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The Effect of Type of Reinforcement, Type of Glue and Reinforcement Place on Mechanical and Physical Properties of LVL

Utjecaj vrste ojačanja, vrste ljepila i mjesta ojačanja na mehanička i fizička svojstva LVL-a

ORIGINAL SCIENTIFIC PAPER
Izvorni znanstveni rad
Received – prispjelo: 24. 7. 2023.
Accepted – prihvaćeno: 15. 1. 2024.
UDK: 630*83; 674.06
https://doi.org/10.5552/drvind.2024.0144

ABSTRACT • *This study investigated the effect of the reinforcement type, glue type, and reinforcement placement on the mechanical and physical properties of LVL. In the study, the glues used were phenol- formaldehyde (FF), epoxy (EX), and polyurethane (PU), while reinforcement materials used were glass fiber, basalt, jute, and cotton fabric. The following three reinforcement combinations were applied: the first was on the bottom surface, the second was on the first adhesive line at the bottom, and the third was on both the bottom and the first adhesive line at the bottom. As part of the study, researchers manufactured 9-layer laminated veneer lumber (LVL) using alder veneers for the surface, and poplar veneers for the middle layers. They produced a total of 39 different combinations of LVL. The mechanical and physical properties of the produced samples were determined. According to the test results, bending strength (BS), modulus of elasticity (MOE), oven-dry specific gravity, and equilibrium moisture content of samples were higher with FF than with other glues. While the samples with EX glue provided the lowest values in water absorption and thickness swelling tests, glass fiber-reinforced samples provided the highest mechanical values. In addition, the samples having reinforcement on the bottom surface provided higher BS and MOE values.*

KEYWORDS: *reinforced LVL; glass fiber; basalt; epoxy; phenol formaldehyde*

SAŽETAK • *U ovom je radu istraživan utjecaj vrste ojačanja, vrste ljepila i položaja ojačanja na mehanička i fizička svojstva LVL-a (lamelirane drvne građe). U istraživanju je rabljeno fenol-formaldehidno (FF), epoksidno (EX) i poliuretansko (PU) ljepilo, dok su materijali za ojačanje bili staklena vlakna, bazalt, juta i pamučna tkanina. Primijenjene su tri kombinacije ojačanja: (1) u donjoj površini, (2) u prvoj liniji lijepljenog spoja od donje površine te (3) u donjoj površini i u prvoj liniji lijepljenog spoja od donje površine. Kao dio studije istraživači su proizveli lameliranu drvnu građu (LVL) od devet slojeva koristeći se furnirima drva johe za površinske slojeve i drva topole za srednje slojeve. Proizvedeno je ukupno 39 različitih kombinacija LVL-a te su određena mehanička i fizička svojstva proizvedenih uzoraka. Prema rezultatima ispitivanja, vrijednosti čvrstoće na savijanje (BS), modula elastičnosti (MOE), gustoće u apsolutno suhom stanju i ravnotežnog sadržaja vode uzoraka s FF ljepilom*

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imale su veće vrijednosti nego u uzoraka izrađenih s ostalim ljepilima. Uzorci s EX ljepilom pokazali su najmanje vrijednosti upijanja vode i debljinskog bubrenja, a uzorci ojačani staklenim vlaknima imali su najbolja mehanička svojstva. Osim toga, uzorci s ojačanjem na donjoj površini imali su veće vrijednosti čvrstoće na savijanje i veći modul elastičnosti.

KLJUČNE RIJEČI: *ojačana lamelirana drvna građa; staklena vlakna; bazalt; epoksid; fenol- formaldehid*

1 INTRODUCTION
1. UVOD

Solid wood has been used in both indoor and outdoor applications from the past to the present. The advantages of solid wood are low price, renewability, easy processing, and good shock resistance. However, solid wood also has some disadvantages such as biodegradability, anisotropic, low dimensional stability, and low mechanical properties (Bozkurt and Erdin, 1997). For this reason, it is challenging to produce large-size carrier elements from a single piece of solid wood. To overcome this problem, engineered wood materials such as oriented strand board (OSB), cross-laminated timber (CLT), plywood, and laminated veneer lumber (LVL) have been developed.

LVL is one of the most essential engineered wood materials. Due to its superior properties, LVL is preferred for many applications, such as scaffold planks, headers, joists, beams, rafters, and truss chords (Çolak *et al*., 2007). They are manufactured using low-density, fast-growing, and economically inexpensive tree species, such as poplar, alder Douglas fir, and spruce. LVL produced from these tree species has low mechanical properties. In order to increase the mechanical properties of wood-based composites, researchers focused on reinforcement studies.

Many researchers have studied fiber reinforcement of LVLs, mainly synthetic glass fiber and carbon fiber (Laufenberg *et al*., 1984). Bal (2014) produced LVL reinforced with phenol formaldehyde adhesive by placing glass fiber between the poplar veneers. With the reinforcement, the increase in impact bending strength and specific impact bending strength was reported. The shear strength of reinforced laminated veneer lumber was significantly greater than that of laminated veneer lumber, and the percentage increase was 213 %. There was also an improvement in physical properties, such as volumetric swelling, tangential swelling, and water absorption. Liu *et al*. (2019) manufactured plywood for construction formwork in different combinations using poplar, eucalyptus veneers, and carbon fiber as reinforcement. Generally, the veneers are bonded with phenol formaldehyde adhesive in plywood production, while carbon fiber is bonded with epoxy.

Plywood reinforcing material is essential for its performance. The reinforcement on the surface increases the longitudinal modulus of elasticity (*MOE*) and modulus of rupture (*MOR*) of the plywood. With the reinforcement of the surface, the ultimate load capacity increases while causing delamination failure. Auriga *et al*. (2020) investigated the effect of using carbon fiber reinforcement in parallel and cross structures. Melamine-urea formaldehyde resin was used as an adhesive, and the reinforcements were placed on the outer and internal glue lines. The results displayed that the place of reinforcement was effective on *MOR* and *MOE* and increased the *MOR* and *MOE* values. Studies show that the use of fiber reinforcements in laminated wood materials is vital in improving mechanical and physical properties. Yildirim *et al*. (2020) used 4 layers of 5 mm thick slats obtained by sawing method from poplar wood. Laminated wood composite materials were produced using 100 g/m^2 (Type 1) and 200 g/m^2 (Type 2) GFRP as reinforcement, polyvinyl acid, Polyurethane and double- layer Epoxy resin as glue. The investigation revealed that Type 2 plain woven fabric is stronger than Type 1 plain woven fabric, epoxy glue is stronger than polyurethane and polyvinyl acetate glue, and parallel loading to the glue line produces better performance than perpendicular loading to the glue line. Zor and Kartal (2020) fiber-reinforced finger corner joints were used to create control samples of the pine, beech, and oak species. The glues utilized were Teknobont 200 epoxy and polyvinyl (PVAc). The experimental samples were tested under diagonal loads, keeping in mind the critical loads that can influence their application. Speranzini and Tralascia (2010) reinforced solid wood and LVL with natural fibers such as basalt, flax, and hemp, and synthetic fibers such as glass fiber and carbon fiber. The four-point bending test results showed that the values of the samples with natural reinforcement were lower than those with the synthetic reinforcements, but their strength values were higher than those without reinforcement. Moezzipour *et al*. (2017) investigated the effect of kenaf and date palm fiber reinforcement on the mechanical and physical properties of horn beam plywood bonded with urea-formaldehyde. The study determined that kenaf fiber performed better than date palm fiber. Jorda *et al*. (2020) produced three-dimensional molded plywood reinforced with flax fibers using epoxy glue. The study showed increased load capacity and stiffness of the reinforced plywood with the reinforcement. Valdes *et al.* (2020) produced a three- and five-layer Cross Laminated Timber (CLT) reinforced with flax fabrics bonded with epoxy. As a result of the study,

Figure 1 Produced test samples
Slika 1. Proizvedeni ispitni uzorci

the load capacity and stiffness of the three-layer CLTs increased significantly with the reinforcement, while in the five-layer CLTs, it was negligible.

In the literature, some studies focus on natural and synthetic fibers and the most used glues preferred in the laminated wood sector. However, no study examines the interaction of natural and synthetic reinforcement materials, water-based and non-water-based adhesives, and the reinforcement placed together. This study investigated the changes in the mechanical and physical properties of LVLs produced by using four different types of natural and synthetic reinforcements, three types of glue, and reinforcement at three locations.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

The study used poplar and alder rotary-peeled veneers as raw wood material. The rotary-peeled veneer thickness of poplar was 2.2 mm, while alder was 1.5 mm. The width and length of the veneer for both species was 50 cm. The veneers were dried to 8-10 % moisture content before production. Phenol formaldehyde (FF) resin Polifen 47 (Polisan, Turkey), epoxy (E) resin LR300/LH300 (Dostkimya, Turkey), and polyurethane (PU) resin PUR 501 (Kleiberit,Germany) were used as adhesives. Glass fiber, basalt, jute, and cotton woven fabrics with a density of 200 g/m^2 were used as reinforcement material. Reinforcement materials were also in 50 cm ×50 cm dimensions.

2.2 LVL production
2.2. Proizvodnja LVL-a

Nine-layer LVLs were produced in 39 different combinations using three different glues, four different reinforcing materials, and three different reinforcement materials in place of use. Test examples are presented in Figure 1. LVLs had alder veneer in the outer and poplar veneer in the middle layers. The placement of reinforcement materials in LVL and the production plan are presented in Figure 2 and Table 1, respectively. The adhesive application per glue line was set to 200 g/m^2. The hydraulic hot press was set at 140 °C for phenol formaldehyde, 110 ºC for other glues, and 10 kg/cm^2 press pressure with 1 mm/min + 3 min press time.

2.3 Physical and mechanical characterization of LVLs
2.3. Fizička i mehanička karakterizacija LVL-ova

The physical properties, oven-dry density, density profile, equilibrium moisture content, thickness swelling, and water absorption tests were carried out. In addition, the images of the test samples were taken with a Canon EOS 70D (EF 100 mm f/2.8L Macro IS

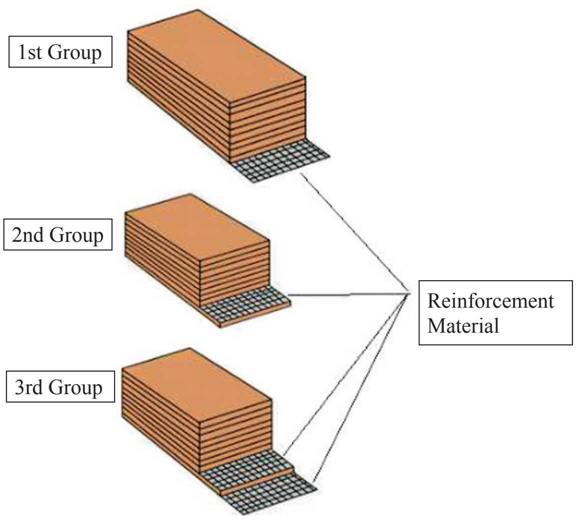

Figure 2 Reinforcement place of use
Slika 2. Položaj ojačanja

Table 1 Production plan
Tablica 1. Plan proizvodnje

No *Broj*	**Sample code** *Oznaka uzorka*	**Glue type** *Vrsta ljepila*	**Reinforcement type** Vrsta ojačanja	**Reinforcement place** *Položaj ojačanja*	
				Bottom outer surface *Donja vanjska površina*	**1st glue line from the bottom** / *Prva linija lijepljenog spoja od donje površine*
1	F-Control	FF	---	---	---
2	FC-1	FF	Glass Fiber	X	---
3	FC-2	FF	Glass Fiber	---	X
4	FC-3	FF	Glass Fiber	X	X
5	FB-1	FF	Basalt	X	---
6	FB-2	FF	Basalt	---	X
7	FB-3	FF	Basalt	X	X
8	FJ-1	FF	Jute	X	---
9	FJ-2	FF	Jute	---	X
10	FJ-3	FF	Jute	X	X
11	FP-1	FF	Cotton	X	---
12	FP-2	FF	Cotton	---	X
13	FP-3	FF	Cotton	X	X
14	E-Control	E	---	---	---
15	EC-1	E	Glass Fiber	X	---
16	EC-2	E	Glass Fiber	---	X
17	EC-3	E	Glass Fiber	X	X
18	EB-1	E	Basalt	X	---
19	EB-2	E	Basalt	---	X
20	EB-3	E	Basalt	X	X
21	EJ-1	E	Jute	X	---
22	EJ-2	E	Jute	---	X
23	EJ-3	E	Jute	X	X
24	EP-1	E	Cotton	X	---
25	EP-2	E	Cotton	---	X
26	EP-3	E	Cotton	X	X
27	P-Control	PU	---	---	---
28	PC-1	PU	Glass Fiber	X	---
29	PC-2	PU	Glass Fiber	---	X
30	PC-3	PU	Glass Fiber	X	X
31	PB-1	PU	Basalt	X	---
32	PB-2	PU	Basalt	---	X
33	PB-3	PU	Basalt	X	X
34	PJ-1	PU	Jute	X	---
35	PJ-2	PU	Jute	---	X
36	PJ-3	PU	Jute	X	X
37	PP-1	PU	Cotton	X	---
38	PP-2	PU	Cotton	---	X
39	PP-3	PU	Cotton	X	X

USM) camera and measured with the MShot Image Analysis System program.

Oven-dry specific gravity, equilibrium moisture content, thickness swelling, and water absorption tests for ten samples each were determined according to EN 323, EN 322, and TS EN 317, respectively. Density profile values were measured on a DAX 5000 GreCon X-ray density-measuring device. The water absorption and thickness swelling test were performed at 2, 24-, 168-, 336- and 504-hour intervals.

Mechanical properties, bending strength, modulus of elasticity, and compressive strength parallel to the grain were measured according to EN 310 and TS 2595, respectively. The span/depth ratio was adjusted to 16 for bending test samples. Ten samples were prepared for each group. Figure 3 presents the bending strength and compressive strength test image.

The data were analyzed using SPSS 20 statistical program. Analysis of variance (univariate) was conducted to determine the effects of glue type, reinforce-

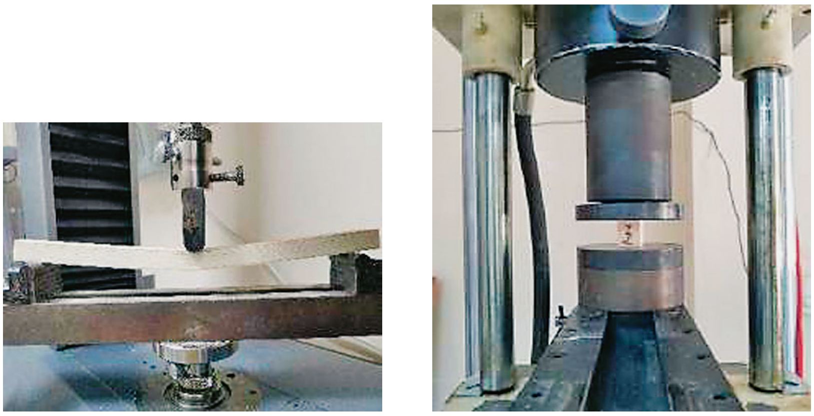

Figure 3 Bending strength and compressive strength test image
Slika 3. Prikaz ispitivanja čvrstoće na savijanje i čvrstoće na tlak

ment type, and reinforcement place on mechanical and physical properties. Besides, Duncan's Multiple Range Test (α=0.05) determined significant differences between groups.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Oven-dry density
3.1. Gustoća u apsolutno suhom stanju

Statistical analysis showed that glue type, reinforcement type, and reinforcement place significantly affected oven-dry density. Table 2 shows the homogeneity groups found as the result of the test for oven-dry density. According to the test results, the highest oven-dry density was found in the group produced with phenol-formaldehyde (0.547 g/cm^3), while the lowest oven-dry density was found for the group glued with polyurethane (0.511 g/cm^3).

When the effect of the reinforcement type was examined, the highest oven-dry density was found in the samples using glass fiber. In contrast, the lowest oven-dry density was determined in the samples without reinforcement. Other studies reported similar results stating that the board oven-dry density values increased with reinforcement (Bal, 2014; Kramar and Kral, 2019) because the reinforcing material density was higher than the veneer density. In addition, the amount of glue increases with the use of the reinforcing agent, which increases the oven-dry density (Bal *et al*., 2015).

Regarding the effect of reinforcement placement in the LVLs, the third group provided the highest oven-dry density (the one having two reinforcing sheets). In contrast, samples without reinforcement had the lowest oven-dry density. As expected, the first and second group provided similar oven-dry density since only one reinforcement material was present in both groups. The oven-dry density in the third group was higher than that in the first and second group due to the increased reinforcement and glue.

3.2 Equilibrium moisture content
3.2. Ravnotežni sadržaj vode

Glue type, reinforcement type, and reinforcement placement statistically significantly affected equilibri-

Table 2 Duncan test results for oven-dry density and equilibrium moisture content (α = 0.05)
Tablica 2. Rezultati Duncanova testa za gustoću uzoraka u apsolutno suhom stanju i ravnotežni sadržaj vode (α = 0,05)

Groups / *Grupe*		**Oven-dry density, g/cm^3** *Gustoća u apsolutno suhom stanju,* g/cm^3	**Equilibrium moisture content, %** *Ravnotežni sadržaj vode,* %
Glue type *vrsta ljepila*	Phenol formaldehyde	0.547 **a**	9.33 **a**
	Epoxy	0.538 **b**	7.04 **c**
	Polyurethane	0.511 **c**	7.46 **b**
Reinforcement type *vrsta ojačanja*	Control group	0.494 **d**	7.83 **c**
	Glass Fiber	0.544 **a**	7.84 **c**
	Basalt	0.535 **b**	7.85 **c**
	Jute	0.523 **c**	8.12 **a**
	Cotton	0.538 **b**	8.00 **b**
Reinforcement place *položaj ojačanja*	Control group	0.494 **c**	7.83 **c**
	1. Group	0.530 **b**	7.82 **c**
	2. Group	0.533 **b**	8.12 **a**
	3. Group	0.543 **a**	7.92 **b**

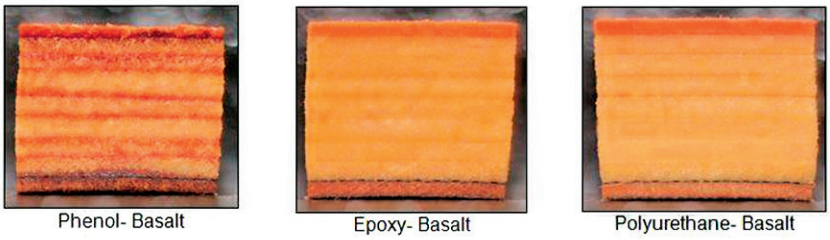

Figure 4 Images of samples after 504 hours
Slika 4. Slike uzoraka nakon 504 sata potapanja u vodi

um moisture content. Table 2 presents the homogeneity groups found as the result of the test for equilibrium moisture content. According to the test results, the highest equilibrium moisture content was found in the phenol-formaldehyde group (9.33 %), while the lowest equilibrium moisture content was found in the epoxy group (7.04 %). None of the groups reached 12 % equilibrium moisture.

Examining the effect of the reinforcement type showed that the samples with jute reinforcement had the highest equilibrium moisture content. In contrast, samples without reinforcement had the lowest equilibrium moisture content. The equilibrium moisture content of the control group and samples using glass fiber and basalt were similar. Since jute and cotton are cellulosic materials, they increase the amount of equilibrium moisture by taking moisture from the atmosphere.

In the case of reinforcement placement, the second group provided the highest equilibrium moisture content, while the first group provided the lowest.

3.3 Thickness swelling and water absorption
3.3. Debljinsko bubrenje i upijanje vode

Statistical analysis showed that glue type, reinforcement type and placement, as well as soaking time, significantly affected thickness swelling. Table 3 presents the homogeneity groups for thickness swelling tests. The test results showed that, while samples produced with phenol- formaldehyde glue had the highest thickness swelling, samples produced with epoxy, on the other hand, had the lowest thickness swelling. Since phenol-formaldehyde glue is water-based, it compels more in a hot press than epoxy and polyurethane, resulting in a more spring back in the water. In addition, the phenol-formaldehyde glue line weakened more over time in water than epoxy and polyurethane glues resulting in a thickness increase. During gluing, some epoxy penetrates the veneer (slightly impregnated) and hardens there. For this reason, the thickness swelling of the samples produced with epoxy glue was less than that of

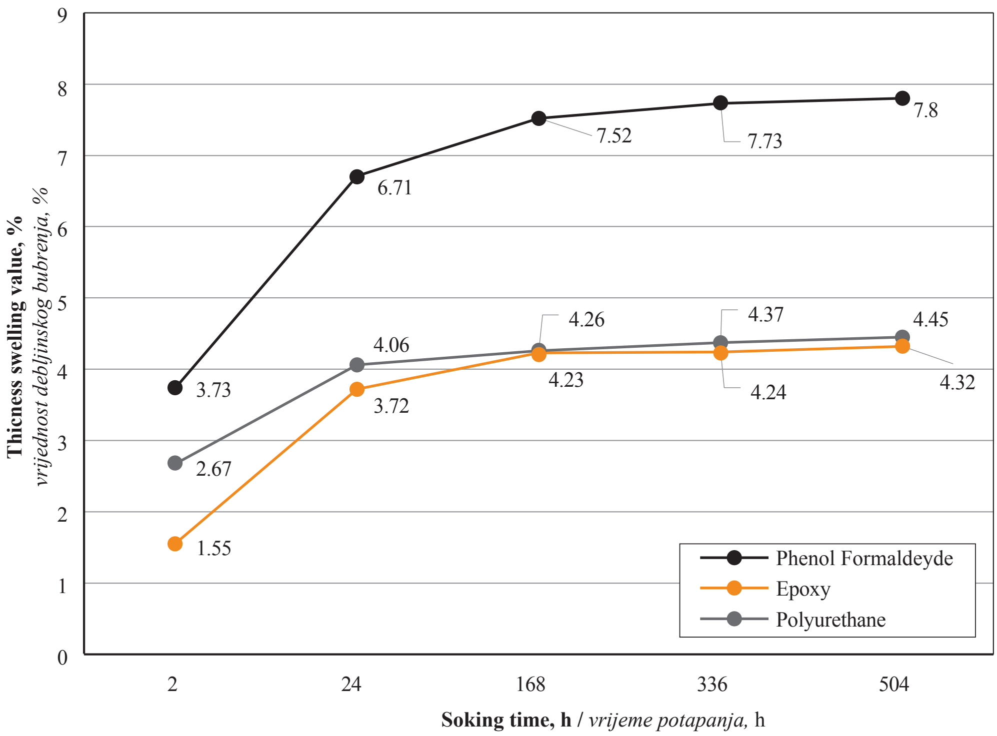

Figure 5 Interaction graph showing average thickness swelling of boards according to soaking time and glue type
Slika 5. Grafikon ovisnosti srednje vrijednosti debljinskog bubrenja ploča o vremenu potapanja i vrsti ljepila

Table 3 Duncan test results for thickness swelling and water absorption (α = 0.05)
Tablica 3. Rezultati Duncanova testa za debljinsko bubrenje i upijanje vode (α = 0,05)

Groups / *Grupe*		**Thickness swelling salue, %** *Vrijednost debljinskog bubrenja, %*	**Water absorption value, %** *Vrijednost upijanja vode, %*
Glue type *vrsta ljepila*	Phenol Formaldehyde	6.70 **a**	81.53 **a**
	Epoxy	3.61 **c**	66.96 **c**
	Polyurethane	3.96 **b**	76.88 **b**
Reinforcement type *vrsta ojačanja*	Control Group	3.91 **d**	88.82 **a**
	Glass Fiber	4.79 **b**	71.92 **e**
	Basalt	4.68 **c**	73.49 **d**
	Jute	5.19 **a**	75.94 **b**
	Cotton	4.66 **c**	74.58 **c**
Reinforcement place *položaj ojačanja*	Control Group	3.91 **d**	88.82 **a**
	1. Group	5.13 **a**	76.33 **b**
	2. Group	4.57 **c**	74.16 **c**
	3. Group	4.79 **b**	71.46 **d**
Soaking time, h *vrijeme potapanja,* h	2	2.65 **d**	22.25 **e**
	24	4.83 **c**	52.30 **d**
	168	5.34 **b**	88.42 **c**
	336	5.47 **a**	103.24 **b**
	504	5.50 **a**	109.40 **a**

polyurethane glued samples since polyurethane glue remains on the veneer surface and forms the foam.

The reinforcement worsened the thickness swelling of LVLs. The jute samples had the highest thickness swelling values, while the control samples had the lowest ones. In reinforced samples, the bottom of the samples expanded less than the non-reinforced upper sides. The reinforcing material reduced the increase in the width direction. While this caused concave bending on the reinforced surface during the test, it caused convex bending on the non- reinforced upper surface (Figure 4); this bending possibly caused an increase in thickness.

Considering the waiting time in the water, the thickness swelling increased with time. Thickness swelling increased significantly up to the 336th hour (Figure 5).

Statistical analysis showed that glue type, reinforcement type, reinforcement place, and soaking time

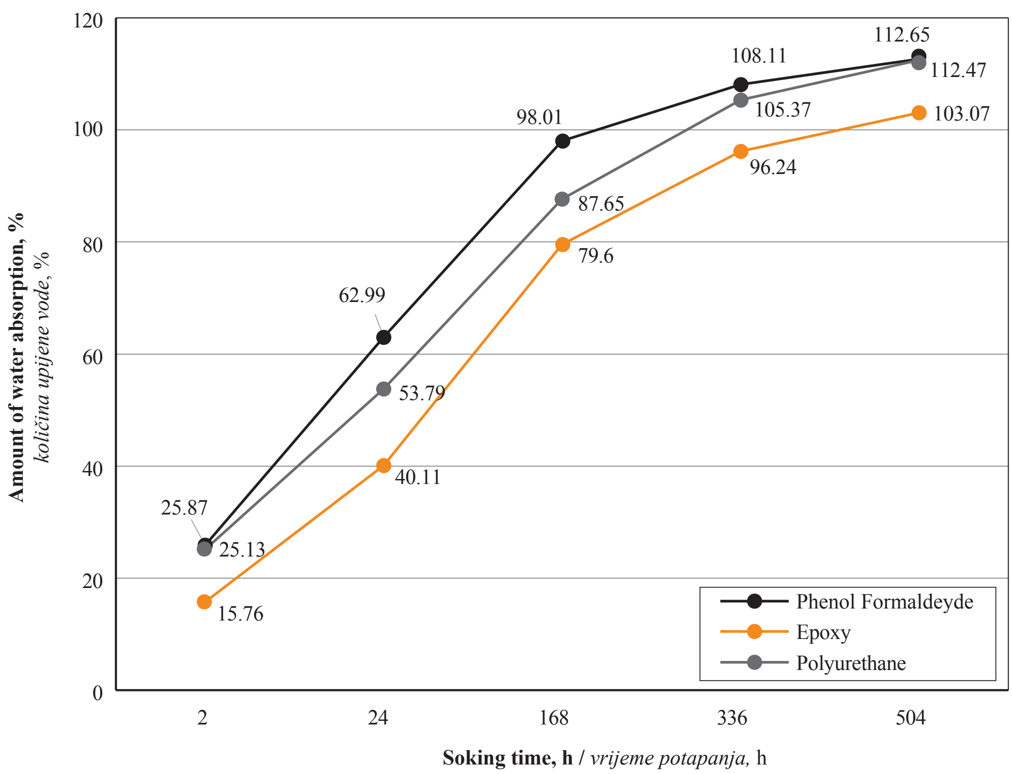

Figure 6 Interaction graph showing average water absorption of boards according to soaking time and glue type
Slika 6. Grafikon ovisnosti srednje vrijednosti upijanja vode ploča o vremenu potapanja i vrsti ljepila

significantly affected water absorption. Table 3 presents the homogeneity groups of the water absorption test result. Results showed that the group produced with phenol- formaldehyde had the highest water absorption, while the group glued with epoxy had the lowest. Similar results were reported in another study. Moradpour *et al*. (2018) reported that the boards produced with water-based UF glue absorb more water than those produced with non-water-based PMDI glue.

With the use of the reinforcement, the water absorption values of the samples decreased. The samples reinforced with glass fiber provided the lowest water absorption, while those reinforced with jute had the highest water absorption. The lower values for glass-fiber and basalt-fiber reinforced LVLs were due to their hydrophobic nature. Jute and cotton have hygroscopic natures, and their LVLs had higher water absorption values.

The reinforcement place had a significant effect. The control group had the highest water absorption value. In contrast, the third group provided the lowest water absorption values. With the increase in the number of reinforcements, water absorption decreased. Increasing the number of reinforcements also raised the amount of glue used in samples. Glue prevents water penetration into the sample, and this reduces the water absorption of the samples (Sulaiman *et al*., 2009; Wang and Chui, 2012a; Wang and Chui, 2012b).

Considering the soaking time in the water bath, water absorption values increase with the increase of the soaking time. A significant increase in water absorption value was observed until the 504th hour.

3.4 Bending strength and modulus of elasticity
3.4. Čvrstoća na savijanje i modul elastičnosti

Statistical analysis showed that glue type, reinforcement type, and reinforcement place significantly affected bending strength. Table 4 presents the homogeneity groups for bending strength test results. The results showed that the phenol-formaldehyde glued group provided the highest bending strength (102.49 MPa), while the polyurethane glued group had the lowest bending strength (83.01 MPa). Samples produced with phenol-formaldehyde and epoxy gave similar results. As phenol formaldehyde contains water, the evaporation of water in the hot press softens the veneers and causes them to compress more. This compression gives resistance to the board. Since epoxy and polyurethane glues are not water-based glues, water vapor does not occur in the hot press. The epoxy penetrates a little into the veneer compared to polyurethane, providing more compaction in the hot press. Therefore, the boards produced with polyurethane are thicker than those produced with phenol-formaldehyde and epoxy-glued LVLs, and their strength is low.

Table 5 presents the results of a simple analysis of variance test showing the effect of glue type on compaction rate. Statistical analysis showed that glue type had a significant effect on compression ratio. According to the statistical analysis results, the highest compression ratio was observed in the samples with phenol formaldehyde, while the lowest compression ratio was observed in the samples using polyurethane.

When looking at the reinforcement types, the best results were found in the samples using glass fiber (102.83 MPa), while the lowest was found in samples using cotton (91.24 MPa). Jute and cotton gave similar results. Since the strength values of glass fiber and basalt are higher than those of cotton and jute, the bending strength of the samples using glass fiber and basalt was higher. In addition, since the thickness of jute and cotton is thicker than that of glass fiber and basalt, it thickens the glue line and is thought to affect the bend-

Table 4 Duncan test results for bending strength, modulus of elasticity and compression strength parallel to grain (α = 0.05)
Tablica 4. Rezultati Duncanova testa za čvrstoću na savijanje, modul elastičnosti i čvrstoću na tlak paralelno s vlakancima (α = 0,05)

Groups / *Grupe*		**Bending strength value, MPa** *Vrijednost čvrstoće na savijanje,* MPa	**Modulus of elasticity value, MPa** *Vrijednost modula elastičnosti,* MPa	**Compression strength parallel to grain value, MPa** *Vrijednost čvrstoće na tlak paralelno s vlakancima,* MPa
Glue type *vrsta ljepila*	Phenol Formaldehyde	102.49 **a**	10934.49 **a**	59.15 **b**
	Epoxy	100.37 **a**	10484.38 **b**	61.22 **a**
	Polyurethane	83.01 **b**	9096.16 **c**	50.33 **c**
Reinforcement type *vrsta ojačanja*	Control Group	86.44 **d**	8659.43 **d**	50.71 **c**
	Glass Fiber	102.83 **a**	10835.52 **a**	59.68 **a**
	Basalt	98.62 **b**	10423.38 **b**	58.72 **a**
	Jute	91.42 **c**	10008.09 **c**	55.70 **b**
	Cotton	91.24 **c**	9923.80 **c**	55.57 **b**
Reinforcement place *položaj ojačanja*	Control Group	86.44 **c**	8659.43 **b**	50.71 **d**
	1. Group	101.89 **a**	10348.63 **a**	53.07 **c**
	2. Group	92.90 **b**	10225.61 **a**	58.72 **b**
	3. Group	93.29 **b**	10318.86 **a**	60.56 **a**

Table 5 Duncan test results for compaction rate
Tablica 5. Rezultati Duncanova testa za vrijednosti stupnja ugušćenja

Groups / *Grupe*	α=0.05		
	a	b	c
Glue type / *Vrsta ljepila*	%	%	%
Phenol Formaldehyde	17.74		
Epoxy		5.27	
Polyurethane			0.37

ing strength negatively. Figure 7 presents the images of glue lines using reinforcement. With the use of reinforcement material, the density of the bottom surface of the board increases, resulting in a raised bending strength (Figure 8).

Considering the effect of the reinforcement place, the best results were found in the first group, while the lowest bending strength was found in samples with no

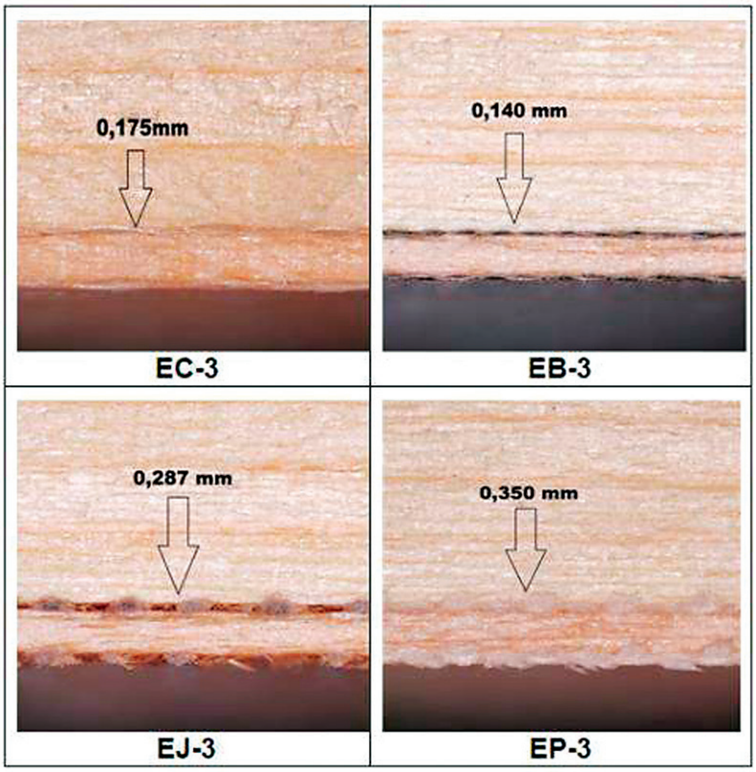

Figure 7 Image of glue line with reinforcement
Slika 7. Slika lijepljenog spoja s ojačanjem

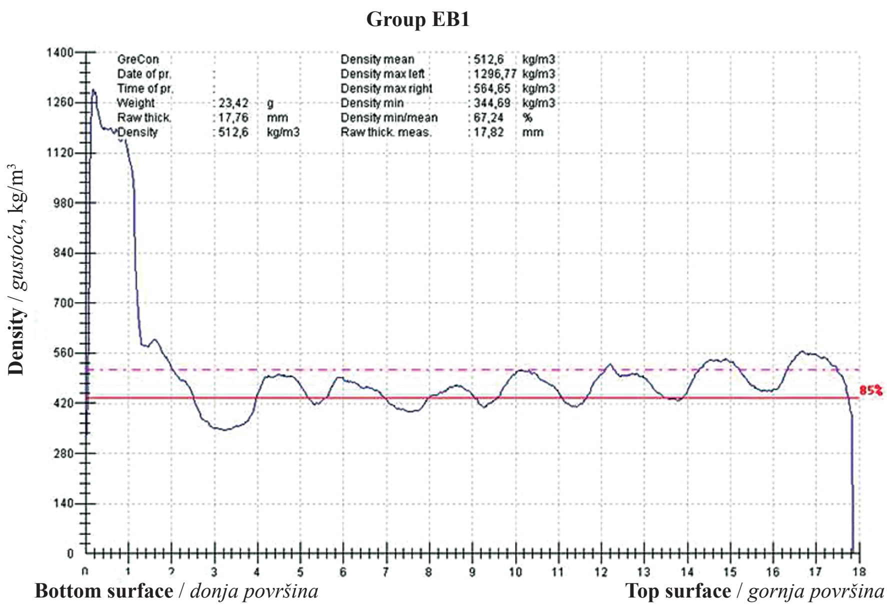

Figure 8 Density profile graph of EB1 sample
Slika 8. Grafikon profila gustoće uzorka EB1

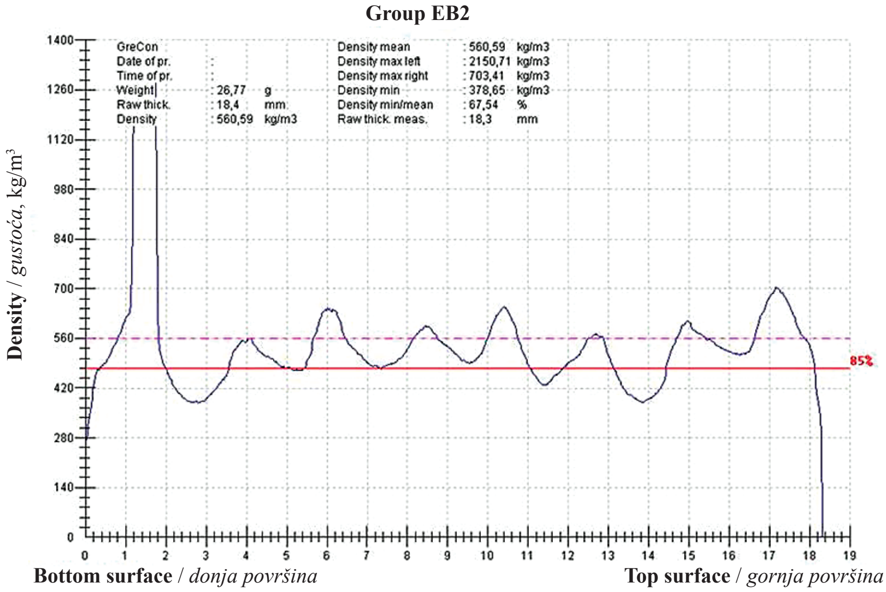

Figure 9 Density profile graph of EB2 sample
Slika 9. Grafikon profila gustoće uzorka EB2

reinforcement. The bending strength of samples in the second and third groups provided similar results. Bending strength increased with the use of reinforcement. Samples exposed to bending strength broke from the bottom surface where tensile stress occurs. Therefore, the bending strength of the first group was improved compared to the control group. In the second group, reinforced in the first glue line from the bottom of the boards, bending strength was lower than in the first group. The reinforcement material cannot prevent the deformation of the sub-veneer where cracking begins. Figure 9 presents the density profile graph. In the second group, the density of the first glue line from the bottom increased, while the density of the bottom layer where the fracture started remained low. In the third group, the bending strength increased more than in the second group. The deformation of the bottom layer, where the fracture occurs, was prevented by the reinforcement material. In a similar study, the reinforcement of the bottom surface of plywood gave better results than the ones reinforced from the upper surface (Kramar and Kral, 2019). In another study, strengthening the bottom surface with natural fibers increased the bending strength of the solid wood material (Borri *et al*., 2013).

The statistical analysis showed that the glue type and the reinforcement type significantly affected the modulus of elasticity, while the reinforcement place did not. Table 4 shows the homogeneity groups of the modulus of elasticity test result. According to the test results, the phenol-formaldehyde glued group provided the highest modulus of elasticity (10934.49 MPa), while polyurethane glued group provided the lowest modulus of elasticity (9096.16 MPa). The modulus of elasticity was low because the boards using polyurethane were less compressed in the hot press than those using phenol and epoxy and foaming in the glue line. Since phenol formaldehyde is water-based, the board is compressed more by the effect of water vapor in the hot press, improving the modulus of elasticity of the board.

Regarding the effect of reinforcement types, the best results were found in the samples using glass fiber (10835.52 MPa), while the lowest were found in the samples using cotton (9923.8013 MPa). Jute and cotton gave similar results. Since the modulus of elasticity of glass fiber and basalt itself is higher than that of cotton and jute, the modulus of elasticity of the samples using glass fiber and basalt was also higher. The reinforcement place also affected modulus of elasticity. The first, second, and third group provided similar results. However, the modulus of elasticity of the reinforced boards was significantly higher than that of the control group.

3.5 Compression strength parallel to grain
3.5. Čvrstoća na vlak paralelno s vlakancima

Statistical analysis showed that glue type, reinforcement type, and reinforcement place significantly affected compression strength parallel to the grain. Table 4 shows the homogeneity groups of the test result for compression strength parallel to the grain. According to the test results, the epoxy-glued group provided the highest compression strength parallel to grain (61.22 MPa); on the contrary, polyurethane glued group supplied the lowest compression strength parallel to grain (50.33 MPa). Since the density of the polyurethane boards (0.511 g/cm^3) was lower than that of the boards produced with phenol-formaldehyde (0.547 g/cm^3) and epoxy (0.538 g/cm^3), the compression strength parallel to grain determined for the groups was also low. In the compression strength parallel to the grain, separation occurred in the reinforcement line in

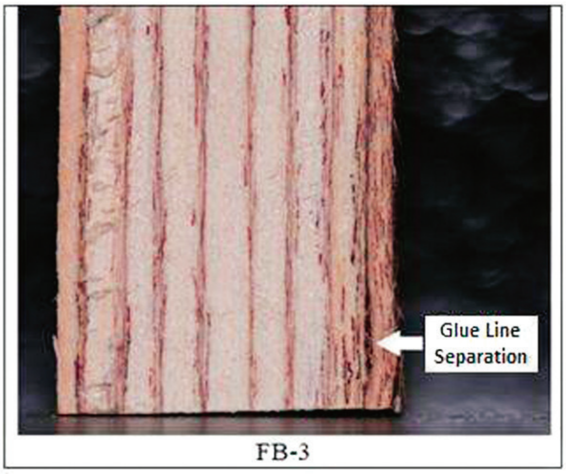

Figure 10 Glue line separation as a result of compression strength parallel to grain
Slika 10. Odljepljivanje sljubnice nakon ispitivanja čvrstoće na vlak

the phenol group samples. In contrast, no separation from the reinforcement in the epoxy-glued group was observed (Figure 10).

When considering the reinforcement types, the best results were found in the samples using glass fiber and basalt, while the lowest ones were found in samples using cotton and jute. Since the glass fiber and basalt thickness is less than that of cotton and jute, the glue line thickness of the samples using glass fiber and basalt was thinner and had higher densities resulting in an increased compression strength parallel to the grain.

Considering the effect of the reinforcement place, the third group provided the best results (60.56 MPa), while the unreinforced control group had the lowest compression strength parallel to the grain. With the increase in the number of reinforcements used, the density of the board increases, as well as the compression strength parallel to the grain. The density of the glue line using the reinforcement material increases, and as this density increases and approaches the middle point of the board, the compression strength parallel to the grain increases, too. For this reason, the compression strength parallel to the grain of the second group was higher than that of the first group.

4 CONCLUSIONS
4. ZAKLJUČAK

This study investigated the effects of three different glue types, four reinforcement types, and three reinforcement places on the physical and mechanical properties of LVL.

As a result of the study, the following conclusions were made:

Among them, phenol-formaldehyde (FF) glued LVLs had the highest density compared to other glues. Regardless of the type, reinforcement increased the density of the resulting samples.

The epoxy-glued samples had the lowest equilibrium moisture, while phenol- formaldehyde glued samples had the highest ones. In addition, samples having jute and cotton reinforcement had higher equilibrium moisture than the ones reinforced with glass fiber and basalt.

Epoxy-glued samples provided the lowest thickness swelling, while the reinforcement increased thickness swelling. The jute reinforcement resulted in the highest increase in thickness swelling.

Epoxy-glued samples had the lowest water absorption, while phenol- formaldehyde-glued samples had the highest ones. With the use of reinforcement, the amount of water absorption decreased.

The samples reinforced with glass fiber and glued with phenol-formaldehyde provided the highest bending strength. The samples produced with phenol-formaldehyde and epoxy provided statistically similar bending strength properties. Also, reinforcement increased the bending strength of the boards. The reinforcement at the tension surface of the sample provided the highest bending strength.

For the modulus of elasticity, samples glued with FF provided the highest value, while those glued with polyurethane had the lowest value. The modulus of elasticity of the samples increased with reinforcement.

The epoxy-glued samples provided the highest compression strength parallel to the grain when using glass fiber and basalt. The compression strength parallel to the grain increased with the number of reinforcements.

Acknowledgements – Zahvala

This study was supported by the Scientific Research Projects Coordination Unit of Kahramanmaras Sutcu Imam University.

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