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Production of Lightweight Three-Layered Particleboards Using Waste Tire Rubbers

Proizvodnja laganih troslojnih iverica iskorištenjem otpadnih autoguma

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ABSTRACT • *The aim of the study is to investigate the production possibilities of particleboard by using waste tire rubbers with different properties as fillers and find a solution to a serious environmental pollution problem caused by waste tires. For this purpose, waste summer and winter tires were ground, rubber powders were obtained by separating rubber materials from other materials, and particleboards with different properties were produced using this sawdust in different percentages. The oven-dry density, air-dry density, and equilibrium moisture content at (65±5) % RH and (20±2) °C, thickness swelling (TS, 2 hours and 24 hours), water absorption (WA, 2 hours and 24 hours) characteristics, bending strength, modulus of elasticity, and internal bond strength were determined according to the applicable European standards. The hydrophobic nature of the tire rubber enhanced the water absorption ratios of particleboards. In addition, mechanical performance of groups was affected by tire content, and it was mainly determined that the values decreased dramatically with increasing tire content. It was especially observed that this decrease was more pronounced when subtracting 30 % to 20 % waste tire content. The groups including winter waste tire rubber achieved better performance than summer waste tire groups. The use of waste rubber in boards resulted in a decrease in the equilibrium moisture content and mechanical strength of the samples.*

KEYWORDS: *mechanical properties, particleboard, physical properties, waste summer tire, waste winter tire*

SAŽETAK • *Cilj ovog rada bio je istražiti mogućnosti proizvodnje ploča iverica iskorištenjem otpadnih autoguma različitih svojstava kao punila te pronalaženje rješenja za ozbiljno onečišćenje okoliša otpadnim autogumama. Za potrebe eksperimenta samljevene su otpadne ljetne i zimske autogume, a odvajanjem gumenih od negumenih dijelova dobiven je prah gume, koji se u različitim omjerima upotrebljavao za proizvodnju ploča iverica različitih svojstava. Prema europskim standardima određena su ova svojstva ploča iverica: gustoća u apsolutno suhom i prosušenom stanju, relativni sadržaj vode pri (65±5) RH i (20±2) °C, debljinsko bubrenje (TS, nakon 2 sata i 24 sata) i upijanje vode (WA, nakon 2 sata i 24 sata). Zbog hidrofobne prirode praha autoguma povećani su omjeri upijanja vode ploča iverica. Osim toga, udjel dodane količine praha autoguma utjecao je na mehanička svojstva ploča iverica te je utvrđeno da se te vrijednosti drastično smanjuju s povećanjem količine praha autoguma u pločama. Posebno je naglašeno smanjenje mehaničkih svojstava ploča iverica kada udio praha autoguma prijeđe 20 %. Uzorci ploča iverica s prahom od zimskih guma imali su bolja svojstva od uzoraka s prahom od ljetnih guma. Uporaba otpadnih autoguma u proizvedenim ivericama rezultirala je smanjenjem ravnotežnog sadržaja vode i mehaničke čvrstoće uzoraka.*

KLJUČNE RIJEČI: *mehanička svojstva, ploča iverica, fizička svojstva, otpadna ljetna guma, otpadna zimska guma*

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1 INTRODUCTION
1. UVOD

Wood is one of the most commonly used natural raw materials for various applications ranging from power generation to construction panels. This variety in the usage of wood materials increases the need for raw materials. As a result, problems related to intensive natural resources and environmental issues increase gradually (Couto *et al.,* 2013).

Waste tires are generally burned or left uncontrolled at landfills, but nature is not coping with the consequences of its devastation (Svoboda *et al.,* 2018; Dwivedi *et al.,* 2020). The primary reason of this problem is a change in the physical and chemical structure of tires resulting from production goals such as extended service life, safety, noise reduction, and unforeseen changes due to unknown alterations performed by manufacturers in production recipes. Furthermore, the three-dimensional cross-linked structure generated by the irreversible vulcanization process makes scrap tires a durable and non-biodegradable material in the face of various environmental influences. As a result, the issue of the inability to manage waste tires has long been a source of concern for scientists, industry representatives, and governments (Ayrilmis *et al.,* 2009a; Hejna *et al.,* 2020). In order to solve this problem, different recycling methods and usage areas for waste tires should be developed (Saputra *et al.,* 2020; Formela, 2021).

Recycled rubber materials are already utilized in the rubber manufacturing industry following appropriate cleaning, repair, or refining operations (Xu *et al.,* 2020). In addition, waste tires may also be utilized in various sectors, including matting, waterproofing systems, membrane linings, artificial reefs, sports fields, and erosion control (Ramarad *et al.,* 2015; Svoboda *et al.,* 2018; Xu *et al.,* 2020). However, these utilization sectors were judged insufficient to limit the number of tires found in landfills and thrown on fields at random (Martínez-Barrera *et al.,* 2020).

In 2015, the Turkish Ministry of Environment and Urbanization reported that 315.000 metric-ton scrap tires were sold to the recycling sector. Furthermore, it has been reported that around 300,000 tons of trash tires are generated in Türkiye each year (Başboğa *et al.,* 2020). For this reason, it is urgently necessary to develop different applications for the evaluation of waste tires (Ayrilmis *et al.,* 2009a).

In addition to conventional recycling processes, one of the innovative approaches to solving this problem is to create new composites using various polymers or polymer combinations from waste tires as filling/reinforcing components (Dwivedi *et al.,* 2020; Hejna *et al.,* 2020).

In contrast to isotropic materials such as concrete and steel, wood materials have greater mechanical behavioral complexity because they are an anisotropic material (Pereira *et al.,* 2019). Wood-based boards are more isotropic composite materials than solid wood, produced by bonding different shaped pieces of wood under pressure and at high temperatures (Mesquita *et al.,* 2019). These high temperatures used in the production of wood-based composite boards cause a decrease in the hygroscopicity of the materials (López *et al.,* 2018). Improving the dimensional stability of wood-based panels such as particleboard and the development of water-resistant wood composites have long been the target of wood technology experts and the industry (Mesquita *et al.,* 2019).

In this regard, waste tire rubbers are a promising alternative raw material in terms of usability in wood-based composites with many advantages such as high durability against chemicals and fungi, high energy absorption, high elasticity, etc. (Ayrilmis *et al.,* 2009a; Ayrilmis *et al.,* 2009b; Terzi *et al.,* 2009; Ashori *et al.,* 2015; Ghofrani *et al.,* 2016). It was reported that the addition of rubber to wood composites positively affected shock absorbing, energy absorbing, water repellent, anti-rot, and electrical insulation properties (Vilela *et al.,* 2017; Xu *et al.,* 2020) and negatively affected mechanical properties (Hejna *et al.,* 2020).

The aim of the study is to investigate the production possibilities of particleboard by using waste tire rubbers with different properties as fillers and find a solution to a serious environmental pollution problem caused by waste tires. In addition, it is aimed to reduce the need for wood raw material in the particleboard industry. For this purpose, waste summer and winter tires were ground, rubber powders were obtained by separating rubber materials from other materials, and particleboards with different properties were produced using this sawdust in different percentages. Experimental samples were cut from the produced particleboards and related experiments were carried out.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

In the study, continental™ brand summer and winter tires, which have completed their useful life, were used. Used tires were removed from steel wires and ground into a fine powder (size of powders were from 0.11 mm to 2 mm as shown in Table 1) at the recycling factory. This powdered material was then mixed with wood chips and used to make particleboard. The core and surface layer chips (size distributions shown in Table 1) used in production, urea-formaldehyde glue with

Table 1 Size distribution of wood chips and waste tire powders
Tablica 1. Distribucija veličine drvnog iverja i praha od otpadnih autoguma

Sieve size *Veličina sita*	**Surface layer chips, %** *Iverje površinskog sloja, %*	**Sieve size** *Veličina sita*	**Core layer chips, %** *Iverje središnjeg sloja, %*	**Sieve size** *Veličina sita*	**Summer tire powders, %** *Prah od ljetnih guma, %*	**Winter tire powders, %** *Prah od zimskih guma, %*
4 mm	0.00	6.3 mm	0.00	2 mm	0.00	0.00
2 mm	1.00	4 mm	5.00	0.84 mm	5.10	4.80
1 mm	5.00	2 mm	40.00	0.59 mm	8.80	9.80
0.8 mm	7.00	1 mm	35.00	0.42 mm	23.70	25.20
0.6 mm	10.00	0.8 mm	7.00	0.25 mm	28.10	27.60
0.4 mm	30.00	0.5 mm	5.00	0.18 mm	13.50	11.40
0.315 mm	20.00	0.315 mm	3.00	0.15 mm	9.60	13.50
0.2 mm	15.00	0.2 mm	2.00	0.13 mm	6.80	4.50
0.1mm	10.00	0.1mm	2.00	0.11 mm	3.80	2.75
< 0.1 mm	2.00	< 0.1 mm	1.00	< 0.11mm	0.60	0.45

65 % solids content, and ammonium chloride (NH_4Cl) hardeners prepared with water as a 20 % solution, were all supplied by the Kastamonu Entegre™ company. After the chips were taken from the dry chip silo with a humidity of 3-5 %, they were placed in nylon bags to prevent moisture absorption.

2.2.1 Production of test samples
2.2.1. Proizvodnja ispitnih uzoraka

The average density of the particleboards was targeted at 500 kg/m^3, and in line with this target, the amounts and ratios of chip-waste rubber-resin-hardener were calculated from the Equation 1 to 3 according to the volume of the press mold measuring 500 mm × 500 mm × 18 mm, and the production was carried out on these calculated values.

$$d\ target \times V\ mold = m\ oven\ dry\ chips + m\ solid\ content\ adhesive + m\ solid\ content\ hardener \quad (1)$$

$$m\ solid\ content\ adhesive = 0.10\ m\ oven\ dry\ chips \times solid\ content\ of\ adhesive \quad (2)$$

$$m\ solid\ content\ hardener = 0.01\ m\ oven\ dry\ chips \times solid\ content\ of\ solution \quad (3)$$

Surface and core layer chips or chips- waste tire mixtures were added to a drum gluing mixer separately. The urea-formaldehyde resin was applied in 10 %, and the ammonium chloride solution was applied in 1% based on the weight of oven-dried chips. The mixture (resin and hardener) was applied separately to the surface layers and core layer of the chip-waste tire mixture by spraying with the help of compressed air in a 100 lt sample volume drum gluing mixer (no brand, Kastamonu Türkiye) with two points injection, and 5 rpm rotating speed. Gluing machine and chips blend are given in Figure 1. In addition, the use of chip-waste rubber in test board production also varies, and the chip-waste tire mixture ratios used in test board production are given in Table 2.

The glued chips were laid out by hand as surface layer + core layer + surface layer, paying attention to the equal distribution in the press mold. Next, the pre-cold pressing process was applied to the prepared board draft by applying a pressure of around 1 kN. Then, the prepared board draft was applied to hot pressing for 10 minutes, including the heating time of the loading press platens, at a temperature of 190 ºC

Table 2 Tire and wood mixture ratios in board production
Tablica 2. Omjeri praha guma i drvnog iverja u proizvodnji ploča

Groups *Grupe*	**Surface/core/surface layer ratio, %** *Površinski sloj /središnji sloj / površinski sloj, %*	**Wood chip ratio, %** *Udio drvnog iverja, %*	**Summer tire (*S*) waste ratio, %** *Udio praha otpadnih ljetnih autoguma (S), %*	**Winter tire (*W*) waste ratio, %** *Udio praha otpadnih zimskih autoguma (W), %*
Control *Kontrolni uzorak*	20-60-20	100	0	0
S 10		90	10	0
S 20		80	20	0
S 30		70	30	0
S 40		60	40	0
W 10		90	0	10
W 20		80	0	20
W 30		70	0	30
W 40		60	0	40

Figure 1 A) Gluing machine, B) Surface layer blend, C) Core layer blend
Slika 1. A) Oprema za obljepljivanje iverja, B) smjesa za površinski sloj, C) smjesa za središnji sloj

Figure 2 A) Hot press and mold, B) W 10 group samples, C) S 40 group samples
Slika 2. A) Vruća preša i kalup, B) skupina uzoraka W 10, C) skupina uzoraka S 40

and a pressure of 20 kg/cm^2. Cemilusta brand SSP 125 model (İstanbul, Türkiye) hot press was used in the production. Three boards were produced for each group. Hot press and test samples are given in Figure 2.

After pressing, the particleboards were kept in a Protech brand climate chamber (Antalya, Türkiye) adjusted to (65±5) % humidity and (20±2) ºC until they reached a constant weight and reached air-dry humidity after cooling.

2.2 Methods
2.2. Metode

According to EN 322 (1999) and EN 323 (1999), the oven-dry density, air-dry density, and equilibrium moisture content at (65±5) % RH and (20±2) ºC were determined. The EN 317 (1999) standard was used to measure the thickness swelling (TS, 2 hours and 24 hours) and water absorption (*WA*, 2 hours and 24 hours) characteristics. Bending strength and modulus of elasticity properties were determined by using Shimadzu (Made in Japan) brand AG/IC 50KN model universal test machine according to EN 310 (1999), and the EN 319 (1999) standard was used for determining internal bond strength. Mitutoyo brand digital micrometers with 0.01 mm graduations were used to measure the thickness and length of all test samples. Nucleon brand NKD-400 model oven (Ankara, Türkiye) was used to dry the samples. Mass of specimens was measured by using Radwag brand WTB 200 model laboratory scales. All experiments were performed in the Wood Mechanics and Technology Laboratories, Forest Faculty of Kastamonu University. To perform descriptive statistics, SPSS Version 22.0 software was used.

A stereo microscope and scanning electron microscope (SEM) were used to examine the structure of the panels. The stereo microscope was an Olympus SZ61 (Tokyo, JAPAN), equipped with a digital microscope camera and a magnification range from 6.7x to 45x. A Quanta FEG 250 (FEI, USA) was used for SEM analysis, and after that the particleboards were coated with a thin layer of gold to improve surface resolution of the boards using a Cressington Sputter Coater 108 Auto Au-Pd Coating Machine, at Kastamonu University Central Research Laboratory, under 40 mA for 30 seconds.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Physical properties
3.1. Fizička svojstva

The determined physical properties and standard deviations of the produced boards are shown in Table 3. As a result of the experiments, the average dry density (d_{Dry}) of the produced particleboards was 520 kg/m^3. The average air-dry density ($d_{Air\ Dry}$) was 540 kg/m^3. It was concluded that the targeted density objective was mostly met. When the data was examined, it was observed that the highest equilibrium moisture was 9.1 % in the control samples. Depending on the amount of waste tire rubber contained in the boards, there was a decrease in the air-dry equilibrium moisture of the samples. The

Table 3 Physical properties of boards with a standard deviation
Tablica 3. Fizička svojstva ploča (u zagradi su standardne devijacije)

Groups *Skupine*	d_{Dry} kg/m^3	$d_{Air\ Dry}$ kg/m^3	**Equilibrium moisture, %** *Ravnotežni sadržaj vode, %*	***TS* 2 hours, %** *TS nakon 2 sata %*	***TS* 24 hours, %** *TS nakon 24 sata %*	***WA* 2 hours, %** *WA nakon 2 sata %*	***WA* 24 hours, %** *WA nakon 24 sata %*
Control	528.32 (20.07)	554.13 (20.81)	9.09 (0.21)	17.23 (0.99)	18.46 (1.33)	107.42 (5.69)	110.66 (6.07)
S 10	522.75 (12.44)	543.86 (9.98)	8.12 (1.29)	15.48 (1.61)	16.84 (1.66)	101.80 (4.98)	108.18 (5.79)
S 20	514.24 (38.03)	536.17 (40.10)	8.29 (0.28)	13.09 (1.16)	14.16 (1.34)	90.62 (5.43)	95.44 (5.42)
S 30	506.05 (24.58)	521.90 (24.41)	6.74 (0.08)	9.02 (0.65)	9.48 (0.53)	88.96 (4.75)	93.50 (4.09)
S 40	542.19 (13.21)	574.12 (23.88)	6.12 (0.13)	7.68 (1.09)	8.84 (0.82)	72.26 (8.27)	83.48 (6.71)
W 10	503.39 (6.93)	528.17 (9.38)	8.89 (0.41)	13.71(1.44)	15.37 (1.30)	97.57 (4.40)	101.05 (3.88)
W 20	504.02 (15.91)	522.94 (15.79)	7.46 (0.10)	10.61 (1.19)	12.09 (1.32)	83.80 (5.36)	92.06 (3.52)
W 30	529.55 (17.54)	544.94 (19.36)	6.88 (0.52)	10.15 (1.29)	11.59 (1.59)	74.42 (4.33)	84.21 (3.74)
W 40	525.38 (15.76)	539.25 (15.83)	5.99 (0.23)	6.88 (0.73)	7.45 (1.02)	89.94 (7.37)	94.29 (6.31)

Table 4 Results of variance analysis of thickness swelling
Tablica 4. Analiza varijance rezultata debljinskog bubrenja

Experiment *Eksperiment*	**Source** / *Izvor*	**Type III Sum of squares** *Zbroj kvadrata, tip III*	***df***	**Mean square** *Srednji kvadrat*	***F***	***Sig.***
2 hours *TS*, % *nakon 2 sata TS*, %	Waste type (A) /*vrsta otpada (A)*	22.795	1	22.795	15.390	.000
	Ratios (B) /*udjeli (B)*	704.459	3	234.820	158.540	.000
	Waste type * Ratios (A*B) *vrsta otpada * udjeli (A*B)*	44.209	3	14.736	9.949	.000
	Error / *pogreška*	146.632	99	1.481		
	Total / *ukupno*	15740.310	108			
24 hours TS, % *nakon 24 sata TS*, %	Waste type (A) / *vrsta otpada (A)*	11.948	1	11.948	6.920	.010
	Ratios (B) / *udjeli (B)*	843.293	3	281.098	162.810	.000
	Waste type * Ratios (A*B) *vrsta otpada * udjeli (A*B)*	65.133	3	21.711	12.575	.000
	Error / *pogreška*	170.928	99	1.727		
	Total / *ukupno*	18951.260	108			

lowest equilibrium moisture was in the winter tire group, with 40 % of waste tires. No correlation was observed between fully dry densities and moisture.

It was observed that the percentage of thickness swelling of the samples after soaking in water for 2 hours was at most 17.23 % in the control group, and for 24 hours, it was at the highest of 18.46 % in the control group. Therefore, to understand whether there was a statistically significant difference between the 2-hour and 24-hour thickness swelling results of the groups in Table 2, the results of the variance analysis are shown in Table 4, and the homogeneity results of the groups according to the Duncan analysis are shown in Table 5.

When the results of the analysis of variance were examined, it was seen that the tire type and tire amount have a combined effect on the changes in the thickness swelling values after 2 hours and 24 hours in water. As a result of the DUNCAN analysis, it was observed that there was a significant difference in the 95 % confidence interval between the control group, the summer group, and the winter groups in the samples kept in water for 2 hours. According to the analysis, swelling to the lowest thickness was observed in the groups using waste winter tires, while swelling to the maximum thickness was observed in the control groups.

When analyzing Table 4, it was observed that there was a significant difference in the 95 % confidence level between the groups as the amount of waste tire increased. However, after the 24-hour thickness swelling test, there was no significant difference in the

Table 5 Duncan's results of thickness swelling value
Tablica 5. Rezultati Duncanova testa debljinskog bubrenja

	Waste type / *Vrsta otpada*			**Mixture ratio** / *Omjer smjese*				
	Control *kontrolni uzorak*	Summer *ljetne*	Winter *zimske*	0 %	10 %	20 %	30 %	40 %
2 hour *TS*, % / *nakon 2 sata TS*, %	A	B	C	A	B	C	D	E
24 hour *TS*, % / *nakon 24 sata TS*, %	A	B	B	A	B	C	D	E

Table 6 Results of WA variance analysis
Tablica 6. Analiza varijance rezultata upijanja vode

Experiment *Eksperiment*	**Source** / *Izvor*	**Type III Sum of squares** *Zbroj kvadrata, tip III*	***df***	**Mean square** *Srednji kvadrat*	***F***	**Sig.**
2 hours *TS*, % *nakon 2 sata TS, %*	Waste type (A) / *vrsta otpada (A)*	93.622	1	93.622	2.586	.111*
	Ratios (B) / *udjeli (B)*	5357.367	3	1785.789	49.323	.000
	Waste type * Ratios (A*B) *vrsta otpada * udjeli (A*B)*	3436.747	3	1145.582	31.641	.000
	Error / *pogreška*	3584.393	99	36.206		
	Total / *ukupno*	884659.506	108			
24 hours *TS*, % *nakon 24 sata TS, %*	Waste type (A) / *vrsta otpada (A)*	121.518	1	121.518	4.127	.045
	Ratios (B) / *udjeli (B)*	3969.748	3	1323.249	44.938	.000
	Waste type * Ratios (A*B) *vrsta otpada * udjeli (A*B)*	1470.487	3	490.162	16.646	.000
	Error / *pogreška*	2915.190	99	29.446		
	Total / *ukupno*	1004140.459	108			

*Not significant $p < 0.05$ / *nije značajno za p < 0,05*

Table 7 Duncan's results of WA value
Tablica 7. Rezultati Duncanova testa upijanja vode

	Waste type / *Vrsta otpada*			**Mixture ratio** / *Omjer smjese*				
	Control *kontrolni uzorak*	Summer *ljetne*	Winter *zimske*	0 %	10 %	20 %	30 %	40 %
2 hours *TS*, % / *2 sata TS, %*	-	-	-	A	B	C	D	D
24 hours *TS*, % / *24 sata TS, %*	A	B	B	A	B	C	D	D

95 percent confidence interval between the summer and winter groups. The 95 percent confidence range decreased significantly as the amount of waste tire increased in both values.

The results of groups of 2-hour and 24-hour water absorption in Table 2 were analyzed with a variance test. The results of the variance test are shown in Table 6, and the homogeneity results of the groups according to the Duncan analysis are shown in Table 7. At the 95 percent confidence level, there was no statistically significant difference between tire types and control groups for 2-hour water absorption values, according to the analysis of variance. However, at the 95 percent confidence level, both the tire ratio and the intersection of the tire type and tire ratio have a statistically significant influence on the 2-hour water absorption values. The tire type, ratio, and interaction are statistically successful in the 95 percent confidence interval for the 24-hour test findings.

When the statistical distribution of the groups was investigated, it was discovered that as the number of waste tires increased, the weight gain percentages dropped. There was no statistically significant difference in the 95 percent confidence interval between the groups with 30 % and 40 % waste tire additives.

Thickness swelling in the samples showed a decrease between 8.77 % and 59.64 % compared to the control group. Weight gains decreased between 2.24 % and 24.56 %. When the studies in the literature were examined, the strength of the samples to water intake increased due to the increase in the percentage of rubber powders in the particleboard sample. The swelling values of particleboards to their thickness were between 14 % and 53 % lower than those of the control group (Ayrilmis *et al.,* 2009b). In addition, the average thickness swelling values of OSBs with rubber powder were determined to be between 11.4 % and 32.2 % lower than the values obtained from the control sample. It was stated that this decrease was between 16.4 % and 42.1 % with the use of polyisocyanate glue in another study (Ayrilmis *et al.,* 2009a). In addition, the study results showed significant improvements in the water absorption strength and thickness swelling properties of the samples depending on the increase in the waste tire powder ratio in the model (Ashori *et al.,* 2015; Abasi *et al.,* 2018).

3.2 Bending strength (*MOR*) and modulus of elasticity of bending (*MOE*)
3.2. Čvrstoća na savijanja (*MOR*) i modul elastičnosti (*MOE*)

Table 8 shows the results of the evaluated mechanical properties of the particleboard groups, while Tables 9 and 10 provide the results of variance analysis and Duncan's evaluation of the research.

Control samples showed the highest mechanical performance, according to Table 8. The second-best performance was 10 % added winter tire group, and generally, the mechanical performance of particleboards decreased with increasing tire content. A sig-

Table 8 Mechanical properties of boards with a standard deviation
Tablica 8. Mehanička svojstva ploča (u zagradi su standardne devijacije)

Groups	**Bending strength (*MOR*), N/mm²** *Čvrstoća na savijanje, (MOR), N/mm²*	**Modulus of elasticity (*MOE*), N/mm²** *Modul elastičnosti, (MOE), N/mm²*	**Internal bonding (*IB*), N/mm²** *Čvrstoća na raslojavanje, (IB), N/mm²*
Control *Kontrolni uzorak*	5.14 (0.69)	1100.33 (119.33)	0.33 (0.02)
S 10	3.63 (0.34)	807.11 (52.34)	0.26 (0.04)
S 20	2.77 (0.24)	629.25 (55.91)	0.22 (0.03)
S 30	2.10 (0.27)	460.15 (59.71)	0.20 (0.03)
S 40	1.60 (0.25)	310.82 (37.94)	0.15 (0.01)
W 10	4.88 (0.38)	973.75 (64.28)	0.32 (0.05)
W 20	4.41 (0.29)	902.77 (70.85)	0.31 (0.02)
W 30	2.72 (0.19)	661.84 (64.66)	0.22 (0.02)
W 40	2.46 (0.23)	454.36 (30.72)	0.23 (0.03)

Table 9 Results of mechanical properties variance analysis
Tablica 9. Analiza varijance rezultata mehaničkih svojstava

Experiment *Eksperiment*	**Source** / *Izvor*	**Type III Sum of squares** *Zbroj kvadrata, tip III*	***df***	**Mean square** *Srednji kvadrat*	***F***	**Sig.**
MOR	Waste type (A) / *vrsta otpada (A)*	21.470	1	21.470	156.180	.000
	Ratios (B) / *udjeli (B)*	57.347	3	19.116	139.052	.000
	Waste type * Ratios (A*B) *vrsta otpada * udjeli (A*B)*	2.688	3	.896	6.517	.001
	Error / *pogreška*	9.898	72	.137		
	Total / *ukupno*	1009.343	81			
MOE	Waste type (A) / *vrsta otpada (A)*	693958.038	1	693958.038	140.958	.000
	Ratios (B) / *udjeli (B)*	2712510.255	3	904170.085	183.657	.000
	Waste type * Ratios (A*B) *vrsta otpada * udjeli (A*B)*	43449.679	3	14483.226	2.942	.039
	Error / *pogreška*	354466.807	72	4923.150		
	Total / *ukupno*	45121340.646	81			
IB	Waste type (A) / *vrsta otpada (A)*	.060	1	.060	34.587	.000
	Ratios (B) / *udjeli (B)*	.143	3	.048	27.466	.000
	Waste type * Ratios (A*B) *vrsta otpada * udjeli (A*B)*	.016	3	.005	3.137	.031
	Error / *pogreška*	.125	72	.002		
	Total / *ukupno*	5.847	81	5.847		

nificant decrease in bending strength and modulus of elasticity was determined when the waste tire content exceeded 20 %. Generally, the winter tire groups have higher mechanical performance than the summer tire groups, according to Table 8. The waste tire type, waste tire content, and interactions significantly affect bending strength, modulus of elasticity, and internal bonding. The mechanical performance of the particleboards was observed with significant differences ($\alpha = 0.05$) according to the DUNCAN test (Table 10) and it was proved that mechanical performance decreased with increasing tire content.

As a result, it was observed that there was a decrease between 5.06 % and 68.87 % in the bending strength of the samples compared to the control samples and a reduction between 11.50 % and 71.75 % in the modulus of elasticity. It was reported that the bending strength and modulus of elasticity of particleboards

Table 10 Duncan's results of mechanical properties
Tablica 10. Rezultati Duncanova testa mehaničkih svojstava

	Waste type / *Vrsta otpada*			**Mixture ratio** / *Omjer smjese*				
	Control / *kontrolni uzorak*	Summer / *ljetne*	Winter / *zimske*	0 %	10 %	20 %	30 %	40 %
MOR	A	C	B	A	B	C	D	E
MOE	A	C	B	A	B	C	D	E
IB	A	C	B	A	B	C	D	D

and plywood decreased as the percentage of rubber powder in the sample increased. In the literature, the average bending strength values of the samples were found to be between 13 and 58 percent lower than the values of the control samples (Ayrilmis *et al.*, 2009b; Abasi *et al.,* 2018). A similar decreasing trend was shown in the bending strength and modulus of elasticity of the samples.

It was reported that winter tire rubbers contain pores in their structure. These pores absorb the water film formed on the road surface due to sun or contact pressure that causes snow melting. In addition, it was stated that winter tires have different hysteresis properties from summer tires due to the different polymer structure and additives content (Dörrie *et al.,* 2010; Ludvigsen, 2017). Therefore, it was thought that the bending strength and modulus of elasticity of the samples produced from winter tire wastes are higher than those of the summer tire group due to the formation of a stronger bond between glue-chip and waste tire. On the other hand, the Poisson's ratio of rubber is close to 0.5; this indicates that the rubber material is almost incompressible in bulk. Therefore, changing the ratios between wood chips and rubber powders negatively affects the bending strength of the particleboard (Ayrilmis *et al*., 2009b).

A decrease between 4.51 % and 54.66 % was observed in the internal bonding values compared to the control samples. It was stated that there was a significant decrease due to the increase in the percentage of tire content in the board, the average internal bonding values of OSB panels being between 17.6 % and 48.5 % lower than the values of the control samples (Ayrilmis *et al.,* 2009a). The reason for this situation was that the strength of the chip was not sufficient due to the concentration of the tensile force applied to the sample in the rubber chip, which has low strength properties. This situation causes a significant decrease in the internal bonding values of the samples (Ayrilmis *et al.,* 2009b).

The incorporation of waste tire particles into the polymer matrix often results in the deterioration of the mechanical performance of the materials because of insufficient interfacial interaction between the matrix and the filler (Ramarad *et al.,* 2015; Xu *et al.,* 2020). In addition, it was stated that the increase in porosity in the structure causes a decrease in the strength of the boards (Nazerian *et al.,* 2020). The porosity in the board structure and microstructure can be seen in Figure 3 and Figure 4. In Figure 3, waste tire powders can be seen with the naked eye within the board structure. It can also be seen that the core layer porosity is significantly higher than that of the control group. Similarly, it was observed that the rubber powders showed an uneven distribution among the wood chips in the surface layer. The SEM photographs in Figure 4 show that there are incompatibility and local micro gaps between the wood and rubber structures in the microstructure compared to the control group. On the other hand, it was reported that unmodified waste tire powders are mostly non-polar and contain few functional groups in the surface layer necessary for bonding (Hejna *et al.,* 2020). For this reason, it was stated that it would be very beneficial to create various functional groups on the waste tire powder surfaces that could increase the interfacial interactions between the continuous and dispersed phases (Hejna *et al.,* 2020). For this purpose, it was recommended to add a suitable coupling agent to the waste tire powders and thus modify or improve these wood particles. To enhance mechani-

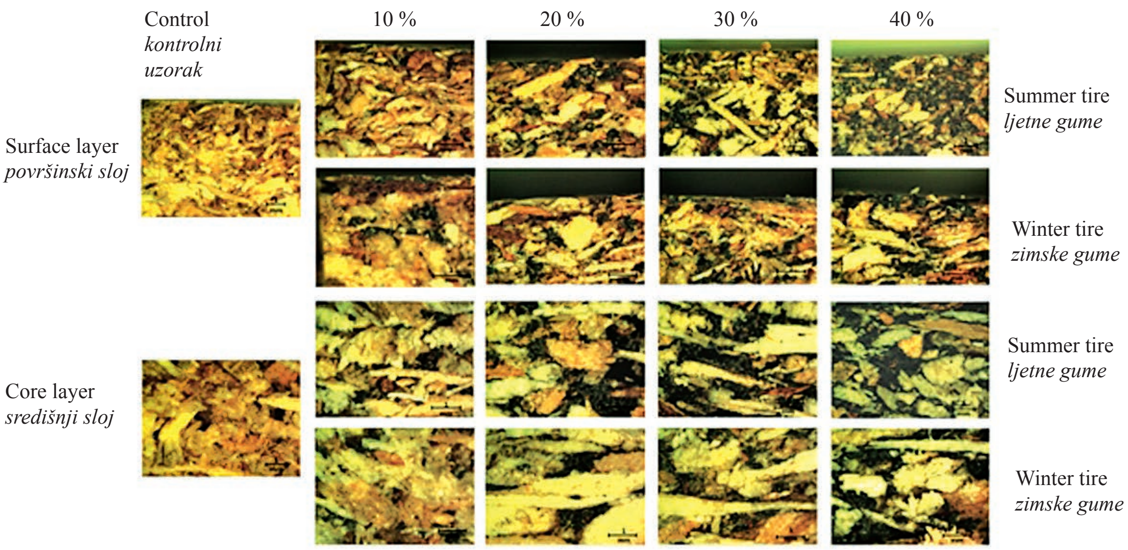

Figure 3 Stereo microscope examination
Slika 3. Pregled stereomikroskopom

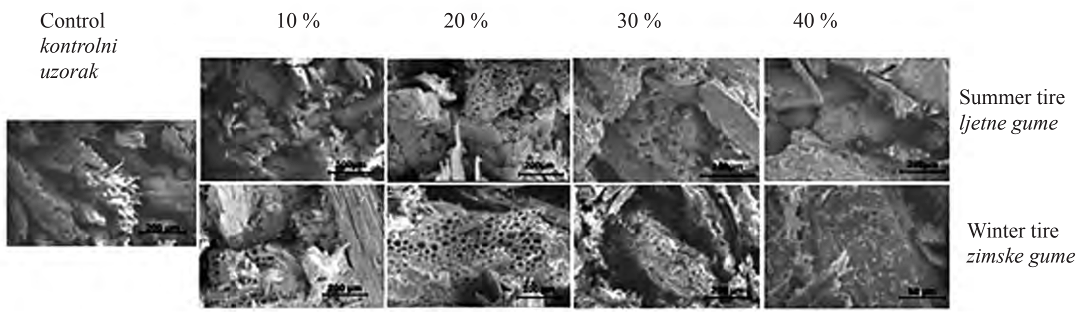

Figure 4 Scanning electron microscope (SEM) examination
Slika 4. Pregled pretražnim elektronskim mikroskopom (SEM)

cal strength, it would be recommended to use chemicals such as maleic anhydride or glycidyl methacrylate as binders in future studies. (Wang *et al.,* 2003). On the other hand, an excessive increase in press temperature can reduce the strength of fiber components. Therefore, it would be recommended to increase the press time as an alternative to higher press temperature to guarantee a complete cure of the resin (Nazerian *et al.,* 2020).

4 CONCLUSIONS
4. ZAKLJUČAK

The following conclusions have been made from the results of the present study:

- The groups containing waste winter tire powder achieved better performance than summer waste tire groups.
- The use of waste rubber in sample production resulted in a decrease in the equilibrium moisture content of the samples.
- The hydrophobic nature of the tire rubber enhanced the water absorption strength of particleboards.
- Mechanical performance of groups was affected by tire content, and it was mainly determined that the values decreased dramatically between 20 % to 30 % waste tire ratio groups.

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