Mechanical Performance of L-Shaped Corner Joints Manufactured by 3D Printing with a Polylactic Acid–Wood Composite

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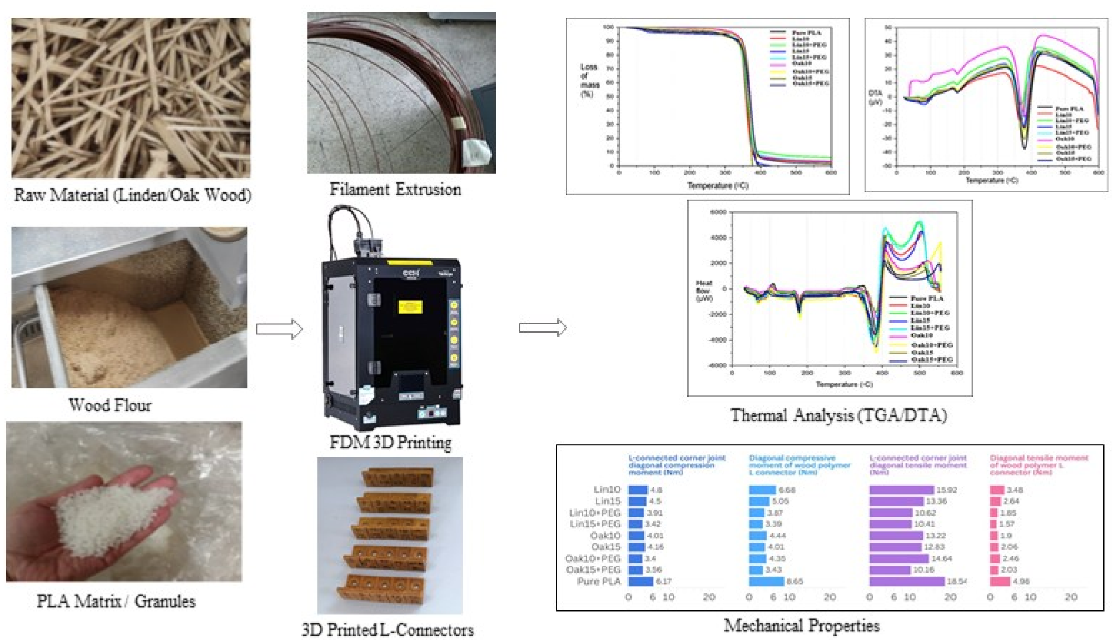
GRAPHICAL ABSTRACT



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Filaments were produced with eight different blends for use in Fused Deposition Modeling (FDM) printers by adding 10% and 15% linden and oak wood flours as support materials to a polylactic acid (PLA) matrix. Wood polymer L-shaped connectors were printed from the produced filaments in the FDM printer. These L-shaped connectors were fixed to the particleboard corner joints to produce L-shaped corner joint specimens. These specimens were subjected to cross-compression and cross-tension tests using special molds in a universal testing machine to determine the effects of wood flour, wood species, and additive ratio on cross-compression and tensile moments. Thermogravimetric analysis, differential thermal analysis, and differential scanning calorimetric analyses were performed to determine the thermal properties of the wood-polymer composites, while scanning electron microscope imaging was performed to determine their morphological structures. Additionally, the tensile strength of the composites was also determined. The results showed that the mechanical properties of the samples produced with different wood flour types and additive ratios were lower than those of pure PLA. However, in diagonal compression and diagonal tensile tests conducted using L-joint elements obtained from different wood species and printed on an FDM printer.

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Keywords: L-Connected joint; 3D printer; Additive manufacture; Furniture

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INTRODUCTION

Although the furniture industry is one of the world's most important sectors, companies and scientists have been forced to seek alternatives due to the more efficient use of existing forest resources and the high cost of solid wood as raw material. In addition to composite materials produced using natural fibers, the production of wood-plastic composite materials has also become well established (Janíková *et al*. 2025). As a result of the parallelism between industry developments and technology, additive manufacturing methods have become increasingly popular. One of the most widely used additive manufacturing methods is Fused Deposition Modeling (FDM). A 2017 study conducted in Italy showed that 3D printing technologies are primarily used by accessory manufacturers (Murmura and Bravi 2018). FDM printers use filament, and a wide variety of materials are used for filament production. Among these materials, polylactic acid (PLA) and PLA-based filaments are the most preferred (Nampoothiri *et al*. 2010). PLA, which is considered an environmentally friendly material and a promising alternative to petroleum-based polymers, is being researched by scientists and companies to create wood-like products by incorporating wood and wood waste. A summary of some of these studies on the production of wood-reinforced filaments using PLA as a base material is provided in Table 1.

Table 1. Some Studies on Wood-Reinforced Filaments Using PLA

	Materials Used	Results Obtained	Source
1	Teak Wood Fluor (*Tectona grandis*), PLA, Acrylic processing aid (APA), Acrylic core shell rubber 3 (CSR), Poly(methyl methacrylate (PMMA)	Although filament production was achieved with both teak wood flours sifted at 74 micron and 125-micron particle sizes, only filaments with 74 micron particle size added could be printed successfully.	(Petchwattana *et al*. 2019)
2	Olive tree waste, PLA.	Adding olive tree waste to the resulting filaments after experimental treatments reduced PLA's bending properties and stiffness. Despite these reductions, waste utilization appeared to have environmental benefits according to EU policies.	(Fico *et al.* 2022)
3	Walnut bark, PLA.	Single gradient PW samples exhibited better tensile, flexural and compressive properties compared to standard walnut reinforced PLA samples.	(Palaniyappan *et al*. 2023)
4	Cellulose nanocrystal, PLA.	The highest tensile strength of the PLA/CNC composite filaments was found in the 1 wt% CNC, with an 18.2% increase compared to pure PLA. Furthermore, the highest tensile strength of the 3D-printed sample was demonstrated in the sample containing 0.75 wt%, with an 11% increase. For all CNC contents, the filaments exhibited higher tensile strength compared to the 3D-printed samples.	(Ahmad *et al*. 2023)
5	Soy hulls, soy protein isolate (SPI), poly (2-ethyl-2-oxazoline) (PEOX), PLA	Tensile strength and glass transition temperature decreased with increasing soy hull percentage. Values similar to those obtained with PLA were obtained when 87.5% PLA and 2.5% SPI were added, and 7.5% soy hulls and 2.5% PEOX were added. The use of PEOX improved the bond between the matrix and the filler.	(Dey *et al*. 2023)
6	Waste walnut shells powder, egg shells, white marble powder, PLA.	The lowest tensile strength was observed in the combination of eggshell powder, walnut shell powder, and PLA. The lowest elongation occurred in the combination of eggshell powder, walnut shell powder, white marble powder, and PLA.	(Lohar *et al*. 2022)
7	Poplar wood flour, PLA, Thermoplastic poly urethane (TPU), Polycaprolactone (PCL), PE Wax.	Poplar wood flour, the hardener added to PLA composites, provided a 33.98% increase in tensile strength and a 10.38% increase in bending strength of TPU composites.	(Guo *et al*. 2018)
8	Larch sawing waste, PLA.	It was determined that the addition of wood additives caused a decrease in tensile strength, but increased bending strength values.	(Narlıoğlu *et al*. 2021)
9	Beech wood flour, PLA.	Surface roughness increased with increasing wood flour amount. Wettability decreased with increasing wood flour amount.	(Ayrilmis *et al*. 2019)
10	Aspen shavings, PLA.	The initial deformation resistance of samples with added wood flour increased compared to pure PLA.	(Tao *et al*. 2017)
11	Wood flour, PLA, silane (KH550), acetic anhydride (Ac2O), acrylic ester resin (ACR).	It was observed that the addition of ACR improved the mechanical properties of all samples. Although the study investigated the effects of chemical modification on mechanical, thermal, dynamic, and water uptake properties, the relationship between	(Yu *et al*. 2022)

		the printing parameters and chemical modification was not investigated.	
12	Beech wood flour, PLA.	It was determined that there was a decrease in tensile strength with increasing the amount of wood added. The tensile strength increased by 3% with the addition of 10% wood flour and decreased by 45% with the addition of 50% wood.	(Kariza *et al*. 2018)
13	Recycled wood flours, PLA.	Wood flour added to PLA at 2.5% provided a 9% increase in tensile strength.	(Estakhrianhaghighi *et al*. 2020)
14	Undried spruce cellulose pulp, PLA, chloroform, acetic acid, sodium acetate, celluclast.	While the tensile strength of the composite filaments obtained by mixing with 3% and 5% e-NFC10 increased compared to PLA, it had no effect on the elongation at break.	(Perić *et al*. 2020)
15	Heat-treated ash, PLA, silver nanoparticles.	AgNPs synthesized with 5% heat-treated wood flour/leaf extract added to the PLA matrix increased the tensile strength, while this situation was reversed with the increase in the amount of wood flour.	(Yurttaş 2022)

EXPERIMENTAL

Materials

Linden (*Tilia rubra* DC.) and sessile oak (*Quercus petraea* (Mattuschka) L.) wood flours were used as additives in the filament production. Wood flours that would be examples of hard and soft wood types were preferred in the selection of wood type. Total Corbion Luminy L175 brand polylactic acid (PLA) was used as matrix material, polyethylene glycol (PEG 6000) for dimensional stability and plasticize of the filament and polyethylene wax as a lubricant for the easy movement of the filament during the printing phase were used.

Melamine faced chipboard, 18-mm thick and 0.63 g/cm^3 density was used for the pieces of L-corner joints which the L-shaped brackets would be fixed to 3.5 × 20 mm chipboard screws and 8 × 20 mm solid plastic dowels were used in fixing L-corner joint elements to each other.

Method

Wood flour (WL) derived from linden and oak was sieved using a 200-mesh (approximately 74 microns) stainless steel vibrating screen. Through this process, particles with a size of 74 microns or smaller were separated and selected for use in production. The selected WF was dried in an oven at 103 ± 2 °C until fully dried to eliminate all moisture content.

To achieve a more homogeneous mixture with WF, PLA in granule form was ground into powder using a polymer grinder. This process ensured that the particle size of PLA was similar to that of the WF, reducing the risk of phase separation in the composite. The powdered PLA was then dried in an oven at 55 °C for 6 h to minimize its moisture content. To enhance the dimensional stability of the filament and improve processability during 3D printing, PEG-6000 and polyethylene (PE) wax were used as auxiliary additives. PEG-6000 was added to improve the dimensional stability of the final filament, while PE wax facilitated the smooth flow of the filament during the extrusion process. Samples of PLA, WF, PEG-6000, and PE wax were weighed according to the ratios specified in Table 2, and mechanically homogenized in a Turbula mixer for 60 min to obtain uniform powder mixtures. In total, eight different filament formulations were prepared in this manner.

The prepared mixtures were processed using a twin-screw extruder with an 18 mm diameter and a length-to-diameter (*L/D*) ratio of 40, operating at 200 ± 5 °C. The extruded output was then pelletized using a granulation unit to form granules. In the final stage, the granulated biopolymer blends were processed in a single-screw extruder with a diameter of 16 mm and an *L/D* ratio of 25, and extruded into filaments with a diameter of 1.75 mm.

Table 2. Biopolymer Mixing Ratios

Mixture Name	PLA (%)	Wood Flour (%)		PE Wax (%)	PEG (%)
		Linden	Oak		
Pure PLA	100	-	-	-	-
Lin10	87	10	-	3	0
Lin15	82	15	-	3	0
Lin10+PEG	86	10	-	3	1
Lin15+PEG	81	15	-	3	1
Oak10	87	-	10	3	0
Oak15	82	-	15	3	0
Oak10+PEG	86	-	10	3	1
Oak15+PEG	81	-	15	3	1

In order to determine the tensile strength of the obtained composite materials, samples were produced using the plastic injection method, while L-shaped connectors were printed on an FDM printer.

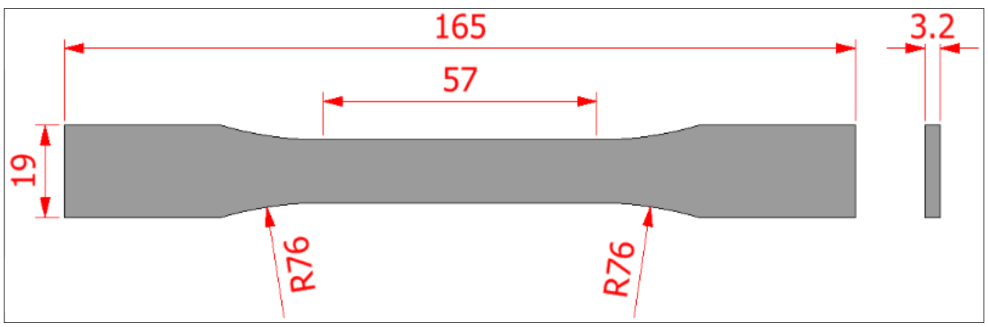


Fig. 1. Technical drawing of tensile sample in accordance with ASTM D638-22 (2022) Type-1 standard (mm)

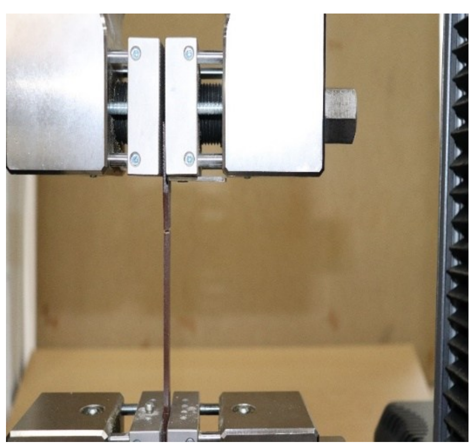


Fig. 2. Tensile strength test

In order to determine the tensile strength properties of composite materials composed of different mixtures, tensile test specimens were produced in accordance with the ASTM D638-22 (2022) Type-1 standard (Fig. 1). The test specimens were produced by setting the first heating cell of an injection molding machine with 3 heating cells to 170 °C, the second heating cell to 190 °C, and the last heating cell to 200 °C. Tensile strength tests (Fig. 2) were applied to the tensile test specimens extracted from the injection mold using a 50 kN Instron 5969 Universal testing machine. The loading rate applied in the tests was 4 mm/s.

Tensile test results were calculated according to Eq. 1, and the measurement areas of the tensile sample are specified in Fig. 3,

$$\delta_t = \frac{F_{max.}}{a \times b} \ \text{N/mm}^2 \tag{1}$$

where δ_t is tensile strength (N/mm^2), F_{max} is the maximum load at break (N), a denotes thickness of the rupture area of the sample (mm), and b is the width of the rupture area of the sample (mm)

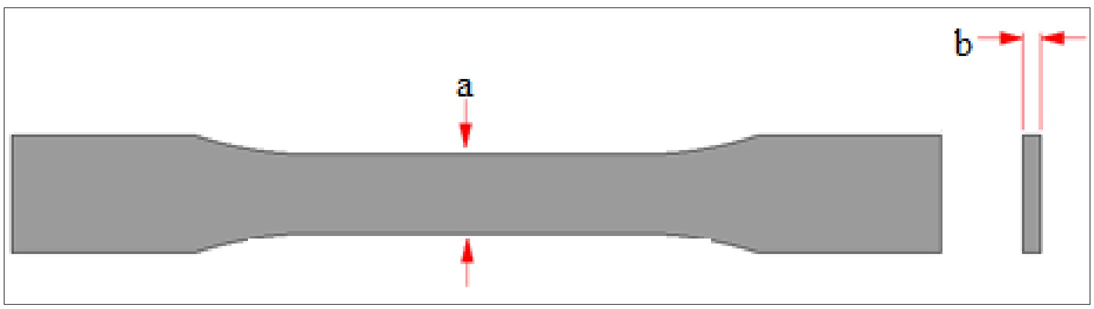


Fig. 3. Tensile test sample measurement areas

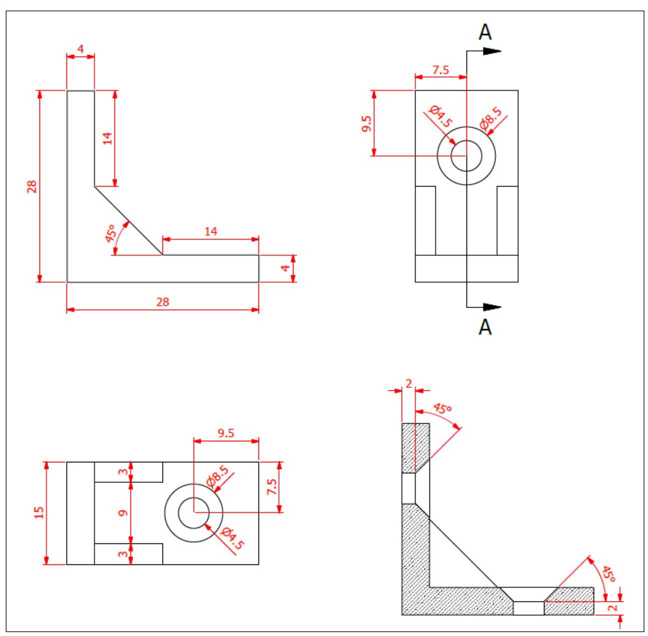
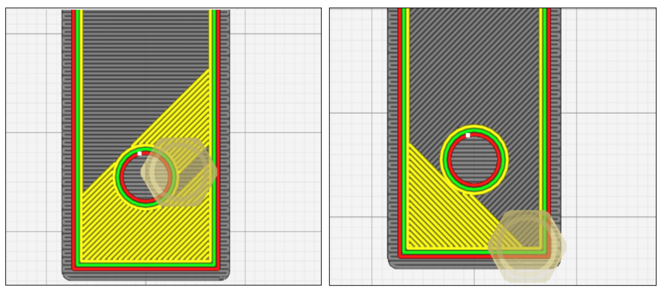


Fig. 4. Technical drawing of the L-shaped bracket

Table 3. Printing Parameters with a 3D Printer

Fill rate	100%
Print shape	Cubic
Print temperature	215 ºC
Print speed	45 mm/sn
Layer thickness	0.2 mm

The L-shaped brackets (LSBs) shown in Fig. 4 were printed with the printing parameters given in Table 3 by using filaments extracted with the mixing ratio given in Table 2. The specimens were prepared with a CCH brand Z23 model closed system 3D printer. The printing angle was 90 degrees, the fan operating at 100% power had an air volume of 9.43 CFM, and the extrusion flow rate was 30 mm/s. Images of the layers in the printer interface program during the printing process are given in Figs. 5 (a-b).



(a) **(b)**

Fig. 5. Display of the layer in the interface program during the printing process (a and b)

For the corner joints, the melamine faced chipboard was cut into the dimensions specified in Fig. 6, and the LSBs were assembled.

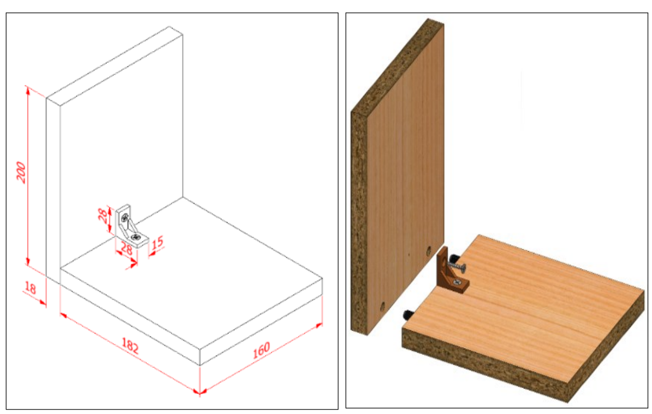


Fig. 6. Corner joint with L shaped bracket (CJWLSB)

Then the samples of the corner joints (Fig. 7) were subjected to diagonal compression and the tensile tests were performed using special molds in the 50 kN Instron 5969 Universal testing machine.

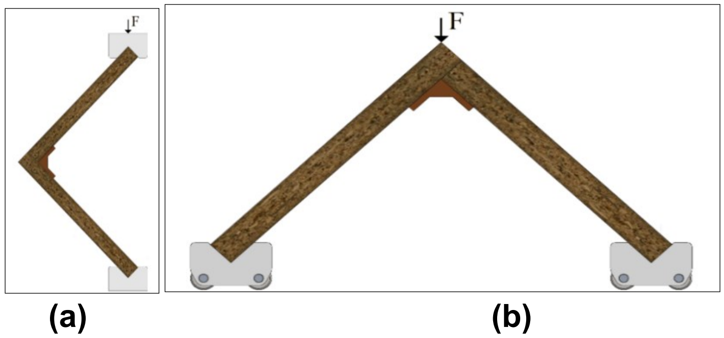


Fig. 7. Diagonal compression (a), and tensile (b) tests of the corner joints

The samples printed on the FDM printer were tested without being assembled as well as being assembled, and the test results were calculated as specified in Eqs. 2 and 3.

Diagonal compression moment values were calculated with the following equation:

$$M_c = F_{maxc} \times L_c \text{ (Nm)} \quad (2)$$

M_c: Moment (Nm)
F_{maxc}: Maximum force at the moment of fracture (N)
L_c: Moment arm (m)

Diagonal tensile moment values were calculated with the following equation:

$$M_t = \frac{F_{maxt}}{2} \times L_t \quad (3)$$

M_t: Moment (Nm)
F_{maxt}: Maximum force at the moment of fracture (N)
L_t: Moment arm (m)

A Hitachi STA7300 device was used for Thermo-gravimetric Analysis/Differential Thermal Analysis (TGA/DTA) and a Hitachi DSC 7020 device was used for Differential Scanning Calorimetric (DSC) analysis to determine the thermal properties of wood polymer composites. In the TGA/DTA analysis, the samples were heated up to 600 °C starting from 25 °C with a temperature increase of 20 °C/min, and in the DSC analysis, the samples were heated up to 600 °C starting from 25 °C in a nitrogen environment.

To determine the morphological structure of the obtained wood polymer composite materials, samples were examined with a scanning electron microscope (SEM). Imaging was performed using Hitachi SU5000 brand SEM.

Statistical Analysis of Data

The statistical evaluation of the data was performed with the SPSS-22 package program. The normal distribution of the obtained data was evaluated according to the Skewness-Kurtosis method.

After the evaluation, the data showing normal distribution were used directly for statistical operations, and the normalization process was performed for the wood polymer L connection element tensile moment data that did not show normal distribution. The Levene test was performed to evaluate the equality of variances for the data showing normal distribution, and it was determined that the variances of the data groups were homogeneous.

The Duncan test was used to determine the difference between the groups for the groups with homogeneous variances.

RESULTS

Density

In Fig. 8, the density values of 100% fill ratio (LSB) obtained with 8 different blends and pure PLA are given.

While the LSBs obtained with Lin10+PEG and Oak15+PEG mixtures had the lowest density value of 1.06 g/cm^3, the highest density value of 1.26 g/cm^3 was obtained from the LSBs produced from pure PLA.

The ANOVA test conducted to determine whether different mixtures influence the density of wood polymer L-joints is given in Table 5.

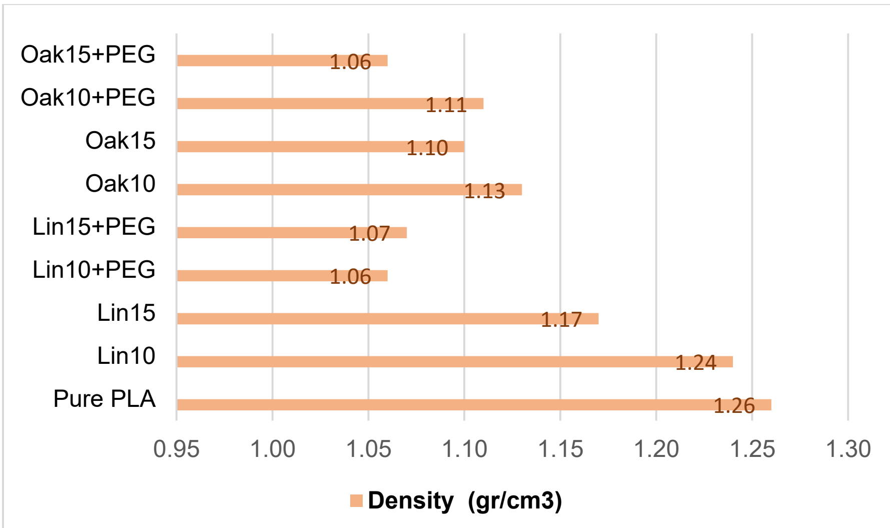


Fig. 8. Densities of the LSBs

Table 5. ANOVA Test to Determine Effect of Different Mixtures on Density of LSBs

	Sum of Squares	df	Mean Square	F-Value	Sig. $P \leq 0.05$
Between groups	0.17	8	0.02	1.57	0.15
Within groups	1.10	81	0.01		
Total	1.27	89			

As presented in Table 5, the p-value obtained from the analysis of variance (ANOVA) for the different mixtures was found to be above 0.05. This indicates that the differences between the groups were not statistically significant.

Effects of Different Mixtures on Diagonal Compression and Diagonal Tensile Moment of LSBs and CJWLSBs

Diagonal compression and diagonal tensile moment values of LSBs produced with FDM printer using different mixtures and corner joints fixed using these LSBs are given in Fig. 9.

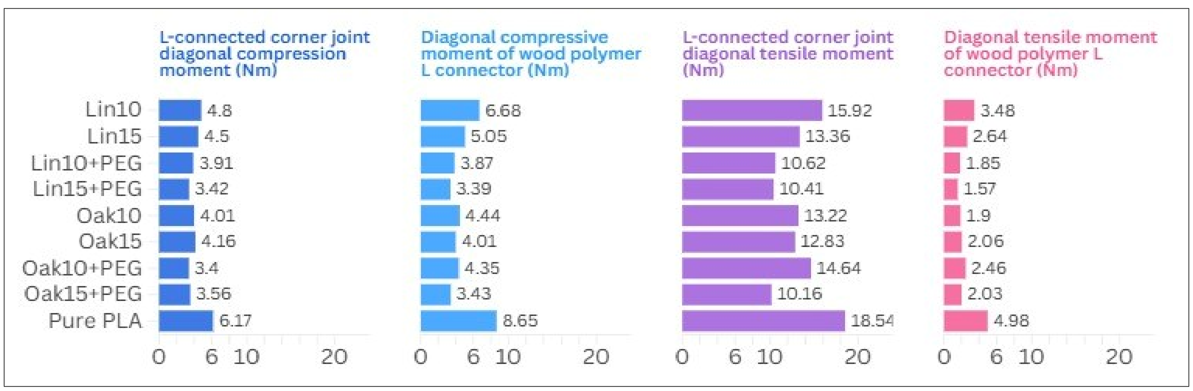


Fig. 9. Diagonal compression and tension moments of wood polymer L-joints and L-joint corner joints according to wood species and mixture ratios

The diagonal compressive moment of pure PLA L-joint corner joints was the highest compared to that of L-joint corner joints of all blends. Based on all wood-forget additives, the highest diagonal compressive moment was obtained in L-joint corner joints with Lin10 blend, while the lowest diagonal compressive moment was obtained in L-joint corner joints with Oak10+PEG blend.

Regarding wood-polymer L-joints, the ranking of L-joint corner joints with wood flour additives remained unchanged, and the diagonal compressive moment of pure PLA L-joints ranked first compared to L-joints of all blends.

The diagonal tensile moment of pure PLA L-joint corner joints was the highest compared to that of all L-joint corner joints of all mixtures. Considering all wood flour-added variables, the highest diagonal tensile moment was achieved in corner joints with L-joints using the Lin10 blend, while the lowest diagonal tensile moment was achieved in corner joints with L-joints using the Lin15+PEG blend.

The diagonal tensile moment of pure PLA L-joints ranked first among all mixtures in terms of wood-polymer L-joint tensile moment. Regarding wood-polymer L-joints, the ranking remained unchanged for both linden flour-added and oak flour-added mixtures.

Effects of Different Mixtures on Diagonal Compression Moment of LBSs and CJWLSBs

Diagonal compression moment values of wood polymer L-joints produced with FDM printer using different mixtures and corner joints fixed using these L-joints are given in Table 6.

Table 6. Diagonal Compression Moment Values of LBSs and CJWLSBs according to Wood Species and Mixture Ratios

Wood Type	Mixtures	CJWLSBs Diagonal Compression Moment (Nm)				Wood Polymer LSBs Diagonal Compressive Moment (Nm)			
		Min.	Max.	Mean	Coeff. of Variation (%)	Min.	Max.	Mean	Coeff. of Variation (%)
L-joints produced with filaments containing linden flour	Lin10	3.58	5.57	4.80	14.86	5.46	7.51	6,68	10.75
	Lin15	3.76	5.62	4.50	15.28	4.30	6.06	5,05	11.84
	Lin10+PEG	3.07	4.92	3.91	20.17	2.52	5.92	3,87	30.07
	Lin15+PEG	2.11	4.28	3.42	23.05	1.81	4.50	3,39	26.25
L-joints produced with oak flour added filaments	Oak10	3.18	5.17	4.01	19.17	3.13	6.14	4,44	28.20
	Oak15	2.98	5.36	4.16	22.59	1.62	5.64	4,01	36.13
	Oak10+PEG	2.88	4.34	3.40	15.06	2.64	6.21	4,35	34.92
	Oak15+PEG	2.89	3.98	3.56	13.86	2.26	4.29	3,43	21.61
Pure PLA		4.76	7.47	6.17	15.97	4.91	10.52	8,65	22.37

As can be seen from the table, regarding CJWLSBs, the highest diagonal compressive moment was obtained in Lin10 blended CJWLSBs among the linden added variables, while the lowest was obtained in Lin15+PEG blended CJWLSBs. Among the oak added variables, the highest diagonal compressive moment was obtained in Oak15 blended CJWLSBs, while the lowest was obtained in Oak10+PEG blended CJWLSBs. Considering all variables, the highest diagonal compressive moment was obtained in CJWLSBs with Lin10 mixture, followed by CJWLSBs with Lin15 mixture, and the lowest diagonal compressive moment was obtained in CJWLSBs with Oak10+PEG mixture. The diagonal compressive moment of CJWLSBs made of pure PLA was the highest compared to that of CJWLSBs of all mixtures.

Regarding the wood polymer LSBs, the order did not change in the variables with linden flour additive, while in the variables with oak flour additive, the highest diagonal compressive moment was obtained in the LSBs with Oak10 mixture, while the lowest was obtained in the LSBs with Oak15+PEG. The diagonal compressive moment of the LSBs made of pure PLA was again in the first place compared to that of the LSBs of all mixtures. The ANOVA test conducted to determine whether different mixtures have an effect on the diagonal compressive moment of the CJWLSBs is given in Table 7.

Table 7. ANOVA Test to Determine whether Different Mixtures Influence the Diagonal Compressive Moment of CJWLSBs

	Sum of Squares	df	Mean Square	F Value	Sig. $P \le 0.05$
Between groups	30.61	8	3.83	5.32	0.00*
Within groups	25.89	36	0.72		
Total	56.50	44			

Different mixtures were effective on the diagonal compression moment of CJWLSBs, and the differences between the diagonal compression moment values of the groups were important. The results of the Duncan homogeneity test performed to determine which groups have the differences between the diagonal compression moment values are given in Table 8.

Table 8. Duncan Homogeneity Test

Mixture Variables	Duncan Homogeneity Groups		
	1	2	3
Oak10+PEG	3.40		
Lin15+PEG	3.42		
Oak15+PEG	3.56		
Lin10+PEG	3.91	3.91	
Oak10	4.01	4.01	
Oak15	4.16	4.16	
Lin15	4.49	4.49	
Lin10		4.80	
Pure PLA			6.17
Significance	0.08	0.15	1.00

According to this grouping, increasing the wood flour additive ratio for both wood types and adding PEG to the mixture along with wood flour decreased the diagonal compressive moment values of CJWLSBs. In addition, the diagonal compressive moment values of CJWLSBs with linden flour additive were higher than those with oak flour additive.

ANOVA test was performed to determine whether different mixtures have an effect on the diagonal compressive moment of wood polymer LSBs and the result is given in Table 9.

According to Table 8, different mixtures were effective on the diagonal compression moment of wood polymer LSBs, and the differences between the diagonal compression moment values of the groups were important. The results of the Duncan homogeneity test performed to determine which groups have the differences between the diagonal compression moment values are given in Table 10.

Table 9. ANOVA Test to Determine the Effect of Different Mixtures on the Diagonal Compressive Moment of Wood Polymer LSBs

	Sum of Squares	df	Mean Square	F-Value	Sig. P ≤ 0.05
Between groups	120.18	8	15.02	8.14	0.00*
Within groups	66.48	36	1.84		
Total	186.67	44			

Table 10. Duncan Homogeneity Test

L-joints	Duncan Homogeneity Groups		
	1	2	3
Lin15+PEG	3.39		
Oak15+PEG	3.43		
Lin10+PEG	3.87		
Oak15	4.01		
Oak10+PEG	4.35		
Oak10	4.44		
Lin15	5.05	5.05	
Lin10		6.68	
Pure PLA			8.65
Significance	0.10	0.07	1.00

Based on this grouping, increasing the linden flour content and adding PEG to the mixture along with linden flour decreased the diagonal compressive moment values of the LSBs. In the samples with oak flour content, increasing the flour content and adding PEG to the mixtures did not create a significant difference in the diagonal compressive strength of the LSBs.

Effects of Different Mixtures on the Diagonal Tensile Moment of Wood Polymer LSBs and CJWLSBs

The diagonal tensile moment values of LSBs produced with FDM printers with different mixtures and corner joints fixed using these L-connectors are given in Table 11.

As can be seen from the table, regarding CJWLSBs, among the linden flour added variables, the highest diagonal tensile moment was obtained in Lin10 blended CJWLSBs, while the lowest was obtained in Lin15+PEG blended CJWLSBs. Among the oak flour added variables, the highest diagonal tensile moment was obtained in Oak10+PEG blended CJWLSBs, while the lowest was obtained in Oak15+PEG blended CJWLSBs. When all variables were taken into consideration, the highest diagonal tensile moment was obtained in Lin10 blended CJWLSBs, followed by Oak10+PEG blended CJWLSBs, and the lowest diagonal tensile moment was obtained in Lin15+PEG blended CJWLSBs. The diagonal tensile moment of pure PLA L-connector corner joints was the highest compared to that of all mixtures.

The ranking of wood polymer LSBs did not change with both linden flour and oak flour additives. The diagonal tensile moment of pure PLA LSBs was the first in the wood polymer LSBs tensile moment ranking of all mixtures.

Table 11. Diagonal Tensile Moment Values of Wood Polymer LSBs and CJWLSBs Based-on Wood Flour Type and Mixture Ratios

Wood Type	Mixtures	CJWLSBs Diagonal Tensile Moment (Nm)				Wood Polymer LSBs Diagonal Tensile Moment (Nm)			
		Min.	Max.	Mean	Coeff. of Variation (%)	Min.	Max.	Mean	Coeff. of Variation (%)
L-joints produced with filaments containing linden flour	Lin10	14.15	17.13	15.92	6.94	3.00	3.89	3.48	8.44
	Lin15	11.78	15.45	13.36	9.43	2.13	3.19	2.64	13.41
	Lin10+PEG	8.32	12.88	10.62	17.67	1.19	2.29	1.85	19.60
	Lin15+PEG	6.95	12.31	10.41	17.92	1.10	2.22	1.57	27.47
L-joints produced with filaments containing oak flour	Oak10	10.29	15.70	13.22	16.31	1.17	3.47	1.90	44.46
	Oak15	9.83	15.90	12.83	18.89	1.59	2.94	2.06	22.34
	Oak10+PEG	10.82	16.36	14.64	13.85	1.73	2.86	2.46	15.84
	OAK15+PEG	7.16	16.24	10.16	31.80	1.64	2.80	2.03	19.86
Pure PLA		12.33	22.59	18.54	20.32	3.57	6.97	4.98	23.53

ANOVA test was performed to determine whether different mixtures have any effect on the diagonal tensile moment of wood polymer CJWLSBs and the result is given in Table 12.

Table 12. ANOVA Test to Determine the Effect of Different Mixtures on Diagonal Tensile Moment of Wood Polymer CJWLSBs

	Sum of Squares	df	Mean Square	F Value	Sig. $P \leq 0.05$
Between groups	308.56	8	38.57	5.66	0.00*
Within groups	245.49	36	6.82		
Total	554.04	44			

As shown in Table 11, different mixtures were effective on the diagonal tensile moment of CJWLSBs. Differences between the tensile moment values of the groups were significant. Results of the Duncan homogeneity test performed to determine which groups have the differences between the diagonal tensile moment values are given in Table 13.

Table 13. Duncan Homogeneity Test

L-joints	Duncan Homogeneity Groups		
	1	2	3
Oak15+PEG	10.16		
Lin15+PEG	10.42		
Lin10+PEG	10.62		
Oak15	12.83	12.83	
Oak10	13.22	13.22	
Lin15	13.36	13.35	
Oak10+PEG		14.64	
Lin10		15.92	15.92
Pure PLA			18.54
Significance	0.09	0.10	0.12

According to this grouping, the diagonal tensile moment decreased with the increase in the additive ratio in the CJWLSBs with linden flour additive and in the CJWLSBs with oak flour additive. Similarly, in PEG additives, the increase in the wood flour ratio decreased the diagonal tensile moment of the corner joint.

ANOVA test was performed to determine whether different mixtures are effective on the diagonal tensile moment of wood polymer LSBs and the results are given in Table 14.

Table 14. ANOVA Test to Determine the Effect of Different Mixtures on the Diagonal Tensile Moment of Wood Polymer LSBs

	Sum of Squares	df	Mean Square	F Value	Sig. $P \leq 0.05$
Between groups	1.03	8	0.13	10.57	0.00*
Within groups	0.44	36	0.01		
Total	1.47	44			

As can be seen from Table 13, different mixtures were effective on the diagonal tensile moment of wood polymer LSBs elements, and the differences between the values of the groups were important. The results of the Duncan homogeneity test conducted to determine which groups have the differences between the diagonal tensile moment values are given in Table 15.

Table 15. Duncan Homogeneity Test

L-joints	Duncan Homogeneity Groups				
	1	2	3	4	5
Lin15+PEG	0.18				
Oak10	0.24	0.24			
Lin10+PEG	0.26	0.26			
Oak15+PEG	0.30	0.30	0.30		
Oak15	0.30	0.30	0.30		
Oak10+PEG		0.38	0.38		
Lin15			0.42	0.42	
Lin10				0.54	
Pure PLA					0.69
Significance	0.12	0.08	0.13	0.09	1.00

Based on this grouping, while the increase in the linden flour additive ratio and the PEG addition were effective in reducing the diagonal tensile moment of the fastener in the LSBs with linden flour additives, both the increase in the wood flour additive ratio and the PEG addition were ineffective on the moment value in the ones with oak flour additives.

Deformations

The deformations that occurred in the corner joint and the wood polymer L connection element after the diagonal compression test are given in Figs. 10 and 11.

In CJWLSBs, after the diagonal compression test, wood polymer LSB deformations occurred in the rib part of the material. The deformations that occurred after the diagonal compression test applied to the wood polymer LSBs occurred near the screw hole and at the beginning or end of the rib. The deformations that occurred are shown in Figs. 12. and 13.

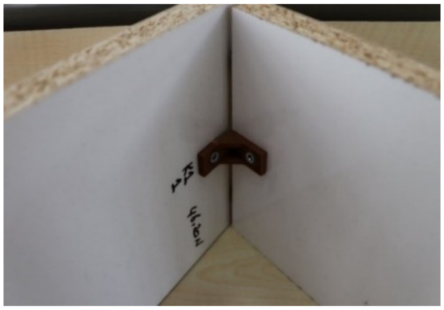


Fig. 10. Example of deformation after diagonal compression test in CJWLSBs

Fig. 11. Example of deformation after diagonal compression test on wood polymer LSBs

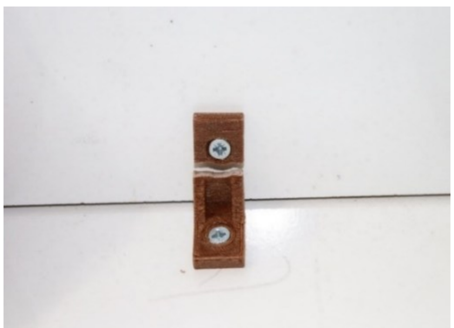


Fig. 12. Example of deformation after diagonal tensile test in CJWLSBs

Fig. 13. Example of deformation after diagonal tensile test on wood polymer LSBs

After the diagonal tensile tests in the CJWLSBs and wood polymer LSBs samples the deformation occurred near the screw hole and at the beginning of the rib, as in the diagonal compression moment.

Thermogravimetric Analysis and Differential Thermal Analysis

The thermal deteriorations that occurred under the effect of temperature and time in wood polymer composites prepared with pure PLA and 8 different wood flour additives were determined with TGA-DTA analyses and the obtained data are given in Table 17 and the obtained graphs are given in Figs. 14 and 15.

Table 17. Mass Loss-Temperature Graph

Mixtures	$T_{\%10}$ (°C)	$T_{\%50}$ (°C)	Amount of Remaining Substance (%)
Pure PLA	348	370	0
Lin10	339	359	3.13
Lin15	336	362	6.31
Lin10+PEG	334	364	0
Lin15+PEG	337	362	3.80
Oak10	347	370	3,25
Oak15	344	369	2.11
Oak10+PEG	332	363	0
Oak15+PEG	338	369	1.05

The 10% mass loss temperature was measured at the highest 348 °C in pure PLA material, while the lowest temperature was measured at 332 °C in Oak10+PEG blended filaments. The 50% mass loss was measured at the highest 370 °C in pure PLA and Oak10 blended filaments, while the lowest temperature was measured at 359 °C in Lin10 blended filaments. When the table is examined, it is apparent that the wood flour and PEG additive added to pure PLA did not reduce the thermal decomposition temperature to a high extent. For 10% mass loss, the thermal temperature decreased by a maximum of 4% in Oak10+PEG blended filaments, while the least decrease was detected in Oak10 blended filaments with a maximum of 1%.

When thermal decomposition occurred, the lowest amount of remaining material was observed in pure PLA, Lin10+PEG, and Oak10+PEG (0%), while the highest amount of remaining material was observed in Lin15 blends. The amount of remaining material, in other words, the ash amount efficiency is a measure of the flame reaching the inner parts of the material in combustion events. For this reason, high ash efficiency contributes to the development of the fireproof properties of the material (Kocatürk 2022).

According to Table 16, Lin15 was the mixture with the best combustion properties.

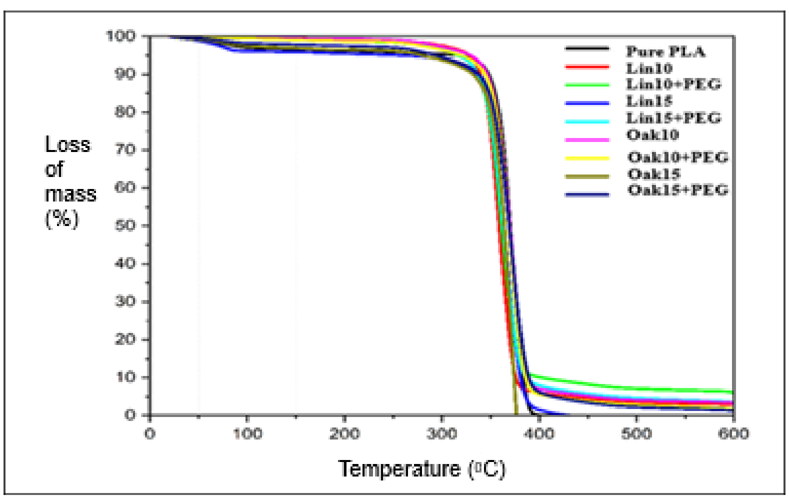


Fig. 14. Temperature-mass loss graph

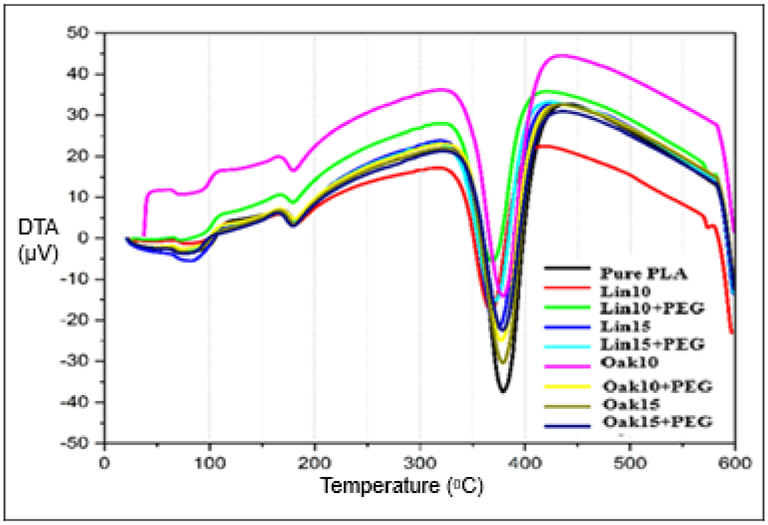


Fig. 15. Temperature-energy loss graph

Based on the DTA graph, the glass transition temperature was determined to be approximately 75 °C for all wood polymer blends and pure PLA. The melting temperature is approximately 178 °C and the decomposition temperatures are approximately 380 °C for both 8 different blends and pure PLA.

Differential Scanning Calorimetry (DSC)

Differential scanning calorimetric (DSC) thermograms of wood polymer filaments consisting of different blends and filaments obtained from pure PLA are given in Fig. 16.

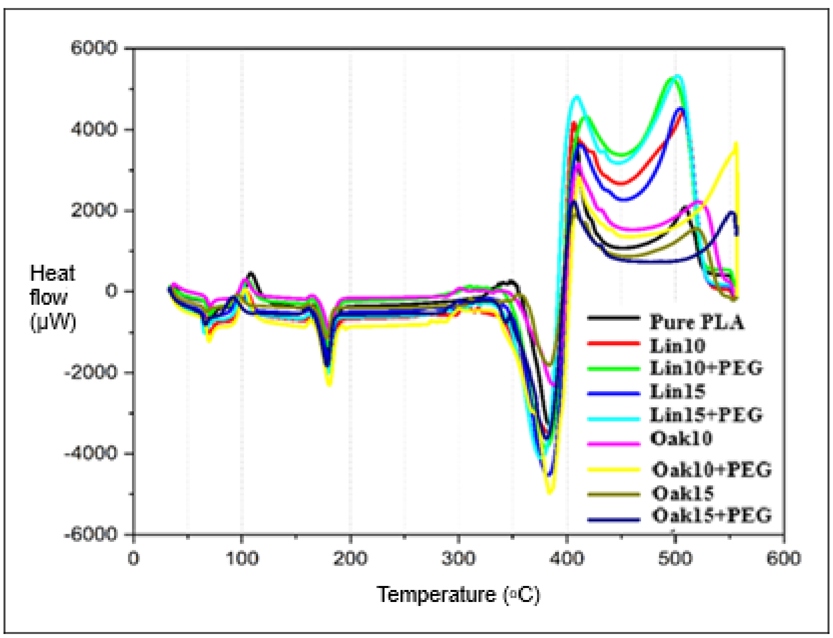


Fig. 16. DSC thermograms

The glass transition temperature did not change with the addition of wood flour and PEG, and this temperature was approximately 75 °C in pure PLA and wood polymer mixtures. While crystallization began at approximately 120 °C, the melting temperature was approximately 178 °C and the decomposition temperature was approximately 380 °C.

Scanning Electron Microscope

The SEM images from the fracture-surface of pure PLA and linden and oak flours added L-joint elements after the diagonal compression test are given in Figs. 18 and 19.

As the wood flour additive ratio increased, the voids in the matrix also increased. This is due to the insufficient adhesion between the wood material and PLA. When the images are examined, it is seen that the wood flours are distributed homogeneously in the matrix. Tensile strength values of the test samples produced by injection molding method according to wood flour type and mixing ratios are given in Fig. 17.

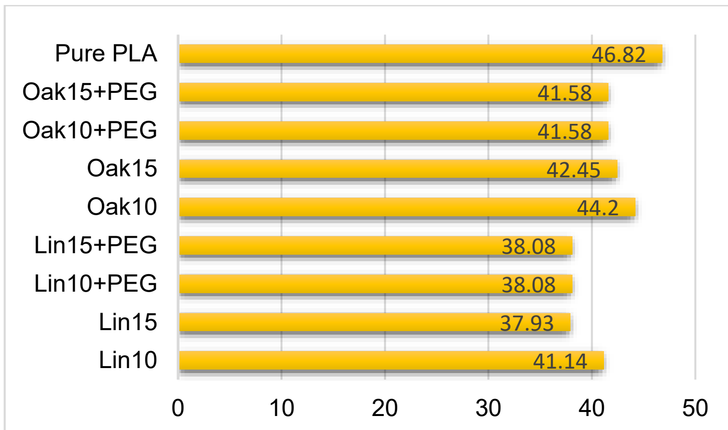


Fig. 17. Tensile strength values of test samples produced by injection molding (N/mm^2)

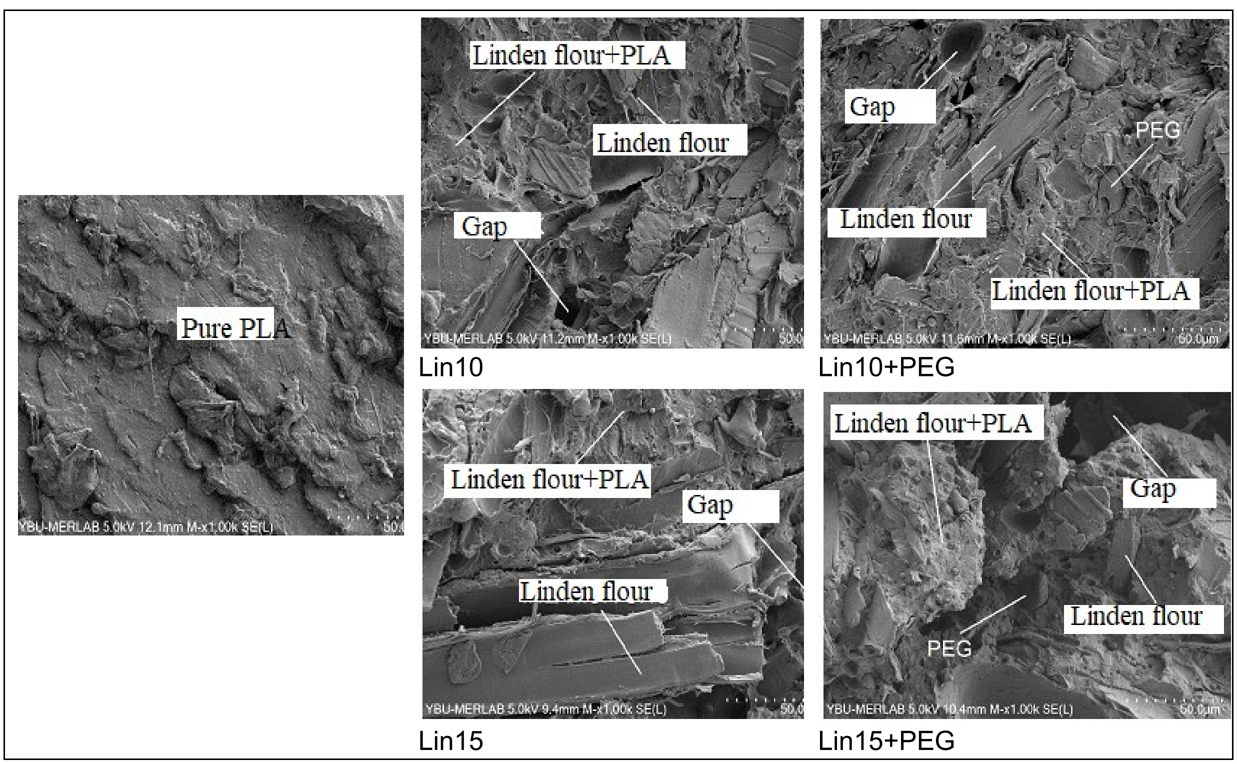


Fig. 18. SEM images of the fracture surface of linden flour added wood polymer L-joints

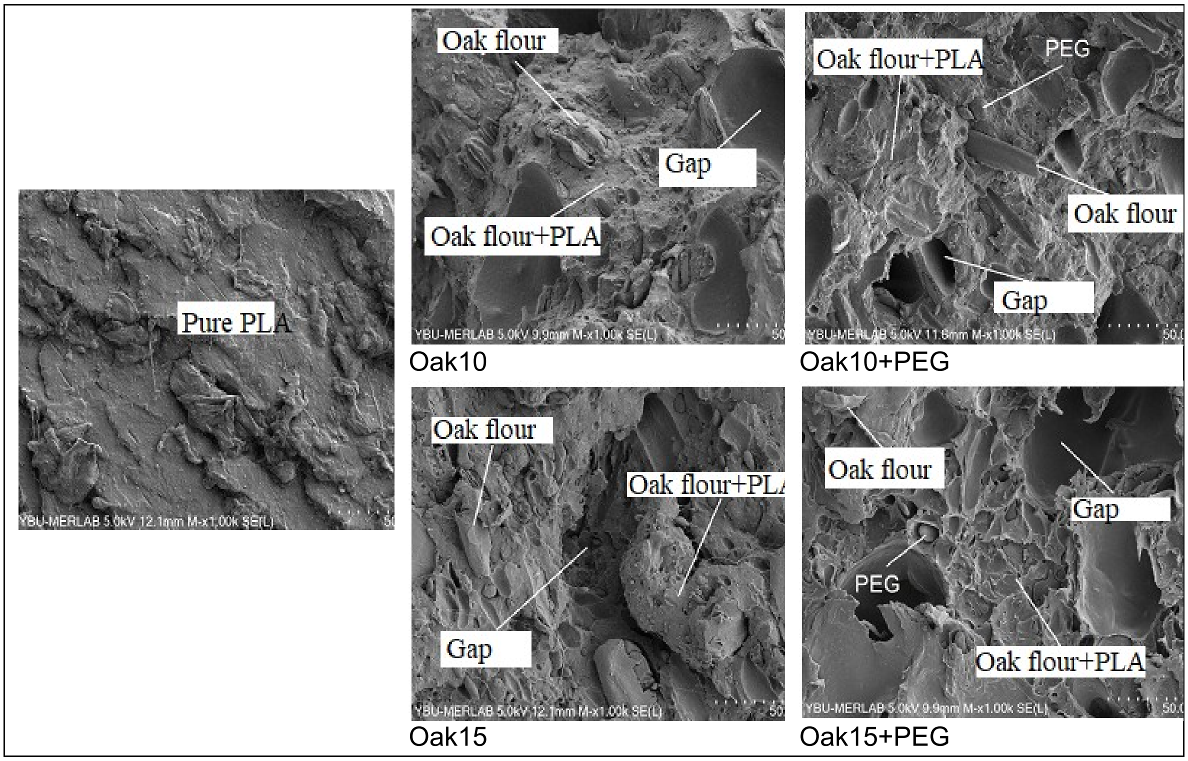


Fig. 19. SEM images of the fracture surface of oak flour added wood polymer L-joints

As can be seen from Fig. 17, among the linden added variables, the highest tensile strength was obtained from the Lin10 blended samples, while the lowest was obtained from the Lin10+PEG blended samples. Among the oak added variables, the highest tensile strength was obtained from the Oak10 blended samples, and the lowest tensile strength was obtained from the Oak10+PEG blended samples and the Oak15+PEG blended samples. Considering all variables, the highest tensile strength was obtained from samples blended with Oak10, while the lowest tensile strength was obtained from samples blended with Oak15. Samples produced from pure PLA had the highest tensile strength.

ANOVA test was performed to determine whether different mixtures had an effect on tensile strength and the result is given in Table 18.

Table 18. ANOVA Test to Determine Whether Different Mixtures have an Effect on Tensile Strength

	Sum of squares	df	Mean square	F Value	Sig. p≤0.05
Between groups	362.32	8	45.29	1.00	0.45*
Within groups	1623.44	36	45.10		
Total	1985.75	44			

As can be seen from Table 17, different mixtures had no effect on the tensile strength of the samples produced by injection molding method since the significance level is $P \geq 0.05$.

DISCUSSION

Density

Adding wood flour and reinforcing agents into PLA decreased the density value. The density value of wood polymer L connectors obtained from filaments produced with Lin10 (PLA+%10 linden flour+PE wax) mixture was 1.6% lower than the density value of L connectors produced from pure PLA (Shi 2021).

Deformations

Deformations occurring after the applied pressure in diagonal compression and tension moments applied to CJWLSBs were observed in both test types, mainly in the parts close to the screw hole and in the beginning or end sections of the rib. This situation may be due to the fact that the screw hole area is a weak point and the rib loses its support function. Increasing the length of the rib may be effective in solving the problem (Haeusler *et al.* 2017; Nicolau *et al.* 2022).

Diagonal Compression Moment

Other studies have shown that wood flour additive reduced the mechanical properties of PLA. Among the reinforcement materials such as metal, ceramic, carbon fibers, when added to PLA, increased the mechanical properties of PLA while wood fluor decreased it. In addition, the change in the additive ratio also affected the mechanical strength of the material (Wang *et al*. 2011; Liu *et al*. 2019; Sun *et al*. 2020; Yurttaş 2022).

When the diagonal compression moment values were examined, there were significant differences between the diagonal moments of the LSBs and CJWLSBs in the samples with linden flour additive, while this difference was not present in the test samples with oak additive. The reason for this may be that the density of oak is high and the use of less oak flour by volume prevents the diagonal compression moment differences between the mixtures (Karaman *et al.* 2020; Yıldırım *et al.* 2019).

Diagonal Tensile Moment

When the effects of wood flour additive ratio and PEG addition were considered together regarding corner joints, increasing the wood flour additive ratio decreased the diagonal tensile moment of CJWLSBs. In PEG additives, increasing the oak and lime flour additive ratio decreased the diagonal tensile moment of corner joints. The oily structure of PEG may prevent the materials entering the mixture from bonding to each other in PEG mixed samples.

When the effects of wood flour and PEG addition were evaluated together regarding L-joints, increasing the lime flour additive ratio caused a decrease in the diagonal tensile moment of wood polymer LSBs, while both the increase in wood flour additive ratio and PEG addition had no effect on the moment value in oak flour additives. The fact that lime flour is more in volume and oak flour is less in volume may influence these results.

In mixtures with linden flour additives, the linden flour additive ratio and the PEG addition to the mixture had a negative effect on both the diagonal tensile moments of CJWLSBs and the diagonal tensile moments of wood polymer L-connectors. This may be the reason for the low moment values since the number of particles entering the mixture increases due to the low density of linden. This situation can be turned into a positive one by using high-density wood flours.

In mixtures with oak flour additives, the oak flour additive ratio and the PEG addition to the mixture did not have a significant effect on the diagonal tensile moments of both CJWLSBs and wood polymer LSBs. The high density of oak may have an effect on this result.

Thermal Analysis Results

According to the thermal analysis results, wood flour and PEG additives did not significantly reduce the thermal melting and glass transition temperatures. The amount of remaining material, in other words, the amount of ash, was found to be the highest in Lin15 mixtures. This shows that the products obtained from this mixture have better fireproof properties than other mixtures.

Scanning Electron Microscope Analysis

When SEM images were examined, the wood flour particle size was 74 microns and below, and the wood flour was distributed homogeneously and without much clustering into the melted PLA with the use of a twin-screw extruder in the mixing process of PLA and wood flour. On the other hand, mechanical resistances decreased due to the gaps formed as a result of the decrease in adhesion with the increase in wood flour. This situation was also parallel to the diagonal compression and diagonal tension moment results.

In this study, when the diagonal compression and diagonal tension moments of the L-connection elements produced by printing the filaments obtained from the mixtures prepared using linden and oak flours on the FDM printer were examined, the moments of both the wood polymer L-connection elements and the L-connected corner joints were higher in the mixtures prepared with linden flour. When the thermal properties were examined, it was seen that there was no major change, especially in the glass transition temperature.

Tensile Strength

Following a tensile strength test conducted on wood-polymer composite mixtures produced using plastic injection molding, no significant difference was observed between the mixtures. This may be due to the homogeneous mixing of wood flours within the PLA and the particle size of the flours used being 74 microns or less. The resulting mixtures can be used as filament for FDM printers or can be utilized in various ways using plastic injection molding.

CONCLUSIONS

This study investigated the effects of adding different proportions of linden and oak wood flours and PEG to PLA on the density, mechanical, and thermal properties of L-shaped connectors. The results indicated that:

1. The addition of wood flour slightly reduced the density; more significant decreases in diagonal compressive and tensile moments were observed, particularly in mixtures containing linden flour.
2. The addition of poly(ethylene glycol) (PEG) negatively affected the mechanical properties, particularly in mixtures containing linden flour.

3. No significant change in thermal properties was observed, but the Lin15 mixture was found to be advantageous in terms of fire resistance due to its higher ash content.
4. Scanning electron micrograph (SEM) analyses indicated that the wood flour was homogeneously distributed, but adhesion weakened as the proportion increased, and this was associated with losses in mechanical strength.

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