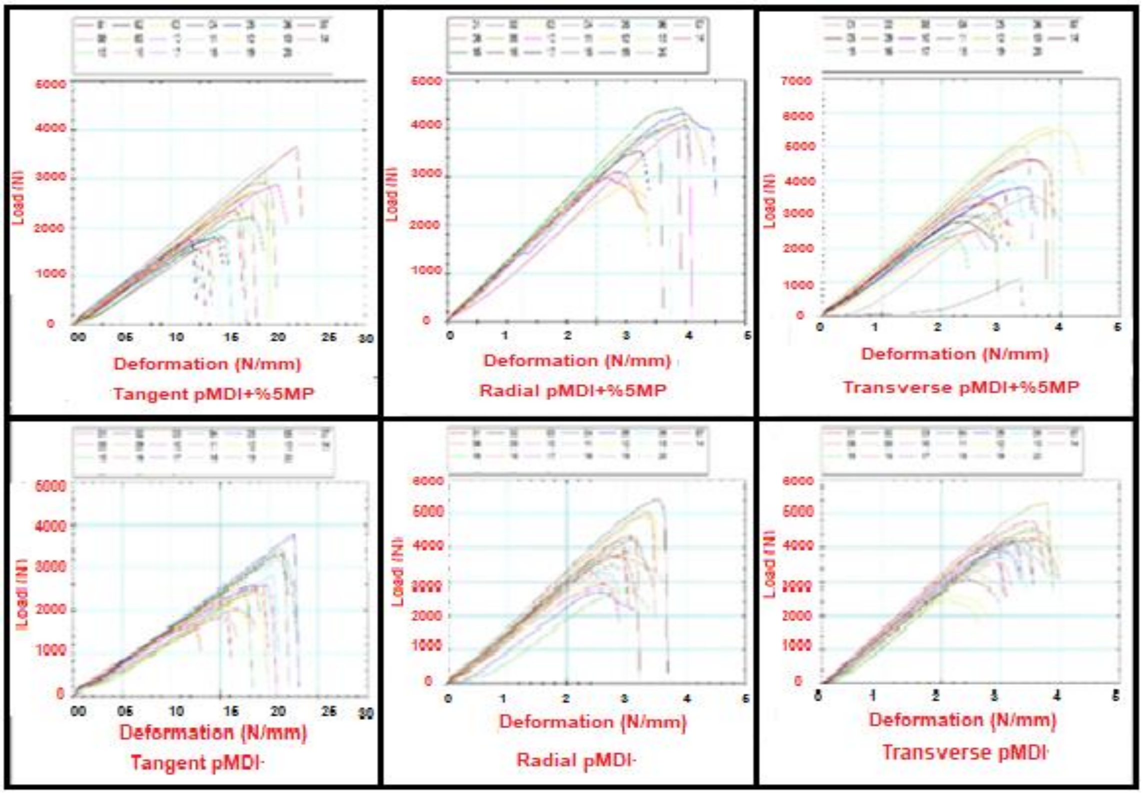

Fig. 5. The load-deformation graphs obtained of screw-holding capacity

The load-deformation graphs obtained during the screw-holding capacity test are shown in Fig. 5. It can be seen that the areas under the load-deformation graphs were different from each other, and the largest area was obtained from the radial directions of the test samples prepared with both pMDI and pMDI + 5% polyol adhesives. Relatively wide failure load ranges were observed in Fig. 5. It is normal to obtain different load-deformation curves on different surfaces in this way for the screw-holding capacity. The gaps created by the parallel placement of the strands that make up the PSL can cause wide failure load ranges.

According to the load-deformation graphs in Fig. 5, at the end of the tests performed on the tangential and radial surfaces, it is seen that the screw gradually comes out of the test specimens, whereas on the transverse surfaces, the screw comes out of the test specimens abruptly.

In previous studies, it has been reported that wood type and screwing surfaces affect screw-holding capacity. In this sense, the data obtained are consistent with the literature (Çavuş and Ayata 2018; Efe 2020). Because of the anisotropic nature of the wood, its properties are highly dependent on direction. It is stated that wood directions are effective on the screw-holding capacity (Kılıç *et al.* 2007; Çağatay *et al.* 2012; Gašparík *et al.* 2015; Çavuş and Ayata 2018). Sometimes screw-holding capacity depends on wood density (Bal 2016).

CONCLUSIONS

In this study, parallel-strand lumber, one of the structural composite lumber products in the group of engineered wood materials, was successfully produced from bamboo. Some mechanical and physical properties of the produced material were analyzed.

1. The average air-dry density values of the test samples manufactured with both poly(methyldiphenyldiisocyanate) (pMDI) and pMDI+5% modified with polyol (MP) were 1.02 gr/cm³ and 0.99 gr/cm³, oven-dry density values of 0.99 gr/cm³ and 0.94 gr/cm³, and average moisture content values of 5.13% and 4.92%, respectively.
2. The average thickness swelling values both pMDI and pMDI+5%MP adhesives of the test samples were 3.78% and 2.49%, the corresponding values were 12.41% and 9.66% at the end of 22 h. respectively. The average water absorption values for both pMDI and pMDI+5%MP at the end of 2 h were 5.96%, and 4.73%, 18.72%, and 16.76% after 24 h, respectively.
3. Modulus of rupture and modulus of elasticity of the test specimens using pMDI+5%MP adhesive from mechanical properties were higher than those of the test specimens using pMDI.
4. The screw-holding capacity values of the test samples produced with both pMDI and pMDI+5%MP adhesives were 43.61, 47.22, 35.15, and 47.21, 48.61, and 32.47 N/mm² for tangential, radial, and transverse surfaces, respectively. The average SHC of the tangential direction was higher than the transverse and radial directions. The lowest SHC was determined in the axial direction. The screw-holding capacity showed more anisotropic characteristics than the glue type. This is due to the atomic orientation of the fibers in the bamboo strips as in the wood material.
5. It has been determined that both resin types improve some physical and mechanical properties of parallel-strand lumber.

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