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Model Calibration of Prefabricated Timber Wall Frames Made of *Hieronyma Alchorneoides* and *Gmelina Arborea* Timber Using Nail and Screw Fasteners

Kalibracija modela montažnih drvenih zidnih okvira izrađenih od drva *Hieronyma alchorneoides* i *Gmelina arborea* uz pomoć čavala i vijaka

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ABSTRACT • *The object of this research is to develop a model for the calibration of prefabricated timber wall frames (PTWFs) with dimension of 244 by 244 cm (width by height) respectively made of Gmelina arborea Roxb. and Hieronyma alchorneoides Allemão wood and two types of fastener (nails and screws). The PTWFs were submitted to a lateral load test and the vertical and horizontal displacement, maximum load (P_m), strength, stiffness values and mode of failure were determined. Results showed a greater failure percentage in the joint between the central stud and the top and bottom plates for both species and both fastener types used. PTWFs made of H. alchorneoides timber using screws showed greater values than PTWFs made of G. arborea for load at the proportionality limit and maximum load. Finally, computational model showed that the highest calibration percentage was achieved in the vertical orientation in PTWFs made using nails in both species. Meanwhile, PTWFs using screws showed calibration percentages of 58.0 and 43.5 %. The highest calibration percentage of 89.9 % was recorded in G. arborea PTWFs joined with nails, whereas the lowest calibration percentage of 69.4 % was recorded in H. alchorneoides PTWFs joined with screws.*

Keywords: *structural timber, vertical diaphragms, lateral loads, light frame, fastener, calibration model*

SAŽETAK • *Cilj istraživanja bio je razviti model za kalibraciju montažnih drvenih zidnih okvira (PTWF) dimenzija 244 × 244 cm (širina × visina) izrađenih od drva Gmelina arborea Roxb. i Hieronyma alchorneoides Allemão te uz upotrebu dviju vrsta vezivnih elemenata (čavala i vijaka). PTWF-ovi su podvrgnuti testu bočnog opterećenja*

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te su utvrđeni vertikalni i horizontalni pomak, maksimalno opterećenje (P_m), čvrstoća, krutost i način oštećenja. Rezultati su pokazali najveći postotak oštećenja u spoju između središnjeg nosača i gornjega odnosno donjeg okvira za PTWF-ove od obiju vrsta drva i spojenih obama tipovima vezivnih elemenata. PTWF-ovi izrađeni od drva H. alchorneoides i spojeni vijcima imali su veće vrijednosti opterećenja na granici proporcionalnosti i maksimalnog opterećenja od PTWF-ova proizvedenih od drva G. arborea. Konačno, računalni je model pokazao da je najveći postotak kalibracije postignut u vertikalnom smjeru u PTWF-ova izrađenih od obiju vrsta drva i spojenih čavlima. Istodobno, PTWF-ovi spojeni vijcima pokazali su postotke kalibracije 58,0 i 43,5 %. Najveći postotak kalibracije bio je 89,9 %, a zabilježen je u PTWF-u od drva G. arborea i spojenom čavlima, dok je najniži postotak kalibracije ustanovljen u PTWF-u od drva H. alchorneoides spojenom vijcima, a iznosio je 69,4 %.

Ključne riječi: *građevno drvo, vertikalne membrane, bočna opterećenja, svjetlosni okvir, vezni elementi, model kalibracije*

1 INTRODUCTION
1. UVOD

Wood was among the first materials used by humans for construction (Rathod, 2015). However, to date the use of structural timber has decreased due to the arrival of new construction materials (Sheikh and Ahmad, 2015; Demirkir *et al*., 2013). In Costa Rica, a small country of Latin America, the main consumer of sawn wood is the construction sector (Serrano and Moya, 2011). However, the construction sector has experienced an accelerated process of change toward metallic, plastic and concrete materials (Serrano and Moya, 2011).

Furthermore, a great variety of species has been planted as part of the reforestation activities in Costa Rica, resulting in an important contribution to the lumber market (Tuk, 2010; Moya *et al*., 2015; Tenorio *et al*., 2016). Mechanical properties of *G. arborea* lumber are among the most extensively studied in Costa Rica and their great potential has been demonstrated for uses such as structural components (Tenorio *et al*. 2016), in lumber, and other specific uses (Tenorio *et al*., 2011; Tenorio, 2012). Regarding *H. alchorneoides* lumber, Tenorio *et al*. (2016) noted that this species might have a potential for structural applications due to its mechanical properties. However, among the noted disadvantages of the use of plantation timbers in construction, is that only recently the allowable design stress data for plantation species has became available (Moya and González, 2013; Tenorio *et al*., 2016).

It is important to mention that timber structures allow proper habitability under adequate stress of the structural elements (Bongers *et al*., 2013). In order to guarantee optimal structural behavior of a structure, nonetheless, research must be done on different properties of wood as well as on joints between wooden elements, as these represent the weak spot of timber structures (Prevatt *et al*., 2014). This opens the trail for the development of studies on framing structures (Tenorio *et al*., 2011). A series of structural aspects of the wall can be observed from the action of the forces present in it, such as the behavior of displacement in relation to forces applied, strength, stiffness values and the mode of failure of the joint (Zheng *et al*., 2015).

On the other hand, timber structures are extensively used in the United States as residential houses, schools, and office buildings. Timber diaphragms (walls, floors, and ceilings), which provide lateral stability, are important components of these buildings. They consist of framing (studs, joists, and blocking), sheathing (timber structural panels), and fasteners (nails, screws, or staples), which connect the sheathing to the framing (Demirkir *et al*., 2013). However, wood construction has not been widely used especially in developing countries (Sawata *et al*., 2013), such as Costa Rica.

Despite all information on timber wall frame behavior under lateral loads available for species from other regions of the world, there is a lack of knowledge on the structural properties of wall frames made of tropical timber species for framing constructions. In face of this situation, the object of this research is to develop a model for the calibration of prefabricated timber wall frames (PTWFs) with dimension of 244 by 244 cm (width x height) made of *Gmelina arborea* Roxb. and *Hieronyma alchorneoides* Allemão timbers using two types of fastener (nails and screws).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Timber used

Gmelina arborea Roxb. and *Hieronyma alchorneoides* Allemão timber from 15 years old plantation were used. Both species are widely used in civil constructions in Costa Rica (Moya, 2004). Two species were sampled in two sawmills in Costa Rica. Dimensions of lumber in green condition were 7.5 cm wide by 2.5 cm thick; this lumber was dried in an experimental kiln and a target moisture content of 14 % was established for both species (Tenorio *et al*., 2016; Muñoz and Moya, 2008). The PTWFs were assembled using grade 2 timber, in accordance with the Costa Rican standard for structural timber classification (INTECO, 2011).

Design and construction of timber wall frames

PTWFs were designed with measurements of 244 cm wide by 244 cm high (Figure 1a). PTWFs were designed aiming at a solid structure and fabricated with timber from logs of plantation trees, which produces timber with limited dimensions. The shape and dimensions were selected with objective to cover the PTWFs with two panels i.e. plywood, fiberboards or OSB, which presents dimension of 122 x 244 cm and these can be supported in vertical and horizontal frame timber components with separations of 61 cm. Twelve PTWFs were built per type of lumber species. Two types of fastener were used, and then six PTWFs were joined with nails and six with screws.

Three king studs with dimensions of 5.1 cm x 7.6 cm x 239.0 cm form the PTWFs: one on each lateral part of the structure and one on the central part. In addition, two common studs with dimensions of 2.5 cm x 7.6 cm x 239.0 cm were placed each between the central column and a lateral column, at the middle of the distance (61 cm). These five studs were joined by two horizontal pieces of 2.5 cm x 7.6 cm x 234.0 cm: one at the upper part (top plate) and the other at the lower part (bottom plate). Afterwards, in order to achieve a better stability of the timber wall frame, noggins of 2.5 cm by 7.6 cm were placed at every 61 cm. Finally, eight diagonal bracing straps of 2.5 cm by 7.6 cm were placed to give the timber wall frame more rigidity (Figure 1a).

Types of joint

Five different types of joint were used for each PTWF (Figure 1a), derived from PTWF design. Joints must support lateral load and deformation in these parts so that PTWFs had excellent resistance. The joints are marked in Figure 1a and detailed below:

- Joint 1: this type is present in the corners of the timber wall frame, where the faces of the wall studs join the top and bottom plates;
- Joint 2: corresponds to the joint between each lateral king stud and the noggins;
- Joint 3: corresponds to the joint between each common stud and the noggins;
- Joint 4: is the union of the central stud with the top and bottom plates;
- Joint 5: these are the joints between diagonal bracing straps and studs.

Fasteners used

Two types of fastener were used to assemble the aforementioned PTWF, which allow a semi-rigid connection: screws and nails. Screws used were of the flat head Phillips type in two different sizes: size 7.50 cm by 0.49 cm (screw #10) was used in joints 1 and 2; (ii) size 5.00 cm by 0.43 cm (screw #8) was used in joints 3, 4 and 5. The nails used were of two sizes as well: (i) size 7.50 cm by 0.35 cm (nail #10) for joints 1 and 2; (ii) size 5.10 cm by 0.28 cm (nail #12.5) for joints 3, 4 and 5. Finally, all nails and screws were inserted at approximately 2.50 cm from the border of each piece in order to achieve spacing close to 2.50 cm between each pair of fasteners. Two fasteners were used for each piece of timber that forms the joint. Each joint used the following quantity of fastener: joint 1 with 4 fasteners, 2 joint with 4 fasteners, joint 3 with 4 fasteners, joint 4 with 2 fasteners and joint 5 with 8 fasteners.

Structural test for PTWFs

Placed in a steel frame formed by columns and beams, the PTWFs were subjected to a lateral load test (Figure 1b). Each PTWF was placed at the center of the frame, one meter away from each column and, to maintain verticality, it was tied with a rope at each side. To simulate a wooden floor, a piece of lumber (2.5 cm in thick and 10 cm in width) was anchored to the strong concrete floor by means of screws (Figure 1d, 2a). This piece of timber floor was joined to the bottom plate of the PTWFs with 75 mm by 3.5 mm (#10) nails or 75 mm by 4.93 mm (#10) screws, depending on the diaphragm joint type, leaving an approximate spacing of 25 cm between them. For application of the lateral load, the central point of the piston was placed at the height of 239 cm, about 10 cm away from the superior border of the PTWFs (Figure 1c). The "Crackmeter" vibrating wire displacement transducer (VWDT) for recording of horizontal displacement was placed at the same height, whereas the one recording vertical displacement was placed at the lower corner, displacement between the king stud and the floor lumber. The lateral load and the two displacement orientations of the structure were digitally recorded during the test.

Timber characterization

The timber elements were characterized through moisture content (*MC*) at the moment of the test, wood

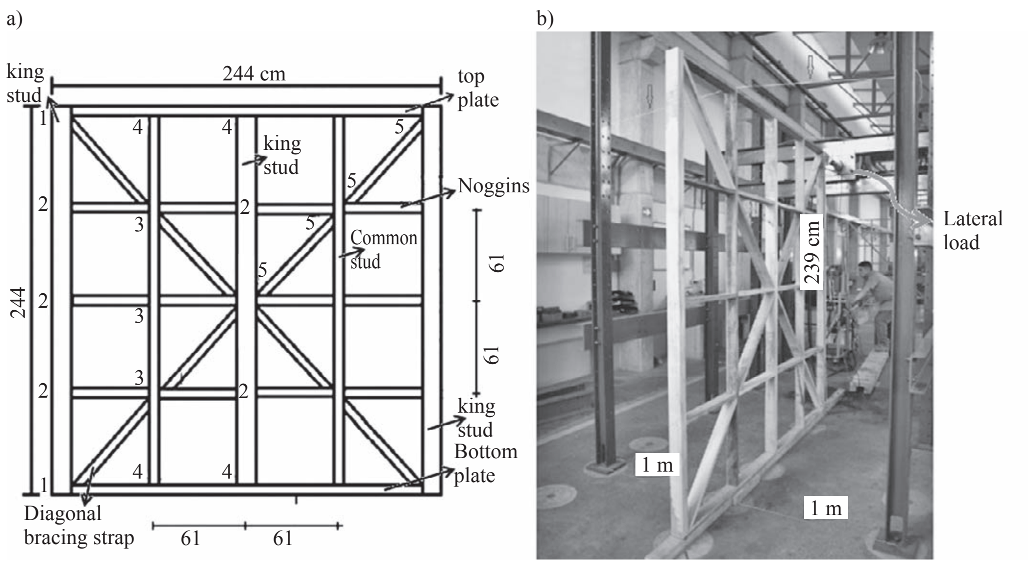

Figure 1 a) Design and type of joint of the PTWFs for *H. alchorneoides* and *G. arborea* lumbers; b) lateral test in PTWFs
Slika 1. a) Dizajn i vrsta spojeva PTWF-ova izrađenih od drva *H. alchorneoides* i *G. arborea*; b) test bočnog opterećenja PTWF-ova

density at the test *MC* (mass volume^{-1}) and specific gravity (*SG*). Additionally, static bending and compression parallel to grain and allowable design stress were calculated. Each one of these tests was performed on 30 different samples per species. All samples were extracted from the PTWFs after the lateral load test was done. First, static bending and compression test, wood density and *MC* were measured according to ASTM D-143 standard (ASTM, 2003a). *SG* was measured according to ASTM D-2395 (2003b). Allowable design stress was calculated for structural timber grade 2. Stress was derived based on the data obtained for the modulus of elasticity and modulus of rupture in flexure, while compressive stress was determined on the defect-free samples. Afterward, the procedure applied was the one indicated in ASTM D-2455 standard (ASMT, 2003c), INTECO (2011) and Moya and González (2013).

Strength values of PTWFs

For the calculation of strength values of PTWFs assembled with nails and screws, curves for load (kN) vs displacement (mm) were generated for vertical and horizontal directions. The values for maximum load (P_m), displacement at maximum load (Δ_m), load at the limit of proportionality (P_{lp}) and displacement at the limit of proportionality (Δ_{lp}) were determined in this curve. Load and displacement values in percentile 75 of the load at the proportionality limit and percentile 75 of the maximum load were also determined in this curve, for each type of PTWFs in both species and for both fastener types. To carry out the comparative analysis on the various PTWFs, the parameter of the ratio load/displacement was calculated for load at the limit of proportionality as well as for maximum load: load/displacement relation at proportionality limit (LDR_{lp}) and load/displacement relation at maximum load (LDR_m), respectively. The ratio load/displacement indicates the load that must be applied for PTWFs to become displaced by 1 mm.

Calibration of model

The purpose of a model is to represent the behavior of the PTWFs during the application of loads. Vertical and horizontal displacement data were adjusted in a digital model (Equation 1 and 2) by means of the modeling software SAP2000, in order to calibrate this model for the PTWFs (Figure 2b). The degree of freedom was 1 for vertical and 1 for horizontal orientation. The allowable design stresses for species used in the model are detailed in Table 1. The model develops vertical (*ka*) and horizontal rigidity (*kb*) and it is derived from the general model of stiffness (force/displacement). Vertical rigidity was applied to all joints of the bottom of PTWFs (Figure 2b) and horizontal rigidity was applied to all horizontal joints on perpendicular axes of PTWFs plane (Figure 2b).

The following steps were taken to calibrate the model for both displacement orientations of the PTWFs (horizontal and vertical). The model was calibrated where the displacement transducer was located, specifically joint type 2, 3 and 4. The joints type 1 and 5 were not taken into consideration because no displacement transducer was located:

1. A lateral load was applied to the PTWFs model in the SAP2000 software (Figure 2b), considering that the load is within the proportional range of the PTWFs, determined in the destructive test.
2. Calibration values were first obtained by using the vertical displacement value and the axial load average of the king stud – obtained when executing the model; then the horizontal displacement value and the average rotational moments in each noggin joining the king studs were obtained.
3. By means of Equation 1, initial vertical rigidity (k_a) of type 4 joints of the PTWFs was determined, while Equation 2 was used for determining horizontal rigidity (k_b) of type 2 and 3 joints.

$$k_a = \frac{F}{\Delta} \tag{1}$$

$$k_b = \frac{M}{\theta} \tag{2}$$

Where: k_a – vertical rigidity; F – applied force; Δ – displacement produced by applied force; k_b – horizontal rigidity; M – moment equivalent to force; θ – angle for moment.

4. Then, for both displacement or rotation orientations, initial rigidity was multiplied by the corresponding displacement obtained when executing the model and this product was divided by the experimental displacement in order to obtain a new

a) b)

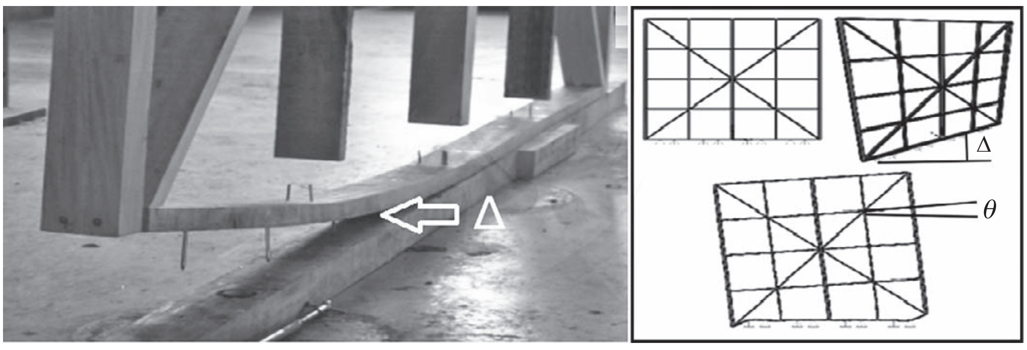

Figure 2 (a) Main failure presented in PTWFs of *G. arborea* and *H. alchorneoides* timber under lateral load: nail extraction and lifting of the king stud and (b) model in SAP2000 for PTWFs
Slika 2. (a) Glavna oštećenja koja su ustanovljena u PTWF-ovima od drva *G. arborea* i *H. alchorneoides* pri bočnom opterećenju: vađenje čavala i podizanje okvira; (b) model PTWF-ova u SAP2000

rigidity. This procedure was applied until a *k* (vertical and horizontal) was produced with a displacement similar to the real one – a process known as iteration.

5. Finally, the calibration percentage of the model was calculated by relationship of real horizontal displacement and horizontal displacement by model, expressed perceptually.

Experimental design and statistical analysis

A statistical 2^2 factorial design was established for the PTWFs: two species (*H. alchorneoides* and *G. arborea*) and two fastener types (nails and screws). Of each treatment, 24 PTWFs were built (2 species x 2 fastener types x 6 repetitions). Normality of the data was verified using the Shapiro-Wilks test for each of the variables measured (P_{lp}, Δ_{lp}, P_m and Δ_m). For variables that did not behave normally, transformation was carried out in order to comply with normality. Next, variance analysis (ANOVA) was performed considering two factors: species (*H. alchorneoides* and *G. arborea*) and the two types of ironwork in the joints (nails and screws). Finally, to determine whether significant differences existed between the treatments, a comparison of the treatments was performed by applying the Tukey test.

3 RESULTS
3. REZULTATI

3.1 Characteristics of the lumber used
3.1. Obilježja upotrijebljene drvne građe

Table 1 and 2 present allowable stress design and the average physical and mechanical characteristics obtained from the plantation-grown *H. alchorneoides* and *G. arborea* lumbers used in constructing the PTWFs. It shows that *H. alchorneoides* timber presented higher values for static bending and compression parallel to grain than *G. arborea* lumber, and therefore *H. alchorneoides* showed stress values higher than *G. arborea*. Regarding moisture content (*MC*), *G. arborea* lumber presented a slightly higher percentage than *H. alchorneoides* lumber. Meanwhile, *SG* and density of lumber from *H. alchorneoides* are superior to those of *G. arborea* lumber.

Table 1 Allowable design stress for species used for construction of wooden diaphragms at the respective moisture content
Tablica 1. Dopušteno naprezanje za vrste drva koje se upotrebljavaju za izradu drvenih membrana pri odgovarajućem sadržaju vode

Species / *Vrsta drva*	***SG***	F_b MPa	E MPa	E_{min} MPa	F_c MPa
Gmelina arborea	0.42	6.3	5314	4517	3.1
Hieronyma alchorneoides	0.50	9.3	6580	5593	4.6

Legend: SG - specific gravity /*specifična gustoća*; F_b - stress in bending / *naprezanje pri savijanju*; *E* - modulus of elasticity / *modul elastičnosti*; E_{min} - minimum modulus of elasticity / *minimalni modul elastičnosti*; F_c - stress in compression parallel to grain / *tlačno naprezanje paralelno s vlakancima*

3.2 Lateral load test
3.2. Test bočnog opterećenja

During lateral load tests, the PTWFs showed various failures in their structure, whose incidence is shown in Figure 3. Joint 4 (the joint between the central stud and the top and bottom plates) presented the greatest percentage of failure in both species and for both fastener types used. The failure mode was by tension (Figure 3). The PTWFs of both *G. arborea* and *H. alchorneoides* lumbers using nails reached high percentages of failure in this joint, up to 100 %, specifically at the lower part of the structure (Figure 3a and 3c; Figure 2a). The PTWFs of both species that used screws, although showing this type of failure as well, recorded a lower percentage, varying from 16.6 % to 66.6 %. Another joint that showed a high percentage of failure was Joint 1, which reached 66.6 % in PTWFs of *G. arborea* that used nails (Figure 3a). The failure mode was by shear. This type of joint failure was practically absent in PTWFs of *G. arborea* using screws as well as in all PTWFs of *H. alchorneoides*.

Failures in type 2 joints were present in low percentages, between 16.6 and 33.3 %, in all PTWFs types and failure mode was compression. In PTWFs of *H. alchorneoides* lumber with screws, no failures appeared for this joint type. Failures in joints type 3 and 5 (Figure 3a) were present in all PTWFs types but in low percentages, between 16.6 and 33.3 %. The failure

Table 2 Values of strength in static bending and compression parallel to grain of *G. arborea* and *H. alchorneoides* lumbers used in construction of prefabricated timber wall frames
Tablica 2. Vrijednosti čvrstoće statičkog savijanja i tlačne čvrstoće paralelno s vlakancima drva *G. arborea* i *H. alchorneoides* upotrijebljenih za izradu montažnih drvenih zidnih okvira

Species *Vrsta drva*	**Static bending** *Statičko savijanje*		**Compression parallel to grain** *Tlačno naprezanje paralelno s vlakancima*		**Moisture content** *Sadržaj vode* %	**Specific gravity** *Specifična gustoća*	**Density at reported *MC*** *Gustoća pri izmjerenom sadržaju vode* kg/m³
	MOE, GPa	*MOR*, MPa	*MOE*, MPa	*MOR*, MPa			
Gmelina arborea	6.4^A (21.7)	44.9^A (25.3)	590^A b (15.2)	24.4^A (14.9)	14.5^A (21.9)	0.42^A (12.11)	520^A (11.82)
Hieronyma alchorneoides	7.9^B (13.9)	66.8^B (15.9)	1079^B (9.9)	36.4^B (10.1)	13.8^A (6.0)	0.50^B (8.87)	590^B (9.20)

Legend: *MOE* - modulus of elasticity / modul elastičnosti; *MOR* - modulus of rupture / modul loma. Values between parentheses correspond to the coefficient of variation for the given variable. Different characters indicate significant differences at $p = 0.05$. / *Vrijednosti u zagradama odgovaraju koeficijentima varijacije za dane varijable. Različita slova pokazuju značajne razlike uz p = 0,05.*

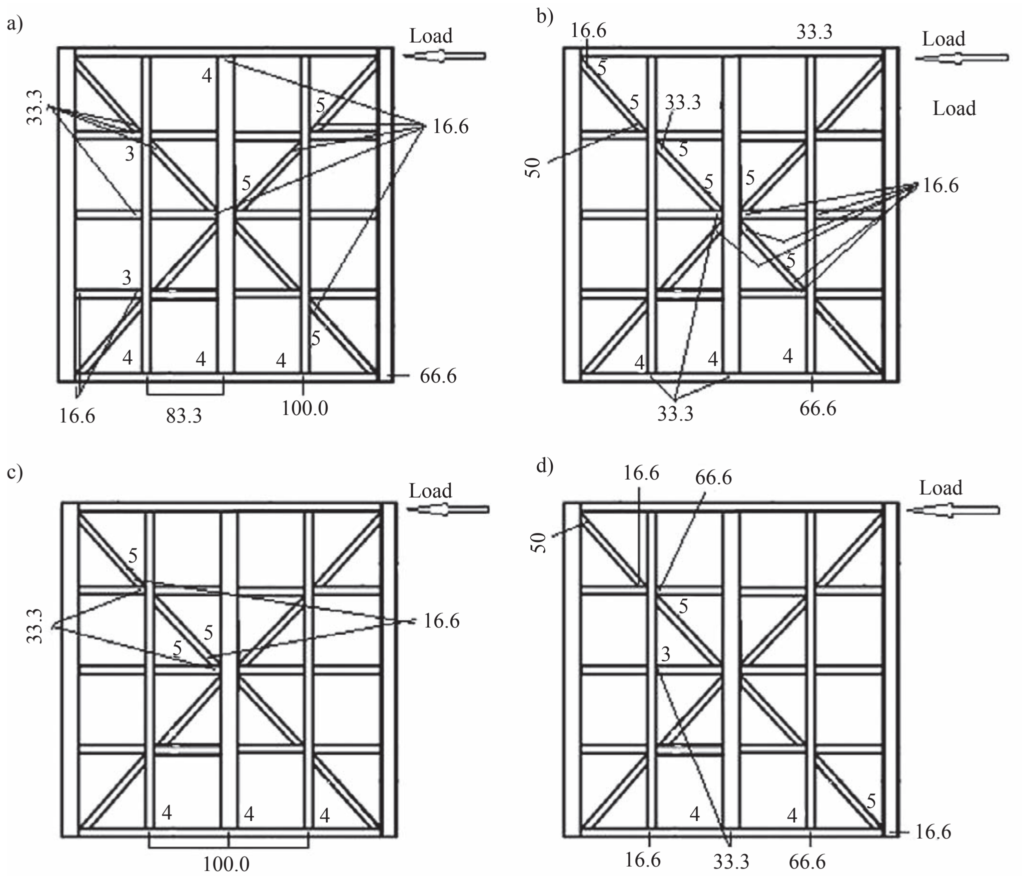

Figure 3 Percentage of failures present in various PTWF joints after lateral load test. PTWFs made of: a) *G. arborea* timber and nails; b) *G. arborea* timber and screws; c) *H. alchorneoides* timber and nails; and d) *H. alchorneoides* timber and screws
Slika 3. Postotak oštećenja uočenih u različitim spojevima PTWF-a nakon testa bočnog opterećenja. PTWF-ovi izrađeni od: a) drva *G. arborea* i čavala; b) drva *G. arborea* i vijaka; c) drva *H. alchorneoides* i čavala; i d) drva *H. alchorneoides* i vijaka.

mode was compression in joint type 3 and tension in joint type 4. Likewise, it is important to note that more failures occurred in PTWFs made of *G. arborea* lumber (Figure 3a-b) than in PTWFs made of *H. alchorneoides* lumber (Figure 3c-d).

Table 3 shows the strength values in horizontal and vertical orientations in relation to the lateral load applied on the PTWFs (average load at proportionality limit (P_{lp}) and displacement at proportionality limit (Δ_{lp}) in percentile 75; average P_m and displacement at maximum load (Δ_m) in percentile 75). It can be observed that, in the horizontal orientation, the P_{lp} of the PTWFs varies from 1.6 to 2.9 kN and the P_m from 1.9 to 3.7 kN. Meanwhile, displacement (Δ) in these points varies from 23.2 to 38.4 mm and from 30.2 to 55.6 mm, respectively. In the vertical orientation, P_{lp} varies from 1.7 to 2.9 kN and the P_m from 1.9 to 3.8 kN, while the Δ_{lp} varies from 4.8 to 10.8 mm and the Δ_m from 8.2 to 27.3 mm.

It is observed that, for both vertical and horizontal orientations, PTWFs using *G. arborea* lumber and nails presented the statistically lowest value in P_{lp} and P_m. For both orientations, P_{lp} was statistically similar in PTWFs made of *G. arborea* lumber with the use of either screws or nails, as well as in *H. alchorneoides* PTWFs using nails, whereas it was statistically higher in PTWFs made of *H. alchorneoides* lumber using screws. The highest P_m was found in the PTWFs made of either lumber species using screws, while PTWFs using *G. arborea* lumber with nails showed a significantly lower P_m in comparison to PTWFs using *G. arborea* lumber and screws and PTWFs using *H. alchorneoides* lumber and either nails or screws.

It was found for the horizontal and vertical Δ_{lp} that PTWFs made of *H. alchorneoides* showed a greater LDR_{lp} than *G. arborea* PTWFs (Table 3), with the exception of the vertical displacement in the *H. alchorneoides* PTWFs using nails, where the LDR_{lp} value shown was lower than that of *G. arborea* PTWFs using screws (Table 3). For both orientations, at the moment of failure, the greatest LDR_m was recorded in *H. alchorneoides* PTWFs using screws; the lowest LDR_m on the horizontal direction was shown in *G. arborea* PTWFs and, for the vertical direction, the lowest LDR_m was recorded in *H. alchorneoides* PTWFs using nails.

Another important aspect is that the average values for P_{lp} and P_m are similar for both orientations in both species and both fastener types, yet a difference can be observed in the displacement values, which are higher in the horizontal orientation (Table 3).

Figure 4 presents the relation between load and displacement in the horizontal and vertical orientations for the various PTWFs of both types of lumber and fasteners. It has been observed that in PTWFs from either lumber species using screws the values of load for a given displacement are superior to those of PTWFs using nails for the same displacement. In the same way, it has been observed that the loads obtained for a given

Table 3 Strength values in horizontal and vertical displacement under lateral load obtained for PTWFs made of *G. arborea* and *H. alchorneoides* lumbers
Tablica 3. Vrijednosti čvrstoće u horizontalnome i vertikalnom smjeru pri bočnom opterećenju PTWF-ova izrađenih od drva *G. arborea* i *H. alchorneoides*

Species *Vrsta drva*	**Type of fastener** *Vrsta vezivnih elemenata*	**Horizontal** / *Horizontalno*					
		P_{lp} kN	Δ_{lp} mm	LDR_{lp} kN/mm	P_m kN	Δ_m mm	LDR_m kN/mm
Gmelina arborea	Nail / *čavli*	1.6^{A} (13.2)	24.9 (21.6)	0.06^{A}	1.9^{A} (12.8)	33.8 (17.4)	0.06^{A}
	Screw / *vijci*	2.8^{BC} (10.3)	38.4 (23.0)	0.07^{AB}	3.6^{BC} (11.9)	55.6 (20.3)	0.06^{AB}
Hieronyma alchorneoides	Nail / *čavli*	2.2^{B} (22.0)	18.1 (15.1)	0.12^{BC}	2.6^{AB} (16.3)	30.2 (15.3)	0.09^{AB}
	Screw / *vijci*	2.9^{C} (16.5)	23.2 (12.9)	0.13^{C}	3.7^{C} (12.2)	30.6 (14.3)	0.12^{B}
		Vertical / *Vertikalno*					
Gmelina arborea	Nail / *čavli*	1.7^{A} (7.7)	9.4 (7.2)	0.18^{A}	1.9^{A} (12.8)	13.0 (21.6)	0.15^{AB}
	Screw / *vijci*	2.8^{BC} (11.5)	7.0 (32.7)	0.40^{AB}	3.5^{BC} (14.5)	8.2 (6.3)	0.43^{BC}
Hieronyma alchorneoides	Nail / *čavli*	2.2^{B} (22.1)	10.8 (37.0)	0.20^{AB}	2.6^{AB} (12.1)	27.3 (18.6)	0.10^{A}
	Screw / *vijci*	2.9^{C} (14.0)	4.8 (17.9)	0.60^{B}	3.8^{C} (3.9)	8.2 (35.0)	0.46^{C}

P_{lp} - load at limit of proportionality / *opterećenje na granici proporcionalnosti*; Δ_{lp} - displacement at limit of proportionality / *pomak na granici proporcionalnosti*; LDR_{lp} - load-displacement relation at limit of proportionality / *odnos opterećenje - pomak na granici proporcionalnosti*; P_m - maximum load / *maksimalno opterećenje*; Δ_m - displacement at maximum load / *pomak pri maksimalnom opterećenju*; LDR_m - load-displacement relation at maximum load / *odnos opterećenje - pomak pri maksimalnom opterećenju*. Values between parentheses correspond to the coefficient of variation for the given variable. / *Vrijednosti u zagradama odgovaraju koeficijentima varijacije za dane varijable.* Different characters indicate significant differences at $p = 0.05$. / *Različita slova pokazuju značajne razlike uz p = 0,05.*

displacement in the PTWFs made of *H. alchorneoides* lumber are greater than those obtained for the PTWFs made of *G. arborea* lumber. Another important aspect to note from the load-displacement relation is that, after the maximum load point is reached, irregularities appear in the load-displacement values of the PTWFs — specifically, fluctuations in these values take place as the structure continues to become displaced.

Calibration

For modeling the PTWFs, the values of rigidity (*k*) and displacement (shown in Table 4) for the joints in the vertical and horizontal orientations were determined by means of the SAP2000 software. The recorded values of *k* for PTWFs using nails were 0.035 kN/mm for *G. arborea* lumber and 0.053 kN/mm for *H. alchorneoides*, whereas PTWFs made of either species using screws showed a superior rigidity, 255 and 485 kN/mm, respectively. Again, the computational model shows that the highest values are present in PTWFs made using *H. alchorneoides* lumber.

In evaluating the computational model with the real values, it was found that the highest calibration percentage was achieved in the vertical orientation in PTWFs made using nails in both species. Meanwhile, PTWFs using screws showed calibration percentages of 58.0 and 43.5 % (Table 4). No uniform calibration percentage appeared in the horizontal orientation: PTWFs made of *G. arborea* lumber using nails achieved 100 %, while PTWFs using *H. alchorneoides* lumber and nails presented a percentage lower than 62.9 %. Finally, the greatest calibration percentage average was obtained in the PTWFs made of *G. arborea* lumber using nails, while the lowest calibration percentage appeared in *H. alchorneoides* PTWFs using screws.

4 DISCUSSION
4. RASPRAVA

4.1 Lateral load test
4.1. Test bočnog opterećenja

As was to be expected, the main faults in PTWFs during lateral load tests were due to the failure of joints, which is caused by the bending of metal pieces acting as transmitters of the load, becoming the most critical regions (Prevatt *et al*., 2014). One aspect that weakens the joints is that elements placed with their axis parallel to the wood fibers offer low or null resistance to extraction, either directly or by action of lateral loads (Prevatt

Table 4 Computed and real values of rigidity and displacement (vertical and horizontal) obtained for PTWFs made of *G. arborea* and *H. alchorneoides* lumbers and calibration percentages of computational model
Tablica 4. Izračunane i stvarne vrijednosti krutosti i pomaka (vertikalno i horizontalno) dobivene za PTWF-ove od drva *G. arborea* i *H. alchorneoides* te postotak kalibracije računalnog modela

Type of PTWFs *Vrsta PTWF-ova*	k_a kN/mm	Δ_{vr} mm	Δ_v mm	$\%_c$	k_b kN/mm	Δ_{hr} mm	Δ_h mm	$\%_c$	**Average** *Prosječno* $\%_c$
G. arborea – nail / *čavli*	0.035	5	6.3	80	756	13	13	100	89.9
G. arborea – screw / *vijci*	255.3	2	3.1	58	6676	9.7	8.6	88	73.2
H. alchorneoides – nail / *čavli*	0.053	5	3.8	78	4104	5.1	8.1	63	70.2
H. alchorneoides –screw / *vijci*	485.2	1	3.1	44	4836	6.2	6.5	95	69.4

k_a - vertical rigidity for calibration / *vertikalna krutost za kalibraciju*; Δ_{vr} - real vertical displacement / *stvarni vertikalni pomak*; Δ_{vm} - vertical displacement by model / *vertikalni pomak prema modelu*; $\%_c$ - calibration percentage / *postotak kalibracije*; k_b - horizontal rigidity for horizontal calibration / *horizontalna krutost za horizontalnu kalibraciju*; Δ_{hr} - real horizontal displacement / *stvarni horizontalni pomak*; Δ_{hm} - horizontal displacement by model / *horizontalni pomak prema modelu* *et al*., 2014). Therefore, PTWFs joints where nails and screws were used in this orientation (joints 3 and 4) failed more frequently. In order to improve the structural performance of these faulty spots, it is necessary to reinforce the joints by using elements with better structural performance, for example dented plates, gluing, steel plates, among others (Fueyo *et al*., 2011). Another factor that contributes in improving the performance of joints and, therefore, the behavior of the PTWFs, is the covering of the walls (Demirkir *et al*., 2013), especially using materials with a better performance under structural loads (Bongers *et al*., 2013; Chen *et al*., 2016).

The PTWFs made of *G. arborea* lumber using nails showed lower strength under lateral load (Table 3) and greater displacement for the same load (Figure 4) in relation to PTWFs made of *H. alchorneoides* lumber using nails. This occurs because the former is considered as lumber of a medium SG (Moya, 2004), inferior to that of *H. alchorneoides* lumber (Table 1). Therefore, timbers of low SG have greater ductility (Demirkir *et al*., 2013), thus causing greater deformation. On the contrary, PTWFs made of *H. alchorneoides* timber showed greater strength and a better behavior under lateral loads because of its superior SG, which provides greater hardness and resistance to extraction of the nails (Celebi and Kilic, 2007). In general, it is considered that strength of the joints increases as density increases (Demirkir *et al*., 2013).

However, it is fair to note that, although the SG of *H. alchorneoides* timber is 16 % higher than that of *G. arborea* timber (Table 2), the differences in strength and displacement values are not as great. In fact, in PTWFs made of *G. arborea* lumber and using screws and PTWFs made of *H. alchorneoides* lumber and using nails, no significant differences were shown in parameters at the limit of proportionality. Another result that confirms little differences between both species is the P_m in PTWFs made of either species using nails, as no significant differences appeared in this value (Table 3).

According to the abovementioned behavior, it is inferred that the strength of the PTWFs model is largely limited by the type of the fastener used (nail or screw) and not by the type of timber used. However, in order to determine the real differences between species, joint structures must be controlled and designed so as to withstand forces and collapse due to the lumber type and not due to the joint type. Nonetheless, the objective of this study was to develop a design mainly oriented toward the failure by the type of joint.

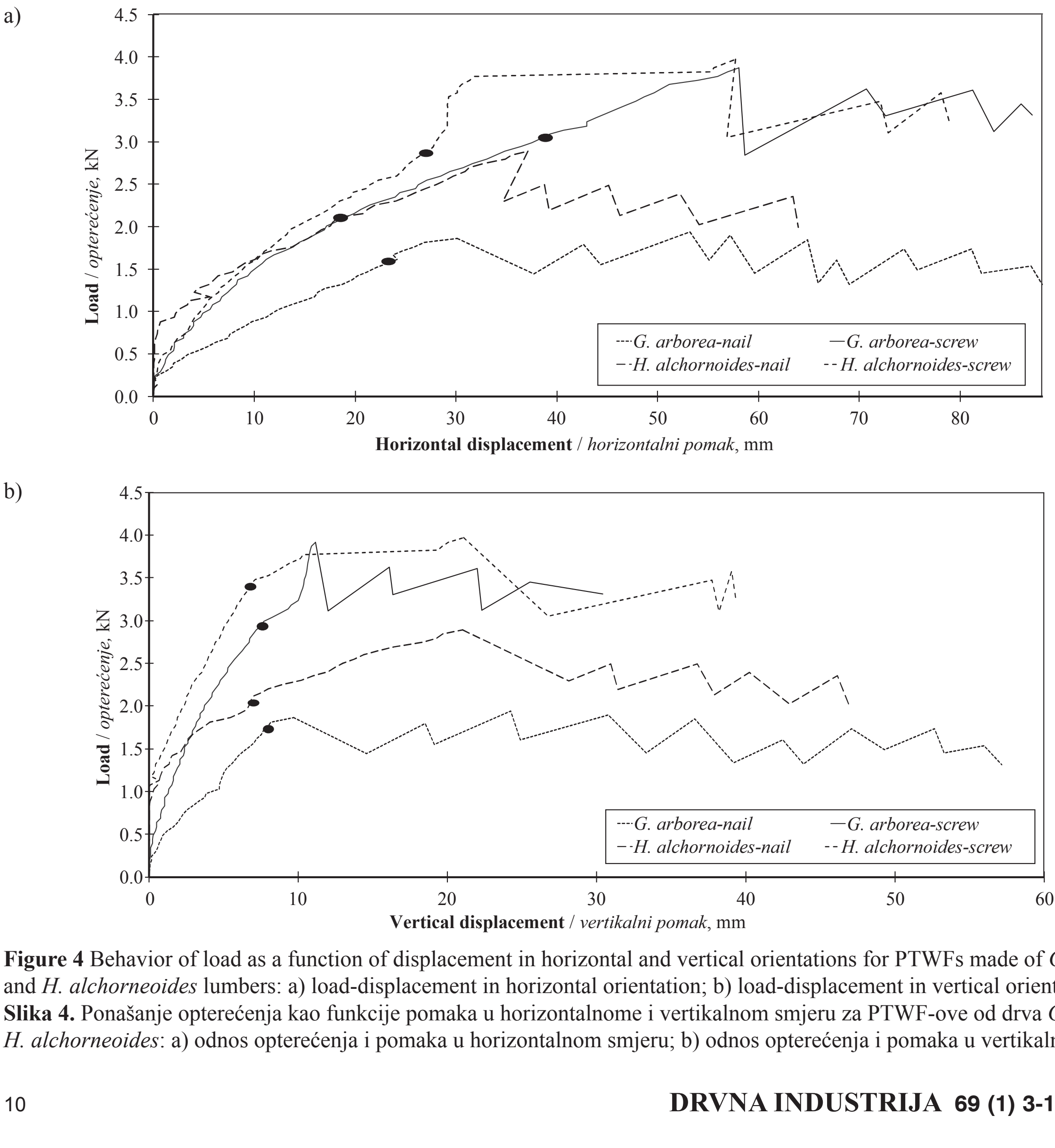

Figure 4 Behavior of load as a function of displacement in horizontal and vertical orientations for PTWFs made of *G. arborea* and *H. alchorneoides* lumbers: a) load-displacement in horizontal orientation; b) load-displacement in vertical orientation
Slika 4. Ponašanje opterećenja kao funkcije pomaka u horizontalnome i vertikalnom smjeru za PTWF-ove od drva *G. arborea* i *H. alchorneoides*: a) odnos opterećenja i pomaka u horizontalnom smjeru; b) odnos opterećenja i pomaka u vertikalnom smjeru

The greater resistance to loads and the lesser displacements shown in PTWFs using screws, mainly in the vertical direction, are due to the threaded area of the screw, which allows for more adherence to the wood fibers and thus more resistance to extraction by various forces (Demirkir *et al*., 2013; Gattesco and Boem, 2015). Nails, lacking this quality, are extracted more easily under lower loads, generating greater displacement of the structure (Demirkir *et al*., 2013). Although screws performed better than nails as expected, the results are interesting since they quantify the difference.

Another aspect observed from the load-displacement curves (Figure 4) is represented by the sudden drops of the load after overcoming maximum resistance of the PTWFs, manifested at the moment of total extraction or failure of the joint elements. Gattesco and Boem (2015) explain that this is due to exceeding the capacity of the joint elements to withstand deformation and, consequently, these lose their ability to transmit the load. These sudden drops in load were also present in a study by Sartori and Tomasi (2013) on structures using metal fasteners and coated walls. However, this irregularity is not a severe problem, as structures with semirigid joints allow for irregular drops of the load, wherein the structure suffers partial damage and the joints are able to dissipate energy (Gattesco and Boem, 2015). Thus, a process of redistribution of loads begins after failure of a joint, which allows the wall not to collapse (Branco and Descamps, 2015) and this enables the diaphragms to support load again, until failure of the joints takes place anew and another sudden drop of load follows (Figure 4).

4.2 Calibration of the model
4.2. Kalibracija modela

In order to obtain reliable predictions from the model in performing a comprehensive analysis of the structure, it is fundamental to calibrate the PTWFs constructed (Chui *et al*., 2016). In the present study, the calibration percentage obtained for PTWFs made of either *G. arborea* or *H. alchorneoides* timbers was 81.5 % and 69.8 %, respectively, which is low in comparison to other type of materials (Rodríguez *et al*., 2011). The moderately low coefficients in the PTWFs model of this study, of less than 82 %, may be explained by the nature of the material used for these structures (lumber), which presents greater variability than other material such as steel, concrete or aluminum (Tuk, 2010). Moreover, another aspect causing the low calibration of the PTWFs is that joints behave as partially rigid elements, which renders calibration of the model more complex. It is advisable to determine rigidity in each joint in order to achieve an adequate degree of freedom in these spots. Another situation that contributes to low correlation is the failure caused by lifting of bottom plate from the floor lumber (Figure 2a). By improving the joint at this point, probably by using large screws instead of nails, the resistance at this point could improve the lateral resistance.

Diaphragms built with nails showed lesser axial rigidity than those built with screws (Table 4), which coincides with the lower load-displacement rate in the vertical orientation (Table 4). This behavior may be considered logical, as less rigid joints would allow greater displacement at lower loads — when nails are used, for example. Rigidity in bending presented higher values in PTWFs with *H. alchorneoides* lumber using screws and nails, a behavior made possible by a combination of factors, among which a greater torque momentum can be noted as a consequence of a more rigid joint (Prevatt *et al*., 2014).

Finally, the lowest calibration percentage was shown in PTWFs made of *H. alchorneoides* timber using screws in the vertical orientation, as well as those made of the same timber using nails in the horizontal direction (Table 4). This low calibration level is the product of lower loads, within the range of 0 to 1 kN (Figure 4), as it was not possible to adjust the modeling software to such low values.

5 CONCLUSIONS
5. ZAKLJUČAK

A model for the calibration of PTWFs made of *Gmelina arborea* and *Hieronyma alchorneoides* lumber using two types of fastener (nails and screws) was developed. Differences between these two types of lumber were determined. It was possible to calibrate the models by means of the modeling software, wherein a greater calibration percentage was obtained for *G. arborea* PTWFs using nails (89.9 %), while the lowest calibration percentage (69.4 %) was obtained for *H. alchorneoides* PTWFs built using screws.

PTWFs made of *G. arborea* lumber presented lower load (from 1.6 to 2.9 kN) and displacement values at the limit of proportionality in both vertical and horizontal orientations (from 18.1 to 38.4 mm). *G. arborea* PTWFs showed a greater P_m in the horizontal direction (3.6 kN), yet there are no clear differences between these two types of timber in the vertical direction. Based on these results, PTWFs made of *H. alchorneoides* timber using screws showed the highest values of the properties measured (from 2.2 to 3.7 kN).

The results obtained for PTWFs made of *G. arborea* and *Hieronyma alchorneoides* timber contribute to the knowledge of the structural properties of wall frames made of tropical timber species for framing constructions.

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The Effect of Nano TiO_2 and Nano Boron Nitride on Mechanical, Morphological and Thermal Properties of WF/PP Composites

Utjecaj nanočestica titanova dioksida i nanočestica boron nitrida na mehanička, morfološka i toplinska svojstva WF/PP kompozita

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ABSTRACT • *This study evaluated the effect of nano boron nitride (BN) and nano titanium dioxide (TiO_2) on some physical, mechanical and thermal properties of WF/PP composites. Polyproplene as a polymer matrix and wood flour obtained from particleboards were used as reinforcing fillers to prepare the composites by using a single screw extruder. It was observed that density in all composites did not change significantly with the increasing of wood flour. It was found that BMOR and BMOE of the composites increased with the increasing of the wood flour content and nanoparticle types, while the TMOR and TMOE decreased. According to the results of thermal properties (TGA), thermal degradation of all composites was found to be lower compared with pure PP.*

Keywords: *wood polymer composites, natural fillers, nanoparticle type, characterization analysis*

SAŽETAK • *U radu je predočeno istraživanje utjecaja nanočestica borova nitrida (BN) i nanočestica titanova dioksida (TiO_2) na neka fizikalna, mehanička i toplinska svojstva drvno-plastičnih kompozita (WF/PP kompozita). Za proizvodnju kompozita upotrijebljeni su polipropilen kao polimerna matrica i drvno brašno dobiveno od ploča iverica kao punilo, uz pomoć jednovijčanog ekstrudera. Uočeno je da se gustoća kompozita ne mijenja značajno s povećanjem količine drvnog brašna. Utvrđeno je da se BMOR i BMOE kompozita povećava s povećanjem sadržaja drvnog brašna i nanočestica TiO_2 i BN-a, dok se TMOR i TMOE smanjuju. Prema rezultatima istraživanja toplinskih svojstava (TGA), zaključeno je da je toplinska degradacija svih istraživanih kompozita manja u usporedbi s čistim polipropilenom.*

Ključne riječi: *drvno-plastični kompoziti, prirodna punila, vrsta nanočestica, analiza svojstava*

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1 INTRODUCTION
1. UVOD

Wood-plastic composites (WPCs) are principally concerned with thermoplastic polymers reinforced by wood and wood derivatives such as fibers or flour (Soccalingame *et al*., 2016). Wood flour (WF) actually represented a waste material, which had to be eliminated from sawmills in the past. Many waste utilization strategies have been introduced over the last century, such as bedding, composting, combustion, gas generation, use as feedstock for chemical industry, etc. Among them, the use of WF as raw material for making new solids is the most positive due to its convenience in application and low energy costs (Ashori, 2008; Okamoto, 2003).

In general, wood flour is used as plastic filler, which tends to increase the stiffness of the composite but does not improve its strength. Natural fibers can be used to reinforce plastics rather than filler rate, which increases strength as well as stiffness. Natural fibers can be used to reinforce filled plastics, by increasing both strength and stiffness. Wood and other lignocellulosic fibers typically have higher particle sizes than those of wood flour (Osswald and Menges, 1995). WPCs combine the best properties of the pure components and can show superior performance in many application areas. Compared with potential traditional competitors, WPCs offer better thermal and acoustic isolation than aluminum, better durability and lower maintenance than wood, and often lower price than pure plastics (Garcia *et al*., 2009).

Lignocellulosic materials have made significant contributions to the thermoplastic industry, which has led to the emergence of wood–plastic composites in the construction industry. Products such as decking, fencing, siding, window framing, and roof tiles are being introduced into the market. The use of WPCs is also increasing in construction, transportation, industrial and consumer industries. Growing interest in renewable resources-based products is due to social and environmental concerns. Commercial thermoplastics such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and styrene maleic anhydride (SMA) are commonly used in the manufacture of plastic/wood fiber composites (Sobczak *et al*., 2013; Bledzki and Gassan, 1999; Rowell *et al*., 1997; Zor *et al*., 2016). The use of technical and standard plastics has approached the application of natural fibers thanks to their low prices and steadily rising performance (Wittig, 1994). The composites reinforced with wood have shown a great growth due to many advantages. Their processing is easy, economic, and ecological. They have relatively high strength and stiffness, low cost, low density, low CO_2 emission, and they are biodegradable and renewable (Deka and Maji, 2011). However, these polymers have low thermal conductivities. Therefore, some researchers have worked to improve the thermal conductivity and electrical insulation of polymers by adding different fillers and fire retardants.

Boron nitride (BN) has been widely used in the thermal management industry for years. BN is a good lubricant and abrasive, and it has a high thermal conductivity, high electrical resistance, and high temperature resistance. The familiar structures of BN are the hexagonal (hBN) and cubic (cBN) crystal structures. The structure of hBN is more stable than that of cBN (Meneghetti *et al*., 2008). BN is a low atomic numbered nonmetallic compound; its melting temperature (~3000 °C) is too high to be used for thermal insulation. BN/polymer composites can decrease thermal expansion and increase thermal conductivity, while enhancing the electrical insulation properties (Zhou *et al*., 2007). Also, the addition of a small amount of BN in polymers might enhance their extrusion by increasing their flowablity (Jung *et al*., 2010). Nano TiO_2 particle is one of the promising inorganic nano fillers used in polymer matrix composites to enhance the mechanical properties (Nayak *et al*., 2016; Bardak *et al*., 2016). Among the investigated inorganic nano fillers, TiO_2 nanopowder is being increasingly investigated because it is non-toxic, chemically inert, low cost, corrosion resistant and has a high refractive index, UV filtration capacity and high hardness (Mirabedini *et al*., 2008).

The goal of this research was to investigate the usability of wood flour obtained from particleboards in wood plastic composites. Furthermore, the effects of nano TiO_2 and nano BN on the physical, mechanical and thermal properties of WF/PP composites have determined.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

2.1 Materials
2.1. Materijali

Wood flours (WF) were supplied by Kastamonu Entegre Ağaç Sanayi A.Ş. Wood flours consist of 50 % *Gymnospermae* (*Pinus nigra* Arn. and *Pinus sylvestris* L.) wood and 50 % *Angiospermae* wood (*Fagus orientalis* L. and *Populus alba* L.). Oven-dry densities of WFs used in the study were 0.54 g·cm^{-3}, 0.48 g·cm^{-3}, 0.63 g·cm^{-3} and 0.40 g·cm^{-3}, respectively. All WF samples were of the same size made using 0.5 mm sieve. Polypropylene (EH241) was supplied by PETKIM Inc, in Turkey. The properties of the PP – EH241 are listed in Table 1.

Table 1 Properties of polypropylene (EH241)
Tablica 1. Svojstva polipropilena (EH241)

Properties / *Svojstva*	**Values** *Vrijednost*
Melt flow index, g/10 min (at 230 °C / 2.16 kg) *indeks fluidnosti,* g/10 min *(pri 230* °C */ 2,16* kg*)*	5 to 20
Density / *gustoća*, g·cm^{-3}	0.92
Water absorption / *upijanje vode*, %	0.1
Processing temperature / *temperatura obrade*, °C	160-170
Tensile modulus / *modul elastičnosti*, MPa	35
Flexural modulus / *modul savitljivosti*, GPa	1.5
Izod Impact, notched / *otpornost na udarce*, kJ·m^{-2}	2

Titanium dioxide (TiO_2) was supplied by mkNANO (Canada). Titanium dioxide nano powder (MKN-TiO_2-015P: Hydrophilic TiO_2) was amorphous and 99.5 % pure. The size of TiO_2 was 50 nm. The specific surface area of titanium dioxide is 150 $m^2 \cdot g^{-1}$.

Hexagonal boron nitride (hBN) was supplied by BORTEK – BOR Technologies, Inc. Boron nitride has the formula BN, so it consists of boron and nitrogen elements. The hexagonal formation is stable and softest among the BN polymorphs. Boron nitrides cannot be naturally obtained, so they are chemically synthesized by reacting boron trioxide or boric acid with ammonia or urea (Rudolph 2000, Robert and Chaitanya 1990). The h-BN has a specific gravity of 2.27 $g \cdot cm^{-3}$ and a melting range of 2700-3000 °C. It consists of thin plates that have an average diameter of about 200 nm and a thickness of 80 nm (Ayrilmis *et al*., 2014).

2.2 Methods
2.2. Metode

WF was oven dried at 103±2 °C to obtain moisture content less than 1 %. PP was used as matrix polymer, while WF was used as fillers. Loading ratios of WF were 10 and 20 % wt. Nano materials (nano TiO_2 and nano boron nitride) loading level varied from 0.5 to 1 % by compounding weight (1000 gr). A general survey of PP/WF compound after mechanical mixing is shown in Figure 1. The production formulations are given in Table 2.

The materials used in the compounding were first mixed to achieve better dispersion by mechanical mixer for 15 minute. The obtained samples were extruded at 50 rpm by a single screw extruder. During the extrusion, the zone temperatures ranged from 170 to 180 °C, the melting pressure of the extruder varied between 5 and 10 bars depending on material blends, the screw speed was 50 rpm, and the material output was 1 $kg \cdot h^{-1}$. When exiting the extrusion, the obtained compounds, which were melted, were cooled and solidified directly in a water-cooling system, while being pulled with end drive conveyors. Then, the solidified

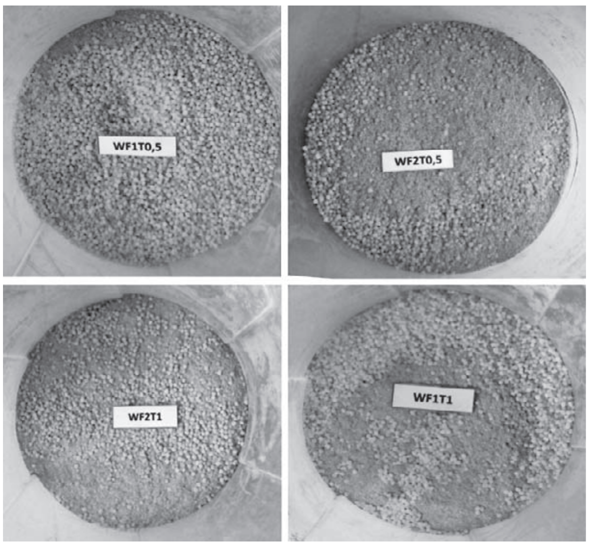

Figure 1 PP/WF compounds
Slika 1. Spojevi PP/WF

Table 2 Materials and ratios used in the study
Tablica 2. Materijali upotrijebljeni u eksperimentu i njihovi omjeri

Sample code *Oznaka uzorka*	**Polypropylene** *Polipropilen* %	**Filling material** *Punilo* %	**Nano material** *Nanomaterijal* %	**Type of nano material** *Vrsta nanomaterijala*
Neat PP	100	-	-	-
PP+W1	90	10	-	-
PP+W2	80	20	-	-
PP+W1B0.5	89.5	10	0.5	BN
PP+W1B1	89.	10	1	BN
PP+W1T0.5	89.5	10	0.5	TiO_2
PP+W1T1	89.	10	1	TiO_2
PP+W2B0.5	79.5	20	0.5	BN
PP+W2B1	79	20	1	BN
PP+W2T0.5	79.5	20	0.5	TiO_2
PP+W2T1	79	20	1	TiO_2

materials were pelletized through a pelletizer. The pellets obtained were injection molded to obtain the test samples. All samples were conditioned at 20 °C and 65 % relative humidity prior to tests. First, the weights of samples (*m*) were measured by 0.001 g precision scales. Sample volumes (*V*) were calculated using dimensions and densities (*D*) of samples determined according to $D=m/V$ equation.

The samples were air dried at 70 °C until a constant weight was reached prior to the immersion in a water bath. The specimens were periodically taken out of the water, wiped with tissue paper to remove surface water, reweighed and measured again and immediately put back into the water. The water absorption of the composites was determined according to ASTM D 1037-93.

Bending strength (*BMOR*), flexure modulus (*BMOE*), tensile strength (*TMOR*) and tensile modulus (*TMOE*) were determined according to ASTM D 790-03 Test Method 1 and ASTM D 638-03 Type I, respectively. These tests were conducted using a Zwick tester with a 10-kN load cell capacity. Test speed was used at a rate of 0.2 $inch \cdot min^{-1}$ for all tests. The izod impact strength (IIS) tests were conducted according to ASTM D 256-06. The notches were provided with a NotchVIS machine (Ceast trademark) and tests were performed with a Resil 50 B impact tester. The morphological properties of the samples were observed with a scanning electron microscope (SEM) (TESCAN MAIA3) with an accelerating voltage of 15 kV under nitrogen. The fracture parts of all samples were sputter-coated with gold using a Denton sputter coater for enhanced conductivity. The thermal stability of all the composites was investigated using a TGA and DSC (Perkin Elmer, TA Instruments, USA). When using a TGA, the samples were heated from 25 ºC to 600 ºC with a heating rate of 10 ºC/min and a nitrogen flow of 100 $mL \cdot min^{-1}$. The samples weighing about 10 mg were used for the tests. Degradation temperatures at 10 %

weight loss ($T_{10\%}$) and 50 % weight loss ($T_{50\%}$), maximum degradation temperature in the derivative thermogravimetric peaks (DTG_{max}), and mass loss of the samples in the TGA curves were measured and compared with the results obtained.

One-way analysis of variance (ANOVA) was performed to identify significant differences at the 99 % confidence level. The Duncan test was used to determine the difference between groups. The important differences between formulations were shown with letters, such as A, B, C, and D.

3. RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Physical and mechanical properties
3.1. Fizikalna i mehanička svojstva

The highest density was determined to be 0.94 g·cm^{-3} in pure PP samples. This was followed, in order, by PP+W1B1, PP+W1 and PP+W1T1 samples. The lowest density was obtained in the W2T1 sample. Low density of wood flour is the factor with the highest impact on decreasing densities. Densities of WFs used in the study varied between 0.40 g·cm^{-3} (*Pinus nigra* Arn.) and 0.63 g·cm^{-3} (*Fagus orientalis* L.). There is a significant difference in variations (F_{ratio} = 4.706; P_{value} = 0.000 < 0.05) according to one–way analysis of the variance (ANOVA). Homogeneity within variations was determined by using Duncan test. Figure 2 and Table 3 show densities and homogeneity groups of WPC, respectively.

Figure 2 and Figure 3 show that the addition of wood flour increased *BMOR* and *BMOE* values. The highest value of *BMOR* was found to be 51.60 MPa in the PP+W1B1 samples. PP+W2B2 samples showed the highest *BMOE* with 2207 MPa strength. Control samples (Pure PP) showed the lowest *BMOR* value with 41.80 MPa and *BMOE* with 1256 MPa, respectively. Supporting WPC with wood flour resulted in the increase of 23.4 % in the bending strength (PP+W1B1), 75 % in the modulus of elasticity (PP+W2B1). Bouafif *et al*., (2009) state that lignocellulosic materials increased the bending and tension strength as well as elasticity modules in bending and tension tests. *BMOR* and *BMOE* values are shown in Figure 3 and Figure 4, respectively.

Table 3 The homogeneity groups of WPC
Tablica 3. Homogene skupine drvno-plastičnih kompozita

Sample code / *Oznaka uzorka*	**Groups** / *Skupine*	
PP+WF1BN0.5	0.8665	A
PP+WF1T0.5	0.8694	AB
PP+WF2	0.8764	ABC
PP+WF1T1	0.8915	ABCD
PP+WF2BN1	0.8928	BCD
PP+WF1	0.8930	BCD
PP+WF2T0.5	0.8989	CD
PP+WF2BN0.5	0.9029	D
PP+WF1BN1	0.9053	D
PP+WF2T1	0.9087	D
Pure PP	0.9360	E

The multi-way ANOVA analysis was conducted to find the effects of nanoparticle type, nanoparticle rates and filler rate on bending strength of WPC and the obtained data are given in Table 4.

The effect of nanoparticle rate (0.5 % and 1 %), nanoparticle type (TiO_2 and BN) and filler rate (10 % and 20 %) on the *BMOR* was found to be significant according to the result of Duncan test as seen in Table 5. The effect of interaction of nanoparticle type and filler rate on the bending strength was statistically significant. Duncan test was applied to determine the differences between groups. The effects of nanoparticle rate, nanoparticle type and filler material rate on the bending strength are given in Table 5. Increasing in nanoparticle rate increased proportionally both *BMOR* and *BMOE* values (Table 5.1). BN increased the *BMOR* strength, while TiO_2 contributed to the development of *BMOE* strength. It can be said that BN is more effective in bending resistance when compared to TiO_2 (Table 5.2). Adding wood flour to pure PP increased the *BMOR* and *BMOE*, but the filler rate was not important in *BMOR* test according to Table 5.3.

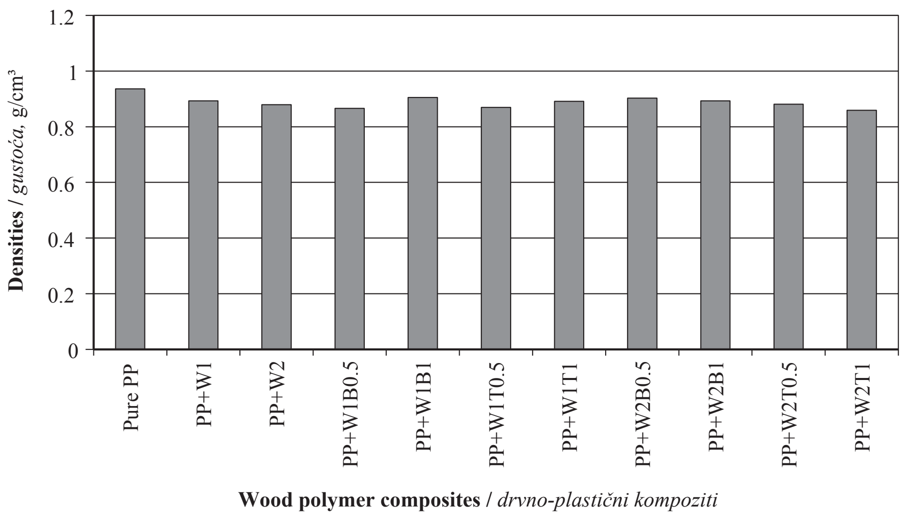

Figure 2 Densities of WPC
Slika 2. Gustoća istraživanih drvno-plastičnih kompozita

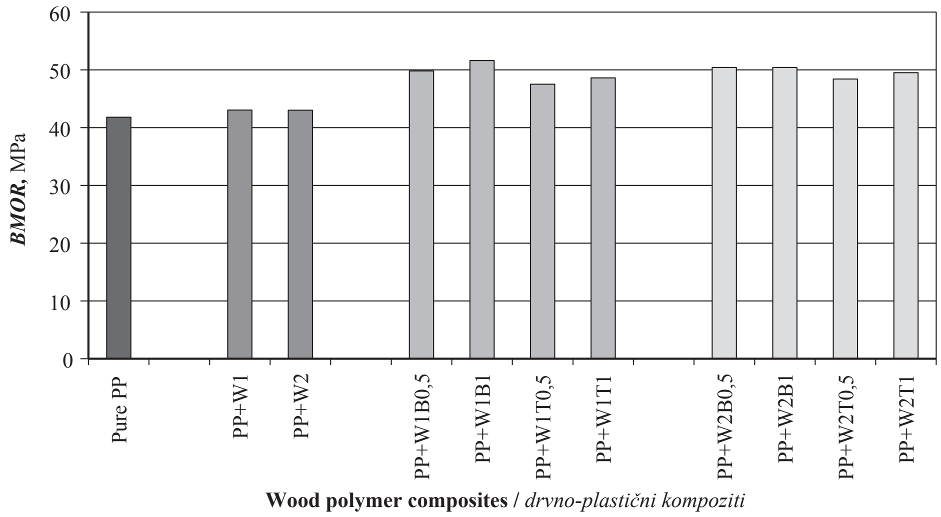

Figure 3 *BMOR* values of WPC
Slika 3. Čvrstoća na savijanje istraživanih drvno-plastičnih kompozita

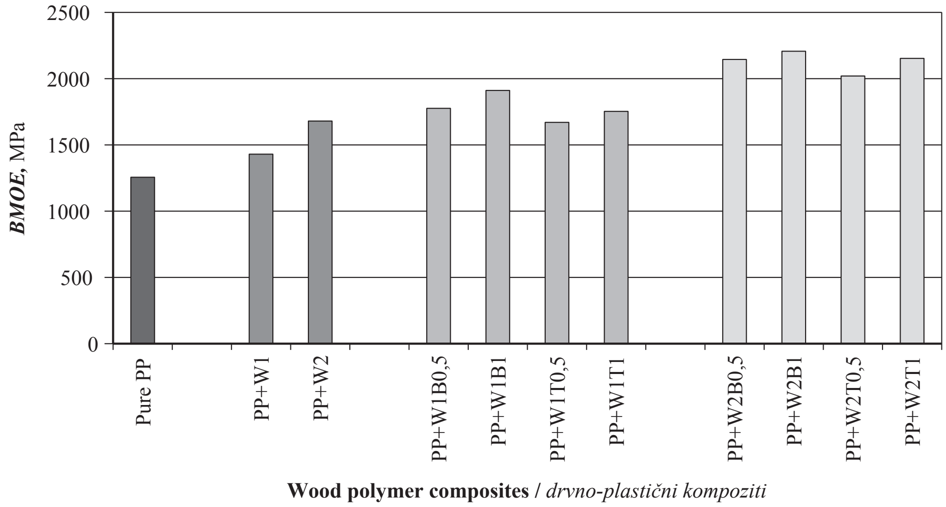

Figure 4 *BMOE* values of WPC
Slika 4. Modul elastičnosti pri savijanju istraživanih drvno-plastičnih kompozita

Table 4 Multi-way ANOVA analysis done for the effects of nanoparticle type, nanoparticle rate and filler rate on bending strength of WPC
Tablica 4. Višefaktorska ANOVA analiza utjecaja vrste nanočestica, količine nanočestica i količine punila na čvrstoću savijanja drvno-plastičnih kompozita

Source / *Izvor varijabilnosti*	**Type III Sum of Squares** *Zbroj kvadrata*	***df***	**Mean Square** *Srednja vrijednost kvadrata*	***F***	**Sig.**
Corrected model / *korigirani model*	575.056[a]	10	57.506	85.748	.000
Intercept / *presjek*	114171.222	1	114171.222	1.702E5	.000
Filler rate (A) / *udjel punila (A)*	5.040	2	2.520	3.757	.031
Nanoparticle type (B) / *vrsta nanočestica (B)*	40.381	1	40.381	60.213	.000
Nanoparticle rate (C) *količina nanočestica (C)*	8.621	1	8.621	12.855	.001
(A) * (B)	4.363	1	4.363	6.505	.014
(A) * (C)	2.093	1	2.093	3.121	.084
(B)* (C)	0.281	1	0.281	0.418	.521
(A) * (B) *(C)	2.678	1	2.678	3.993	.052
Error / *pogreška*	29.508	44	0.671		
Total / *ukupno*	125208.989	55			
Corrected Total / *ispravljeno ukupno*	604.564	54			

Table 5 Effect of nanoparticle rate (A), nanoparticle type (B) and filler rate (C) on *BMOR* according to Duncan test
Tablica 5. Utjecaj količine nanočestica (A), vrste nanočestica (B) i količine punila (C) na čvrstoću na savijanje istraživanih kompozitnih materijala prema Duncanovu testu

Nanoparticle rate / *Količina nanočestica*	**Groups** / *Skupine*		
	A	B	C
Control	42.61		
0.5 %		49.00	
1 %			49.92

A)

Nanoparticle type / *Vrsta nanočestica*	**Groups** / *Skupine*		
	A	B	C
Control	42.61		
TiO_2		48.46	
BN			50.46

B)

Filler rate *Količina punila*	**Groups** *Skupine*	
	A	B
Control	41.82	
10 %		48.07
20 %		48.27

C)

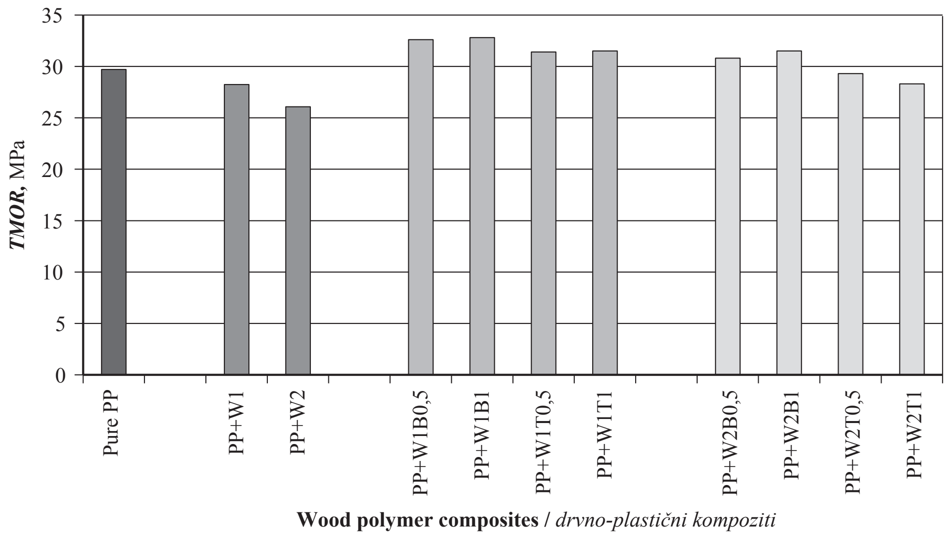

Figure 5 *TMOR* values of WPC
Slika 5. Vlačna čvrstoća istraživanih drvno-plastičnih kompozita

Figure 5 and Figure 6 show *TMOR* and *TMOE* values of the samples, respectively. *TMOR* of pure PP was determined as 29.7 MPa. Decreasing was observed in *TMOR* values of PP+W1 and PP+W2 samples. These decreases were calculated to be 4.94 % and 12.2 %, respectively. All samples containing nano boron nitride showed increased *TMOR* values when compared to control samples. *TMOE* of pure PP increased in all of the samples. The highest increase in *TMOE* of PP+W2B1 and PP+W2B0.5 was determined to be 83 % and 75.8 %, respectively.

According to the multi-way ANOVA analysis, it was found that the filler rate (A), nanoparticle type (B) and nanoparticle rate (C) were statistically significant at 0.05. Table 6 shows the results of multi-way ANOVA analysis.

It was found that the interaction between filler rate (1) and nanoparticle rate (3) was not significant. In-

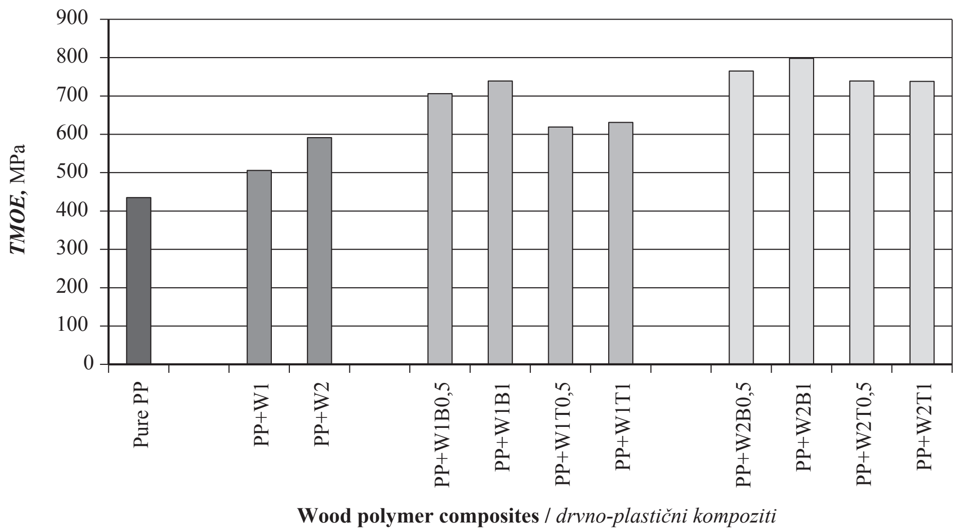

Figure 6 *TMOE* values of WPC
Slika 6. Vlačni modul elastičnosti istraživanih drvno-plastičnih kompozita

Table 6 Multi-way ANOVA analysis determining the effects of nanoparticle type, nanoparticle rate and filler rate on tensile strength of WPC
Tablica 6. Višefaktorska ANOVA analiza utjecaja vrste nanočestica, količine nanočestica i količine punila na vlačnu čvrstoću drvno-plastičnih kompozita

Source / *Izvor varijabilnosti*	**Type III Sum of Squares** *Zbroj kvadrata*	***df***	**Mean Square** *Srednja vrijednost kvadrata*	***F***	**Sig.**
Corrected model / *korigirani model*	216.347[a]	10	21.635	94.949	.000
Intercept / *presjek*	46710.972	1	46710.972	2.050E5	.000
Filler rate (A) / *udjel punila (A)*	76.101	2	38.051	166.994	.000
Nanoparticle type (B) / *vrsta nanočestica (B)*	32.256	1	32.256	141.564	.000
Nanoparticle rate (C) / *količina nanočestica (C)*	.018	1	0.018	.081	.777
(A) * (B)	2.948	1	2.948	12.940	.001
(A) * (C)	.331	1	0.331	1.454	.234
(B)* (C)	2.116	1	2.116	9.287	.004
(A) * (B) *(C)	1.706	1	1.706	7.486	.009
Error / *Pogreška*	10.026	44	0.228		
Total / *Ukupno*	50316.722	55			
Corrected Total / *ispravljeno ukupno*	226.373	54			

creasing the rate of wood flour decreased the tensile strength of WPC when compared to control samples. However, adding nanoparticles to WF/PP compound led to a significant increase. It can be said that BN provided a better fit with wood flour than TiO_2. The effects of nanoparticle rate (1), nanoparticle type (2) and filler rate (3) on the *TMOR* are according to the results of Duncan test. The related test results are shown in Table 7.

As seen in Figure 7, the highest izod impact strength (IIS) was obtained in PP+W1and PP+W2 samples, 2.17 $kJ \cdot m^{-2}$ and 2.07 $kJ \cdot m^{-2}$, respectively. The lowest IIS was determined in W1samples, which contained 0.5 % of nano boron nitride. Generally, it can be said that nanoparticles decreased the izod impact strength of WF/PP composites.

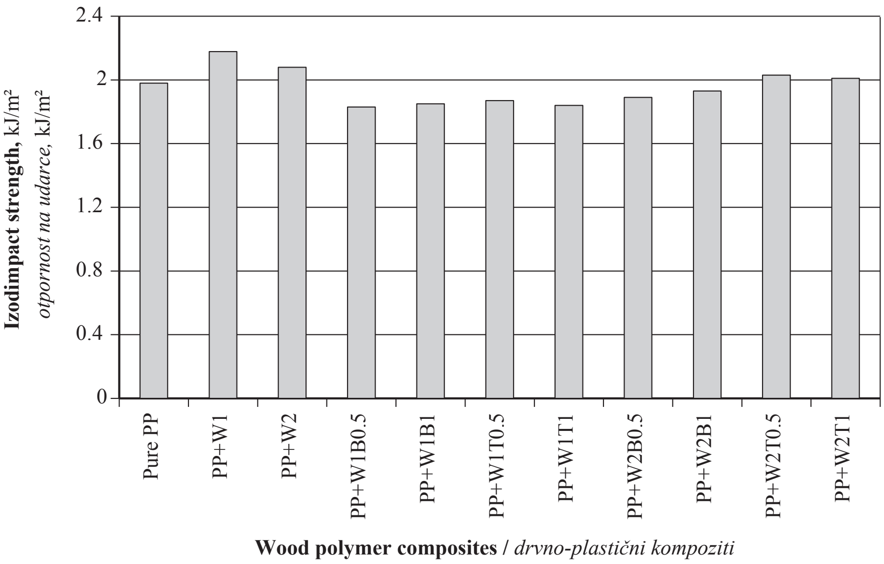

Figure 7 Izod impact strength (IIS) values of WPC
Slika 7. Otpornost na udarce (IIS) istraživanih drvno-plastičnih kompozita

Table 7 Effect of nanoparticle rate (A), nanoparticle type (B) and filler rate (C) on *TMOR* according to Duncan test
Tablica 7. Utjecaj količine nanočestica (A), vrste nanočestica (B) i količine punila (C) na vlačnu čvrstoću istraživanih kompozitnih materijala prema Duncanovu testu

Nanoparticle rate *Količina nanočestica*	**Groups** *Skupine* A	B
Control	27.99	
0.5 %		30.97
1 %		31.01

A)

Nanoparticle type *Vrsta nanočestica*	**Groups** *Skupine* A	B	C
Control	27.99		
TiO_2		30.09	
BN			31.89

B)

Filler rate *Količina punila*	**Groups** *Skupine* A	B
20 %	29.15	
Control	29.68	
10 %		31.30

C)

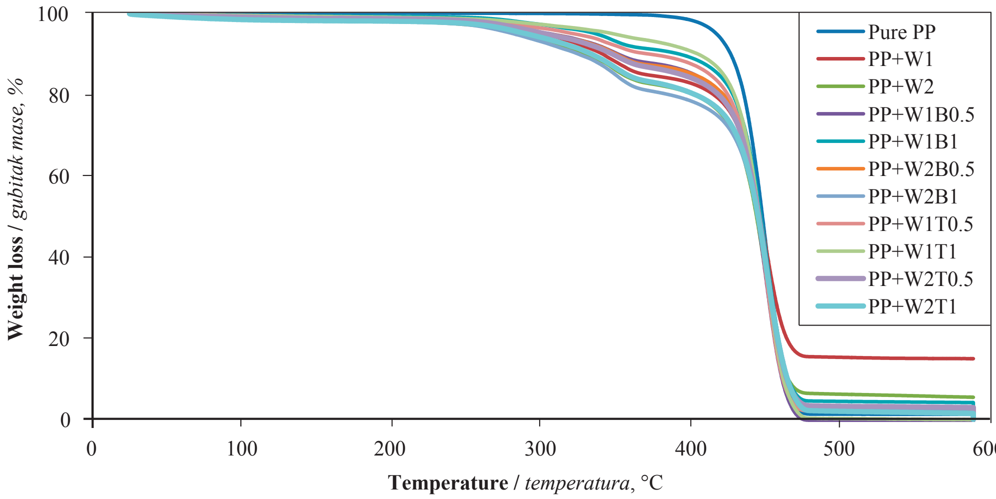

Figure 8 TGA curves of WPC
Slika 8. TGA krivulje istraživanih drvno-plastičnih kompozita

3.2 Thermal Characterization
3.2. Toplinska svojstva

Thermal stability of the samples was investigated using TGA/DTG analysis. As sees in Fig 8, it can be said that no significant difference occured in TGA analysis with the addition of nanoparticle types and filler. The fastest mass losses were observed in samples containing PP+W2T1 and PP+W2NB1. On the other hand, the PP+W1T1 curve was the nearest to the curve of pure PP. Onset temperature of the composites was also determined to decrease with adding the nanoparticle types and filler. Similarly, as the filler loading increased, the thermal stability of the composites slightly decreased, whereas the final ash content monotonically increased (Kiziltas *et al*., 2011a, b).

DTG curves in Figure 9 showed maximum degradation at 453 °C for W2NB1%, and the peaks of the composites were found to be between 350 °C and 470 °C. As seen in Table 8, DTA curves indicated the two peaks of melting peak (T_m) and decomposition peak (T_d). It is well known that PP, which is extremely hygroscopic in nature, is consumed at 426 °C without formation of any char residue (Baeza and Freer, 2001).

As seen in Table 8, the maximum value of T_m was found in the wood composites with 1%NB (167.5 °C), whereas the minimum value of T_m was determined in the wood composites with 1%NB. T_d values, the maximum and minimum values, were found to be 1%NB and 0.5%T, respectively. The summary of the thermogravimetric analysis is presented in Table 8.

4 CONCLUSIONS
4. ZAKLJUČAK

Adding wood flour has no significant effect on the density of WPC composites. The *BMOR* and *BMOE* of the composites were increased both with the addition of wood flour and nanoparticle rate. The *TMOR*, *TMOE* and izod impact strength of the composites were negatively affected by the increase of the rate of wood flour. It was found that thermal stability of the composites (TGA) decreased with both nanoparticle

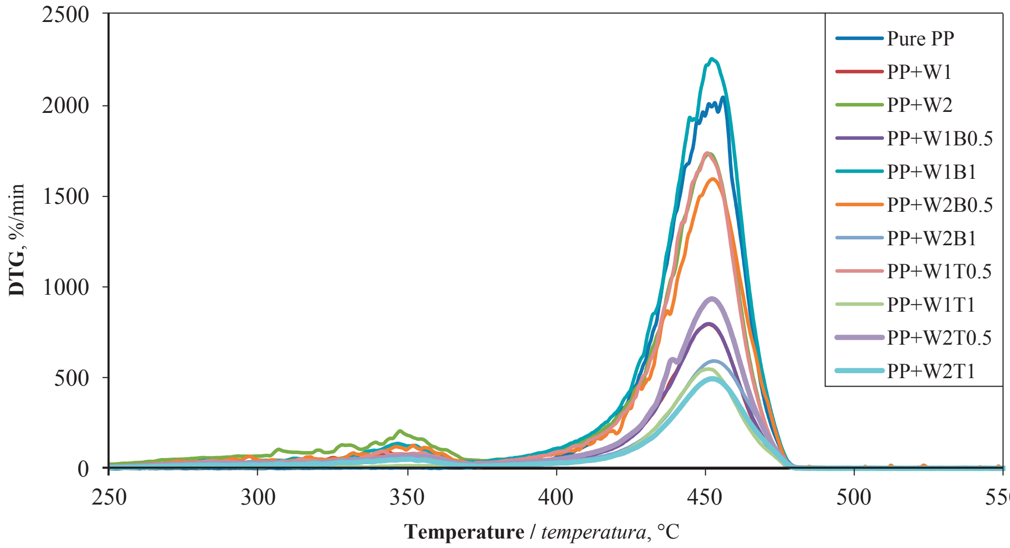

Figure 9 DTG curves of WPC
Slika 9. DTG krivulje istraživanih drvno-plastičnih kompozita

Table 8 Summary of thermogravimetric analysis
Tablica 8. Sažetak termogravimetrijske analize

Samples *Uzorci*	$T_{10\%}$ °C	$T_{50\%}$ °C	$T_{90\%}$ °C	**Residue** %	DTG_{max} °C	T_m °C	T_d °C
PP	427.0	448.3	463.3	98.7	456.0	166.4	450.3
PP+W1	341.18	447.15	465.3	84.9	451.0	158	448.2
PP+W2	330.22	444.39	465.4	94.7	451.5	159.6	451.2
PP+W1B0.5	351.4	444.9	461.4	99.8	451.1	163.4	450.9
PP+W1B1	392.2	447.2	465.4	95.9	452.1	167.5	451.5
PP+W2NB0.5	350.2	446.3	464.6	98.0	452.6	165.6	452.3
PP+W2NB1	324.9	445.2	465.5	98.2	453.0	161.8	456.4
PP+W1T0.5	371.6	445.4	461.8	98.3	450.7	165.9	450.1
PP+W1T1	404.9	446.3	463.0	99.8	451.0	162.3	450.5
PP+W2T0.5	347.6	445.9	464.6	97.1	452.2	164.4	451.4
PP+W2T1	333.6	445.4	464.9	98.5	452.1	163.1	455.8

types. It was concluded that wood flour obtained from particleboards in WPCs has a significant effect on the material characterization (mechanical properties, thermal properties, etc.). Based on the findings obtained from the present study, the use of W1T1 can further increase mechanical performance of all composites.

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Chemical Composition, Fiber Morphology, and Kraft Pulping of Bracken Stalks (*Pteridium aquilinum* (L.) Kuhn)

Kemijski sastav, morfologija vlakana i sulfatni postupak proizvodnje celuloze od stabljika paprati (*Pteridium aquilinum* (L.) Kuhn)

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ABSTRACT • *In this study, kraft, kraft-$NaBH_4$, and kraft-KBH_4 pulp and paper properties of the bracken stalks (Pteridium aquilinum* (L.) Kuhn) *were determined. Also, the chemical composition and fiber properties of bracken stalks were evaluated. $NaBH_4$ and KBH_4 were separately added to cooking liquor by 0.5 %, 1 %, 1.5 %, and 2 % (oven dried wood). The boron compound-free kraft pulp were also made as control pulp. Fiber length and fiber width of bracken stalks were determined as 1.25 mm and 24 µm, respectively. Bracken stalks are composed of 73.34 % holocellulose, 32.55 % α-cellulose, and 30.79 % lignin. In addition, the pulp yield was increased with additions of both boron compounds, while kappa number was decreased. Also, highest strength increases determined in 0.5 % $NaBH_4$ added pulp. These results showed that bracken stalks can be used as a raw material for kraft pulp production.*

Keywords: *bracken, KBH_4, kraft, $NaBH_4$, Pteridium aquilinum* (L.) Kuhn., *paper properties*

SAŽETAK • *U radu su opisana istraživanja svojstava kraft, kraft-$NaBH_4$ i kraft-KBH_4 celuloze i papira proizvedenih od stabljika paprati (Pteridium aquilinum* (L.) Kuhn). *Ocijenjeni su kemijski sastav i svojstva vlakana stabljika paprati. Otopini za kuhanje odvojeno su dodavani $NaBH_4$ i KBH_4 u postotcima 0,5; 1; 1,5 i 2 % (u odnosu prema apsolutno suhom drvu). Kraft celuloza bez spojeva bora proizvedena je kao kontrolni uzorak. Duljina vlakana stabljika paprati iznosila je 1,25 mm, a širina 24 µm. Stabljike paprati sadržavaju 73,34 % holoceluloze, 32,55 % α-celuloze i 30,79 % lignina. Rezultati su pokazali da je uz dodatak obaju spojeva bora prinos celuloze povećan, dok je Kapa broj smanjen. Usto, rezultati su pokazali najveće povećanje čvrstoće za celulozu dobivenu dodatkom 0,5 % $NaBH_4$. Na temelju dobivenih rezultata može se zaključiti da se stabljike paprati mogu upotrebljavati kao sirovina za proizvodnju kraft celuloze.*

Ključne riječi: *paprat, KBH_4, sulfatni postupak, $NaBH_4$, Pteridium aquilinum* (L.) Kuhn., *svojstva papira*

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1 INTRODUCTION
1. UVOD

Bracken (*Pteridium aquilinum* (L.) Kuhn), a weed with a height of 30-200 cm, is the fifth most distributed common weed species of the world. Bracken is widely distributed from the Equator to the northern parts of Europe, in Central Asia, China and Japan, from central South America to subarctic Canada. It can easily grow and spread on many types of soil (Vetter, 2009).

Lignocellulosic biomass are included in wood and non-wood biomass. Wood-based lignocellulosic biomass, main raw material of pulp production, consists of hardwood and softwood species. Non-wood lignocellulosic biomass, such as wheat straw, rice straw, cotton stalks, canola stalks, sugarcane bagasse, switchgrass and reed, has been an important fiber resource for pulp production in countries with a shortage of wood raw material. The main differences between woody and non-wood lignocellulosic biomasses are their chemical compositions and physical properties (Zhu and Pan, 2010). The usability of a raw material in pulp production initially depends on these properties.

Global paper and paperboard production in 2000 and 2015 was 324.6 million ton and 406.3 million ton, respectively (FAOSTAT, 2016). Increasing paper production causes the decrease in forest resources. Non-wood lignocellulosic biomass is abundantly available, low cost, and easy to process. Also, it has a short growth and harvest period. For this reason, it is introduced as a potential raw material for pulp and paper production (Tye *et al.*, 2016). However, in 2015, pulp production from non-wood lignocellulosic biomass was only 12.3 million ton (FAOSTAT, 2016). Many studies have examined the utilization of alternative raw materials in the pulp and paper industry. The utilization as an alternative raw material in paper industry of fruit trees, such as orange tree pruning (Gonzáléz *et al.*, 2011), olive tree pruning (Requejo *et al.*, 2012), pomegranate tree pruning (Gülsoy *et al.*, 2015), white mulberry (Gençer *et al.*, 2013), common hazelnut (Gençer and Özgül, 2016), wild cherry (Gençer and Gül Türkmen, 2016), was previously evaluated. On the other hand, pulp and paper properties of many non-wood plant species were determined by several authors (Deniz *et al.*, 2004; Shatalov and Pereira, 2006; Çöpür *et al.*, 2007; Akgül and Tozluoğlu, 2009; Shakhes *et al.*, 2011; Gençer, 2015; Gençer and Şahin, 2015). However, there is no published report on using bracken stalks in pulp and paper production. The aim of this study was to evaluate the suitability of bracken stalks for papermaking. For this purpose, the kraft, kraft-$NaBH_4$, and kraft-KBH_4 pulp properties of bracken stalks were evaluated. The chemical composition and fiber morphology of bracken stalks (*Pteridium aquilinum* (L.) Kuhn) were also determined.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Plant material and sample preparation
2.1. Biljni materijal i priprema uzoraka

The bracken (*Pteridium aquilinum* (L.) Kuhn) were collected from the Bartin province of Turkey. The roots and leaves of bracken were removed and only the stalks were used. The stalks were chopped to 3-5 cm. Bracken stalks were air-dried and stored in dry conditions.

2.2 Chemical analysis
2.2. Kemijska analiza

The standard methods were used in the main chemical analyses of bracken. The sample preparation (TAPPI T 257), holocellulose (Wise and Karl, 1962), α-cellulose (Han and Rowell, 1997), klason lignin (TAPPI T 222), ash (TAPPI T 211), ethanol solubility (TAPPI T 204), cold and hot water solubility (TAPPI T 207), and 1 % NaOH solubility (TAPPI T 212) were carried out according to relevant standard methods. Three repetitions were made for each experiment.

2.3 Fiber analysis
2.3. Analiza vlakana

Bracken stalk samples were macerated according to chlorite method (Spearin and Isenberg, 1947). After maceration, the samples were agitated to obtain individual fibers (Berlyn and Miksche, 1976). The fiber length, fiber width, lumen width, and cell wall thickness of 50 randomly-selected fibers were measured. The slenderness ratio (fiber length/fiber width), flexibility ratio [(lumen width/fiber width) × 100], and Runkel ratio [(2 × cell wall thickness)/lumen width] were calculated using the measured fiber dimensions.

2.4 Pulping and handsheet properties
2.4. Proizvodnja celuloze i svojstva papira

The kraft pulps made from bracken stalks were prepared under the following conditions: active alkali as Na_2O 25 %, sulfidity 30 %, liquor/wood ratio 5:1, pulping temperature 170 °C, heating time to 170 °C 90 min., and time at temperature 75 min. The same pulping conditions were applied to 0.5 %, 1 %, 1.5 %, and 2 % $NaBH_4$ and KBH_4 added samples. In pulping, laboratory-type 15-L electrically-heated rotary digester was used. In order to remove the black liquor, the pulps were washed and disintegrated. The rejects were retained by a Somerville-type pulp screen with a 0.15-mm slotted plate (TAPPI T 275). All pulps were beaten according to TAPPI T 200 to 25 °SR in a Valley Beater for comparison in the same conditions. The kappa number, screened yield and freeness levels of all pulps were determined according to TAPPI T 236, TAPPI T 210, and ISO 5267-1, respectively. Ten handsheets (75 g/m^2) were formed with a Rapid-Kothen Sheet Former (ISO 5269-2). The handsheets were conditioned according to TAPPI T 402. The tensile index, tensile energy absorption (TEA), and stretch (ISO 1924), burst index (TAPPI T 403), tear index (TAPPI T 414), and brightness (TAPPI T 525) of the handsheets were measured using the relevant standard methods.

2.5 Statistical analysis
2.5. Statistička analiza

All data was performed using SPSS software. The data belonging to the kraft and kraft-$NaBH_4$, and kraft-KBH_4 pulp properties of the bracken stalks were analyzed with analysis of variance (ANOVA). The effects of boron compound addition on paper properties were evaluated statistically. All pair wise multiple comparison procedures were performed using Duncan's test ($p<0.05$). The same letter in figures denotes that there were no statistically significant differences between the groups.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Chemical composition
3.1. Kemijski sastav

The chemical composition of a lignocellulosic raw material has been an important factor in evaluating its suitability for pulp production. The high holocellulose content and low lignin content have been desired for pulping to obtain higher pulp yield and lower kappa number. Also, pulp yield substantially depends on α-cellulose content of raw material used in pulp production. Table 1 shows the chemical composition of bracken stalks and its comparison with other lignocellulosic materials. As can be seen in Table 1, holocellulose content of bracken stalks was found to be 73.34 %, which is comparable with other annual plants, lower than eucalyptus (80.47 %) and aspen (82.68 %), and higher than maritime pine (70.21 %).

The α-cellulose content of raw material is an indicator of pulp yield. Fibers having higher α-cellulose content have been preferred for chemical pulp production. The α-cellulose content of bracken stalks (32.55 %) was lower than that of other annual plants. Also, it was lower than that of eucalyptus (52.79 %), aspen (49.03 %), and maritime pine (47.11 %), higher than that of cotton stalks (29.74 %).

The klason lignin content of bracken stalks (30.79 %) was higher than that of most annual plants. Also, it was higher than that of eucalyptus (19.96 %), aspen (16.69 %), and maritime pine (28.23 %). The high lignin content in raw material causes longer pulping time and increases the requirement of chemicals for delignification. Therefore, low lignin content in lignocellulosic raw material has been seen as an advantage for chemical pulping.

The solubility in water provides no useful information concerning the pulping value of the raw material, but it indicates the nature of certain constituents. In the cold water procedure, inorganic compounds, tannins, gums, sugars, and coloring matters are removed from raw material. The hot water procedure additionally removes starch. Treatment of raw material with 1

Table 1 Comparison of chemical composition of bracken stalks with other lignocellulosic species
Tablica 1. Usporedba kemijskog sastava stabljika paprati s drugim lignoceluloznim sirovinama

Raw materials *Sirovina*	**H %**	**AC %**	**KL %**	**ES %**	**HWS %**	**CWS %**	**NaOH %**	**Ash %**	**Literature**
Bracken stalks / *stabljike paprati*	73.34	32.55	30.79	7.19	15.45	14.60	28.08	7.45	This study
Cotton stalks / *stabljike pamuka*	62.79	29.74	23.79	-	17.91	15.05	48.88	4.99	Ateş *et al*., (2015)
Corn stalks / *stabljike kukuruza*	64.80	35.60	17.40	9.50*	14.8	-	47.10	7.5	Usta *et al*., (1990)
Sorghum stalks / *stabljike sirka*	71.0	40.3	13.0	15.3	19.7	15.1	47.1	-	Gençer and Şahin, (2015)
Sunflower stalks / *stabljike suncokreta*	66.9	37.6	10.8	4.07*	21.1	-	50.4	-	López *et al*., (2005)
Tobacco stalks / *stabljike duhana*	67.79	39.20	18.90	7.10*	20.02	16.85	42.00	6.86	Shakhes *et al*., (2011)
Canola stalks / *stabljike uljane repice*	72.1	39.9	20.6	1.6	8.6	7.5	29.1	5.8	Tofanica *et al*., (2011)
Wheat straw / *slama od pšenice*	69.84	42.07	22.33	9.33*	14.71	11.33	53.67	11.63	Ateş *et al*., (2015)
Barley straw / *slama od ječma*	66.01	38.70	19.47	-	16.25	11.01	56.25	10.97	Ateş *et al*., (2015)
Rice straw / *slama od riže*	70.85	35.62	17.2	3.52*	16.24	10.65	49.15	16.6	Tutus *et al*., (2004)
Rye straw / *slama od raži*	74.1	44.4	15.4	9.2*	13.0	10.2	39.2	3.2	Usta and Eroglu, (1988)
Kenaf / *kenaf*	71.8	46.75	17.30	4.28*	6.42	4.56	28.50	1.56	Dutt *et al*., (2009)
Hemp *konoplja*	86.93	63.77	6.59	4.23*	9.06	7.75	29.55	-	Gümüşkaya and Usta, (2006)
Sugarcane bagasse (depithed) *ostatci od prerade* šećerne *trske*	71.03	42.34	21.7	1.85*	7.42	3.02	32.29	2.10	Agnihotri *et al*., (2010)
Bamboo / *bambus*	68.33	47.67	26.00	3.68*	5.53	4.61	19.82	1.98	Moradbak *et al*., (2016)
Paulownia / *drvo paulovnije*	75.74	43.61	20.5	3.76	10.05	8.50	24.50	0.21	Ates *et al*., (2008)
Eucalyptus globulus	80.47	52.79	19.96	1.15*	2.84	-	12.42	0.57	Jiménez *et al*., (2008)
European aspen / *drvo jasike*	82.68	49.03	16.69	3.22	3.04	3.22	15.34	0.31	Gulsoy and Tufek, (2013)
Maritime pine / *drvo primorskog bora*	70.21	47.11	28.23	4.15	3.67	1.64	9.71	0.27	Gulsoy and Tufek, (2013)

H: Holocellulose / *holoceluloza*, AC: α-cellulose / α-celuloza, KL: Klason lignin / *klason lignin*, ES: Ethanol solubility / *topljivost u etanolu*, HWS: Hot water solubility / *topljivost u vrućoj vodi*, CWS: Cold water solubility / *topljivost u hladnoj vodi*, NaOH: 1 % NaOH solubility / *topljivost u 1 %-tnom NaOH*, *: Alcohol benzene solubility / *topljivost u alkohol benzenu*, **: Acetone solubility / *topljivost u acetonu*, ***: Ethanol-toluene solubility / *topljivost u etanol-toluenu*

% NaOH causes the extraction of low-molecular-weight carbohydrates consisting mainly of hemicelluloses and degraded cellulose. Also, this treatment is an indication of decay degree in the raw material. The high content of 1 % NaOH soluble of the rapeseed stalks and depithed stalks may probably affect the pulp yields and also the chemical consumption (Tofanica *et al.,* 2011). Ethanol, hot water, cold water, and 1 % NaOH solubility of bracken stalks were found to be 7.19 %, 15.45 %, 14.60 %, and 28.08, respectively. These values were similar to those of other nonwood lignocellulosic raw materials, higher than those of hardwood and softwood species. According to chemical composition results, bracken stalks can be evaluated as an alternative raw material for pulp production, although they have low α-cellulose content and high lignin content.

Like most nonwood fibers, the ash content of bracken stalks (7.45 %) was higher than that of wood species. Also, it was similar to that of corn stalks (7.5 %), lower than that of wheat straw (11.63 %), barley straw (10.97 %), and rice straw (16.6 %). High quantity of ash content in the lignocellulosic raw material can cause problems in pulping and papermaking processes. It can have a negative effect on chemical consumption during pulping, refining, and recovery of the cooking liquor.

3.2 Fiber morphology
3.2. Morfologija vlakana

One of the important factors in evaluating the suitability of pulp production of a raw material is its fiber morphological properties. The fiber properties directly affect the runnability on paper machine, strength and optical properties of sheet, response to refining, and fiber-water interactions, such as swelling and water retention of fibers. Long fibers are predisposed to form a porous and less uniform paper structure, coarse paper surface. Also, sheets of long fibers have higher strength properties than sheets of short fibers. On the other hand, fiber flexibility depends on lumen width and cell wall thickness of fibers. Thick-walled fibers have a negative effect on the folding endurance, burst and tensile index of paper, and a positive effect on tear index. Also, the paper obtained from thick walled fibers will be bulky, with a coarse surface, and will contain a large amount of void volume. However, thin-walled fibers provide uniform and denser paper structure.

Table 2 shows fiber properties of bracken stalks and comparison of these fiber properties with some lignocellulosic materials. As seen in Table 2, average fiber length of bracken stalks was 1.25 mm. Fiber length of bracken is similar than that of tobacco stalks (1.23 mm), kenaf (1.29 mm). Fiber length of bracken stalks was shorter than that of maritime pine (2.4 mm), bamboo (1.98 mm), sorghum stalks (1.77 mm), and sugarcane bagasse (1.59 mm), and longer than that of European aspen (1.1 mm), river red gum (0.80 mm), cotton stalks (0.83 mm), sunflower stalks (0.76 mm), rice straw (0.99 mm).

The fiber width of bracken stalks (24 μm) was close to that of corn stalks (24.30 μm), tobacco stalks (24.31 μm), and European aspen (23.9 μm). It was wider than that of cotton stalks (19.60 μm), sorghum stalks (19.53 μm), and rice straw (11.99 μm), and narrower than that of maritime pine (43.7 μm), paulownia (36.3 μm), and hemp (29.5 μm).

The lumen width of bracken stalks (10.30 μm) was similar to that of other nonwood fibers, such as corn stalks (10.70 μm) and wheat straw (10.54 μm). It was wider than that of sorghum stalks (6.60 μm), rice straw (5.26 μm), and river red gum (7.2 μm), and narrower than that of sunflower stalks (16.00 μm), tobacco stalks (15.38 μm), maritime pine (29.5 μm), paulownia (19.2 μm), and hemp (15.2 μm).

The cell wall thickness of bracken stalks (6.85 μm) was close to that of corn stalks (6.80 μm), sorghum stalks (6.46 μm) and European aspen (6.30 μm). It had thicker cell wall than cotton stalks (3.40 μm), canola stalks (5.26 μm), wheat straw (4.39 μm), and thinner cell wall than hemp (7.1 μm), paulownia (8.6 μm), and maritime pine (7.1 μm).

Slenderness ratio, felting ratio, and Runkel ratio, derived from fiber dimensions, have been used to determine the suitability of lignocellulosic raw materials for pulp production. High length to width ratio (slenderness ratio) of fibers results in well bonded paper. High slenderness ratio (>33) means that lignocellulosic raw material is suitable for pulp and paper production (Xu *et al*., 2006). Slenderness ratio of bracken stalks (52.8) was comparable with that of other raw materials as shown in Table 2. It was very close to slenderness ratio of river red gum (53.33), lower than that of sorghum stalks (90.37) and rice straw (86.04), and higher than that of sunflower stalks (30.06) and paulownia (22.58).

Flexibility ratio (lumen to fiber width) of fibers is classified as highly elastic fibers (>75), elastic fibers (50-70), rigid fibers (30-50), and very rigid fibers (<30). Flexibility ratio of bracken stalks (42.92) was comparable with that of other raw materials, as shown in Table 2. It was very close to flexibility ratio of corn stalks (44.03), lower than that of sunflower stalks (64.96) and maritime pine (67.5), and higher than that of sorghum stalks (33.79). According to flexibility ratio, the fibers of bracken stalks can be classified into rigid fibers group.

The flexible fibers, having low Runkel ratio (wall to lumen ratio, <1) are easily collapsible, and give large surface area for interfiber bonding. The rigid fibers, having high Runkel ratio (>1), have low bonded area. These fibers are least suitable for paper production due to their stiff fibers. Runkel ratio of bracken stalks (1.33) was comparable with that of other raw materials, as shown in Table 2. It was very close to Runkel ratio of rice straw (1.31), lower that that of switchgrass (1.5), and higher than that of maritime pine (0.5) and European aspen (1.1). Bracken stalks fibers are classified into rigid fibers category in terms of their Runkel ratio value. According to fiber morphology results, bracken stalks can be used for pulp production as

Table 2 Comparison of fiber properties of bracken stalks with other lignocellulosic biomasses
Tablica 2. Usporedba svojstava vlakana stabljike paprati s drugim vrstama lignocelulozne biomase

Raw materials *Sirovina*	**FL** (***L***) mm	**FW** (***D***) μm	**LW** (***d***) μm	**CWT** (***w***) μm	**SR** ***L/D***	**FR** ***(d/D)x100***	**RR** ***2w/d***	**Literature**
Bracken stalks / *stabljike paprati*	1.25	24.00	10.30	6.85	52.08	42.92	1.33	This study
Corn stalks / *stabljike kukuruza*	1.32	24.30	10.7	6.8	54.32	44.03	1.27	Usta *et al*., (1990)
Cotton stalks / *stabljike pamuka*	0.83	19.60	12.80	3.40	42.35	65.31	0.53	Ververis *et al*., (2004)
Canola stalks *stabljike uljane repice*	1.17	23.02	12.5	5.26	50.83	54.30	0.84	Enayati *et al*., (2009)
Sunflower stalks *stabljike suncokreta*	0.76	25.20	16.00	4.42	30.06	64.96	0.54	Omotoso and Owolabi, (2015)
Sorghum stalks / *stabljike sirka*	1.77	19.53	6.60	6.46	90.37	33.79	1.90	Albert *et al*., (2011)
Tobacco stalks / *stabljike duhana*	1.23	24.31	15.38	4.47	50.59	63.26	1.16	Shakhes *et al*., (2011)
Wheat straw / *slama od pšenice*	1.14	19.32	10.54	4.39	59	54.55	0.83	Kasmani and Samari-ha, (2011)
Rice straw / *slama od riže*	0.99	11.99	5.26	3.36	86.04	45.87	1.31	Kiaei, 2014
Sugarcane bagasse *ostatci od prerade šećerne trske*	1.59	20.96	9.72	5.64	75.86	46.37	1.16	Hemmasi *et al*., (2011)
Kenaf / *kenaf*	1.29	22.1	12.7	4.3	58.3	57.5	0.67	Ververis *et al*., (2004)
Switchgrass / *trave*	1.15	13.1	5.8	4.6	87.7	44.2	1.5	Ververis *et al*., (2004)
Miscanthus / *kineski šaš*	0.97	14.2	5.9	4.1	68.3	41.5	1.3	Ververis *et al*., (2004)
Hemp / *konoplja*	1.8	29.5	15.2	7.1	-	51.5	0.93	Dutt *et al*., (2008)
Musa paradisiaca (banana) *banana*	1.55	22	14.2	5.5	70.5	-	0.77	Goswami *et al*., (2008)
Bamboo / *bambus*	1.98	17.27	8.66	3.74	114.64	50.14	0.86	Moradbak *et al*., (2016)
Paulownia / *drvo paulovnije*	0.82	36.3	19.2	8.6	22.58	53.08	0.89	Ates *et al*., (2008)
River red gum / *drvo eukaliptusa*	0.80	15.0	7.2	4.0	53.33	48.0	1.11	Dutt and Tyagi, (2011)
European aspen / *drvo jasike*	1.1	23.9	11.4	6.3	46.0	47.7	1.1	Gulsoy and Tufek, (2013)
Maritime pine *drvo primorskog bora*	2.4	43.7	29.5	7.1	54.9	67.5	0.5	Gulsoy and Tufek, (2013)

FL: Fiber length / *duljina vlakna*, FW: Fiber width / *širina vlakna*, LW: Lumen width / *širina lumena*, CWT: Cell wall thickness / *debljina stanične stijenke*, SR: Slenderness ratio / *omjer vitkosti*, FR: Flexibility ratio / *omjer fleksibilnosti*, RR: Runkel ratio / *Runkelov omjer*

an alternative raw material, although they have relatively short and rigid fibers.

3.3 Pulp and paper properties
3.3. Svojstva celuloze i papira

Some properties of kraft, kraft-$NaBH_4$, and kraft-KBH_4 pulps are given in Table 3. The screened and total yields of bracken stalks control kraft pulp were relatively lower compared to conventional kraft pulp yield. This result can be explained by low α-cellulose content of bracken stalks (Table 2). On the other hand, pulp yields increased with the addition of $NaBH_4$ and KBH_4. The highest total pulp yield was found to be 36.9 % in 2 % KBH_4 added pulp. Similar total yield increases with the addition of $NaBH_4$ (Akgül *et al*., 2007; Istek and Gonteki, 2009; Tutus *et al*., 2010a,b; Gulsoy and Eroglu, 2011; Gümüşkaya *et al*., 2011; Erişir *et al*., 2015; Saraçbaşı *et al*., 2016) and KBH_4 (Gülsoy *et al*., 2016) have been reported by several authors. This result could be attributed to carbohydrate retention increases with the addition of boron compounds.

Residual lignin content of pulp was calculated by multiplying the kappa number by 0.13. Bleachable-grade chemical pulp (kraft or sulfite) usually contains about 1.5-4.5 % residual lignin (Gellerstedt, 2010). The residual lignin content of bracken stalks control pulp (45.1 x 0.13= 5.86 %) was slightly higher than that of bleachable-grade. This finding could be explained by high lignin content of bracken stalks (Table 2). The kappa numbers of pulps decreased with increasing boron compound addition ratios. This findng can be attributed to the acceleration of delignification rate with $NaBH_4$ and KBH_4 additions. The lowest kappa number was found to be 30.9 in 2 % KBH_4 added pulp. Several authors reported a positive effect of $NaBH_4$ on kappa number (Tutus *et al*., 2010b; Gulsoy and Eroglu, 2011; Gümüşkaya *et al*., 2011; Erişir *et al*., 2015; Saraçbaşı *et al*., 2016). On the other hand, Gülsoy *et al*., (2016) noted that KBH_4 had a negative effect on kappa number of maritime pine kraft pulp. $NaBH_4$, and KBH_4 additions to cooking liquor resulted in pulp viscosity increases. This result can be attributed to the prevention of degradation reactions by $NaBH_4$ and KBH_4 during cooking. The effect of KBH_4 on pulp properties was more prominent than the effect of $NaBH_4$. The highest pulp viscosity was found to be 841 cm^3/g in 2 % KBH_4 added pulp. Several authors reported a positive effect of $NaBH_4$ on pulp viscosity (Akgül and Temiz, 2006; Akgül *et al*., 2007; Istek and Özkan, 2008; Tutus *et al*., 2010b). On the contrary, pulp viscosity decreased with $NaBH_4$ addition (Çöpür and Tozluoğlu, 2008; Gulsoy and Eroglu, 2011; Gümüşkaya *et al*., 2011; Saraçbaşı *et al*., 2016).

Table 3 Some pulp properties of kraft, kraft-$NaBH_4$, kraft-KBH_4 pulps
Tablica 3. Neka svojstva kraft, kraft-NaBH4 i kraft-KBH4 celuloze

Cooking *Kuhanje*	**Screened Yield** *Prinos prosijavanja* %	**Reject** *Škart prosijavanja* %	**Total yield** *Ukupni prinos* %	**Kappa number** *Kapa broj*	**Viscosity** *Viskoznost* cm^3/g
Control	34.43	0.15	34.58	45.10	741
0.5 % $NaBH_4$	34.67	0.17	34.84	43.70	788
1 % $NaBH_4$	36.54	0.17	36.71	42.90	779
1.5 % $NaBH_4$	36.45	0.19	36.64	40.90	795
2 % $NaBH_4$	36.20	0.38	36.58	39.80	812
Control	34.43	0.15	34.58	45.10	741
0.5 % KBH_4	34.84	0.24	35.08	38.00	808
1 % KBH_4	34.94	0.06	35.00	35.20	772
1.5 % KBH_4	36.47	0.30	36.77	36.50	829
2 % KBH_4	36.75	0.15	36.90	30.60	841

The comparison of kraft pulp properties of bracken stalks with other lignocellulosic raw materials is presented in Table 4. Bracken stalks had lower screened yield and brightness, and higher kappa number than other nonwood species. This result can be attributed to low α-cellulose and high lignin content of bracken stalks.

At the similar pulp freeness levels, handsheet strength properties of bracken stalks kraft pulp were determined to be comparable with hardwood and nonwood papermaking raw materials. Tensile index (68.69 N·m/g) of handsheets of bracken stalks kraft pulp at 25 ºSR freeness level was higher than that of European aspen kraft pulp at 30 ºSR freeness level (61.13 N·m/g), kenaf kraft pulp at 30 ºSR freeness (50.23 N·m/g), sweet bamboo kraft pulp at 25 ºSR freeness (63.01 N·m/g), and lower than switchgrass kraft pulp at 30 ºSR freeness level (74.48 N·m/g).

At the similar pulp freeness levels, tear index of handsheets of bracken stalks kraft pulp (7.12 $mN·m^2/g$) was higher than kraft pulps of thistle stalks (6.7 $mN·m^2/g$), switchgrass (6.67 $mN·m^2/g$), European aspen (6.38 $mN·m^2/g$), and river red gum (6.6 $mN·m^2/g$). Also, it was lower than kenaf (10.30 $mN·m^2/g$). Burst index of handsheets of bracken stalks kraft pulp (2.98 $kPa·m^2/g$) were similar to kenaf kraft pulp (2.94 $kPa·m^2/g$). It was lower than kraft pulps of nonwood (thistle stalks and switchgrass) and hardwood (European aspen and river red gum) species (Table 4).

The effect of $NaBH_4$ and KBH_4 additions on tensile index of handsheets is given in Figure 1. Tensile index increased with $NaBH_4$ and KBH_4 additions except for 1.5 % $NaBH_4$ and 1 % KBH_4 added pulps ($p<0.05$). The highest tensile index was determined in 0.5 % $NaBH_4$ added pulp with 74.01 N·m/g. Increased tensile index can be attributed to increasing hemicellulose retention in boron compounds added pulps. Higher hemicellulose content results in an increase of pulp strength. Gulsoy and Eroglu (2011) noted that tensile index increased in European black pine kraft pulp, and Gümüşkaya *et al*., (2011) noted that it increased in stone pine AS-AQ pulp with $NaBH_4$ addition. On the contrary, some authors noted that $NaBH_4$ had a negative effect on tensile index of handsheets (Akgül *et al*., 2007; Çöpür ve Tozluoğlu, 2008; Istek and Özkan, 2008).

Table 4 Comparison of kraft pulp properties of bracken stalks with other lignocellulosic raw materials
Tablica 4. Usporedba svojstava kraft celuloze od stabljika paprati s drugim lignoceluloznim sirovinama

	Bracken stalks *Stabljike paprati* (1)	**Kenaf** *Kenaf* (2)	**Thistle stalks** *Stabljike čička* (3)	**Switchgrass** *Trave* (4)	**Sweet bamboo** *Bambus* (5)	**European aspen** *Jasika* (6)	**River red gum** *Eukaliptus* (7)
Cooking type / *Tip kuhanja*	Kraft	Kraft	Kraft	Kraft	Kraft	Kraft	Kraft
Screened yield, % *Prinos prosijavanja,* %	34.43	51.0	40.00	42.74	46.32	53.8	43.9
Kappa number / *Kapa broj*	45.1	30.2	15.0	14.01	12.54	12.8	24.4
Brightness, % / *Sjajnost*, %	16.29	-	-	29.30	19.67	27.78	25.9
Freeness level (ºSR) / *Razina slobode*	25	30	24	30	25	35	25
Tensile index, N·m/g *Vlačni indeks,* N·m/g	68.69	50.23	63.6	74.88	63.01	61.13	60.2
Tear index, $mN·m^2/g$ *Indeks cijepanja,* $mN·m^2/g$	7.12	10.30	6.7	6.67	-	6.38	6.6
Burst index, $kPa·m^2/g$ *Indeks pucanja,* $kPa·m^2/g$	2.98	2.94	3.4	4.16	3.19	4.71	3.2

1: This study, 2: Dutt *et al*., (2009), 3: Gominho *et al*., (2001), 4: Madakadze *et al*., (1999), 5: Kamthai and Puthson, (2005), 6: Gulsoy and Tufek, (2013), **7:** Khristova *et al*., (2006).

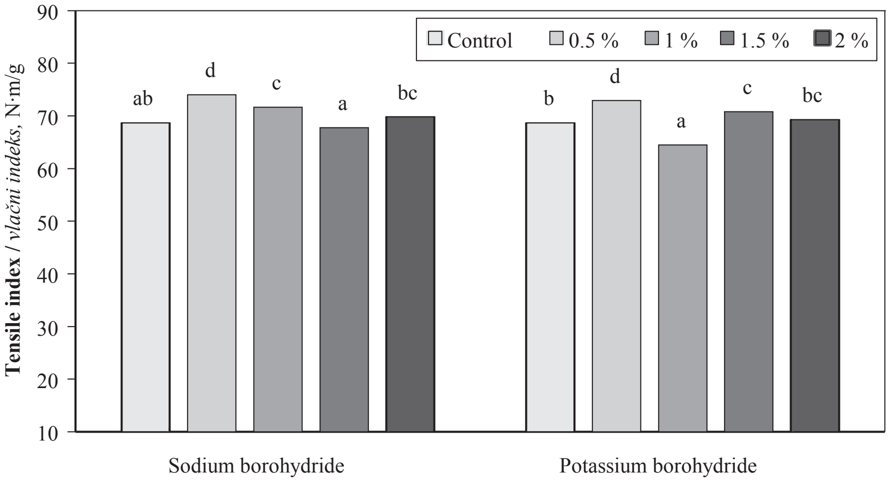

Figure 1 Effect of $NaBH_4$ and KBH_4 additions on tensile index of handsheets
Slika 1. Utjecaj dodavanja $NaBH_4$ i KBH_4 na vlačni indeks uzoraka papira

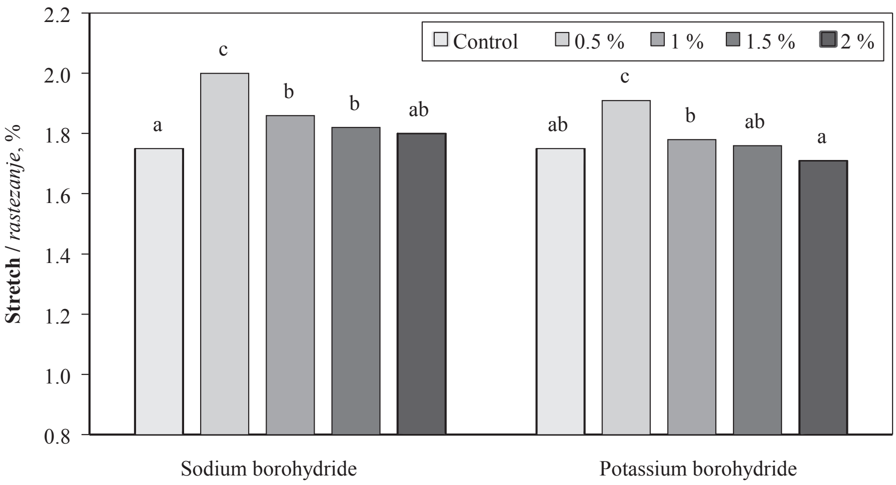

Figure 2 Effect of $NaBH_4$ and KBH_4 additions on stretch of handsheets
Slika 2. Utjecaj dodavanja $NaBH_4$ i KBH_4 na rastezanje uzoraka papira

The effect of $NaBH_4$ and KBH_4 additions on stretch values of handsheets is given in Figure 2. The stretch values of handsheets increased with $NaBH_4$ and KBH_4 additions except for 2 % KBH_4 added pulp ($p<0.05$). The highest stretch value was determined in 0.5 % $NaBH_4$ added pulp with 2.00 %. Istek and Gonteki (2009) noted that $NaBH_4$ addition to maritime pine kraft cooking caused losses in stretch values of handsheets.

The effect of $NaBH_4$ and KBH_4 additions on TEA values of handsheets is given in Figure 3. The TEA val-

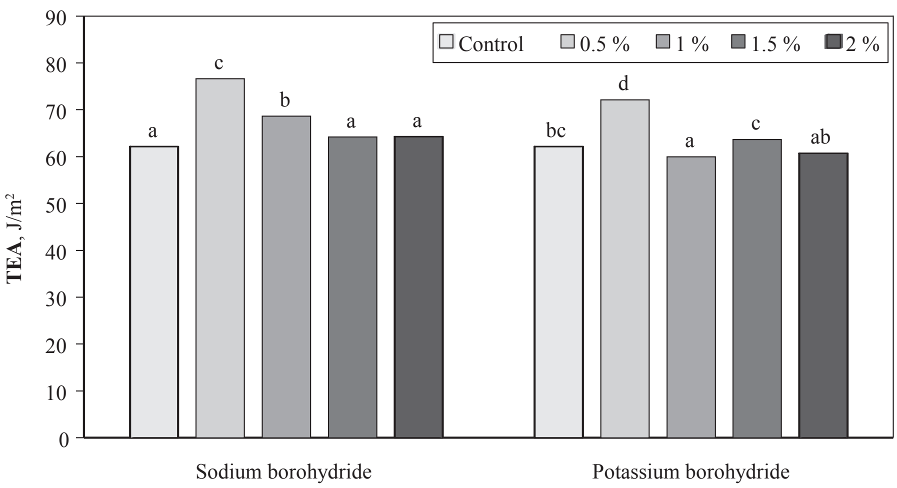

Figure 3 Effect of $NaBH_4$ and KBH_4 additions on TEA of handsheets
Slika 3. Utjecaj dodavanja $NaBH_4$ i KBH_4 na TEA uzoraka papira

ues of handsheets increased with $NaBH_4$ and KBH_4 additions except for 1 % and 2 % KBH_4 added pulps ($p<0.05$). The highest TEA value was determined in 0.5 % $NaBH_4$ added pulp with 76.66 J/m^2. Similar TEA losses were reported by Istek and Gonteki (2009).

The effect of $NaBH_4$ and KBH_4 additions on tear index of handsheets is given in Figure 4. Tear index decreased with $NaBH_4$ and KBH_4 additions ($p<0.05$). Tear index losses can be attributed to higher pulp yield of $NaBH_4$ and KBH_4 added pulps. Increasing in pulp yield causes the decrease of the fiber per unit weight of oven-dried pulp. The lowest tear index was determined in 2 % $NaBH_4$ added pulp with 5.82 mN·m^2/g. Similar tear index losses were reported in earlier studies (Akgül *et al*., 2007; Çöpür and Tozluoğlu, 2008; Istek and Gonteki, 2009; Gulsoy and Eroglu, 2011; Gümüşkaya *et al*., 2011).

The effect of $NaBH_4$ and KBH_4 additions on burst index of handsheets is given in Figure 5. Burst index increased with $NaBH_4$ and KBH_4 additions except for 1 % KBH_4 added pulp ($p<0.05$). The highest burst index was determined in 0.5 % KBH_4 added pulp with 3.27 kPa·m^2/g. Burst index of European black pine kraft pulp (Gulsoy and Eroglu, 2011) and stone pine AS-AQ pulp (Gümüşkaya *et al*., 2011) increased with 1 % $NaBH_4$ addition. On the contrary, Çöpür and Tozluoğlu (2008) noted in Brutia pine kraft pulp and Istek and Gonteki (2009) in maritime pine that $NaBH_4$ had a negative effect on burst index of handsheets.

The effect of $NaBH_4$ and KBH_4 additions on brightness of handsheets is given in Figure 6. Brightness increased with $NaBH_4$ and KBH_4 additions ($p<0.05$). This result can be attributed to lower kappa number of $NaBH_4$ and KBH_4 added pulps than that of control pulp (Table 3). The highest brightness was determined in 2 % KBH_4 added pulp with 20.16 %. Similar brightness increases were reported in earlier studies (Akgül *et al*., 2007; Çöpür and Tozluoğlu, 2008; Istek and Gonteki, 2009; Gulsoy and Eroglu, 2011).

4 CONCLUSIONS
4. ZAKLJUČAK

Chemical composition analysis showed that bracken stalks had higher holocellulose and lignin, and lower α-cellulose content than those of other lignocel-

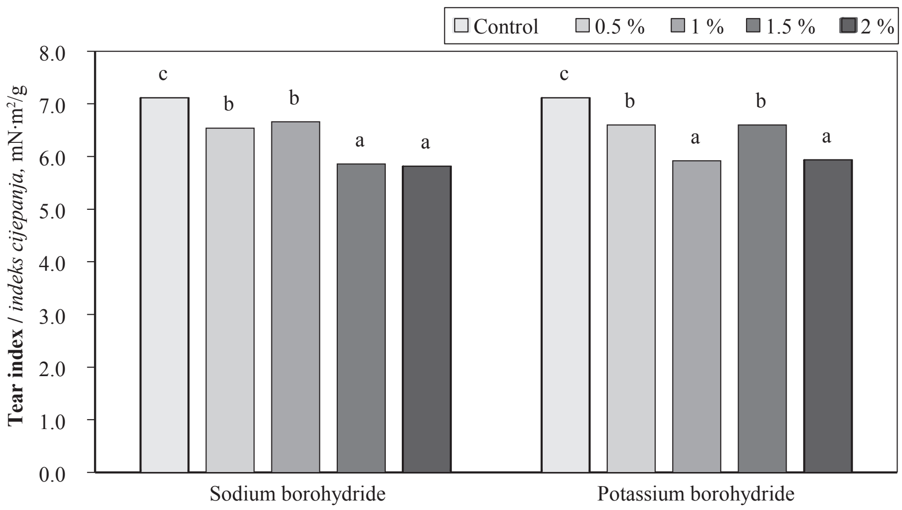

Figure 4 Effect of $NaBH_4$ and KBH_4 additions on tear index of handsheets
Slika 4. Utjecaj dodavanja $NaBH_4$ i KBH_4 na indeks cijepanja uzoraka papira

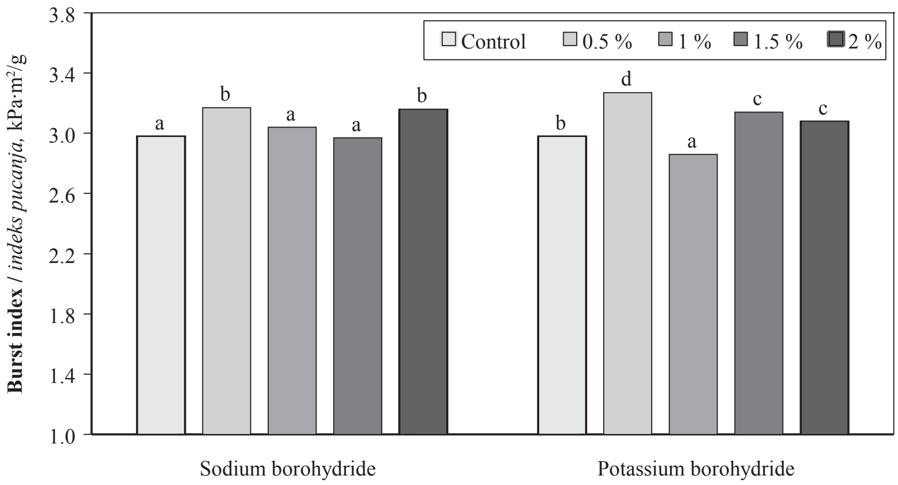

Figure 5 Effect of $NaBH_4$ and KBH_4 additions on burst index of handsheets
Slika 5. Utjecaj dodavanja $NaBH_4$ i KBH_4 na indeks pucanja uzoraka papira

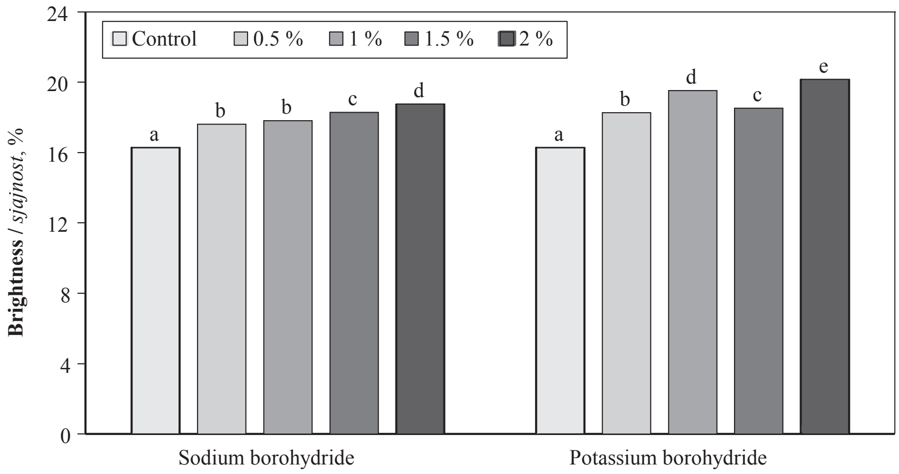

Figure 6 Effect of $NaBH_4$ and KBH_4 additions on handsheet brightness
Slika 6. Utjecaj dodavanja $NaBH_4$ i KBH_4 na sjajnost uzoraka papira

lulosic nonwood resources. The fiber properties of bracken stalks were similar to the fibers of other nonwood resources and aspen. Kraft pulp properties of bracken stalks were determined to be comparable with those of hardwoods (aspen and eucalyptus) and common nonwood papermaking raw materials. $NaBH_4$ and KBH_4 additions caused the increase of pulp yield and decrease of kappa number. Also, strength properties of bracken stalks kraft pulp increased with $NaBH_4$ and KBH_4 additions except for tear index. $NaBH_4$ and KBH_4 had a positive effect on pulp brightness. Consequently, the bracken stalks can be used as a fiber source for paper production.

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Assessment of Sorptive Properties of Selected Tropical Wood Species

Određivanje sorpcijskih svojstava nekih tropskih vrsta drva

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ABSTRACT • *This study is primarily focused on broadening the knowledge on sorptive properties of tropical wood species. The main objective of this research was to determine the equilibrium moisture content (EMC) of 17 selected tropical wood species vital to the flooring industry in Europe. For comparison, selected European wood species – European beech, European oak and Scots pine, were also tested. Differences in the EMC between wood from temperate and tropical zones were established, resulting in the necessity of revising the knowledge, especially in wooden floor production. The results show that the EMC of tropical wood species is generally lower than that of temperate region wood species. African padouk, Teak, Afzelia and Ipe showed the lowest values of moisture content. Furthermore these wood species showed the lowest values of fibre saturation point (17.7 %, 22.5 %, 19.7 % and 18.7 %, respectively). Secondly, it was established that the basic density has significant influence on sorption properties of tested wood species. Further to the above, it was concluded that - the higher wood basic density, the larger are the changes of dimensions. Consequently, based on the results obtained, the possibility of supplementing the recommendations in industry standards regarding wooden floors should be considered.*

Keywords: *equilibrium moisture content, tropical wood, sorption, flooring*

SAŽETAK • *Studija je ponajprije usredotočena na širenje znanja o sorpcijskim svojstvima tropskih vrsta drva. Glavni je cilj istraživanja bio utvrditi ravnotežni sadržaj vode (EMC) za 17 odabranih tropskih vrsta drva važnih za industriju podnih obloga u Europi. Radi usporedbe, ispitane su i ove europske vrste drva: bukva, hrast i obični bor. Utvrđene su razlike u vrijednostima EMC-a između vrsta drva iz umjerenih i vrsta drva iz tropskih zona, što upućuje na potrebu revizije znanja, posebno u proizvodnji drvenih podnih obloga. Rezultati su pokazali da je vrijednost EMC-a tropskih vrsta drva općenito niža nego za vrste iz umjerenog područja. Najniže vrijednosti ravnotežnog sadržaja vode zabilježene su za drvo afričkog padouka, tika, afzelije i ipea. Nadalje, za te su vrste drva dobivene i najniže vrijednosti točke zasićenja vlakanaca (17,7; 22,5; 19,7; 18,7 %). Osim toga, utvrđeno je da nominalna gustoća drva ima značajan utjecaj na sorpcijska svojstva ispitivanih vrsta drva. Iz toga se može zaključiti da će posljedica veće nominalne gustoće drva biti i veće promjene dimenzija drva. Sukladno tome, treba razmotriti donošenje dopune preporuka u industrijskim standardima koji se odnose na drvene podne obloge.*

Ključne riječi: *ravnotežni sadržaj vode, tropske vrste drva, sorpcija, podne obloge*

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1 INTRODUCTION
1. UVOD

The sorption isotherms are essential properties in the analysis and design of various biological material processes such as preservation, drying, storing, packaging, mixing and using in production floors, furniture and others (Salin, 2011). As a hygroscopic material, wood shows significant changes in moisture content depending on climatic conditions. Due to relative humidity changes of the air, the phenomena of swelling and shrinkage of wood causes dimensional changes in finished products. In spite of a large number of wood species, data from the sorption isotherm of fir wood is usually used for the evaluation of the sorption behavior of domestic wood species, (Popper *et al.*, 2007).

The mechanism and rate of wood humidity change is directly dependent on the parameters characterizing the indoors climate, while climate interiors through all the year is molded by exterior conditions and heating system. The air temperature in heated rooms during winter time is much higher than outside temperature. Coming into buildings, the cold atmospheric air (with high relative humidity) causes gradual drying of the indoor air. Relative humidity of the indoor air in summer can be 70 % and decreases at the end of winter to 40 % or even lower. The lower the outside temperature, the greater is the drying effect of external air. The result of these changes is wood moisture content change. In buildings with central heating system, wood moisture content is at the level of approx. 13 % at the end of summer and decreases to even 5 % at the end of winter (Krzysik and Sobczak, 1960).

Many studies were conducted on wood from moderate climate zones (Central Europe, North America). Due to a large number of wood species, the knowledge in this field of expertise is still incomplete. Furthermore, the equilibrium moisture content (*EMC*) of many wood species varies within a relatively broad range (Popper *et al.* 2007, 2009; Adampoulos and Voulgarridis, 2012). Few studies on tropical woods indicate the occurrence of variations in the sorption properties between species, which was corelated to the presence of high extractives content (Wangaard and Granados, 1967; Hernandez, 2007; Popper *et al.*, 2006, 2007; Jankowska and Kozakiewicz, 2016; Jankowska *et al.*, 2017). A comprehensive presentation of the sorption behavior of around 100 wood species was given by Keylwerth (1969). This list of wood species includes a lot of species from moderate climate and tropical zones. However, most of them are not present on European market of wood products, while wood species used nowadays were not included by this author. The studies conducted later give some information that should be included. Deliiski (2011) presents wood sorption isotherms, but no specific data is given on each species. Jannot *et al.* (2006) determined desorption isotherms and estimated specific areas of four selected tropical wood species from Africa (Doussié, Moabi, Ebony, Obeche and Iroko) at different temperatures. Sorption behavior of four tropical woods from Africa was investigated by Sigmo-Tagne *et al.* (2016). Popper *et al.* (2006, 2007) also carried out research about sorptive properties of tropical wood species. Most of the presented data does not find use in practical application of tropical wood species in Europe, because wood species tested in the mentioned research are not currently present on European market. The knowledge in this area is lacking. This has also been confirmed by a number of studies made for the Association of Engineers and Technicians of Forestry and Wood Industry (Poland) dealing with products made of tropical wood such as floor, elevation, furniture, etc. This problem was emphasized in trade press (eg. Wróżek and Romanovski, 2014).

Determining properties of commercial wood available on the European market is an important issue and results of research should be taken into account during the design stage. The knowledge in this area will help to avoid many problems in the use of wooden products such as floor. The main aim of this work was to determine and compare the *EMC* of wood species used in floors production in Europe as well as to improve the knowledge of the tropical wood sorptive properties. The sorption tests were combined with the measurements of physical properties providing the value of fiber saturation point (*FSP*) of wood species selected for the tests. This group includes tropical woods from Africa, South American and tropical parts of Asia.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

The wood species used in this study are presented in Tab. 1. The selected species are widely used in flooring production in Europe. Selection was made in order to have a representative sample of hardwoods, with a wide range of density and different anatomical structures. According to Popper *et al.* (2006, 2007), Jankowska *et al.* (2017), the selected species represent different types and amounts of extraneous substances. European wood species were used as a reference. All test materials were heartwood because it is commercially more important than sapwood. Wood from each species was acquired from DLH Poland, Warsaw, Poland. Material was identified in the laboratory using both macroscopic and microscopic techniques.

The samples of each wood species were collected from one log. Thus, differences in tested properties caused by differences in wood anatomy were avoided. Each part was quarter-sawn to produce planks of 4 cm thickness. Prior to samples preparation, wood was conditioned to air-dry in a room with relative humidity of 40-60 % and temperature of approx. 21 °C. The defect-free planks were sawn and sized to samples for moisture sorption and dimensional stability tests. For each wood species, 10 samples were used. Dimensions of the samples were 30 mm (tangential) × 30 mm (radial) × 5 mm (longitudinal).

Table 1 Wood species used in this study
Tablica 1. Istraživane vrste drva

Wood name* / *Naziv vrste*	**Latin name** / *Latinski naziv*	**Family** / *Porodica*	**Origin**/ *Podrijetlo*
African mahogany / *afrički mahagonij*	*Khaya* sp.	Meliaceae	Ghana
African padouk / *afrički padouk*	*Pterocarpus* sp.	Fabaceae	Gabon
Courbaril / *jatoba*	*Hymenaea* sp.	Caesalpiniaceae	Brazil
Cumaru / *kumaru*	*Dipteryx* sp.	Fabaceae	Brazil
Doussié / *afzelija*	*Afzelia* sp.	Caesaliniaceae	Ghana
European beech / *bukva*	*Fagus* sp.	Fagaceae	Poland
European oak / *hrast*	*Quercus* sp.	Fagaceae	Poland
Ipe / *ipe*	*Tabebuia* sp.	Bignoniaceae	Brazil
Iroko / *iroko*	*Milicia* sp.	Moraceae	Cameroon
Light red meranti / *svjetlocrveni meranti*	*Shorea* sp.	Dipterocarpaceae	Indonesia
Massaranduba / *balata*	*Manilkara* sp.	Sapotaceae	Brazil
Merbau / *merbau*	*Intsia* sp.	Caesalpiniaceae	Burma
Opepe / *opepe*	*Nauclea* sp.	Rubiaceae	Ghana
Owangkol / *bubinga*	*Guibourtia* sp.	Caesalpiniaceae	Ghana
Sapele / *sapele*	*Entandophragma* sp.	Meliaceae	Ghana
Scots pine / *obični bor*	*Pinus* sp.	Pinaceae	Poland
Sucupira / *brazilski lješnjak*	*Bowdichia* sp.	Fabaceae	Brazil
Tatajuba / *tatajuba*	*Bagassa* sp.	Moraceae	Brazil
Tauari / *brazilski hrast*	*Couratari* sp.	Lecythidaceae	Brazil
Teak / *tik*	*Tectona sp.*	Verbenaceae	Burma
Wenge / *wenge*	*Millettia* sp.	Fabaceae	Gabon

* Wood names are given according to PN-EN 13556:2005. / *Nazivi vrsta drva u skladu su s normom PN-EN 13556:2005.*

2.2 Methods
2.2. Metode

The specimens were exposed to moisture sorption test in adsorption and desorption. Five different relative humidities ranging from 9 to 97 % were used followed by immersion treatment in water. As soon as each point of sorption was completed, the mass of specimens was measured to the nearest 0.001 g and their dimensions were taken to the nearest 0.01 mm. The conditioning of specimens to appropriate moisture content was performed with the use of sealed enclosures in which prescribed saturated salt solutions were placed at the temperature close to 20 °C. The relative humidity was monitored and recorded using a hygrometer. The salt solutions used to create various relative humidity of air at 20 ±2 °C are listed in Table 2. A criterion for equilibrium was established as three successive identical mass readings at 24-hour intervals.

Table 2 Relative humidity of air at constant temperature 20 ±2 °C obtained in sealed enclosures with the use of saturated salt solutions
Tablica 2. Relativna vlažnost zraka pri stalnoj temperaturi od 20 ± 2 °C izmjerena u zatvorenim kutijama uz uporabu otopina zasićenih soli

Saturated salt solution *Zasićena otopina soli*	**Relative humidity in (%) at 20 ±2 °C** *Relativna vlažnost zraka (%) pri 20 ±2 °C*
Potassium hydroxide KOH *kalijev hidroksid, KOH*	9
Magnesium chloride $MgCl_2$ *magnezijev klorid,* $MgCl_2$	30
Sodium bromide NaBr *natrijev bromid, NaBr*	55
Sodium chloride NaCl *natrijev klorid, NaCl*	76
Potassium sulfate K_2SO_4 *kalijev sulfat,* K_2SO_4	97

The equilibrium moisture content (*EMC*) of samples was determined according to PN-D-04100:1977 and ISO 3130:1975. The wood basic density of samples was determined according to PN-D-04101:1977 and ISO 3131:1975. The volumetric shrinkage of wood was also determined according to PN-D-04111:1982 and ISO 4858:1982. Moreover, the fiber saturation point (FPS) was estimated by the interpolation method between volumetric shrinkage and moisture content according to Jankowska and Kozakiewicz (2016).

Statistical analysis of the test results was carried out using Statistica v. 10 software (StatSoft, Inc.). Data were analyzed and provided as the mean ± standard deviation and minimum and maximum values. Regression analysis was used to evaluate relationships between the measured properties. The effects of wood basic density on equilibrium moisture content and dimensional stability were determined. Moreover, t-test was used to verify the significance of differences among the average values.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The average values of the measured EMC for adsorption and desorption at 20 °C are shown in Table 3. For each tested wood species, the EMC at different relative humidity of air is individual. The highest differences in moisture content between tested wood species can be seen at higher relative humidity (approx. 97 %). The results show that the EMC of tropical wood

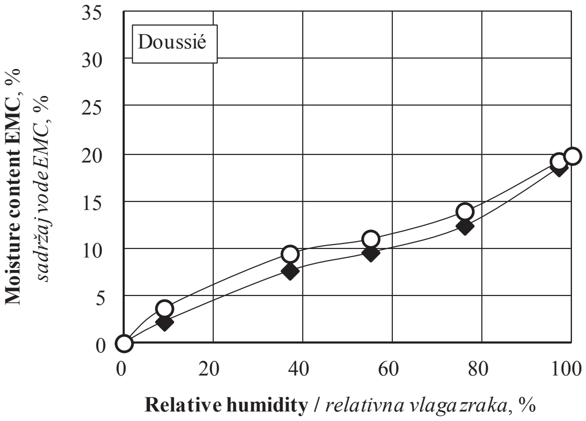

Figure 1 Adsorption and desorption isotherm of Doussié
Slika 1. Krivulje adsorpcije i desorpcije za drvo afzelije

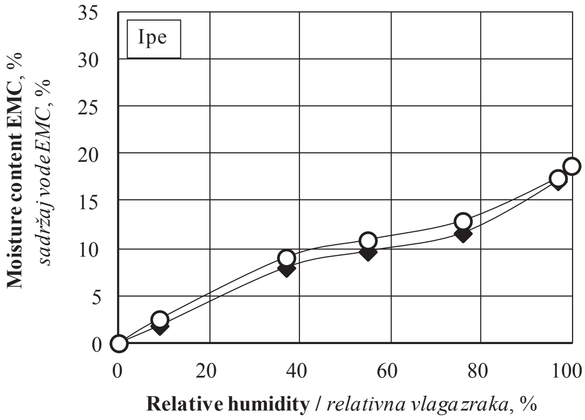

Figure 2 Adsorption and desorption isotherm of Ipe
Slika 2. Krivulje adsorpcije i desorpcije za drvo ipea

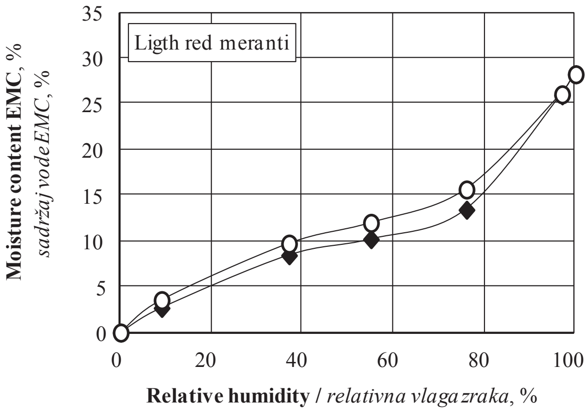

Figure 3 Adsorption and desorption isotherm of Light red meranti
Slika 3. Krivulje adsorpcije i desorpcije za drvo svjetlocrvenog merantija

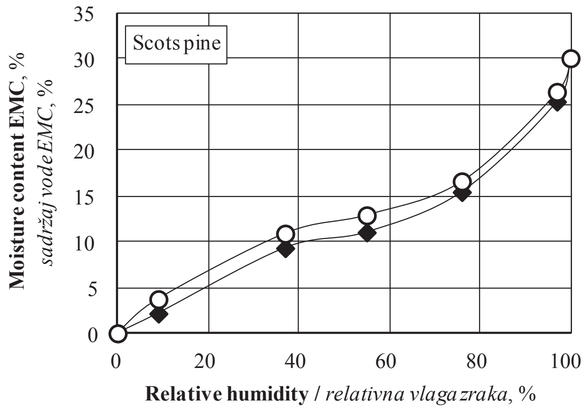

Figure 4 Adsorption and desorption isotherm of Scots pine
Slika 4. Krivulje adsorpcije i desorpcije za drvo običnog bora

species is generally low (Table 3). The highest values of moisture content were observed for European wood species, especially in case of European beech. The lowest values of moisture content were observed for African padouk, Teak, Doussié and Ipe. Among tropical wood species, Light red meranti, Merbau, Massaranduba, Sapele and Tauari showed the highest values of moisture content at different air conditions. This was probably caused by the relatively low content of non-polar extractives of these species (Wanshura *et al.*, 2014; Jankowska *et al.*, 2017). According to t-test results, the difference between equilibrium moisture content of European oak, European beech and Scots pine are not significant. The European wood samples displayed significantly (the significance value was less than 0.05) higher value of equilibrium moisture content than tropical wood samples when air humidity was 55 % and above. In case of low air humidity, the differences were not observed. As it is known from former studies (Choong and Achmadi, 1991; Popper *et al.*, 2007; Adampoulos and Voulgarridis, 2012; Jankowska *et al.*, 2017), the difference between equilibrium moisture content of European wood and tropical wood is caused by the amount of extractives in wood structure, which can be hydrophobic.

Fig. 1-3 show the adsorption and desorption isotherms for selected species used in this study. To avoid double presenting of the results, only isotherms for a few wood species are presented as examples.

This study fills an important gap concerning moisture content of tropical wood species used in Europe. Due to a lack of information on sorptive properties of tropical species, according to the European standards on wooden floors – PN-EN 13227:2004, PN-EN 13629:2012, PN-EN 13226:2009, the proper value of wood moisture content should range from 7 to 11 % when air temperature is about 20 ±3 °C and air humidity 50 ±5 %. Regarding the results obtained during this study, it can be said that such a wide range of recommended wood moisture content causes problems in choosing the proper value, especially due to the fact that tropical wood species are generally characterized by lower moisture content in comparison to European wood species. According to the results obtained, the EMC of wood in the air temperature close to 20 °C and relative humidity of 55 % can range from 7.50 to 12.96 % (Table 3). With so many differences in the sorption properties of wood, (especially in case of tropical wood species), the possibility of supplementing the recommendations in industry standards regarding wooden floors should be considered.

The results of density and shrinkage of the tested wood species are summarized in Table 4. High variation was observed in swelling properties among the tested

Table 3 Change in equilibrium moisture content in adsorption and desorption of selected tropical and European wood species depending on relative humidity
Tablica 3. Promjena ravnotežnog sadržaja vode u adsorpciji i desorpciji istraživanih tropskih i europskih vrsta drva ovisno o relativnoj vlazi zraka

Wood name *Vrsta drva*	**Equilibrium moisture content at relative humidity** *Ravnotežni sadržaj vode pri relativnoj vlazi zraka*				
	9	37	55	76	97
	%				
African mahogany / *afrički mahagonij*	2.85/4.25	7.15/9.14	9.14/12.0	12.39/13.93	24.18/25.01
African padouk / *afrički padouk*	1.46/2.63	4.79/5.55	7.50/8.54	10.32/11.15	14.47/15.81
Courbaril / *jatoba*	2.06/2.99	8.60/9.45	9.84/11.25	11.87/12.98	19.99/20.26
Cumaru / *kumaru*	1.86/3.07	7.55/8.45	9.45/10.67	12.30/13.91	21.20/21.47
Doussié / *afzelija*	2.26/3.66	7.62/9.40	9.54/10.98	12.35/13.8	18.49/19.13
European beech / *bukva*	2.15/2.91	8.67/10.00	11.86/12.96	12.83/15.13	30.81/31.05
European oak / *hrast*	2.19/3.45	8.64/10.20	11.78/12.80	13.64/15.61	26.15/27.01
Ipe / *ipe*	1.83/2.52	7.95/9.01	9.65/10.84	11.59/12.87	17.09/17.40
Iroko / *iroko*	2.17/3.25	6.15/7.25	8.29/9.50	10.55/12.91	18.61/19.95
Light red meranti / *svjetlocrveni meranti*	2.69/3.54	8.44/9.71	10.20/11.98	13.41/15.62	25.90/26.01
Massaranduba / *balata*	2.01/3.51	6.87/8.01	8.40/11.15	12.71/16.21	25.50/27.90
Merbau / *merbau*	2.52/3.47	9.10/10.62	11.84/12.20	13.47/14.52	21.78/21.90
Opepe / *opepe*	2.09/3.01	8.60/9.15	10.45/11.23	12.80/14.64	20.73/21.47
Owangkol / *bubinga*	2.09/3.39	8.58/9.78	10.30/11.51	12.00/13.33	23.00/23.50
Sapele / *sapele*	2.90/4.38	9.16/10.10	11.39/12.49	13.14/15.50	24.77/24.98
Scots pine / *obični bor*	2.16/3.72	9.29/10.87	11.01/12.87	15.41/16.57	25.27/26.33
Sucupira / *brazilski lješnjak*	1.81/2.92	7.47/8.59	8.87/10.68	11.92/13.32	24.20/24.33
Tatajuba / *tatajuba*	2.10/3.20	7.87/8.54	9.95/11.10	11.71/12.81	19.03/19.38
Tauari / *brazilski hrast*	2.03/3.22	8.10/9.32	9.87/11.24	12.44/14.08	23.61/24.00
Teak / *tik*	1.83/2.97	7.77/8.81	9.15/10.34	11.23/13.02	20.17/20.19
Wenge / *wenge*	1.63/2.80	7.15/8.49	8.97/11.20	11.70/12.88	19.16/20.36

wood species. The results of regression analysis (Fig. 5) showed that the wood density had significant influence on the volumetric shrinkage coefficient (βv/FSP) of the tested wood species (R^2 value of 0.57). Regression analysis indicated a statistically significant relationship at the 95 % confidence level (the significance value of the linear regression analysis was less than 0.05). When Teak and Merbau were not included in this analysis, the

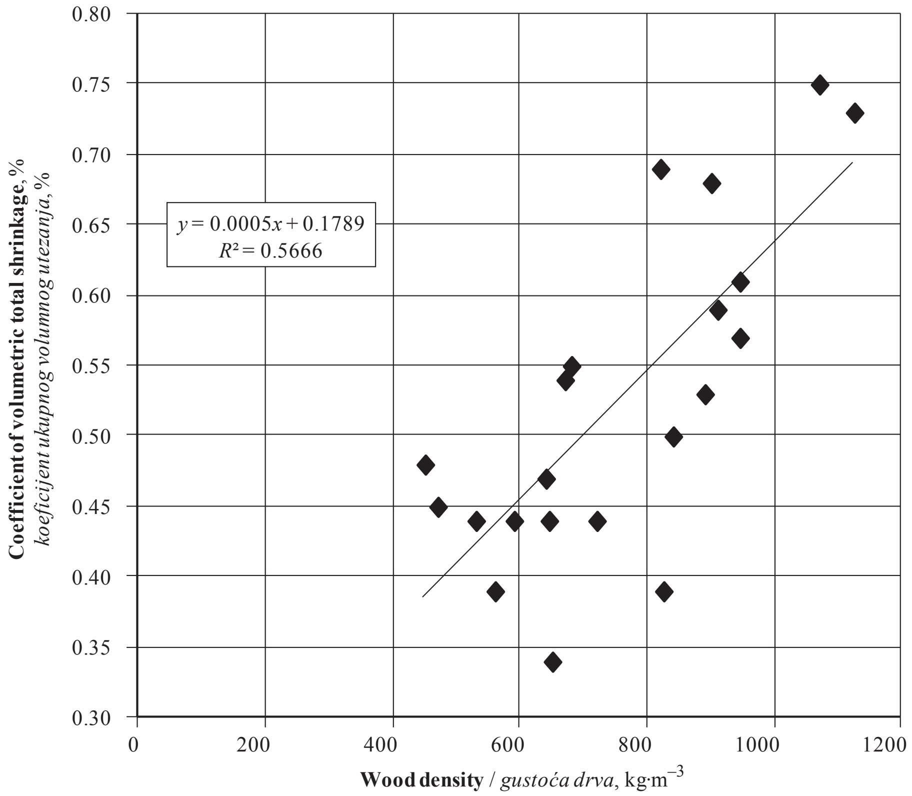

Figure 5 The influence of basic density of tested tropical and European wood species on the coefficient of volumetric total shrinkage
Slika 5. Utjecaj nominalne gustoće istraživanih tropskih i europskih vrsta drva na koeficijent ukupnoga volumnog utezanja

relationship between the basic density and coefficient of volumetric total shrinkage of wood was higher (R^2 value of 0.70). This can be caused by the chemical composition of these wood species. According to former studies (Mantanis *et al.* 1994; Adamopoulos and Voulgaridis 2012; Jankowska *et al.* 2017), it could be predicted that Merbau wood will show relatively low moisture content, because of high content of water soluble extractives. This is due to the bulking effect of extractives, which are partly deposited on the cell walls. The low moisture content values observed in case of Teak wood is an effect of higher content of chloroform-ethanol extractives and relatively low contents of hot water extractives (Jankowska *et al.,* 2017).

Analysis of data given in Table 4 revealed that the values of the volumetric shrinkage of some wood species (African mahagony, Cumaru, Iroko, Massaranduba, Sucupira) are larger than the sum of radial and tangential shrinkage. This phenomenon can be explained by the fact that the above said wood species are characterized by irregular fiber arrangement. Consequently, the main anatomical directions are distorted and as a result dimension changes can be higher than when wood exhibits a simple fiber arrangement (as in case of European beech). Regarding the results presented in Table 4, it can be concluded that fiber saturation point (FSP) of tested wood species varied within a broad range from 17.7 % (in case of African padouk) to 31.2 % (in case of European beech). FSP was negatively correlated with wood density, but the correlation ($R^2 = 0.39$) was rather low. According to previous studies (Jankowska *et al.*, 2017), the relationship between wood density and its sorptive properties can be strongly affected by the high variability of extractives content. The observed volumetric shrinkage varied from 7.65 % to 21.0 %. The lowest value was observed in Teak wood, and the highest in case of Massaranduba wood. The relationship between volumetric shrinkage (sum of radial and tangential shrinkage) and specific density has been already confirmed be several authors (Choong and Achmadi, 1991; Hernández, 2007). Moreover, wood density had an influence on the fiber saturation point during the testing of nine tropical hardwoods from Peru and sugar maple wood from Quebec (Hernández, 2006). According to results of Jankowska *et al.* (2017), the relationship between wood basic density and its sorptive properties is strongly affected by high extractives content and it is clear only when material with high extractives content is analyzed. Despite the reported relationship between volumetric shrinkage and wood density, no significant correlation was found in this study. It has been already confirmed by Hernández (2007) that wood density has a positive effect on total volumetric shrinkage However, the analysis of total volumetric shrinkage and wood density did not give a clear confirmation of significant relationship. The relationship was not significant ($P < 0.1$), and the correlation ($R^2 = 0.24$) was also rather low, indicating

Table 4 Wood basic density, dimensional changes and fiber saturation point of tested tropical and European wood species
Tablica 4. Nominalna gustoća drva, dimenzijske promjene i točka zasićenja vlakanaca istraživanih tropskih i europskih vrsta drva

Wood name *Vrsta drva*	**Wood basic density** *Nominalna gustoća drva*	**Total shrinkage** / *Ukupno utezanje*			**Fiber saturation point** *Točka zasićenosti vlakanaca FSP*
		radial *radijalno* βr	**tangential** *tangencijalno* βt	**volumetric** *volumno* βv	
	kg·m^{-3}	%			%
African mahogany / *afrički mahagonij*	560	3.7	5.6	11.0	28.3
African padouk / *afrički padouk*	590	3.3	5.3	7.8	17.7
Courbaril / *jatoba*	910	4.4	8.6	12.0	20.4
Cumaru / *kumaru*	1125	5.6	7.9	16.1	22.1
Doussié / *afzelija*	720	3.1	4.6	8.7	19.7
European beech / *bukva*	670	6.0	14.1	16.7	31.2
European oak / *hrast*	647	4.5	9.7	13.6	28.0
Ipe / *ipe*	900	5.3	6.7	12.7	18.7
Iroko / *iroko*	530	3.5	5.6	10.2	23.2
Light red meranti *svjetlocrveni meranti*	450	3.9	8.9	13.5	28.2
Massaranduba / *balata*	1070	7.1	9.5	21.0	28.0
Merbau / *merbau*	825	4.1	6.1	11.5	29.6
Opepe / *opepe*	680	4.5	8.1	12.7	23.1
Owangkol / *bubinga*	945	4.1	8.2	13.8	24.2
Sapele / *sapele*	640	5.1	7.3	13.5	28.7
Scots pine / *obični bor*	470	5.1	7.3	13.5	30.0
Sucupira / *brazilski lješnjak*	945	4.9	7.1	14.4	23.6
Tatajuba / *tatajuba*	890	3.8	5.5	10.9	20.5
Tauari / *brazilski hrast*	840	4.5	7.2	14.4	28.7
Teak / *tik*	650	2.5	5.7	7.8	22.5
Wenge / *wenge*	820	5.9	9.1	14.6	21.1

that only 24 % of the variation in volumetric shrinkage was accounted for by wood basic density. However, when European wood species were not included in this analysis, the relationship between the basic density and volumetric shrinkage of wood was statistically significant (R^2 = 0.44). According to Babiak and Kúdela (1995), the wood density and its structure play important roles. The species tested here revealed a similar structure of diffuse-porous wood. In some (Courbaril, Light red meranti) but not all cases, an expanded axial parenchyma was observed.

4 CONCLUSIONS
4. ZAKLJUČAK

In this study, sorptive properties of wood species used in floors production in Europe were determined and compared. In the course of research, 17 tropical wood species were tested and analyzed. For comparison, selected European wood species – European beech, European oak and Scots pine, were also tested.

Findings and results show that equilibrium moisture content of tropical wood species is lower than that of temperate zone wood species. African padouk, Teak, Afzelia and Ipe showed the lowest values of moisture content. Furthermore, these wood species showed the lowest values of fiber saturation point (17.7 % for African padouk, 22.5 % for Teak, 19.7 % for Doussié and 18.7 % for Ipe). Among tropical wood species, Light red meranti and Massaranduba samples showed the highest values of moisture content at different air conditions. Furthermore, it was established that wood density affected positively volumetric swelling of tested tropical hardwoods. Regression analysis indicated a statistically significant relationship when the coefficient of volumetric total shrinkage was considered. Thus, the higher wood density, the higher are the dimensions changes.

The results provide crucial knowledge applicable in practice in using many tropical wood species. Furthermore, this indicates that a common recommendation should be considered for all wood species. Based on the results obtained, the possibility of supplementing the recommendations in industry standards regarding wooden floors and other applications of wood should be considered, especially in case of recommended values of moisture content. It would help to avoid significant problems during production, installation and exploitation of wooden products such as floors.

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The Effect of Nanoboron Nitride on Some Properties of Biopolymer Nanocomposites with Cellulose Nanofibrils and Nanoclays

Učinak nanočestica boron-nitrida na neka svojstva biopolimernih nanokompozita s celuloznim nanovlaknima i nanočesticama gline

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ABSTRACT • *The aim of this study was to investigate the effect of nanoboron nitride (BN) as nano-fire retardant on some properties of polylactic acid (PLA) and polyhydroxybutyrate (PHB) biopolymer nanocomposites reinforced with cellulose nanofibrils (CNFs) and nanoclays (NC). BN particles, as nano-fire retardant, were added to enhance the thermal stability of the obtained biopolymer nanocomposites. PLA and PHB nanocomposites were prepared with a twin screw extruder and characterized with mechanical tests, TGA, and DSC. Densities of the PLA and PHB nanocomposites were found to decrease with the addition of NBN loading. The mechanical properties of biopolymer nanocomposites decreased, except for tensile modulus. According to TGA results, NBN loadings generally improved the thermal stability of the PLA and PHB nanocomposites. The degradation temperature for weight loss at 10 %, 50 % and 85 % ($T_{10\%}$, $T_{50\%}$ and $T_{85\%}$) increased with NBN loadings; the value of DTGmax was determined to improve with the loading of BN. DSC results showed that melt temperature (T_m) and crystallization temperature (T_c) generally increased with BN loadings, whereas crystallinity (Xc) decreased with BN loadings in PLA nanocomposites.*

Keywords: nanoboron nitride, polymer nanocomposites, cellulose nanofibrils, nanoclays, biopolymers

SAŽETAK • *Cilj ove studije bio je ispitati učinak nanočestica boron-nitrida (BN) kao usporivača gorenja na neka svojstva biopolimernih nanokompozita proizvedenih od polilaktične kiseline (PLA) i polihidroksibutirata (PHB) ojačanih celuloznim nanovlaknima (CNFs) i nanočesticama gline (NC). Nanočestice boron-nitrida (NBN), koji je usporivač gorenja, dodane su kako bi se povećala toplinska stabilnost proizvedenih biopolimernih nanokompozi-*

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ta. Nanokompoziti PLA i PHB pripremljeni su uz pomoć dvostrukoga vijčanog ekstrudera i ispitani mehaničkim testovima te TGA i DSC analizom. Utvrđeno je da se gustoća PLA i PHB nanokompozita smanjuje dodatkom NBN čestica. Dodavanjem NBN čestica sva su se mehanička svojstva biopolimernih nanokompozita, osim modula vlačne čvrstoće, smanjila. Prema rezultatima TGA analize, dodane NBN čestice općenito poboljšavaju toplinsku stabilnost PLA i PHB nanokompozita. Dodavanjem NBN čestica povećana je temperatura degradacije za gubitak mase od 10, 50 i 85 % ($T_{10\%}$, $T_{50\%}$ i $T_{85\%}$), a poboljšala se i vrijednost DTG_{max}. Rezultati DSC analize pokazali su da se temperatura taljenja (T_m) i temperatura kristalizacije (T_c) povećavaju s povećanjem udjela NBN čestica, dok se kristaliničnost (X_c) smanjuje s povećanjem količine NBN čestica u PLA nanokompozitu.

Ključne riječi: *nanočestice boron-nitrida, polimerni nanokompoziti, celulozna nanovlakna, nanočestice gline, biopolimeri*

1 INTRODUCTION
1. UVOD

Nanocomposite is a two-phase material, where one of the phases has at least one dimension in nanometer range (1-100 nm) and generally nanoscale materials result in composites with superior thermal, barrier and mechanical properties (Oksman *et al*., 2006; Yao *et al.*, 2002; Zanetti *et al.*, 2001). Due to growing environmental awareness, new standards try to develop environmental friendly and biodegradable systems (Gorrasi *et al.*, 2003; Lee *et al.*, 2002; Oksman *et al.*, 2006; Pluta *et al.*, 2002; Ray *et al.*, 2003). Polylactic acid (PLA) is one of the renewable biopolymer produced from lactic acid derived from sugar cane, potato and corn fermentation process (Aldana *et al.*, 2014; Vink *et al.*, 2003). PLA has high mechanical properties, low hydrophobicity, low cost and good process ability compared to other alternatives. For all this properties, PLA is the biopolymer with the greatest potential for plastic industries (Aldana *et al.*, 2014; Molinaro *et al.*, 2013; Svagan *et al.*, 2012).

Polyhydroxybutyrate (PHB) is another biopolymer produced by fermentation of renewable resources (Steinbuchel, 2003; El-Hadi, 2014). PHB is a thermoplastic, biodegradable, renewable and environmentally friendly polymer. PHB also has a high crystallinity and low glass transition temperature (T_g) (El-Hadi, 2013; Fernandes *et al.*, 2004). Initial bio-sourced polymers were used in short term applications but today environmental concerns and oil shortage issues expand their areas of usage. They are used for construction, transportation and electronics, where fire risk requires the use of fire retardant materials (Bocchini *et al*., 2012; Bourbigot, 2010; Wei *et al*., 2013). Some studies have been conducted with various fire retardants, which are an effective and convenient way to increase thermal properties of polymers (Lee *et al.*, 2006; Yu *et al.*, 2002; Zhang *et al.*, 2011). However, the studies about the effect of boron nitride on thermal behavior of biopolymers are not enough. There are a few studies on biopolymer/BN composites. In a previous study, Pradhan *et al.* (2014) studied the effects of boron nitride on the thermal properties and tensile strength of starch biocomposites. The obtained results showed that thermal stability of the starch was increased with rising concentrations of boron nitride due to the addition of rigid nano BN with starch matrix, and the tensile strength of starch/BN bionanocomposites was found to increase with BN loading. In another study, Dash and Swain (2013) studied nanoboron nitride-soy protein composites. According to the obtained results, the degradation temperature of pure soy protein is lower than that of corresponding soy/BN nanocomposites. Hence, the thermal stability of soy/BN nanocomposite was found to be higher than that of virgin matrix due to the addition of thermally stable nanoboron nitride. Öner *et al*. (2016) used nano boron nitride to improve the thermal properties of polyhydroxybutyrate biocomposites. The barrier properties of the composites decreased with BN addition and it was found that the thermal stability of the composites with BN was higher than that of neat biopolymers. The differential scanning calorimetry results indicated that the addition of BN nanoparticles to the composites increased their crystallinity.

In this study, BN was used to improve the thermal properties of polylactic acid (PLA) and polyhydroxybutyrate (PHB) biopolymer nanocomposites prepared with twin screw extruder. The mechanical and morphological properties of biopolymer composites were also investigated.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

Polyhydroxybutyrate (PHB) and polylactic acid (PLA) were supplied by Good Fellow, England. Density of PHB and PLA was 1.25 g/cm^3 and 1.24 g/cm^3, respectively. Cellulose nanofibrils (CNF) and Nanoclays (NC), used as a reinforcing filler, were obtained from J. Rettenmaier & Sohne (JRS) (Germany) and Nanocor (Canada). Hexagonal nano boron nitride (BN), used as fire retardant, was supplied by Boron Product Tech. San. Tic. A.Ş (BORTEK) (Eskisehir, Turkey). All reinforcing fillers and fire-retardant were dried for 24 hours at 80 °C, and all materials were stored in sealed containers.

2.2 Preparation of Biopolymer Nanocomposites (BNCs)
2.2. Izrada biopolimernih nanokompozita (BNCs)

Polymers and fillers were mixed with speed mixer and then composites were compounded using a twin screw extruder (Aysa Instruments, Turkey). Rotor speed was 5 rpm and process temperature was set at 160 °C – 180 °C. The extruded strand passed across a water bath so that this was pelletized.

The extruded nanocomposites were grounded with a lab-grinder and then the pellets dried for 3-4

Table 1 Formulations and codes for nanocomposites
Tablica 1. Sastav i oznake nanokompozita

Formulations *Sastav*	**Codes** *Oznaka*	**Formulations (weight %)** *Sastav*	**Codes** *Oznaka*
PLA+4%CNFs	LF	PHB+4%CNFs	HF
PLA+4%CNFs+1%BN	LF1	PHB+4%CNFs+1%BN	HF1
PLA+4%CNFs+5%BN	LF5	PHB+4%CNFs+5%BN	HF5
PLA+4%CNFs+10%BN	LF10	PHB+4%CNFs+10%BN	HF10
PLA+4%NCs	LC	PHB+4%NCs	HC
PLA+4%NCs+1%BN	LC1	PHB+4%NCs+1%BN	HC1
PLA+4%NCs+5%BN	LC5	PHB+4%NCs+5%BN	HC5
PLA+4%NCs+10%BN	LC10	PHB+4%NCs+10%BN	HC10

hours before compression molding. The compression molding temperature was 175 °C, barrel temperature 170 °C and compression pressure 25 bar. The formulations of the composites are shown in Tab.1.

2.3 Methods
2.3. Metode

The properties of the PLA and PHB nanocomposites were analyzed with the standard tests such as density, flexure strength (*FMOR*) and modulus (*FMOE*), tensile strength (*TMOR*) and tensile modulus (*TMOE*), Izod impact strength (*Izod–IS*), thermal properties (TG–DTA, DSC), and morphological characterization (SEM). The tension tests were conducted according to the American Society of Testing and Materials (ASTM) standard D 638-03 Type I. All tension tests were conducted at a rate of 0.2 in./min. The flexure tests were conducted according to ASTM D 790-03, Test Method 1, Procedure A, i.e. three-point loading system. The support span was 50.8 mm, resulting in a span-to-depth ratio of 16 (±1). The tests were run at a test speed of 1.27 mm/min. The impact tests were conducted according to ASTM D 256-06. The notches were added using a NotchVIS machine manufactured by Ceast. The specimens were tested on a Resil 50 B impact test machine, manufactured by Ceast. At least eight specimens for all tests were tested for each composition, and the results are presented as an average for tested samples.

TG-DTA was tested using Hitachi STA 7300 analyzer with a heating rate of 10 °C/min from 25 °C to 600 °C, under nitrogen with a flow rate of 20 ml/min to avoid sample oxidation. DTA peaks, such as melting point (T_m) and decomposition point (T_d), were also measured during the thermogravimetric analysis; DSC analysis of the samples was performed using a Perkin Elmer analyzer on samples of about 5 mg. For all specimens, testing was performed by heat/cool methods. All samples were heated to 25 °C to 300 °C at a ramp rate of 10 °C/min and cooled at the same ramp rate. Melting temperature (T_m), crystallization temperature (T_c), melting enthalpy (ΔH_m), crystallization enthalpy (ΔH_c), crystallinity (X_c) of materials was determined from thermograms. The value of theoretical melting enthalpies of 100 % crystalline PLA and PHB was 93.1 J/g and 146 J/g, respectively. The samples were observed with an environmental scanning electron microscope (ESEM), the Tescan MAIA3 XMU-SEM at an acceleration voltage of 5 kV. The surface of all samples was sputter-coated with gold using a Denton sputter coater for enhanced conductivity.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The effects of BN on some properties of biopolymer nanocomposites (BNCs) were investigated in this study. Tab. 2 shows the density and mechanical properties of BNCs.

As seen in Tab. 2, the density for all BNCs generally decreased with BN loading. The decrease in the density was found to be higher as the loading of BN increased. The effects of boron nitride on the mechanical properties were generally found to be negative. It was determined that the effects of BN on the mechanical properties of PHB nanocomposites were higher than on PLA nanocomposites. For all that, in a study on BN, the densities of PP composites were generally found to increase with BN loadings (Ayrilmis *et al.*, 2013). It was determined that the decrease in the density of biopolymers was caused by gaps and porous structure generated by interactions between biopolymer and BN, as shown in Fig. 1. The morphological properties of the BNCs obtained with the help of SEM are presented in Fig. 1.

According to Fig. 1, the BN particles dispersed inside the matrix, and generally showed uniform dispersion in the matrixes. However, some BN aggregates were found in Fig. 1. SEM pictures show that the loading of BN caused the gaps of different diameters, and the porous structure was determined in both matrixes after BN loading. It can be said that this porous structure has a negative effect on the mechanical properties according to Tab.1. TGA analysis of biopolymer nanocomposites is given in Tab.3.

The thermal stability of all nanocomposites was affected by BN loading. The thermal stability at $T_{10\%}$ improved with the addition of BN except for the PLA biopolymer nanocomposites (LF) with 1, 5, and 10 % BN. This showed that the BN loading increased the thermal stability of BNCs at initial response ($T_{10\%}$). The thermal stability at $T_{10\%}$ was found to be better for HF and HC biopolymer nanocomposites with BN compared to PLA biopolymer nanocomposites with BN. As

Table 2 Mechanical properties of polymer nanocomposites with nanoboron nitride
Tablica 2. Mehanička svojstva polimernih nanokompozita s nanočesticama boron-nitrida

Composite formulations (BNCs) *Sastav kompozita*	**Density** *Gustoća* **g/cm^3**	***TMOR*** **MPa**	***TMOE*** **MPa**	***FMOR*** **MPa**	***FMOE*** **MPa**	***Izod IS*** **kJ/m^2**
LF	1.18	50	2983.7	90.9	2983.7	4.8
LF1	1.14	48.2	4699.1	31.27	1547.1	2.3
LF5	1.08	37.5	4122.5	21.7	1069.1	2.7
LF10	1.07	32.1	3980.1	25.4	1174.2	2.4
LC	1.18	55	3324.5	100.5	3324.5	3.9
LC1	1.17	20	2562.3	20.2	998.4	2.2
LC5	1.09	31.4	3858.3	30.1	1075.7	2.1
LC10	1.12	40.2	4682.4	31.5	1249.5	2.5
HF	1.15	16	1436.7	27.4	1711.8	2.1
HF1	1.16	10.1	1418	7.9	515.3	1.9
HF5	1.11	9.1	1321	7.3	462.4	1.3
HF10	1.09	6.2	925	7.1	400.9	1.1
HC	1.19	12.2	1233.5	21.9	2136.5	1.9
HC1	1.07	2.7	296	9.8	1009.2	1.6
HC5	1.18	2.1	325	9.4	885.4	1.4
HC10	1.16	5.1	755.8	8.7	739.2	1.7

TMOR - tensile strength / *vlačna čvrstoća*; *TMOE* - tensile modulus / *vlačni modul elastičnosti*; *FMOR* - flexure strength / čvrstoća pri savijanju; *FMOE* - flexure modulus of elasticity / *modul elastičnosti pri savijanju*; Izod-IS - Izod impact strength / *Izod udarna čvrstoća*. See Table 1 for composite formulations. / *Za sastav kompozita vidjeti tablicu 1.*

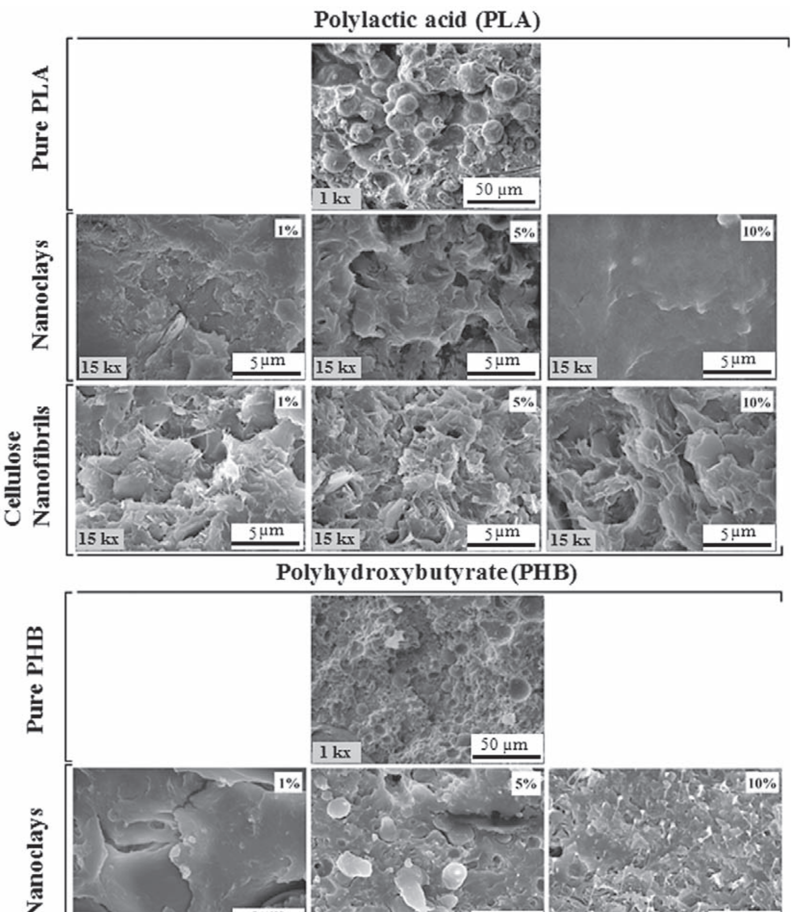

Figure 1 Biopolymer nanocomposites with BN
Slika 1. Biopolimerni nanokompoziti s nanočesticama boron-nitrida

Table 3 Review of thermal properties of polymer nanocomposites
Tablica 3. Sažeti prikaz toplinskih svojstava polimernih nanokompozita

Formulations	TGA, °C			DTG, °C	DTA, °C	
	$T_{10\%}$ °C	$T_{50\%}$ °C	$T_{85\%}$ °C	DTG_{max} °C	*T*m °C	*T*d °C
HF	267.2	284.8	300.5	288.2	156.7	286.2
HF1	277.6	287.1	377.5	287.3	175.7	288.0
HF5	267.5	282.0	352.5	286.0	173.7	284.5
HF10	248.8	263.2	314.2	266.0	168.0	264.1
HC	275.3	289.4	310.9	293.3	159.1	290.5
HC1	285.1	296.2	353.5	304.4	161.8	305.1
HC5	274.7	295.1	357.0	285.9	173.8	281.0
HC10	276.3	286.2	354.8	287.9	173.7	287.5
LF	340.9	356.9	444.1	361.6	152.2	360.1
LF1	337.2	352.4	363.5	354.6	154.5	352.9
LF5	334.6	345.1	356.5	347.6	147.7	353.6
LF10	334.0	345.4	361.0	347.3	148.2	350.1
LC	322.8	356.3	443.4	357.2	148.9	354.9
LC1	342.7	356.3	372.4	358.8	146.8	356.4
LC5	344.7	360.8	379.1	363.6	149.5	362.2
LC10	341.1	357.4	372.2	362.8	150.1	360.8

Table 4 Review of DSC isotherms of nanocomposites
Tablica 4. Sažeti prikaz DSC izotermi nanokompozita

Formulations *Sastav nanokompozita*	Cooling *Hlađenje*		Heating *Zagrijavanje*		*X*c %
	T_c °C	ΔH_c J/g	T_m °C	ΔH_m J/g	
HF	107.7	48.6	166.5	55.1	37.7
HF1	109.3	52.9	168.6	63.6	43.6
HF5	109.0	50.8	166.4	60	41.1
HF10	109.2	48.9	168.5	54.5	37.3
HC	109.8	45.8	165.7	63.1	42.2
HC1	109.5	41.8	153.4	42.8	29.3
HC5	108.2	40.4	169.6	49.7	34
HC10	108.2	54.8	169.7	58.9	40.3
LF	110.0	12.8	164.8	48.4	52.0
LF1	115.6	27.1	152.2	21.2	14.5
LF5	115.1	20.3	151.8	22.2	15.2
LF10	116.6	21.3	153.4	24.5	16.8
LC	108.8	20.8	155.5	38.3	41.1
LC1	115.3	18.7	154.6	19.9	13.6
LC5	115.2	22.1	153.6	21.4	14.6
LC10	113.7	22.4	153.3	22.8	15.6

the temperature was increased, the degradation temperature at $T_{50\%}$ was found to be generally better for HC and LC biopolymer nanocomposites than for neat polymers. At $T_{85\%}$, the thermal stability of HF and HC biopolymer nanocomposites increased as compared to neat biopolymer, whereas the thermal stability of LF an LC biopolymer nanocomposite was determined to decrease with the addition of BN. The best temperature in DTG_{max} was found to be 304.4 °C in HC with 1 % BN, and 363.6 °C in LC with 5 % BN. The maximum T_m and T_d of BNCs were determined to be 175.7 °C in HF with 1 % BN, and 305.1 °C in HC with 1 % BN, and 154.5 °C in LF with 1 % BN and 362.2 °C in LC with 5 % BN, respectively. The other thermal properties of biopolymer nanocomposites with BN were determined by differential scanning calorimetry. Tab. 4 shows the summary of DSC results of all biopolymer nanocomposites.

DSC analysis was conducted by cooling and heating of neat polymers and all biopolymer nanocomposites. The crystallization temperature (T_c) and melting temperature (T_m) changed with the loading of fillers. The highest value of Tc was found to be 109.5 °C for HC without BN in PHB nanocomposites, and 116.6 °C for LF with 10 % BN. The highest Tm was found to be 169.7 °C for HC with 10 % BN for PHB nanocomposites, and 164.8 °C for LF without BN for PLA nanocomposites. Seen as *X*c values, the crystallinity was found to decrease with the addition of BN except for HC1 and HC5.

4 CONCLUSION
4. ZAKLJUČAK

The addition of BN to biopolymer matrixes decreased the density of nanocomposites and mechanical properties except for TMOE of PLA nanocomposites. It was found that the effects of BN were higher on the mechanical properties of PHB nanocomposites than on PLA nanocomposites. The SEM result showed that BN particles dispersed inside the matrix, and generally showed uniform dispersion in the matrixes. However, some BN aggregates were found in the SEM images. Thermal stability of biopolymer nanocomposites was found to improve with the addition of BN. The addition of BN showed improvement of $T_{10\%}$, $T_{50\%}$, and $T_{85\%}$. In DSC analysis, T_m and T_c generally increased with the addition of fillers, and X_c was also raised with the increase of ΔH_c and ΔH_m.

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Metoda procjene svojstava uslojenog drva

Method of Estimation of Laminated Wood Properties

Izvorni znanstveni rad • Original scientific paper
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SAŽETAK • *Cilj je ovog rada pokazati mogućnost primjene računalnih programa za procjenu mehaničkih svojstava uslojenog drva i njihovu daljnju primjenu u kvantitativnim metodama. Analiza je ograničena na dva mehanička svojstva i na tri debljine furnirskih ploča (4,5; 12; 21 mm). Od mehaničkih svojstava određena su savojna čvrstoća i modul elastičnosti, i to paralelno i okomito na vlakanca vanjskog furnira. Kao ulazni parametri za izradu modela korištena su svojstva materijala s unaprijed definiranim vrijednostima u programu WoodLab PlyCalc, specifičnima za tvrde listače s područja sjeverne Europe (PC-Bu) i svojstva materijala karakteristična za naše podneblje utvrđena eksperimentalnim metodama (EM-Bu) te su dobiveni rezultati uspoređeni s rezultatima ispitivanja furnirskih ploča destruktivnim metodama (FP-D). Nakon analize rezultata zaključeno je da na njihovu točnost povoljno utječe primjena eksperimentalno dobivenih vrijednosti svojstava materijala za definiranje modela te da se razlike između mehaničkih svojstava dobivenih računalnim programom i onih dobivenih ispitivanjem smanjuju s povećanjem debljine furnirske ploče odnosno broja slojeva od kojih je napravljena. Može se zaključiti da uz poznata ograničenja i prednosti takvi računalni programi imaju veće mogućnosti pri odabiru optimalnog materijala za izradu proizvoda.*

Ključne riječi: *furnirska ploča, savojna čvrstoća, modul elastičnosti, debljina furnirske ploče, procjena svojstava*

ABSTRACT • *The aim of this paper is to demonstrate the possibility of applying computer programs for the evaluation of mechanical properties of wood, aiming at their further use in quantitative methods. The analysis is done of two mechanical properties and to three thicknesses of veneer plywood (4.5, 12, 21 mm). Mechanical properties that have been determined are flexural strength and modulus of elasticity, both parallel and perpendicular to the outer veneer fiber direction. Input parameters for the modeling were material properties with predefined values in the software used, and they were specific for Northern European hardwoods (PC-Bu) and material properties characteristic for Croatian area, which were achieved by experimental methods (EM-Bu). The results obtained were compared to the results of testing veneer plywood by destructive methods (FP-D). The analysis of the results shows that experimentally obtained values of the properties of the material for the definition of the model have a beneficial effect on the accuracy of the results. The differences between mechanical properties, obtained by the computer program and those obtained by testing, decrease with the increase of thickness or number of layers of veneer plywood. It can be concluded that, considering the known limitations and advantages, such computer programs provide wider possibilities in choosing the optimal material for product development.*

Key words: *veneer plywood, bending strength, modulus of elasticity, thickness of veneer plate, property estimation*

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1. UVOD
1 INTRODUCTION

Pojam dizajna najčešće se povezuje s oblikovnim rješenjem. Donedavno je u proizvodnju namještaja bio uključen relativno mali broj različitih vrsta materijala, a oblikovno-konstrukcijska rješenja najčešće su bila definirana intuitivnom metodom. Za uspješno dizajniran proizvod kakav je, primjerice, stolica od uslojenog drva *Rex* (Hrovatin, 2010.) nisu dovoljne samo umjetničke vještine već su nužna i inženjerska znanja kojima se, ovisno o namjeni proizvoda, objedinjuju oblikovno-konstrukcijska rješenja s materijalom od kojega se proizvod izrađuje (Jackson i Day, 1989.; Prekrat i dr., 2009.). Sustavni odabir najboljeg materijala za određenu primjenu počinje definiranjem svojstava i određivanjem troškova materijala gotovog proizvoda (Dieter, 1997.). Dobro odabrani materijal rezultira i smanjenjem otpada, čime se izravno utječe na zaštitu okoliša.

U razvoju proizvoda moguća su dva pristupa, i to razvoj potpuno novoga, tržištu dotad nepoznatog proizvoda i poboljšanje svojstava postojećeg proizvoda, što također može dovesti do razvoja novog proizvoda. U oba je slučaja za donošenje ispravne odluke bitno da odabrani materijali odgovaraju postavljenim kriterijima. Najčešći preduvjet pri odabiru materijala jest da on ima zahtijevana svojstva te stoga odabir vrste materijala ponajprije ovisi o vrsti, tipu i području primjene proizvoda za koji odabiremo materijal, a potom i o važnosti postavljenih zahtjeva i kriterija. Da bi se udovoljilo svim postavljenim uvjetima, potrebno je poznavati sva relevantna svojstva materijala jer je upravo materijal osnovni tvorbeni element svakog proizvoda što ga, osim konstrukcijskog rješenja, određuju i njegova uporabna i vrijednosna svojstva. Iz toga proizlazi da je za donošenje odluke o optimalnom odabiru materijala nužno definirati i svojstva koja proizvod mora zadovoljiti (Milton i Rodgers, 2013.; Ulrich i Eppinger, 2015.).

Današnji zahtjevi glede svojstava proizvoda sve su složeniji i stroži, što implicira da je i odabir najpovoljnijeg materijala za neku konstrukciju postao zahtjevniji i složeniji, pogotovo ako se ima na umu da je danas potreba za razvojem novih proizvoda u izravnoj vezi s potrebom odabira optimalne kombinacije materijala koji bi mogli pratiti sva očekivanja postavljena pred proizvod.

Iskorištavanjem različitih fizikalno-mehaničkih svojstava odnosno preferiranjem njihovih maksimalnih ili minimalnih vrijednosti određuje se skup materijala i predlažu grafikoni odabira materijala (Ashby, 1999.).

Metode koje mogu pomoći u izboru materijala ovise o broju postavljenih zahtjeva i ciljeva. Za manji broj zahtjeva primjenjuju se metode utemeljene na kvalitativnoj analizi svojstava materijala koji ulaze u izbor. Te se metode temelje na procjeni svakoga relevantnog svojstva, što osigurava dobivanje objektivne procjene izbora materijala i donošenje ispravne odluke. Ako je broj zahtjeva i kriterija velik, nužno je primijeniti kvantitativne metode, koje omogućuju da se pri izboru materijala koristimo kvantitativnim i kvalitativnim kriterijima, što daje objektivniju odnosno pouzdaniju procjenu pri izboru materijala.

Bez obzira na to koja se metoda primjenjuje, jedan od kriterija za odabir uslojenih proizvoda jesu njihova relevantna mehanička svojstva.

Da bi se dobili podatci o relevantnim mehaničkim svojstvima materijala, danas su na raspolaganju različite metode ispitivanja, i to destruktivne i nedestruktivne, te računalni programi koji daju podatke potrebne za procjenu pogodnosti materijala od kojih se izrađuje proizvod.

Nedestruktivno (nerazorno ili bezrazorno) ispitivanje odnosno procjenjivanje postupak je kojim se mogu identificirati neka fizička i mehanička svojstva ili uočiti greške nekog materijala bez narušavanja i mijenjanja njegova izgleda i krajnje uporabnosti (Tanasoiu i dr., 2002.).

Prednost nedestruktivnih metoda testiranja u odnosu prema destruktivnima jest to što one pridonose očuvanju materijala, čime se ostvaruje bolja kontrola kvalitete uz postizanje potpune automatizacije proizvodnje. U tim su ispitivanjima eksperimentalni uzorci manjih dimenzija i na istim je uzorcima moguće odrediti više različitih mehaničkih svojstava. Takve metode ispitivanja omogućuju uvid u stanje materijala bez utjecaja na njegova uporabna svojstva te se mogu primjenjivati u različitim terenskim i atmosferskim uvjetima uz znatno niže troškove testiranja i analize rezultata (Nowak i dr., 2015.).

Druga skupina metoda za određivanje svojstava materijala također je nedestruktivna, ali je utemeljena samo na računalnim programima koji omogućuju dobivanje rezultata za velik broj materijala i njihovih međusobnih kombinacija bez opasnosti od uništenja svojstava materijala destruktivnim ispitivanjima. Za procjenu i analizu svojstava materijala tim metodama materijal ne mora biti fizički prisutan već se analiza provodi na računalnim modelima, što te metode čini ekonomski vrlo prihvatljivima i inženjerski zanimljivima. Iako te metode ne mogu u potpunosti zamijeniti fizička ispitivanja, njima je moguće suziti izbor materijala u fazi projektiranja namještaja ili drugog proizvoda, čime se znatno pridonosi uštedama vremena proizvodnje, uz optimalnu kvalitetu i cijenu finalnog proizvoda.

U ovom će radu biti prikazana metoda utemeljena na računalnom programu koja može poslužiti za procjenu relevantnih svojstava uslojenog drva radi donošenja ispravne odluke pri odabiru materijala ili korištenjem tih podataka u primjeni kvantitativnih metoda za izbor materijala u konstrukciji sklopova ili za izradu proizvoda.

2. MATERIJALI I METODE
2 MATERIALS AND METHODS

Nedestruktivne metode procjene mehaničkih svojstava svoju popularnost zahvaljuju razvoju tehnologije koji je ponudio sofisticirana, brza i efikasna rješenja za ispitivanje materijala uz pomoć raznih računalnih programa i moderniziranih uređaja koji pri ispitivanju štede vrijeme i materijal, a istodobno osiguravaju kvalitetan konačni proizvod. Njima se može ispitivati cjelovito drvo, uslojeni drvni proizvodi i ostale ploče s drvnom osnovom. Kao primjer na kojemu će se provesti analize računalnom metodom poslužit će furnirska ploča koja se svojom građom i postupkom izrade svrstava u materijale s projektiranim svojstvima, iako zbog anizotropne građe drva uvijek postoje određena odstupanja realnih vrijednosti od proračunskih. Danas postoji više metoda za ispitivanje svojstava, no u sklopu normi za proizvode od uslojenog drva trenutačno je važeća europska odnosno službena hrvatska norma HRN EN 14272 – Računska metoda za pojedina mehanička svojstva. Normom su definirani računski postupci za utvrđivanje relevantnih mehaničkih svojstava furnirske ploče simetrične građe, a proračun se zasniva na vrijednostima mehaničkih svojstava one vrste drva od koje su izrađeni listovi furnira. Svaki par furnira ima svoju geometrijsku veličinu ovisno o njegovu položaju unutar poprečnog presjeka konstrukcije ploče, odnosno karakteriziran je momentom tromosti. Za čvrstoću ploče uzima se u obzir samo čvrstoća onih slojeva koji su orijentirani u smjeru vlakanaca (Kljak i dr., 2005.). Za tu će namjenu biti korišten računalni program WoodLab PlyCalc, koji je u potpunosti utemeljen na normi HRN EN 14272 te će omogućiti dobivanje potrebnih podataka o mehaničkim svojstvima furnirskih ploča.

Kako bi se dobila potpunija slika o pouzdanosti te metode za procjenu mehaničkih svojstava furnirske ploča, dobiveni će se rezultati usporediti s onima dobivenim destruktivnom metodom testiranja ploče. Ispitivanja mehaničkih svojstava destruktivnom metodom provodit će se prema točno određenim pravilima koja propisuje norma HRN EN 310.

S obzirom na to da je cilj ovog rada pokazati mogućnosti primjene računalnih programa za procjenu mehaničkih svojstava uslojenog drva i njihove daljnje primjene u kvantitativnim metodama, analiza će se ograničiti na dva mehanička svojstva i na tri debljine furnirskih ploča (4,5; 12; 21 mm). Od mehaničkih svojstava odredit će se savojna čvrstoća i modul elastičnosti, i to paralelno i okomito na vlakanca vanjskog furnira. Analiza će obuhvatiti tri različite debljine furnirskih ploča jer predviđeni računalni program za izračun mehaničkih svojstava simetrično orijentiranih uslojenih ploča u svojim kalkulacijama uzima u obzir samo naprezanje u slojevima s vlakancima orijentiranim paralelno sa smjerom dužine uzorka, dok se naprezanje u slojevima s vlakancima okomitim na smjer dužine uzorka zanemaruje. Time se želi utvrditi utječe li broj slojeva furnira odnosno debljina furnirske ploče na veličinu potencijalne pogreške izračuna, što je ujedno i najveći nedostatak tog načina izračuna mehaničkih svojstava uslojenih ploča.

U primijenjenoj metodi za izradu modela iskoristit će se svojstva materijala unaprijed definiranih vrijednosti u samom programu, specifičnima za tvrde listače s područja sjeverne Europe (PC-Bu) i svojstva materijala tipična za naše podneblje dobivena eksperimentalnim metodama (EM-Bu) (tab. 1.).

Tablica 1. Svojstva furnirske sirovine bukovine
Table 1 Properties of beechwood as veneer raw material

Svojstvo / *Properties*	**PC-Bu**	**EM-Bu**
gustoća, kg/m³ / *Density, kg/m³*	650	714
savojna čvrstoća II, N/mm² *Bending strength II, N/mm²*	80	126
vlačna čvrstoća, N/mm² *Tension strength, N/mm²*	80	126
tlačna čvrstoća, N/mm² *Compression strength, N/mm²*	60	53
smicajna čvrstoća, N/mm² *Shear strength, N/mm²*	8	7,5
modul elastičnosti savijanja, N/mm² *Bending modulus of elasticity, N/mm²*	13000	13347
modul elastičnosti smicanja, N/mm² *Shear modulus of elasticity, N/mm²*	720	954

3. REZULTATI I DISKUSIJA
3 RESULTS AND DISCUSSION

Rezultati mehaničkih svojstava dobiveni destruktivnom metodom ispitivanja furnirskih ploča od bukovih furnira zadanih debljina prikazani su u tablici 2.

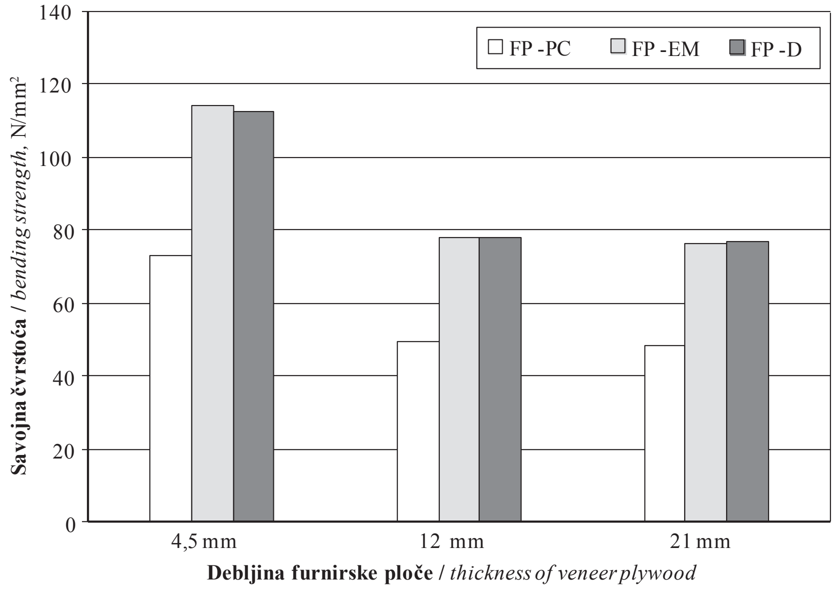
Tablica 2. Rezultati ispitivanja furnirskih ploča destruktivnim metodama (FP-D)
Table 2 Results of destructive testing of veneer boards (FP-D)

Ispitano svojstvo *Examined properties*	**Rezultati ispitivanja** *Results of test*		
debljina, mm *Thickness, mm*	4,5	12	21
broj slojeva *Number of layers*	3	7	11
gustoća, kg/m³ *Density, kg/m³*	747	771	762
savojna čvrstoća II, N/mm² *Bending strength II, N/mm²*	112,6	77,9	76,7
savojna čvrstoća ⊥, N/mm² *Bending Strength ⊥, N/mm²*	57,2	67,9	52,5
modul elastičnosti II, N/mm² *Modulus of elasticity II, N/mm²*	13560	7760	9497
modul elastičnosti ⊥, N/mm² *Modulus of elasticity ⊥, N/mm²*	1212	7578	5741

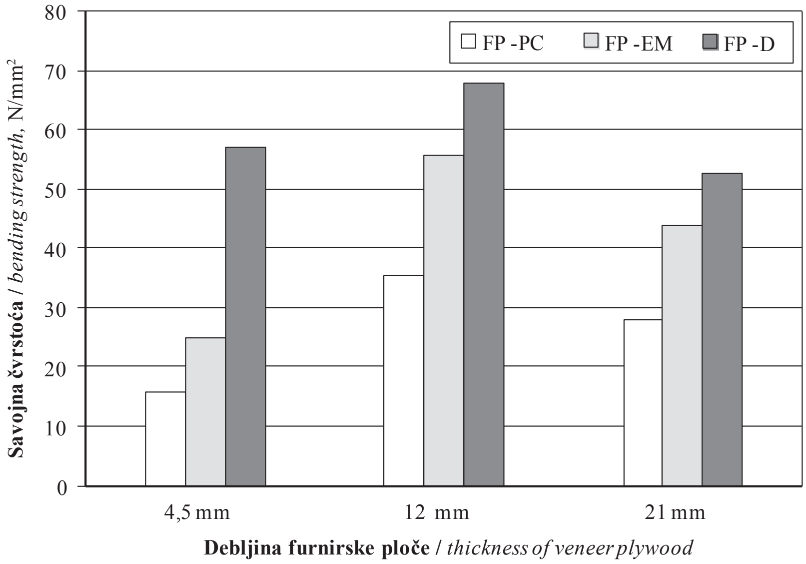
Na grafičkim prikazima slike 1. (a – d) prikazani su rezultati ispitivanja furnirskih ploča za koje su svojstva furnira kao materijala unaprijed definirana u samom programu (FP-PC) i furnirskih ploča čija su svojstva drva od kojega je furnir izrađen dobivena eksperimentalnim metodama (FP-EM) u usporedbi s rezultatima ispitivanja furnirskih ploča destruktivnim metodama (FP-D).

Analizom promatranih svojstava moguće je zaključiti da su pri definiranju modela furnirske ploče primjenom svojstava drva utvrđenih ispitivanjem (EM-Bu) dobivene vrijednosti mehaničkih svojstava furnirskih ploča (FP-EM) mnogo bliže vrijednostima dobivenim eksperimentalnim ispitivanjem mehaničkih svojstava furnirskih ploča (FP-D).

Primjerice, za furnirsku ploču debljine 4,5 mm pri ispitivanju savojne čvrstoće paralelno s vlakanci-



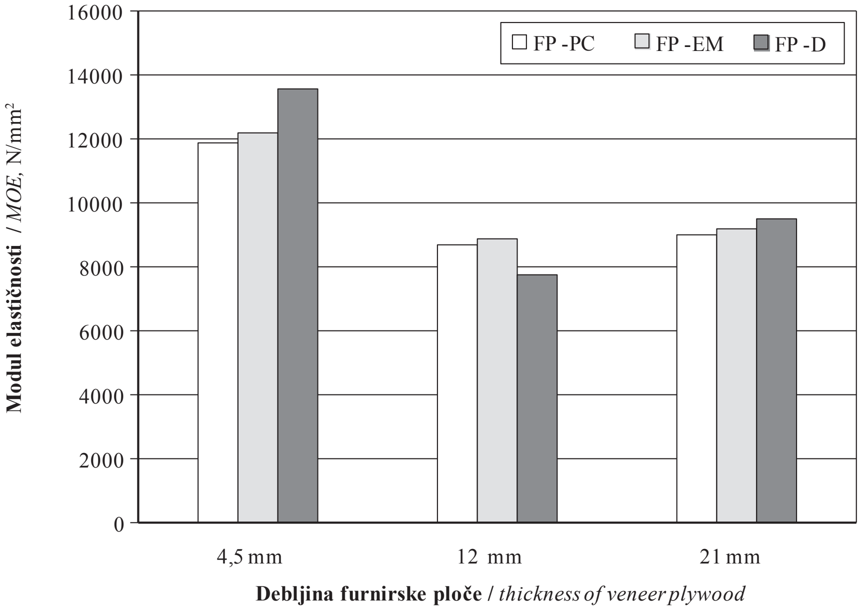
a) Savojna čvrstoća paralelno s vlakancima / *bending strength parallel to the grain*



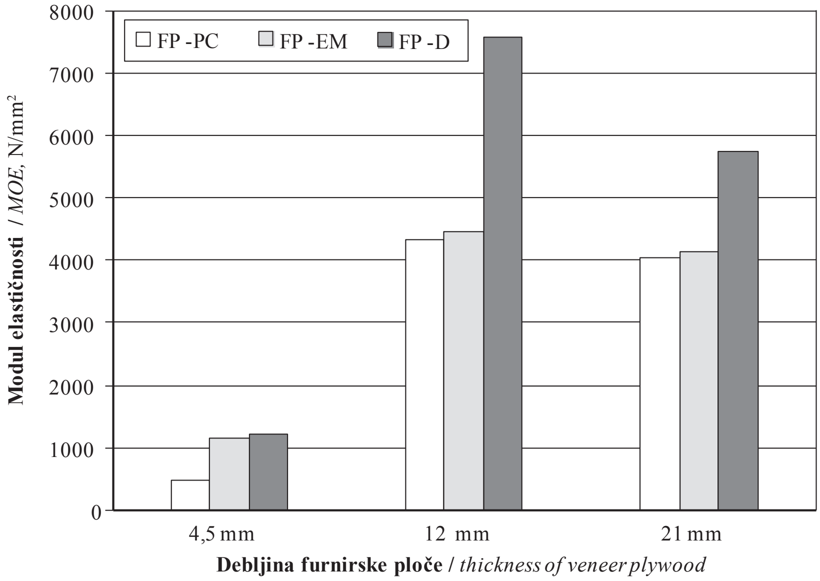
b) Savojna čvrstoća okomito na vlakanca / *bending strength perpendicular to the grain*

Slika 1. Svojstva furnirskih ploča
Figure 1 Properties of veneer plywoods

ma uvrštenjem unaprijed definiranih vrijednosti materijala (FP-C) i usporedbom sa savojnom čvrstoćom iste ploče dobivenom ispitivanjem (FP-D) razlika između rezultata iznosi 35,2 %, a usporedbom savojne čvrstoće furnirske ploče čiji je model izrađen primjenom eksperimentalno dobivenih vrijednosti svojstava materijala ta razlika iznosi 2,1 %. Usto, iz prikaza rezultata vidljivo je da na točnost dobivenih vrijednosti osim svojstava materijala utječe i analizirani smjer promatranog svojstva. To je bilo i očekivano jer se u kalkulacijama na kojima se primijenjeni program temelji u obzir uzimaju samo naprezanja u slojevima s vlakancima orijentiranim paralelno sa smjerom dužine modela, dok se naprezanja u slojevima s vlakancima okomitim na smjer dužine uzorka ta naprezanja zanemaruju. U promatranom primjeru razlike između rezultata dobivenih računalnim programom i onih dobivenih ispitivanjem značajno su veće iako je i u tom slučaju vidljiv pozitivan utjecaj svojstava materijala dobivenih ispitivanjima na kreiranje modela. Tako je vrijednost savojne čvrstoće okomito na vlakanca furnirske ploče debljine 4,5 mm FP-PC 72,4 % manja od one dobivene ispitnim metodama furnirske ploče FP-D jednake debljine, dok je ta razlika za ploču FP-E manja i iznosi 56,5 %. Za furnirske ploče većih debljina i većeg broja slojeva ta se razlika smanjuje te za furnirsku ploču FP-PC debljine 12 mm ona iznosi 47,9 %, a za furnirsku ploču FP-PC debljine 21 mm iznosi 46,9 %. Iako se ta razlika između promatranog svojstva dobivenoga simulacijom i svojstva dobivenoga ispitivanjem s povećanjem debljine ploče smanjuje, ona je i dalje značajno prevelika kad je riječ o vrijednosti svojstava okomito na vlakanca. Iznimkom se pokazala vrijednost modula elastičnosti savijanja



c) Modul elastičnosti paralelno s vlakancima / *modulus of elasticity parallel to the grain*



d) Modul elastičnosti okomito na vlakanca / *modulus of elasticity perpendicular to the grain*

okomito na vlakanca za furnirske ploče FP-EM debljine 4,5 mm, za koje razlika u odnosu prema eksperimentalno dobivenoj vrijednosti promatranog svojstva iznosi prihvatljivih 5,9 %. Taj primjer treba dodatno istražiti te utvrditi je li ta činjenica za troslojne furnirske ploče pravilo ili je dobiveni rezultat izuzetak zabilježen samo u ovom ispitivanju.

Povoljnije je, kao što je već rečeno, kada se za definiranje modela primjenjuju svojstva materijala dobivena ispitivanjem. Tada su razlike u vrijednostima promatranog svojstva između furnirske ploče FP-EM debljine 12 mm i furnirske ploče FP-D istovjetne debljine 18,0 %, a za furnirsku ploču FP-EM debljine 21 mm ta je razlika još manja i iznosi 16,4 %. Za odabir najpovoljnijeg rješenja među svih promatranim primjerima, presudna je činjenica da je najbolje rezultate pokazala ploča debljine 21 mm, čiji je model izrađen primjenom eksperimentalno dobivenih vrijednosti materijala. Savojna čvrstoća paralelno s vlakancima za tu je furnirsku ploču 0,4 % veća od one dobivene ispitivanjima, dok je vrijednost modula elastičnosti savijanja paralelno s vlakancima 3,1 % manja od vrijednosti dobivene ispitivanjem.

4. ZAKLJUČAK
4 CONCLUSION

1. Na točnost rezultata povoljno utječe primjena eksperimentalno dobivenih vrijednosti svojstava materijala za definiranje modela.
2. U glavnome konstrukcijskom smjeru – paralelno s vlakancima, vrijednosti mehaničkih svojstava dobivene simulacijom iznosima su bliske vrijednostima dobivenim ispitivanjima.

3. Razlike između mehaničkih svojstava dobivenih računalnim programom i onih dobivenih ispitivanjem smanjuju se s povećanjem debljine furnirske ploče odnosno s brojem slojeva od kojih je izrađena.
4. Uz sva poznata ograničenja i prednosti, primijenjeni računalni programi daju veće mogućnosti pri odabiru optimalnog materijala za izradu proizvoda.

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Lightweight Flat Pressed Wood Plastic Composites: Possibility of Manufacture and Properties

Lagane drvno-plastične kompozitne ploče: mogućnost proizvodnje i svojstva

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ABSTRACT • *Usually the conventional wood plastic composites (WPC) are produced with the densities of approximately 800-1000 kg/m³. The possibility of manufacture and properties of the lightweight flat pressed WPC using expanded polystyrene was described in this study. The shredded recycled low density polyethylene (rLDPE), wood particles (WP) and expanded polystyrene (EPS) were used for making one-layer lightweight WPC boards (non-laminated and laminated). Bending strength (MOR), modulus of elasticity (MOE), tensile strength perpendicular to the plane of the board (IB) and thickness swelling after immersions in water for 2 hours (TS/2h) and 24 hours (TS/24h) of the lightweight WPC boards were evaluated. It was established that the EPS content and boards' density as well as the lamination process have a significant impact on the properties of lightweight WPC boards. Thus, it was found that the use of expanded polystyrene enables the production of lightweight WPC within a density range of 500-700 kg/m³, which is almost twofold less than the density of the conventional WPC. The results of research have shown that the bending strength, modulus of elasticity and internal bond strength of non-laminated lightweight WPC boards meet the requirements (for lightweight particleboards) of EN 16368 (type LP1) and ANSI A208.1 (types LD-1 and LD-2) standards. The bending strength and modulus of elasticity of laminated lightweight WPC boards meet the requirements of ISO 13894-2.*

Keywords: *lightweight wood plastic composites, recycled low density polyethylene, expanded polystyrene, wood particles, lamination*

SAŽETAK • *Konvencionalni drvno-plastični kompoziti (WPC) obično se proizvode s gustoćom od približno 800 – 1000 kg/m³. Tema ove studije jest mogućnost proizvodnje lakih WPC ploča proizvedenih dodatkom ekspandiranog polistirena i njihova svojstva. Za izradu jednoslojnih laganih WPC ploča (nelaminiranih i laminiranih) upotrijebljeni su: usitnjeni reciklirani polietilen niske gustoće (rLDPE), drvne čestice (WP) i ekspandirani polistiren (EPS). Istraživanjem su određena ova svojstva laganih WPC ploča: čvrstoća na savijanje (MOR), modul elastičnosti (MOE), vlačna čvrstoća okomito na ravninu ploče (IB) i debljinsko bubrenje nakon uranjanja ploča u vodu u trajanju 2 sata (TS/2 h) i 24 sata (TS/24 h). Utvrđeno je da udio EPS-a i gustoća ploča, kao i proces laminiranja imaju značajan utjecaj na svojstva laganih WPC ploča. Tako je utvrđeno da upotreba ekspandiranog polistirena omogućuje proizvodnju laganih WPC ploča u rasponu gustoće 500 – 700 kg/m³, što je gotovo dvostruko manje od gustoće konvencionalnih WPC ploča. Rezultati istraživanja pokazali su da čvrstoća na savijanje, modul elastičnosti i čvrstoća unutarnje veze nelaminiranih laganih WPC ploča udovoljavaju zahtjevima (za lagane ploče*

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iverice) standarda EN 16368 (tip LP1) i ANSI A208.1 (tip LD-1 i LD-2). Čvrstoća na savijanje i modul elastičnosti laminiranih laganih WPC ploča udovoljavaju zahtjevima norme ISO 13894-2.

Ključne riječi: *lagani drvno-plastični kompoziti, reciklirani polietilen niske gustoće, ekspandirani polistiren, drvne čestice, laminiranje*

1 INTRODUCTION
1. UVOD

Wood plastic composites (WPC) can be used in different sectors of economy and are produced by different methods: extrusion, injection and compression moulding, etc., which depends on the configuration forms of the products and the field of their use (Niska and Sain, 2008). They are characterized by good performance properties and could be considered as the "green composites" (Lyutyy *et al*., 2017). One of the disadvantages of the WPC is their high density in comparison with other conventional wood based composites, such as particleboards and medium density fibreboards (MDF). The density of the conventional flat pressed WPC is approximately about 800-1000 kg/m^3 (Lyutyy *et al*., 2014), the density of MDF and particleboards is approximately about 650-750 kg/m^3. It is well known that high density composite materials have some disadvantages: rapid tool wear, material and transportation costs, handwork, high weight of construction. In this regard, the high density WPC is difficult to compare with particleboards and MDF.

The development of lightweight boards has been dictated by the fast-growing market of knockdown furniture, the shortage of raw material and the need to reduce costs in the wood-based composites industry, customers' packaging and transportation demands (Barbu and Van Riet, 2008). As a matter of fact, these trends draw attention towards both the use of so far underutilized resources and the innovation of new products and production concepts which increase the resource efficiency (Eder *et al*., 2010). Nevertheless, during recent decades all strategies, which are used for the reduction of board density, can be segregated in three major groups: technology, materials and sandwich concept (Shalbafan, 2013).

Low matt-furnish compaction is one of the strategies to produce low or ultra-low density fibreboards with the density of about 55 kg/m^3 without applying any pressing pressure (Yongqun *et al.*, 2011). Mechanical properties of such boards still remain low in comparison with MDF due to their extremely low density. However, those boards can provide low thermal conductivity and thus could be considered as good building insulation materials (Yongqun *et al.*, 2011).

The tubular extrusion technology is another way to manufacture low density wood based boards (Kollmann *et al.,* 2013), but the bending strength (*MOR*) of those boards is unsatisfactory. Different foamable polystyrene and already foamed polystyrene particles could be used for the production of wood based boards with the density that varies from 200 to 600 g/m^3 (BASF, 2012).

Moreover, lightweight wood based boards (density of 400 kg/m^3) could be produced by using different raw materials, for example, by replacing wood particles and fibres by low weight agricultural particles: hemp, kenaf, sunflower, maize, rape, miscanthus, topinambur (Balducci *et al.,* 2008). Unfortunately, the bending strength of lightweight boards made from annual/perennial farm plants does not meet the requirement of EN 312 (2010) type P2 (Balducci *et al.,* 2008).

Another way to make low density composites is the use of different foam-type resins. The foam-type urea-formaldehyde (UF) resins were prepared by mixing three kinds of foaming agents with UF resin for the production of lightweight MDF with the density of 600 kg/m^3 (Wen *et al.,* 2014). Such MDF showed satisfactory mechanical properties and dimensional stability.

The largest strategy for the production of lightweight wood based composites is the sandwich concept. Different materials, such as honeycomb (Thoemen *et al.,* 2007), foam core (Shalbafan 2013), and profiled spacers (webs) (Nilsson *et al*., 2013), could be used for the middle layer of the sandwich boards. However, honeycomb sandwich boards are acceptable for the manufacture of the boards with thickness higher than 25 mm (Cremonini *et al*., 2008).

Some researchers make combinations of different strategies to reduce density of boards. The usage of expanded polystyrene and rape straw for the manufacture of lightweight particleboards was one of them (Dziurka *et al*., 2013; Dziurka *et al*., 2015). Those studies showed that lightweight wood chip-rape straw particleboards, substituted in the core layer with 10 % expanded polystyrene, meet the requirements of the relevant European standard (EN 312, 2010) for P2 boards, concerning their bending strength, modulus of elasticity and tensile strength perpendicular to their planes. Another advantage of that type of boards is their high-water resistance.

Unfortunately, most of the methods mentioned above cannot be used to produce lightweight flat pressed WPCs. The production of WPCs having a density similar to the one of particleboard or MDF could greatly expand their field of application. However, to the best of the author's knowledge, no study has been reported in literature concerning the manufacture and properties of lightweight WPCs. Therefore, the objective of this study was to investigate the possibility of the manufacture and properties of lightweight flat pressed wood plastic composites using expanded polystyrene.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

In this study, the particles of laboratory shredded recycled low density polyethylene (rLDPE) and wood particles (WP) with moisture content of 2-3 % commercially produced for particleboard mill, and expanded polystyrene (EPS) were used for making WPC boards. The rLDPE particles were used as the polymer

Table 1 Fraction analysis (by % weight)
Tablica 1. Granulometrijska analiza (udio frakcija izražen postotcima mase)

Components *Sastavnice*	**Screen hole size, mm** / *Veličina otvora sita,* mm						
	-/5	5/4	4/2	2/1	1/0.63	0.63/0.315	0.315/0
WP	4.75	12.2	15.79	40.28	15.67	9.13	2.18
rLDPE	9.53	3.04	53.14	32.45	1.83	-	-

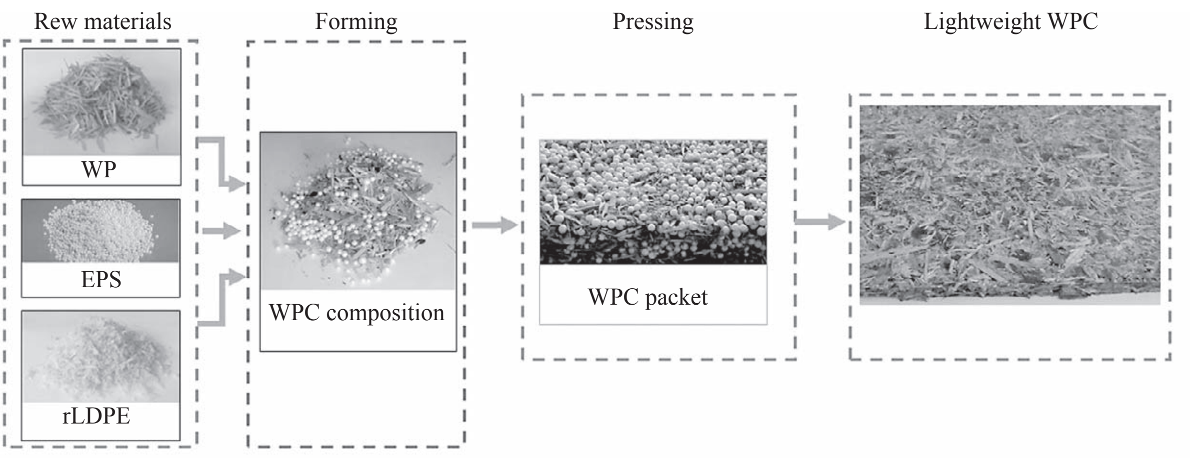


Figure 1 Manufacturing process of non-laminated one-layer lightweight WPC boards
Slika 1. Proces proizvodnje nelaminiranih jednoslojnih laganih WPC ploča

matrix. The melting point of LDPE is in a range of 105-115 °C (Tice, 2003). The rLDPE and WP particles fraction analysis is presented in Table 1. The diameter of EPS granules was 2-4 mm and the bulk density was in the range from 6 to 10 kg/m^3. High pressure laminate (HPL) with the thickness of 0.5 mm was used for the lamination of lightweight WPC boards.

Two types of one-layer lightweight WPC boards were manufactured: non-laminated and laminated. The ratio of WP to rLDPE was 60:40. The EPS content was about 1, 2 and 3 % of the weight of the WP/rLDPE composition. No adhesive was used due to the presence of 40 % polyethylene, which melts and acts as a bonding adhesive for the mat particles.

The manufacture of non-laminated lightweight WPC boards

WP, rLDPE and EPS (in the natural dry state) were mixed by hand for 10 minutes. The mat of WPC composition was formed into the open form and afterwards transferred to the hot press (Figure 1).

The manufacture of laminated lightweight WPC boards

The back sheet of HPL was put into open press-form. The mixing of WPC composition (wood parti-

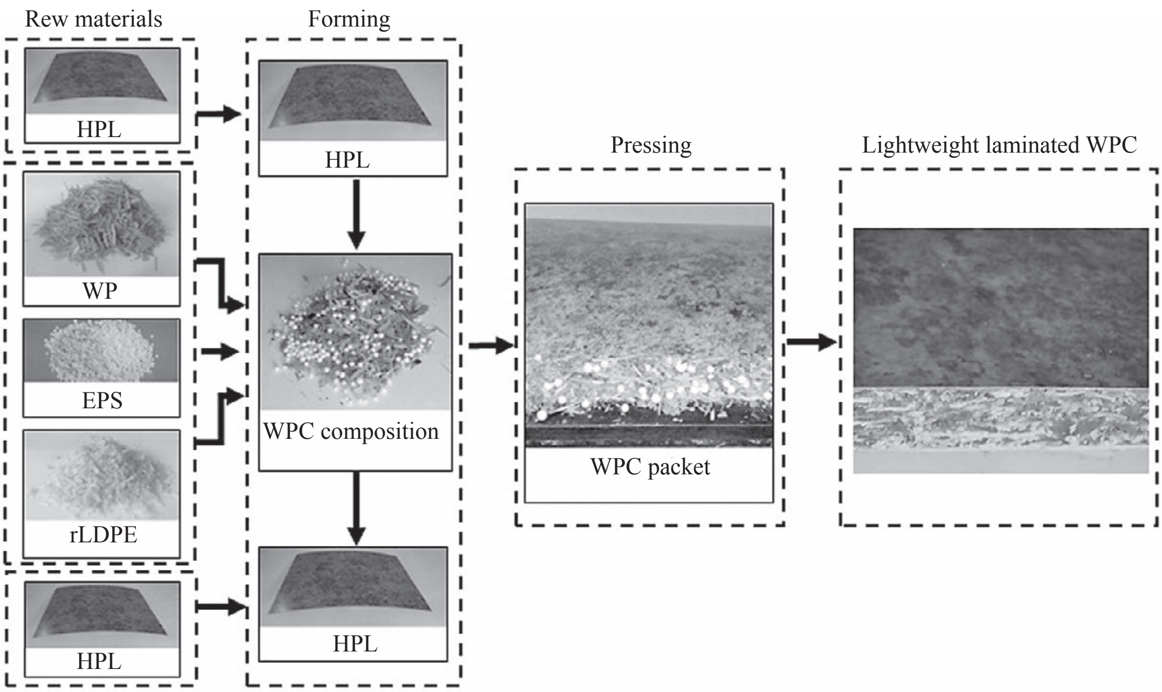


Figure 2 Manufacturing process of laminated one-layer lightweight WPC boards
Slika 2. Proces proizvodnje laminiranih jednoslojnih laganih WPC ploča

cles/rLDPE/EPS) was made in the same way as for non-laminated one-layer lightweight WPC boards. Then WPC composition was formed on HPL sheet and laminated by face HPL sheet (Figure 2). The WPC packets were hot pressed under the pressure of 3.5 MPa at the temperature of 180 °C for 1 min/mm in a one-step process. At the end of the hot-pressing cycle, the WPC board was immediately moved from the hot press into the cold press at the temperature of 20 °C for cooling to the temperature of 30-40 °C. The WPC boards with 8 mm thickness were trimmed to a final size of 250 mm × 230 mm. The target densities of lightweight WPC boards were of 500, 600 and 700 kg/m^3. The WPC boards with the same target density but without EPS (control board) were manufactured with the same pressing parameters.

Finally, the manufactured WPC boards were conditioned in a climate room with the relative humidity of 65 ± 5 % and the temperature of 20 ± 2 °C before being cut into test specimens.

The bending strength (*MOR*), modulus of elasticity (*MOE*), tensile strength perpendicular to the plane of the board (or internal bond) (IB) and thickness swelling after immersions in water for 2 hours (TS/2h) and 24 hours (TS/24h) of the lightweight WPC boards were evaluated according to the standard EN 310 (1993), EN 319 (1993) and EN 317 (1993), respectively.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Statistical analysis of variance (ANOVA) was conducted to determine whether there was a significant difference between the mechanical and physical properties of lightweight WPC with EPS content and density of boards (Table 2 and 3). It was found that significant difference existed among all properties of the samples made with different EPS content and density of board. ANOVA showed that the content of EPS, board density and lamination of lightweight WPC significantly influenced the board properties.

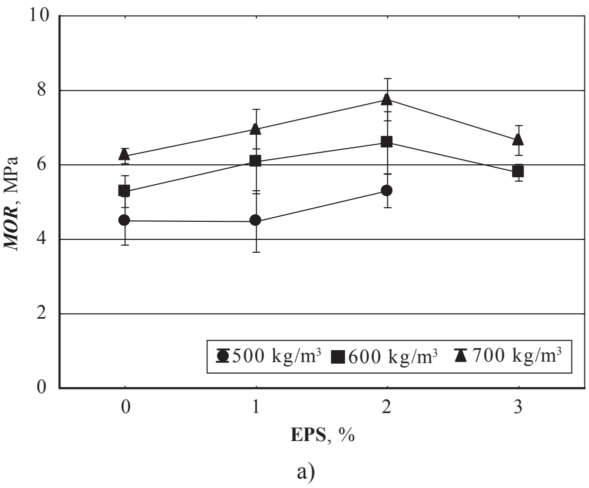
The highest values of *MOR* and *MOE* were observed in lightweight WPC boards with 2 % EPS content (Figure 3). The increase of EPS content leads to the increase of the volume and quantity of EPS granules in the WPC composition. The bulk density of EPS is very low and the EPS content is higher than 2 %. There were many weak bonds between the EPS granules in the board, and they had low adhesive strength. The proof of this could be the decrease of IB at the EPS content of

Table 2 Test results of Two-Way ANOVA for properties of non-laminated lightweight WPC samples (α=0.05)
Tablica 2. Rezultati dvosmjerne ANOVA analize svojstava nelaminiranih laganih WPC ploča (α = 0,05)

Source *Izvor varijacije*	**Dependent variable** *Zavisna varijabla*	**Sum of Squares** *Zbroj kvadrata*	***df*** *Stupanj slobode*	**Mean Square** *Srednja vrijednost kvadrata*	***F***	**Sig.**
EPS *ekspandirani polistiren*	*MOR*	13.027	3	4.342	19.437	.000
	MOE	212455.562	3	70818.521	34.469	.000
	IB	.070	3	.023	7.737	.000
	TS/2h	136.068	3	45.356	31.137	.000
	TS/24h	383.207	3	127.736	31.181	.000
Density *gustoća*	*MOR*	43.990	2	21.995	98.458	.000
	MOE	980173.873	2	490086.937	238.538	.000
	IB	.118	2	.059	19.564	.000
	TS/2h	154.526	2	77.263	53.041	.000
	TS/24h	106.047	2	53.024	12.943	.000
EPS × Density *ekspandirani polistiren × gustoća*	*MOR*	1.299	5	.260	1.163	.341
	MOE	31220.242	5	6244.048	3.039	.018
	IB	.015	5	.003	.968	.443
	TS/2h	28.019	5	5.604	3.847	.005
	TS/24h	8.455	5	1.691	.413	.838

Table 3 Test results of Two-Way ANOVA for properties of laminated lightweight WPC samples (α=0.05)
Tablica 3. Rezultati dvosmjerne ANOVA analize svojstava laminiranih laganih WPC ploča (α = 0,05)

Source *Izvor varijacije*	**Dependent variable** *Zavisna varijabla*	**Sum of Squares** *Zbroj kvadrata*	***df*** *Stupanj slobode*	**Mean Square** *Srednja vrijednost kvadrata*	***F***	**Sig.**
EPS *ekspandirani polistiren*	*MOR*	174.546	2	87.273	36.129	0.000
	MOE	1127864.486	2	563932.243	13.752	0.000
	TS/24h	58.386	2	29.193	19.205	0.000
Density *gustoća*	*MOR*	561.082	2	280.541	116.136	0.000
	MOE	2806866.400	2	1403433.200	34.224	0.000
	TS/24h	41.623	2	20.812	13.692	0.000
EPS × Density *ekspandirani polistiren × gustoća*	*MOR*	11.665	4	2.916	1.207	0.332
	MOE	1038309.607	4	259577.402	6.330	0.002
	TS/24h	4.144	4	1.036	0.682	0.611



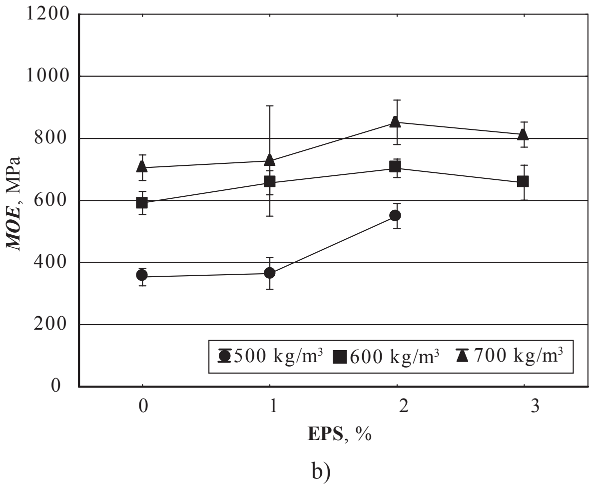


Figure 3 The influence of EPS content and density of board on *MOR* (a) and *MOE* (b) of non-laminated lightweight WPC boards
Slika 3. Utjecaj sadržaja ekspandiranog polistirena i gustoće nelaminiranih laganih WPC ploča na (a) *MOR* i (b) *MOE*

more than 2 % (Figure 4). The values of *MOR* and *MOE* were also reduced when the EPS content was less than 2 %. It can be explained by the low content of the EPS and the existence of some voids in WPC, which lead to the decrease of *MOR* and *MOE* values.

The increase of board density from 500 to 700 kg/m^3 leads to a significant increase of *MOR*/*MOE* of 1.44/1.81 times, as well as the increase of *IB* values of 1.5 times. Another important moment is that the mean deviation from *IB* average values increased with the increase of EPS content. The EPS granules statically attracted each other during the formation and mixing of WPC composition. That is why, the increasing of EPS content leads to generate a zone with a high content of EPS, which has different *IB* values. It is, therefore, necessary to add antistatic agent to the composition (BASF, 2012).

However, it should be mentioned that the values of *MOR*, *MOE* and *IB* of the investigated WPC boards were a little bit lower when compared to the values in other lightweight wood based boards (at the same density). For example, the *MOR*/*MOE* values of the wood

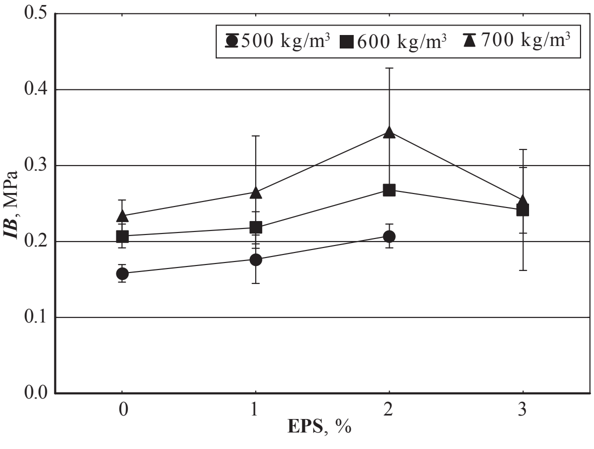


Figure 4 The influence of EPS content and density of board on IB of non-laminated lightweight WPC boards
Slika 4. Utjecaj sadržaja ekspandiranog polistirena i gustoće nelaminiranih laganih WPC ploča na čvrstoću unutarnje veze

chip-expanded polystyrene particleboards at the target density of 500 kg/m^3 were 10.1/2080 MPa (Dziurka *et al*., 2015). However, in that work, the particleboards were manufactured with melamine-urea-formaldehyde resin, which is intended for the manufacture of waterproof wood-based materials. Similar results concerning the values of *MOR* and *MOE* were also observed in the work (Shalbafan *et al*., 2016). The *MOR* values of the boards (with density of 500 kg/m^3) were almost identical but the *MOE* values were a little bit higher. This can be explained by the fact that Shalbafan *et al*., (2016) used UF resins and three-layered structure of particleboards. Moreover, the EPS granules were only used in the core layer (not in the face layers), and, therefore, the face layers have higher density than the core layer. It is well known that the face layers are most loaded during bending test. Also, the rLDPE particles are not able to provide the same rigidity and adhesive strength with wood particles as with UF resins. That is why the values of *MOE* could be a little bit lower for the investigated lightweight WPC boards when compared to UF particleboards.

The values of TS/2h and TS/24h of the lightweight WPC boards are improved with the increasing of EPS content and board density (Figure 5). The EPS is an inert material to the impact of water and does not swell too much during the immersion in water. In our case, only one component (wood particles) of the WPC composition had significant effect on the TS/2h and TS/24h. The increase of EPS granules content accordingly leads to the reduction of wood particles content and gives higher water resistance to the lightweight WPC boards (low values of thickness swelling).

The increase of board density, as well as the EPS, leads to a closer contact between the wood particles and thermoplastic polymer. The increase of density also leads to the creation of a thermoplastic film on the surface of wood particles and prevents the interaction between the molecules of water and wood components that reduces thickness swelling (Lyutyy *et al*., 2014). The values of TS/24h of the investigated boards were

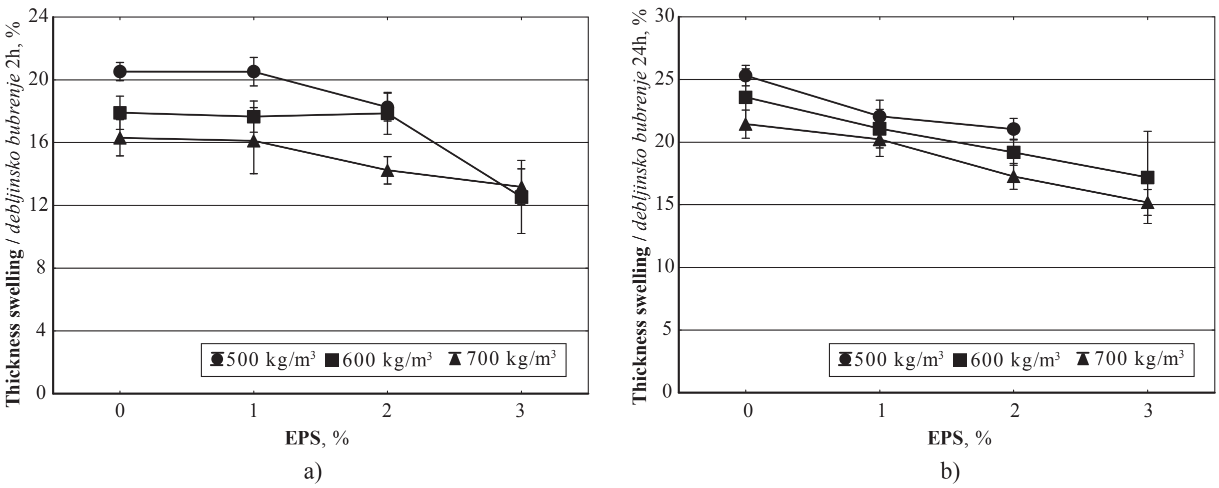


Figure 5 The influence of EPS content and board density on TS/2h (a) and TS/24 (b) of non-laminated lightweight WPC boards
Slika 5. Utjecaj sadržaja ekspandiranog polistirena i gustoće nelaminiranih laganih WPC ploča na (a) TS/2 h i (b) TS/24 h

lower in comparison with the values for wood chip-expanded polystyrene board and wood chip-rape straw-expanded polystyrene board (Dziurka *et al*., 2015). In contrast, the values of TS/2h and TS/24h of the investigated WPC boards were much higher than the values of the WPC boards made of milled foam core (Shalbafan *et al*., 2016). This can be explained by the higher (1.4-2.0 times) target density (1000 kg/m³) of those boards when compared to the density of the investigated lightweight WPC boards.

The lightweight non-laminated WPC boards with 2 % EPS content could be classified as type LP1 (EN 16368, 2011), LD-1 and LD-2 (ANSI A208.1, 2009) (Table 4). The boards with 3 % EPS content do not comply with the EN and American norms regarding the values of *MOE*. According to ANSI A208.1 (2009), the investigated non-laminated boards could be used for door core. However, non-laminated WPC boards do not comply with the requirements of EN 312 (2010) conventional particleboards regarding mechanical (*MOE*, *MOR* and IB) and physical (TS/24h) properties. As a result, non-laminated lightweight WPC boards could be laminated by different materials such as HPL, MDF, HDF, and plywood for the improvement of their mechanical and physical properties (Jivkov *et al*., 2012).

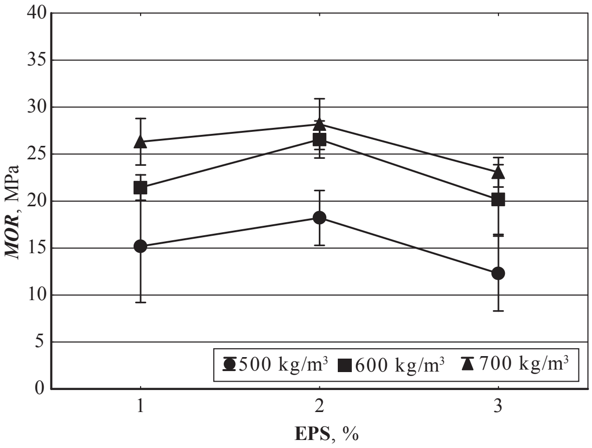
It was found that the lamination of lightweight WPC boards had a significant effect (Table 3) on *MOE* and *MOR* values. The influence of density and EPS content on *MOR* and *MOE* is shown in Figure 6. The highest values of *MOR* and *MOE* were observed for 2 % EPS content and board density of 700 kg/m³.

Higher values of *MOR* and *MOE* were observed for the investigated laminated WPC boards in comparison with other lightweight particleboards (Shalbafan *et al*., 2016; Jivkov *et al*., 2012). Separately, the lowest *MOE* values of the investigated laminated boards (density of 500 kg/m³ and EPS content of 3%) were 2.7 times higher than the values of the honeycomb panel commercially manufactured by Egger; and 3.86 times higher than the values of the five-layer board from

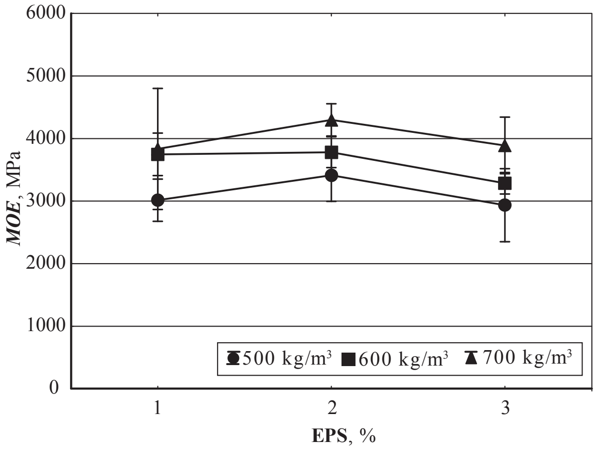
Table 4 Requirements for properties of lightweight particleboards and conventional particleboards according to EN standards
Tablica 4. Zahtjevi EN standarda za svojstva laganih ploča iverica i konvencionalnih ploča iverica

Board type / *Vrsta ploče*	***MOR*** **(*MOE*), MPa**	***IB*, MPa**	***TS/24h*, %**
Investigated non-laminated lightweight WPC boards *istraživane nelaminirane lagane WPC ploče*	4.3-7.7 (350-850)	0.16-0.34	15.51-25.51
Lightweight particleboards / *lagane ploče iverice* (EN 16368, 2011):			
LP1	4.0 (550)	0.28	-
LP2	8.0 (1000)	0.40	-
Particleboards / *ploče iverice* (EN 312, 2010):			
P1	10.5	0.28	-
P2	11.0 (1800)	0.4	-
P3	15.0 (2050)	0.45	17.0
Low density particleboards / *ploče iverice male gustoće* (ANSI A208.1, 2009)			
LD-1	2.8 (500)*	0.10**	-
LD-2	2.8 (500)*	0.14**	-

*According to test requirements, the width of specimens shall be 76 mm (instead of 50 mm in accordance with European standard) if the nominal thickness is greater than 6 mm; the length of span calculates with the same formula as in European and American standards. **The method of internal bond (IB) measurement in American standard complies with the relevant European standard.
** Ako je nominalna debljina ploča veća od 6 mm, prema zahtjevima ispitivanja, širina uzoraka mora biti 76 mm (umjesto 50 mm, prema Europskoj normi); duljina raspona izračunava se prema istoj formuli kao u europskim i američkim standardima. **Metoda mjerenja čvrstoće unutarnje veze (IB) u američkom standardu u skladu je s odgovarajućim europskim standardom.*



a)



b)

Figure 6 The influence of EPS content and board density on *MOR* (a) and *MOE* (b) of laminated lightweight WPC boards
Slika 6. Utjecaj sadržaja ekspandiranog polistirena i gustoće laminiranih laganih WPC ploča na (a) *MOR* i (b) *MOE*

EPS, MDF with thickness of 8 mm and HPL; 11.9 times higher than the values of the multi-layer board from MDF, five-layer corrugated cardboard and face layer from HPL; 1.3 times higher than the values of the multi-layer board from plywood and cardboard; 2.7 times higher than the values of the five-layer board from EPS, MDF with 4 mm thickness and face layer from HPL; 3.0 times higher in comparison with multi-layer board from three-layer corrugated cardboard and face layer from HPL (Jivkov *et al*., 2012). The same trend was observed for *MOR* values.

The TS/24h values of the laminated lightweight WPC boards (Figure 7) were reduced by 1.06-1.13 times compared to the values of non-laminated boards. The HPL has high water resistance and prevents water absorption by surface layers of WPC boards. Accordingly, it leads to the decrease of the thickness swelling of boards. However, it is well known that wood composites absorb liquid water to a much greater degree through the swollen edge than through the surface of boards. That is why the lamination of boards has not such significant effect on water resistance when compared to mechanical properties.

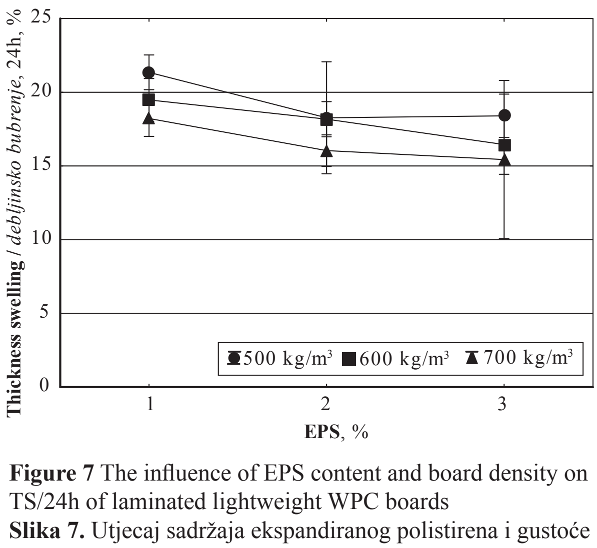


Figure 7 The influence of EPS content and board density on TS/24h of laminated lightweight WPC boards
Slika 7. Utjecaj sadržaja ekspandiranog polistirena i gustoće laminiranih laganih WPC ploča na debljinsko bubrenje nakon 24 h

It should be noted that *MOR* and *MOE* values of the investigated laminated WPC boards with 2 % content of EPS practically meet the requirements of ISO EN 13894-2 (2005). However, TS/24h values of the boards with the same EPS content do not comply with the requirements of this standard, being higher than 15 %. Laminated lightweight WPC boards meet TS/24h requirements according to this standard only for 3 % EPS content and board density of 700 kg/m³. According to ISO EN 13894-2 (2005), particleboards should be laminated by HPL with the thickness of 0.7 mm and bonded by UF resins. The thickness of HPL and type of resin have significant effect on the properties of boards. Moreover, the use of UF resins leads to the increase of formaldehyde emission, whereas the investigated lightweight WPC boards could be classified as E1 class according to EN 13986 (2015) without any testing. Therefore, the lightweight WPC boards made in the experiment are intended to substitute the traditional wood-based composites used in the furniture industry and door production.

4 CONCLUSIONS
4. ZAKLJUČAK

The outcome of this research demonstrates the possibility to manufacture lightweight wood plastic composites within the density range of 500-700 kg/m³ by flat pressing using expanded polystyrene. The EPS content, board density and lamination of lightweight WPC significantly influenced the board properties. The results of research have shown that the bending strength, modulus of elasticity and internal bond strength of non-laminated lightweight WPC boards meets the requirements (for lightweight particleboards) of EN 16368 (type LP1) and ANSI A208.1 (types LD-1 and LD-2). The values of bending strength and modulus of elasticity of the laminated lightweight WPC boards with 2 % content of EPS practically meet the requirements of ISO 13894-2. Moreover, the lightweight WPC boards made in the experiment could also be classified as E1 class according to EN 13986. Therefore, these lightweight WPC boards are intended as a possible substitute for traditional wood-based composites used in the furniture industry and door production. To increase the applications of lightweight WPC, future work is highly recommended to investigate the face and edge screw withdrawal resistance and the impact of various materials and processing factors on WPC performance.

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Physical and Mechanical Properties of Hornbeam Wood from Dominant and Suppressed Trees

Fizikalna i mehanička svojstva drva graba dominantnih i potisnutih stabala

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ABSTRACT • *Physical and mechanical properties are important factors in determining the suitability and application of wood material. This study aimed to investigate physical and mechanical properties of hornbeam wood (Carpinus betulus L.) in dominant and suppressed trees. Disks and logs of wood were cut at breast height to examine physical properties (oven-dried density, basic density, longitudinal shrinkage, tangential shrinkage, radial shrinkage, and volumetric shrinkage) and mechanical properties (static bending, compression strength parallel to the grain, compression perpendicular to the grain and hardness). T-test analysis indicated that forest mass (dominant-suppressed trees) affected the mechanical properties significantly (except modulus of elasticity). No significant difference was found between dominant and suppressed trees in terms of physical properties. MOE and MOR are higher in suppressed trees than in dominant trees. The average values of compression strength parallel to the grain, compression strength perpendicular to the grain and hardness of hornbeam wood were higher in the dominant trees than in the suppressed stands. In terms of mechanical properties of hornbeam wood in suppressed and dominant trees, the quality of wood is fair.*

Keywords: *suppressed trees, dominant trees, hornbeam, physical properties, mechanical properties*

SAŽETAK • *Fizikalna i mehanička svojstva važni su čimbenici pri određivanju prikladnosti i primjene drvnog materijala. Ova je studija usmjerena na istraživanje fizikalnih i mehaničkih svojstava drva graba (Carpinus betulus L.) dominantnih i potisnutih stabala. Diskovi i uzorci drva izrezani su na prsnoj visini stabla kako bi se odredila fizikalna svojstva (gustoća apsolutno suhog drva, nominalna gustoća drva, uzdužno utezanje, tangencijalno utezanje te radijalno i volumno utezanje) i mehanička svojstva (statičko savijanje, tlačna čvrstoća paralelno s vlakancima, tlačna čvrstoća okomito na vlakanca i tvrdoća). Analiza statističkim T-testom pokazala je da je šumska biomasa dominantnih i potisnutih stabala značajno utjecala na mehanička svojstva drva graba (osim na modul elastičnosti). Međutim, nije zabilježena značajna razlika u fizikalnim svojstvima drva dominantnih i potisnutih stabala. Dobivene vrijednosti MOE i MOR za drvo potisnutih stabala veće su od vrijednosti dobivenih za drvo dominantnih stabala. Prosječne vrijednosti tlačne čvrstoće paralelno s vlakancima, tlačne čvrstoće okomito na vlakanca i tvrdoće grabova drva dominantnih stabala bile su veće u usporedbi s drvom stabala iz potisnutih sastojina. Prema dobivenim vrijednostima mehaničkih svojstava drva može se zaključiti da je drvo graba i dominantnih i potisnutih stabala prosječne kvalitete.*

Ključne riječi: *potisnuta stabla, dominantna stabla, grab, fizikalna svojstva, mehanička svojstva*

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1. INTRODUCTION
1. UVOD

The genus *Carpinus*, belonging to the Betulaceae family, comprises approximately 35 woody species. It occurs widely in Europe, Eastern Asia and North and Central America. Hornbeam is a native, diffuse-porous hardwood species in the Caspian forests; it grows in mixed stands with oak and beech and in some areas with *Parrotia persica* (Sabeti, 2008). It prefers a warm climate for good growth and is usually found at elevations up to 1000 m a.s.l. (Kiaei, 2012; Parsapajouh, 1998). Hornbeam has the maximum fiber length among Iranian hardwood species, which is suitable for papermaking industries. According to Garmaroody *et al*. (2012) and Gunduz *et al*. (2009), *Carpinus betulus* L. has a low resistance to insects and fungi.

Because of different lighting needs, reducing competition among trees, and different soil needs, mixed stands are better than pure stands. There are many reports about wood properties and growth of dominant and suppressed hardwood species in Northern Iran. In this direction, Rouhi-Moghaddam *et al.,* (2009) reported that better results were achieved for oak trees in mixed plantations with hornbeam (based on survival, diameter at breast height and H/D ratio) and Siberian elm (based on total height and pruning height), while pure plantations and the plantations mixed with maple showed unsuitable results. Sayad *et al.,* (2006) indicated in a study entitled "Growth and qualitative properties in pure and mixed plantations of *Populus deltoides"* that poplar trees in mixed plantations had higher diameter at breast height and total height than in pure stands. Jalali *et al.,* (2003) reported that wood density, lignin and extractives contents in mixed plantations of poplar trees were higher than in pure plantations. Also, pure plantations had high cavity diameter and high cellulose content compared to mixed plantations. Kabiri *et al.* (2009) indicated that the trees heights and trunks length in pure beech stands were significantly higher than in mixed stands.

There are few studies about trees growth in suppressed and dominant stands, such as the studies of Kozlowski and Peterson (1962) and Rathgeber *et al*., (2011). They reported that dominant trees, which started growing earlier, grew faster, and had a longer growing season than suppressed trees. So far, there has been no information about the variation of wood properties of suppressed and dominant horn beam trees. Therefore, the objectives of this research were: a) to examine physical and mechanical properties of hornbeam wood (*Carpinus betulus* L.) in dominant and suppressed trees and b) to investigate wood quality according to mechanical properties of hornbeam wood in dominant and suppressed stands.

2 MATERIALS AND METHODS
2. MATERIJAL I METODE

In this research, 6 samples were randomly selected from dominant (3 trees) and suppressed (3 trees) hornbeam (*Carpinus betulus* L.) trees with straight stem and with no obvious signs of decay from a natural forest at the Behshahr-Mazandran site located in the north of Iran (Table 1). The annual rainfall and average annual temperature in Behshahr site were 480.3 mm and 13.1°C. Suppressed hornbeam trees were mixed with Iron (*Parrotia persica*), and hornbeam dominant trees were mixed with beech (*Fagus orientalis*). The hornbeam trees growing with beech and Persian iron trees were suppressed trees and dominant trees, respectively. From each of these trees, a log (6 logs in total) 200 cm in length was cut out at breast height to determine physical and mechanical properties. Mechanical and physical properties were determined and evaluated for mature wood only, as it is more stable than juvenile wood regarding mechanical properties (Figure 1). Previous researches claimed that the age demarcation point between juvenile and mature wood is estimated at round 18 years old (from ring 18 onwards; Makhmalbaf *et al*., 2007).

2.1 Physical properties
2.1. Fizikalna svojstva

In order to determine the physical properties, such as density and shrinkage, samples with dimensions of 25 mm (long) and 20 mm × 20 mm (transverse dimensions) were prepared according to ISO-3131 and ISO-4858 (referring to ISO 4469). Then the dimensions of 50 wood specimens (for each physical property) in all 3 directions were calculated and the weights of samples were measured in the first step. In the second step, the specimens

Table 1 Characteristics of the test and trees at the Behshahr site
Tablica 1. Podatci o istraživanju stabala iz područja Behshahr

Properties *Obilježje*	Suppressed trees *Potisnuta stabla*	Dominant trees *Dominantna stabla*
Stands / *Sastojina*	Mixed (hornbeam-beech) *Mješovita (grab - bukva)*	Mixed (hornbeam-Iron) *Mješovita (grab - perzijska parocija)*
Altitude, m / *nadmorska visina,* m	715	625
Number of trees / *broj stabala*	3	3
Tree age, year / *starost stabala,* god.	60	58
Tree height* / *visina stabala*	19.4	20.6
Bark, %* / *kora,* %	7.1	5.6
Wood, %* / *drvo,* %	92.9	94.4
Annual ring width, mm* / *širina goda*, mm	3.1	2.4

* These values are average for all selected trees. / *U tablici su navedene prosječne vrijednosti za izabrana stabla.*

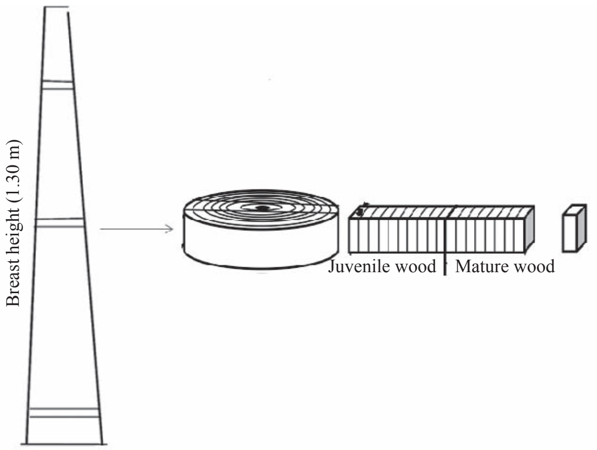

Figure 1 Sawing pattern used on each stem section for the analysis of physical and mechanical wood properties
Slika 1. Prikaz mjesta uzimanja uzoraka sa stabla za analizu fizikalnih i mehaničkih svojstava drva

were placed in distilled water for 72 hours to ensure that moisture content was above the fiber saturation point. Then the dimensions in all 3 principal directions were measured with a digital caliper to the nearest 0.001 mm. Samples were weighed to the nearest 0.001 g for saturated weight, and the saturated volume was calculated based on these dimensions. In the third stage, the samples were placed in an oven for 72 h, at 103 ± 2 °C, until the samples dried completely. The volume and weight of the samples were measured in absolutely dry state. The samples were again weighed and the dimensions in all 3 directions were measured. Finally, wood basic density, oven-dry density, longitudinal shrinkage, radial shrinkage, and tangential shrinkage were calculated by specific formulas. The physical properties of the wood measured were basic density (oven-dry weight / saturated volume) and oven-dry density (oven-dry weight / oven-dry volume). Dimensional differences of the samples were used to estimate longitudinal (L), radial (R), tangential (T) and volumetric shrinkage (V) [(saturated - oven-dry dimension)/saturated dimension] x 100.

2.2 Mechanical properties
2.2. Mehanička svojstva

The mechanical properties of 30 specimens (for each mechanical property) were determined in accordance with ASTM D 143-94 (2000). Regarding this standard, the sample dimensions were 25 × 25 × 410 mm for static bending strength tests (to determine modulus of rupture and modulus of elasticity), 25 × 25 × 100 mm for compression parallel to the grain, and 50 × 50 × 150 mm for compression perpendicular to the grain and hardness. The samples were conditioned at a temperature of 20 °C and 65 ± 5 % relative humidity and they reached equilibrium moisture content of about 12 % (Kiaei, 2013). Then, the wood density was based on the ratio of weight to volume at 12 % moisture content. Four mechanical qualities were determined by the following formulas (Korkut and Guller, 2008; Bektas *et al*., 2002; Parsapajouh, 1998):

$$SQV = \frac{CPG}{100 \cdot D_{12}} \quad (1)$$

$$SBI = \frac{MOR}{100 \cdot D_{12}} \quad (2)$$

$$SQ = \frac{MOR}{CPG} \quad (3)$$

$$q = \frac{CPG}{D_0} \quad (4)$$

Where, *CPG* is compression parallel to grain, *MOR* is modulus of rupture, D_0 is oven-dried density, *SQV* is static quality value, *SBI* is static bending index, *SQ* is Strong quotation, D_{12} is density at 12 % moisture content.

2.3 Statistical analysis
2.3. Statistička analiza

The influence of suppressed-dominant trees on physical and mechanical properties of hornbeam wood at Behshahr-Mazandran site was analyzed by T-test (SPSS statistical software, IBM software, Armonk, New York; Version 20).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Physical properties
3.1. Fizikalna svojstva

3.1.1 Oven-dry density
3.1.1. Gustoća apsolutno suhoga drva

T-test analysis indicated that the effect of suppressed-dominant trees on oven-dry density was not significant. The average oven-dry density of hornbeam wood in suppressed and dominant trees was 750 and 740 kg/m³, respectively. The average value of hornbeam wood in suppressed trees is slightly higher than in dominant tress (Table 2). The mean oven-dry density

Table 2 Physical properties of hornbeam wood
Tablica 2. Fizikalna svojstva drva grabovine

Physical properties *Fizikalna svojstva*	**Suppressed** *Potisnuta stabla*	**Dominant** *Dominantna stabla*
Oven-dry density / *gustoća apsolutno suhoga drva, kg/m³*	750 a	740 a
Basic density / *nominalna gustoća drva, kg/m³*	620 a	620 a
Density at 12 % moisture content / *gustoća drva pri 12 % sadržaja vode, kg/m³*	790 a	790 a
Lognitudinal shrinkage / *uzdužno utezanje, %*	0.60 a	0.60 a
Radial shrinkage / *radijalno utezanje, %*	6.80 a	6.70 a
Tangential shrinkage / *tangencijalno utezanje, %*	11.85 a	12.95 a
Volumetric shrinkage / *volumno utezanje, %*	19.30 a	20.30 a

in suppressed and dominant trees is higher than in other sites in Iran such as Golestan (Golbabeai *et al.*, 2004), Veysar-Mazandran (Hossinzade *et al.*, 2000), Sangedeh-Sari (Nasernakheai *et al.*, 1997) and Asalom Guilan (intermediate and low altitudes- Golbabeai et al., 2001), and lower than in high altitude of Asalom Guilan site (Golbabeai *et al.*, 2001). The average wood density of Turkish hornbeam wood is the same (Gunduz *et al.*, 2009; Table 3).

3.1.2 Basic density
3.1.2. Nominalna gustoća drva

T-test analysis indicated that the effect of suppressed-dominant trees on the basic density of hornbeam wood was not significant. The average basic density of hornbeam wood in both suppressed and dominant trees was 620 kg/m^3. The average basic density of hornbeam wood is the same in suppressed and dominant trees (Table 2).

3.1.3 Density at 12 % moisture content
3.1.3. Gustoća drva pri 12 % sadržaja vode

T-test analysis indicated that the effect of suppressed-dominant trees on wood density was not significant. The average MOR in suppressed and dominant trees was 790 kg/m^3. This average is the same in suppressed and dominant trees (Table 2).

3.1.4 Longitudinal shrinkage
3.1.4. Uzdužno utezanje

T-test analysis indicated that the effect of suppressed-dominant trees on longitudinal shrinkage was not significant. The average longitudinal shrinkage of hornbeam wood in suppressed and dominant trees was 0.6 %. The average longitudinal shrinkage of hornbeam wood is the same in suppressed and dominant trees (Table 2).

3.1.5 Radial shrinkage
3.1.5. Radijalno utezanje

T-test analysis indicated that the effect of suppressed-dominant trees on radial shrinkage of hornbeam wood was not significant. The average radial shrinkage of hornbeam wood in suppressed and dominant trees was 6.80 and 6.70 %, respectively. This average radial shrinkage of hornbeam wood is lower in suppressed trees than in dominant tress (Table 2).

3.1.6 Tangential shrinkage
3.1.6. Tangencijalno utezanje

T-test analysis indicated that the effect of suppressed-dominant trees on tangential shrinkage of hornbeam wood was not significant. The average tangential shrinkage of hornbeam wood in suppressed and dominant trees was 11.85 and 12.95 %, respectively. This average tangential shrinkage is lower in suppressed trees than in dominant tress (Table 2).

3.1.7 Volumetric shrinkage
3.1.7. Volumno utezanje

T-test analysis indicated that the effect of suppressed-dominant trees on volumetric shrinkage of hornbeam wood was not significant. The average volumetric shrinkage of hornbeam wood in suppressed and dominant trees was 19.30 and 20.30 %, respectively. This average volumetric shrinkage is lower in suppressed trees than in dominant tress (Table 2).

There are three classifications (Parsapajouh, 1998) according to volumetric shrinkage, low (until 15 %), median (15-20 %) and high shrinkage (above 20 %). Therefore, the volumetric shrinkage of hornbeam in suppressed and dominant trees falls under the second and third category. According to the results, hornbeam wood has a high volumetric shrinkage, which can be considered as a disadvantage of hornbeam wood.

3.2 Mechanical properties
3.2. Mehanička svojstva

3.2.1 Modulus of rupture (MOR)
3.2.1. Čvrstoća loma (MOR)

T-test analysis indicated that the effect of suppressed-dominant trees on the MOR of hornbeam wood was significant. The averag MOR in suppressed and dominant trees was 153.5 and 140.9 MPa, respec-

Table 3 Comparison of wood properties of Behshahr site (this study) with other sites
Tablica 3. Usporedba svojstava drva iz područja Behshahr sa svojstvima drva iz drugih sastojina

Site / *Područje*		A	B	C	D	E	F	G
Aslom Guilan	High altitude / *viša nadmorska visina*	790	-	-	-	-	-	-
	Intermediate / *srednja n. v.*	730	130.52	15.60	41.36	-	-	-
	Low / *niža n. v.*	700	-	-	-	-	-	-
Golestan	High altitude / *viša nadmorska visina*	723	104.1	10.51	63.27	-	-	12.30
	Intermediate / *srednja n. v.*	711	116.26	11.74	70.63	-	-	13.75
Veysar-Mazandran		736	101.47	14.44	38.75	-	-	-
Sangedeh-Sari- Mazandran		706	-	-	-	-	-	-
Supressed trees (present study) *potisnuta stabla (rezultati ovih istraživanja)*		750	153.5	14.76	63.2	91.8	75	9.7
Dominant trees (present study) *dominantna stabla (rezultati ovih istraživanja)*		740	140.9	14.70	64.5	97.8	84.1	11.50
Turkey		794	-	-	72.29	83.09	45.27	-

A - oven-dry density / *gustoća apsolutno suhog drva*, kg/m^3; B - Modulus of Rupture (*MOR*) / *čvrstoća loma*, MPa; C - Modulus of Elasticity (*MOE*) / *modul elastičnosti*, GPa; D - Compression parallel to grain / *tlačna čvrstoća paralelno s vlakancima*, MPa; E - cross-section hardness / *tvrdoća na poprečnom presjeku*, MPa; F - radial hardness / *tvrdoća na radijalnom presjeku*, MPa; G - compression perpendicular to grain / *tlačna čvrstoća okomito na vlakanca*, MPa

Table 4 Mechanical properties of hornbeam wood
Tablica 4. Mehanička svojstva drva graba

Mechanical properties *Mehanička svojstva*	**Suppressed** *Potisnuta stabla*	**Dominant** *Dominantna stabla*
MOR, MPa	153.5 b	140.9 a
MOE, GPa	14.76 a	14.70 a
Compression strength parallel to grain, MPa *Tlačna čvrsto*ća para*lelno s vlakancima*, MPa	63.20 a	64.5 b
Compression strength perpendicular to grain, MPa *Tlačna čvrstoća okomito na vlakanca*, MPa	9.70 a	11.5 b
Hardness in cross-section, MPa / *Tvrdoća na poprečnom presjeku*, MPa	91.8 a	97.8 b
Hardness in radial-section, MPa / *Tvrdoća na radijalnom presjeku*, MPa	75 a	84.1 b

tively. The average MOR is higher in suppressed trees than in dominant tress (Table 4). The mean MOR in suppressed and dominant trees is higher than in other sites in Iran such as Golestan (Golbabaei *et al.*, 2004), Veysar-Mazandran (Hossinzade *et al.*, 2000), and Asalom Guilan (Golbabeai *et al.*, 2001) (Table 3).

3.2.2 Modulus of elasticity (MOE)
3.2.2. Modul elastičnosti (MOE)

T-test analysis indicated that the effect of suppressed-dominant trees on the MOE was not significant. The average MOE in suppressed and dominant trees was 14.76 and 14.70 GPa, respectively. This average MOE is higher in suppressed trees than in dominant tress (Table 4). The mean MOE of hornbeam wood in suppressed and dominant trees is higher than in Golestan site (Golbabaei *et al.*, 2004), lower than in Asalom Guilan site (Golbabaei et al., 2001) and similar to Veysar-Mazandran site (Hossinzade *et al.*, 2000; Table 3).

3.2.3 Compression parallel to the grain
3.2.3. Tlačna čvrstoća paralelno s vlakancima

T-test analysis indicated that the effect of suppressed-dominant trees on the compression parallel to the grain of hornbeam wood was significant. The average compression parallel to the grain in suppressed and dominant trees was 63.20 and 64.50 MPa, respectively. This average is lower in suppressed trees than in dominant tress (Table 4). The mean compression parallel to the grain in suppressed and dominant trees is higher than in other sites in Iran such as Veysar-Mazandran (Hossinzade *et al.*, 2000), and Asalom Guilan (Golbabaei et al., 2001) sites, lower than Golestan (Golbabaei et al., 2004 - intermediate altitude) and Turkish sites (Gunduz *et al.*, 2009), and similar to Golestan site (high altitude, Golbabaei *et al.*, 2004; Table 3).

3.2.4 Compression strength perpendicular to the grain
3.2.4. Tlačna čvrstoća okomito na vlakanca

T-test analysis indicated that the effect of suppressed-dominant trees on the compression perpendicular to the grain of hornbeam wood was significant. The average compression perpendicular to the grain in suppressed and dominant trees was 9.70 and 11.50 MPa, respectively (Table 4). This average of hornbeam wood is lower in suppressed trees than in dominant tress. The mean compression perpendicular to the grain in suppressed and dominant trees is lower than in Golestan (Golbabaei *et al.*, 2004, high and intermediate altitude; Table 3).

3.2.5 Cross section hardness
3.2.5. Tvrdoća na poprečnom presjeku

T-test analysis indicated that the effect of suppressed-dominant trees on the hardness of hornbeam wood in cross-section was significant. The average hardness in cross-section in suppressed and dominant trees was 91.8 and 97.8 MPa, respectively. This average is lower in suppressed trees than in dominant tress (Table 4). The average hardness (cross-section) is higher than that of Turkish hornbeam wood (Gunduz *et al.*, 2009; Table 3).

3.2.6 Radial hardness
3.2.6. Tvrdoća na radijalnom presjeku

T-test analysis indicated that the effect of forestry mass on the hardness in radial section of hornbeam wood was significant. The average hardness in radial-section in suppressed and dominant trees was 75 and 84.1 MPa, respectively. This average is lower in suppressed trees than in dominant tress (Table 4). The average hardness (radial section) is higher than that of Turkish hornbeam wood (Gunduz *et al.*, 2009; Table 3).

3.3 Wood mechanical quality
3.3. Klasifikacija mehaničke kvalitete drva

According to the static quality index (SQV), wood quality can be classified as low, fair and good (Bektas *et al.*, 2002; Korkut and Guller, 2008). In this case, SQV<7 is low quality, 7< SQV <8.5 is fair quality, and 8.5<SQV is good quality. Static quality index in dominant trees was 8.32, and in suppressed trees it was 8.26. This index is higher in dominant trees than in suppressed trees. According to this classification, the Iranian hornbeam wood in suppressed and dominant trees falls under the second category (fair category).

According to the static bending index (Parsapajouh, 1998), wood quality can be classified as weak index (between 10 and 15), fair index (between 15 and 20) and resistance index (between 20 and 25). This index in suppressed and dominant trees was 20 and 18.18. According to this classification, the Iranian hornbeam wood in suppressed and dominant trees falls under the second category (fair quality). This index is lower in dominant trees than in suppressed trees.

According to the strong quotation (Parsapajouh, 1998), wood quality can be classified as low tolerance (less than 2), fair (between 2 and 3) and resistance index (between 3 and 4). This index in suppressed and dominant trees was 2.42 and 2.18, respectively. This index is lower in dominant trees than in suppressed trees. According to this classification, the Iranian hornbeam wood in suppressed and dominant trees falls under the second category (fair quality index).

Another classification according to the strong quotation was reported by Bektas *et al.*, (2002) and Korkut and Guller, (2008). They reported that for an ordinary wood species, according to the strong quotation value, the ratio between static bending strength and compression strength is considered to be 1.75. In the present study, it was found that the calculated index for dominant and suppressed trees was higher than 1.75.

Another criterion for the evaluation of wood properties is the value of q, a ratio between compression strength and density (Korkut and Guller, 2008; Bektas *et al.*, 2002,). Each wood species has a specific q value but there is no adequate classification; nevertheless, this value is used to compare the wood with other non-wood materials and it is used in some calculations for industrial applications. According to this criterion, the q index in dominant and suppressed trees was 888 and 859, respectively. This index is higher for hornbeam wood from trees grown in dominant stands than hornbeam wood from trees grown in suppressed stands.

In mixed forests, suppressed trees had higher modulus of rupture (MOR) and modulus of elasticity (MOE) and lower compression parallel to the grain, compression perpendicular to the grain, impact strength and hardness (in cross-section and radial section) than dominant trees. In diffuse porous hardwood such as hornbeam, anatomical properties play an important role in the variation of mechanical properties. It is necessary to know its anatomical properties to predict the mechanical behavior of wood.

4 CONCLUSION
4. ZAKLJUČAK

In this study, differences between hornbeam wood from trees grown in dominant stands and hornbeam wood from trees grown in suppressed stands were investigated. The following conclusions were drawn from this research:

1- Statistical results indicated that there are significant differences in mechanical properties of hornbeam wood (except MOE) from trees grown in suppressed and dominant stands. Suppressed-dominant trees had no significant effects on physical properties of hornbeam wood.

2- The average MOE (about 0.4 %) and MOR (about 8.94 %) of hornbeam wood are higher in suppressed trees than in dominant trees. The averages of compression parallel to the grain (2.05 %), compression perpendicular to the grain (18.55 %), hardness in cross-section (6.53 %) and hardness in radial section (12.13 %) of hornbeam wood are higher in dominant trees than in suppressed trees.

3- According to mechanical indices, wood quality of hornbeam wood from trees grown in dominant stands and hornbeam wood from trees grown in suppressed stands was fair.

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Determinants of Job Satisfaction in the Spanish Wood and Paper Industries: A Comparative Study across Spain

Odrednice zadovoljstva poslom u španjolskoj drvnoj i papirnoj industriji: komparativna studija s tržištem rada u Španjolskoj

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ABSTRACT • *This paper analyses job satisfaction of a group of workers in the logging, wood and paper industries and results were compared with the entire Spanish labor market. Fourteen quantitative variables of job-related features were selected. For this purpose, data from the Quality of Labor Life Survey (Encuesta de calidad de vida en el trabajo – ECVT) administered by the Spanish Ministry of Employment and Social Security was used. The first objective was to find relationships between the 14 variables that were involved, and make associations and classifications between them via statistical methods. Secondly, the effects of six new variables that resulted from the above groups on a labor satisfaction variable were investigated. The analysis in both groups allowed a comparison to see if the conclusions were the same or different according to activity. In both cases, wage was one of the last factors that explained labor satisfaction, whereas motivation and personal development ranked first.*

Keywords: *job satisfaction, wood and paper industry, motivation, salary, personal development*

SAŽETAK • *U radu se analizira zadovoljstvo poslom skupine radnika u iskorištavanju šuma te u drvnoj i papirnoj industriji, a rezultati su uspoređeni s podatcima za cijelo tržište rada u Španjolskoj. Odabrano je 14 kvantitativnih varijabli vezanih za obilježja posla. Za tu namjenu korišteni su podatci iz Ankete o kvaliteti života na radu (Encuesta de calidad de vida en el Trabajo – ECVT) koje administrira španjolsko Ministarstvo zapošljavanja i socijalne sigurnosti. Prvi cilj istraživanja bio je pronaći povezanost između 14 varijabli uključenih u analizu te formirati skupine i provesti klasifikaciju među njima primjenom statističkih metoda. Drugi je cilj bio istražiti učinke šest novih varijabli nastalih od formiranih skupina varijabli zadovoljstva poslom. Analiza varijabli zado-*

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voljstva poslom u obje skupine podataka omogućuje usporedbu kako bi se vidjelo jesu li zaključci prema aktivnostima bili jednaki ili različiti. Analizom obiju skupina podataka dobiven je rezultat da je plaća jedan od posljednjih čimbenika koji utječu na zadovoljstvo poslom, a motivacija i osobni razvoj bili su na prvome mjestu.

Ključne riječi: *zadovoljstvo poslom, drvna i papirna industrija, motivacija, plaća, osobni razvoj*

1 INTRODUCTION
1. UVOD

The origin of the analysis of job satisfaction as an important variable in the study of human resources and organizational behavior arose from Hoppock, who wrote the book *Job Satisfaction* in 1935. This contribution attempted to demonstrate the relevance of job satisfaction and its positive effect on labor productivity. Job satisfaction can be studied from many different approaches and empirical models, and involves focusing on worker features, job circumstances or a combination of both. Job satisfaction is influenced by multiple variables, which all have different relevance.

The Van Der Meer and Wielers (2013) model studied job characteristics, motivation, and their effects on job satisfaction. Similarly, this study included, as independent variables, job-related features, because it was assumed that job-related features were the best for predicting job satisfaction (Sánchez-Sellero *et al.*, 2014). Other studies that support this theory are: Dueñas *et al.* (2010), who proposed the low explanatory power of personal variables on job satisfaction, and Robles-García *et al.* (2005), who showed that satisfaction was strongly associated with a positive valuation of job-related features.

Guest and Conway (2002) found a positive relationship between the organizational communication and concepts such as job satisfaction, organizational commitment, motivation, and the positive evaluation of employment relationships. Cequea and Núñez Bottini (2011) showed that productivity was affected by motivation, job satisfaction, participation, and labor climate, among others. Different studies proposed a complex relationship of psychosocial factors and motivation, not only with positive business outcomes through a better performance of workers (Grant and Sumanth, 2009), but also with workers' well-being (Rego *et al.*, 2009).

Some models developed by Cuadra-Peralta and Veloso-Besio (2010) and Bòria-Reverter *et al.* (2012) studied the relationship between the job environment and job satisfaction, including variables, such as job features, organizational climate, and social information, as the basic motivators of job satisfaction. Cuadra-Peralta and Veloso-Besio (2010) showed that a good working atmosphere was related to appropriate organizational functioning. Bòria-Reverter *et al.* (2012) analyzed the possible relations between salary, different intangible assets, and job satisfaction in organizations. Chiang Vega *et al.* (2010) reported that job satisfaction was important to organizational behavior. Job satisfaction and dissatisfaction were associated with organizational indicators, such as performance quality, *etc*. Judge *et al.* (2001) made a qualitative and quantitative review of the relationship between job satisfaction and job performance.

Job motivation is a personal stimulus that directs behavior, for better or for worse, in the workplace. Pérez (1997) studied different approaches around motivation and job satisfaction based on orientations, aspirations, and expectations of workers, from a historical-sociological perspective. Kanfer (1995) pointed out that motivation and performance had a reciprocal influence, because motivation can affect performance, and performance can affect motivation. Research results of Alnıaçık *et al.* (2012) showed that motivation had a positive correlation with organizational commitment and job satisfaction. A recent study by Shah *et al.* (2016) identified some of the factors that affected job motivation (adequate remuneration, good job environment, *etc.*).

"The model of job satisfaction determinants", proposed by Lawler (1973), focused on the relationship of "expectations-rewards" from different aspects of a job. The relationship between expectation and reward can lead to job satisfaction or dissatisfaction. This theory considered reward not only as an economic remuneration, but also as a wide range of results (recognition, promotion, valuation of superiors, *etc.*).

Petrescu and Simmons (2008) studied the relationship between human resources management and workers' satisfaction with remuneration. They focused on the impact of overall job satisfaction and satisfaction associated with pay. Singh and Loncar (2010) examined the relationship between satisfaction with wages, satisfaction with employment, and change of employment. The study results by Tremblay *et al.* (2012) demonstrated that family motivations and those related to professional development had a positive effect on satisfaction, and that the motivation to work towards good economic conditions was not enough. Casas *et al.* (2002) established that the salary was one of the most valued aspects of a job, and for these authors, stability in the workplace implied a positive relationship with job satisfaction as well as an organization commitment.

Organizations may be less motivated to provide good working conditions for temporary workers because they are not the organizational core. This understanding implies that their job satisfaction may be lower than that of permanent workers (Wagenaar *et al.* 2012). Sánchez-Sellero *et al.* (2017) studied the lack of job stability in the Spanish economic crisis that began in 2008, as well as the degree of job satisfaction of salaried workers. They found that temporary workers had lower levels of satisfaction than those with permanent contracts, although, from 2008, the satisfaction average increased slightly for both kinds of workers. This result was explained by the high unemployment rate. Thus, any employed worker was considered lucky to be employed and their level of demand for having a job decreased even if employed as a temporary employee.

According to Westover (2012), job satisfaction was a dynamic concept. In this sense, time and context were useful for a better examination and understanding of the main factors that affected job satisfaction. For this reason, this study proposed the analysis of job satisfaction in the forestry, wood, and paper industries, and compared the results with the Spanish national data.

In a study of job satisfaction, Erol (2016) stated that forestry workers had responsibilities, such as ecological management, sustainability, balance, and social responsibilities that demanded satisfaction, in addition to income generation. Moreover, the lack of motivation of young people to start a professional career in this sector was a threat to the future of the forestry sector. An additional paper about job satisfaction in furniture manufacturing companies was made by Lorincová *et al*. (2016a). Jelačić *et al.* (2010) and Lorincová *et al*. (2016b) conducted an analysis of the motivational factors in wood industry firms. Hitka *et al.* (2014) and Kropivšek *et al.* (2011) studied the impact of the economic crisis on the changes in job motivation within the wood industry.

One of the objectives of this paper is to analyze the current Spanish labor market, affected by a long-term economic crisis with high job destruction. It compared the data of the logging, wood, and paper industries with the Spanish national set to find the determinants that most notably influenced job satisfaction. This study considered *DScurrentjob* as the dependent variable, and a set of variables that measured the degree of subjective satisfaction with labor issues (motivation, activity, salary, *etc*.) as independent variables. Thus, this paper answered the following questions: What variables affected the degree of satisfaction with one's current job more than others? What was considered to be more important: degree of satisfaction with one's salary, degree of satisfaction with one's activity, or degree of satisfaction with the valuation by one's superiors?

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

This study used data from the 2010 Quality of Labor Life Survey (*Encuesta de calidad de vida en el trabajo* – ECVT), administered by the Spanish Ministry of Employment and Social Security (2010 is the last available data in 2017) (Spain). Our idea was to explain the degree of satisfaction with current work based on several independent variables.

The geographical scope of this survey was Spain as a whole country, except for the cities of Ceuta and Melilla. The population consisted of workers aged 16 years and over residing in family dwellings.

The ECVT sample was designed using stratified three-stage sampling. First, the data was collected only from workers employed in activities that corresponded to sections 02, 16, and 17 of the Clasificación Nacional de Actividades Económicas (National Classification of Economic Activities in 2009) (CNAE 2009); in other words, forestry and logging, wood and cork industry, (except furniture), straw, and plating and paper industry. The results were compared with the Spanish national set.

The ECVT sample included 8,061 people, out of 18,409,625 people of the whole Spanish population, but by eliminating the lack of response to some questions, it was narrowed down to 5,841 people. Once the cases were filtered and weighted corresponding to the logging, wood, and paper industries, they represented 136,153 workers.

2.2 Methods
2.2. Metode

Figure 1 describes the variables used. All of these variables have values from 0 to 10, where 0 presents a very low level of satisfaction, while 10 presents a high level of satisfaction (see Figure 1).

Job-related features were considered based on the type of contract, working day, hours worked, *etc*. Thus, the degree of satisfaction with salary could be considered a personal-related feature, because it depended on each person. For instance, two people could have different levels of satisfaction with salary even though they received the same salary. Age and gender were also usually considered personal-related features. They could be considered job-related features because they referred to a personal perception of job-related features such as salary, organization, activity, *etc*.

Principal component analysis and cluster analysis are methods of grouping variables. Principal component analysis (PCA) allows grouping of 14 independent variables into homogeneous groups, thus constructing new variables, with mean 0 and variance 1, as a result of previous groups. This method is used to transform a set of variables (interrelated original variables), in a set of variables, linear combination of the original, called principal components (or factors). So, principal component variables are typically uncorrelated with each other, and they can also be organized

Variable dependent {DScurrent job (0,10)

Variables independent
DSpromotionpossibilities (0,10)
DSbossvaluation (0,10)
DSactivity (0,10)
DSpersonaldevelopment (0,10)
DSautonomy (0,10))
DSdecisionparticipation (0,10)
DSmotivation (0,10)
DSworkday (0,10)
DSscheduleflexibility (0,10)
DSholidayspermission (0,10)
DSstability (0,10)
DSwage (0,10)
DSrelaxationtime (0,10)
DSjoborganization (0,10)

Figure 1 Descriptors of variables and scale (elaboration from the ECVT – Ministry of Employment and Social Security, 2010)
Slika 1. Opisnice varijabli i ljestvica (napravljeno na temelju ECVT-a – Ministarstvo zapošljavanja i socijalne sigurnosti, 2010.)

according to their own information. Dunteman (1989) proposes variance as a measure of the incorporated information in a component. This process can continue until there are as many components as variables. The first few principal components usually represent the biggest variation in variables.

A cluster analysis is a statistical method for dividing variables into groups based on their similarity (Bryant, 2000). This study attempted to find the greatest homogeneity in each group and the greatest heterogeneity between groups. Previously, the variables were typified to compare them, as suggested by previous literature. It was advised to perform a model with standardized variables (De la Fuente, 2011).

In order to obtain clusters in a hierarchical classification, groups are merged according to a priority or hierarchy and are based on distances between elements or variables. Hierarchical methods are agglomerative (ascending) if they successively merge larger groups in each step. As groups form, they are less homogeneous (the distances between initial groups are smaller than between final groups). The Ward method minimizes intra-group variation. This is one of the most used grouping methods. The representation of the hierarchy of groups is usually done through a diagram called "dendrogram". It reports successive mergers of groups into groups of higher level with higher and lower homogeneity. Variables are represented on vertical axis and distances on horizontal axis.

This study used the stepwise multiple linear regression method, a method also studied by Derksen and Keselman (1992) and Thompson (2001), among others. The method organized variables in a hierarchy, trying to know the relevant variables in a lot of possible independent variables. The stepwise regression with the extracted factors (new variables) of the principal component analysis (PCA) was performed. The models were improved by incorporating factors, as the sum of squares of the regression increases in different steps, while the sum of squared residuals decreases.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Table 1 shows the means of 15 variables mentioned (a dependent variable and 14 independent variables). The degree of satisfaction with salary, *DSwage*, was the second variable with the lowest mean, because of the effect of the Spanish economic crisis. *DSpromotionpossibilities* was the variable that produced less satisfaction in the logging, wood and paper industries as a national set.

3.1 Hypothesis 1: Job-related variables having influence on job satisfaction were classified in homogeneous groups
3.1. Hipoteza 1: Varijable povezane s poslom koje su utjecale na zadovoljstvo radnika poslom klasificirane su u homogene grupe

To test Hypothesis 1, this study included only job-related variables because they better explained job satisfaction. First, groupings were made between related variables. A principal component analysis (PCA) was used to group independent variables in homogeneous groups, and new variables from the previous groupings were constructed, with a mean of 0 and a variance of 1.

Table 1 Descriptive statistics and variations with respect to the national set (job-related variables)
Tablica 1. Deskriptivna statistika i varijacije u odnosu prema nacionalom skupu podataka (varijable vezane za posao)

Variables *Varijable*	**Logging Wood industry Paper industry** *Radnici u iskorištavanju šuma, drvnoj i papirnoj industriji*		**Spanish population** *Španjolsko stanovništvo*		**Increments or decreases compared with the national mean** *Povećanje ili smanjenje u usporedbi s nacionalnim prosjekom*
	Mean *Srednja vrijednost*	Standard Deviation *Standardna devijacija*	Mean *Srednja vrijednost*	Standard Deviation *Standardna devijacija*	
DScurrentjob	7.6	1.45601	7.4	1.81885	(+)
DSpromotionpossibilities	5.3	3.46425	5.2	3.19625	(+)
DSbossvaluation	7.7	1.53162	7.2	2.18227	(+)
DSactivity	7.8	1.42380	7.8	1.78792	(=)
DSpersonaldevelopment	7.6	1.90947	7.6	1.98172	(=)
DSautonomy	7.3	2.10119	7.5	2.22668	(-)
DSdecisionparticipations	6.5	2.67007	6.9	2.62675	(-)
DSmotivation	6.9	2.43171	7.2	2.32801	(-)
DSworkday	7.6	1.60609	7.1	2.34677	(+)
DSscheduleflexibility	6.6	3.17289	6.5	3.09382	(+)
DSholidays.permissions	7.5	2.51057	7.1	2.69060	(+)
DSstability	6.9	2.71186	7.1	2.75592	(-)
DSwage	6.2	2.36568	5.8	2.41210	(+)
DSrelaxationtime	6.5	2.78229	6.7	2.63654	(-)
DSjoborganization	7.4	1.76960	7.1	2.19004	(+)

*Note: the dependent variable was *DScurrentjob*; (elaboration from the ECVT - Ministry of Employment and Social Security, 2010) / *Zavisna varijabla bila je DScurrentjob (napravljeno na temelju ECVT-a - Ministarstvo zapošljavanja i socijalne sigurnosti, 2010.)*

Table 2 Matrix of Rotated Components[a] (Data from the Logging, Wood, and Paper Industries)
Tablica 2. Matrica rotirajućih komponenti[a] (podatci za iskorištavanje **šuma**, drvnu i papirnu industriju)

Variables *Varijable*	**Component** / *Komponenta*					
	1	2	3	4	5	6
DSmotivation	**0.852**	0.126	0.085	-0.024	-0.031	0.001
DSjoborganization	**0.830**	0.130	-0.041	0.008	0.287	0.091
DSpersonaldevelopment	**0.562**	0.435	0.131	0.249	-0.511	0.134
DSbossvaluation	**0.534**	0.319	0.491	0.280	-0.142	0.175
DSautonomy	0.038	**0.917**	-0.013	0.096	-0.162	0.007
DSdecisionparticipations	0.276	**0.829**	-0.034	0.047	0.308	0.018
DSpromotionpossibilities	0.168	**0.607**	0.240	-0.023	-0.024	0.577
DSactivity	0.467	**0.600**	0.255	0.147	0.075	0.084
DSworkday	0.096	0.019	**0.845**	0.096	0.216	0.217
DSscheduleflexibility	0.280	0.419	**0.610**	0.256	-0.010	-0.277
DSholidays.permissions	-0.035	0.187	0.274	**0.855**	0.108	-0.198
DSstability	0.423	0.190	0.033	**0.745**	0.034	0.352
DSrelaxationtime	0.276	0.125	0.302	0.200	**0.804**	0.069
DSwage	0.507	0.138	0.122	0.015	0.062	**0.700**

Extraction method: Principal component analysis; Rotation method: Quartimax with Kaiser Normalization; [a]The rotation converged in six iterations (elaboration from the ECVT - Ministry of Employment and Social Security, 2010) /
Metoda izlučivanja: analiza glavne komponente; metoda rotacije: Quartimax s Kaiserovom normalizacijom; [a]rotacija se konvergira u šest *iteracija (napravljeno na temelju ECVT-a - Ministarstvo zapošljavanja i socijalne sigurnosti, 2010.)*

The determinant of the correlation matrix of variables was almost zero and the Kaiser-Meyer-Olkin (KMO) measure was higher than 0.500 (this was good). The Bartlett test had a *p*-value equal to zero and lower than 0.05, which allowed the rejection of the hypothesis of the identity matrix. A previous PCA study of job satisfaction was conducted by Platis *et al.* (2015) and Leung *et al.* (2015).

Six factors (new variables) were extracted through the Quartimax rotation system. This is an orthogonal alternative, which minimizes the number of factors needed to explain each variable. In addition, the coefficients were ordered by size. Thus, the percentage of explained variability by the extracted factors was 81 %. The matrix of rotated components is shown in Table 2. These factors had a mean of zero and a standard deviation of one, and they were uncorrelated with one another. *DSwage* was not grouped with any other variable. A high association was found between the initial variables, because the saturations were higher than 0.500.

These 14 variables were summarized into six new factors. Factor 1 was the degree of satisfaction with motivation, job organization, personal development, and superiors' valuation. Factor 2 included autonomy, participation in decisions, possibility of promotion, and activity. Factor 3 considered the working day and schedule flexibility. Factor 4 contained stability, holidays, and leaves; factor 5 considered rest time; and factor 6 considered salary. Sánchez-Sellero and Sánchez-Sellero (2016) performed the same study with the Spanish set. Some factors were the same, such as the factor for salary, another for holidays, leaves, and stability, and another for schedule flexibility, working day, and rest time. These variables were logically associated. The variable of holidays and leaves was grouped with stability because some unstable and short-term jobs did not generate vacation entitlement. However, the minimum number of items in each factor was to be three, which according to Costello and Osborne (2005), presents one of the requirements for "clean" factor structure (see both groups in Table 3).

Figure 2 shows a cluster analysis through a hierarchical cluster analysis and Ward's method applied to the data of the logging, wood, and paper industries. This study applied the same methodology with the data of the Spanish set in Fig. 2. Both figures (A and B) have more similarities than differences. Activity and personal development form one of the groups, and autonomy and participation in decisions form another. These two groups were the most homogeneous because the variables were the closest, *i.e.*, the distances were the smallest in the upper axis. The number of clusters can be counted with much subjectivity. In this case, 5 clusters (indicated on the left of the graph) were considered for the group of wood and paper industry, because the distances on the right of a hypothetical vertical line marked in Figure 2.A are much larger. It is difficult to name the clusters because in this case all variables are job-related features. Faletar *et al.* (2016) applied the same methodology in wood firms. Some other papers about satisfaction applied a cluster analysis, such as Błachnio *et al.* (2016) and Van Aerden *et al.* (2016). It should be noted that Van Aerden *et al.* (2016) used the data from the Quality of Labor Life Survey in European countries.

3.2 Hypothesis 2: Motivation, activity, and personal development were the most influential variables in job satisfaction
3.2. Hipoteza 2: Varijable motivacija, aktivnost i osobni razvoj najviše su utjecale na zadovoljstvo poslom

In addition, a stepwise regression with factors extracted from the principal component analysis (PCA) was applied to verify Hypothesis 2. Sánchez-Sellero and Sánchez-Sellero (2016) performed the same study with data from the Spanish set over a period of three years. A regression analysis performed

Table 3 Factors obtained from principal component analysis, variables in the logging, wood and paper industries compared with variables in the Spanish set
Tablica 3. Faktori dobiveni iz analize glavnih komponenata; usporedba skupa varijabli za iskorištavanje šuma, drvnu i papirnu industriju sa skupom varijabli za ukupno španjolsko tržište rada

	Variables: Logging, wood, and paper industries *Varijable: iskorištavanje* šuma*, drvna i papirna industrija*		**Variables: Spanish Set**[a] *Varijable: španjolski skup*
Factor 1	*DSmotivation* *DSjoborganization* *DSpersonaldevelopment* *DSbossvaluation*	Factor 1	*DSactivity* *DSpersonaldevelopment* *DSmotivation*
Factor 2	*DSautonomy* *DSdecisionparticipations* *DSpromotionpossibilities* *DSactivity*	Factor 2	*DSscheduleflexibility* *DSrelaxationtime* *DSworkday*
Less than three variables by each factor *manje od tri varijable za svaki faktor* ⬇		Factor 3	*DSpromotionpossibilities* *DSbossvaluation* *DSjoborganization*
Factor 3	*DSworkday* *DSscheduleflexibility*	Less than three variables by each factor *manje od tri varijable za svaki faktor* ⬇	
Factor 4	*DSholidays.permissions* *DSstability*	Factor 4	*DSstability* *DSholidays.permissions*
Factor 5	*DSrelaxationtime*	Factor 5	*DSdecisionparticipations* *DSautonomy*
Factor 6	*DSwage*	Factor 6	*DSwage*

[a] This column is the result of Sánchez-Sellero and Sánchez-Sellero (2016) / *Taj je stupac rezultat rada* Sánchez-*Sellero and Sánchez-Sellero (2016.)* (elaboration from the ECVT (Ministry of Employment and Social Security, 2010) / *(napravljeno na temelju ECVT-a - Ministarstvo zapošljavanja i socijalne sigurnosti, 2010.)*

through the factors extracted from a PCA can also be seen in Aizawa *et al.* (2015). This regression method was useful to explain a dependent variable (in this case *DScurrentjob*) from several potential independent variables (predictors) in the case that there was no theory that allowed the advance selection of a subset of predictors to evaluate the model. Thus, this study attempted to select a set of variables that contributed significantly (p-value < 0.01) to the model. Only variables that were significant predictors of job satisfaction were included. The same methodology was applied to the job field by Senise Barrio and Lloréns Montes (1996), and García Sedeño *et al.* (2003), among others. Goetz *et al.* (2015) proposed a stepwise regression model in the field of job satisfaction, although with different variables.

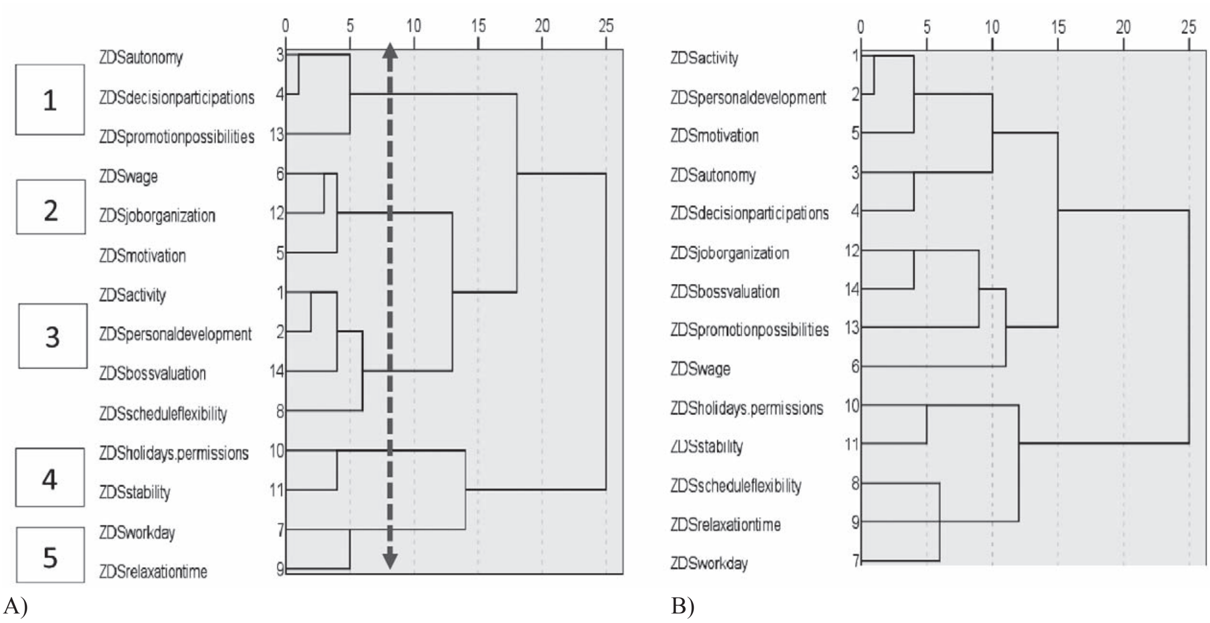

Figure 2 A) Dendrogram using Ward's Linkage, a group combination of rescaled distance (Data from the Logging, Wood, and Paper Industries); B) Dendrogram using Ward's linkage, group combination of rescaled distance (Data from the Spanish Set)
Slika 2. A) Dendrogram primjenom Wardove metode, kombinacije skupina na temelju izmjerene udaljenosti (podatci iz djelatnosti iskorištavanja šuma te drvne i papirne industrije); B) dendrogram primjenom Wardove metode, kombinacije skupina na temelju izmjerene udaljenosti (podatci iz nacionalne baze podataka)

Table 4 Summary of stepwise regression models obtained from the principal component analysis factors[g]
Tablica 4. Sažetak modela postupne regresije dobivenih od faktora analize glavnih komponenata

Logging, wood and paper industries / *Iskorištavanje* **šuma**, *drvna i papirna industrija*									
Model	R	R^2	Corrected R^2	Standard Deviation	Statistics of change / *Statistika promjene*				
					Change in R^2	Change in F	gl1	gl2	Significant change in F
1	**0.537[a]**	**0.288**	**0.288**	**1.16288**	**0.288**	**45152.693**	**1**	**111,566**	**0.000**
2	**0.691[b]**	**0.477**	**0.477**	**0.99691**	**0.189**	**40243.482**	**1**	**111,565**	**0.000**
Introducing the other factors / *Uvođenje novih faktora*									
3	0.705[c]	0.497	0.497	0.97749	0.020	4477.027	1	111,564	0.000
4	0.711[d]	0.506	0.506	0.96879	0.009	2014.616	1	111,563	0.000
5	0.713[e]	0.508	0.508	0.96707	0.002	397.211	1	111,562	0.000
6	0.713[f]	0.508	0.508	0.96698	0.000	22.610	1	111,561	0.000
Spanish Set / *Španjolska nacionalna baza podataka*									
Model	R	R^2	Corrected R^2	Standard deviation	Statistics of change / *Statistika promjene*				
					Change in R^2	Change in F	gl1	gl2	Significant Change in F
1	**0.615[a]**	**0.379**	**0.379**	**1.39223**	**0.379**	**8,356,032.222**	**1**	**13,701,262**	**0.000**
2	**0.687[b]**	**0.472**	**0.472**	**1.28406**	**0.093**	**2,405,825.898**	**1**	**13,701,261**	**0.000**
Introducing the other factors / *Uvođenje novih faktora*									
3	0.737[c]	0.543	0.543	1.19413	0.071	2,141,265.884	1	13,701,260	0.000
4	0.768[d]	0.589	0.589	1.13204	0.046	1,544,262.917	1	13,701,259	0.000
5	0.788[e]	0.621	0.621	1.08801	0.031	1,131,339.509	1	13,701,258	0.000
6	0.794[f]	0.630	0.630	1.07476	0.009	339,948.845	1	13,701,257	0.000

Logging, wood and paper industries: [a]Predictor variables: (Constant), factor 1; [b]Predictor variables: (Constant), factor 2 was added to the previous ones; [c]Predictor variables: (Constant), factor 4 was added to the previous ones; [d]Predictor variables: (Constant), factor 3 was added to the previous ones; [e]Predictor variables: (Constant), factor 5 was added to the previous ones; [f]Predictor variables: (Constant), factor 6 was added to the previous ones
Spanish Set: [a]Predictor variables: (Constant), factor 1; [b]Predictor variables: (Constant), factor 3 was added to the previous ones; [c]Predictor variables: (Constant), factor 2 was added to the previous ones; [d]Predictor variables: (Constant), factor 4 was added to the previous ones; [e]Predictor variables: (Constant), factor 6 was added to the previous ones; [f]Predictor variables: (Constant), factor 5 was added to the previous ones; [g]Dependent variable: *DScurrentjob*
(elaboration from ECVT – Ministry of Employment and Social Security, 2010)

This study included a variable into the model if the critical level associated with its partial correlation coefficient was less than 0.05 in an independent hypothesis (probability of entry), according to the stepwise method. The variable stayed out of the model if that critical level was greater than 0.10 (probability of exit). Table 4 shows a summary of the stepwise regression models derived from the PCA factors. It collected the R and R^2 in each step. The standard deviation decreased (1.16288 to 0.96698 with data from the logging, wood, and paper industries). One way to estimate the effect of applying these selection criteria was to observe the change in R^2 as variables were added to the model. A big change in R^2 indicated that this variable (in this case factor 1) contributed noticeably to explain the dependent variables. The F-statistic and its critical level contrasted the hypothesis that the change in R^2 was zero in the population. The six independent variables (the PCA factors) explained 50.8 % of the variable variance *DScurrentjob*. A model with all factors or only with factors formed by 3 or more variables can be proposed. It has been verified that the factors that contribute the highest percentage of explanation to *DScurrentjob* variable correspond to these first factors obtained from PCA analysis (see Table 4).

The model improved when the factors were introduced because the sum of squares of the regression increased, whereas the residual sum of squares decreased. Factor 1 had the greatest influence on job satisfaction in both data sets in the stepwise regression made with the above factors (Table 4). In terms of explanation degree, the wage factor (factor 6) was the last, or penultimate, in both models. Factor 1 was motivation, personal development, job organization, and superiors' valuation in the logging, wood, and paper industries, and it included motivation, personal development, and activity in the Spanish set.

These significant contributions to the literature were based on a cross-sectional study. Longitudinal studies can be carried out to more accurately describe the subject.

4 CONCLUSION
4. ZAKLJUČAK

This study contributed to the understanding of job satisfaction through a combination of different statistical methodologies and a comparative analysis of the results in the logging, wood, and paper industries and those in the national Spanish set, and explained the differences and similarities between them.

All in all, the degrees of satisfaction were high because all of them were in the range of six to seven points on a scale from zero to ten. The degree of satisfaction with salary was one of the variables valued low. The reason may be in the reduction of workers' salary during the Spanish economic crisis.

Workers in the logging, wood, and paper industries evaluated the lowest their satisfaction with the possibility of promotions, which was also a possible consequence of the Spanish economic crisis. Although recently there has been no survey, it is believed that satisfaction with wages and the possibility of promotions will recover as a result of the current economic recovery.

Many coincidences were found in the homogeneous groups of variables that affected the job satisfaction between the logging, wood, and paper industries and the Spanish set. These appeared in the following groups: motivation and personal development; stability, holidays, and autonomy; and participation in decisions. These groups were coherent in their explanation. Salary was included in a separate group.

A principal component analysis showed in both groups (the logging, wood, and paper industries and the Spanish set) that the group with the greatest influence on job satisfaction was motivation and personal development, whereas salary was the one with the lowest influence (explanation percent).

The stepwise regression shows the first factors obtained in PCA analysis, which explain better satisfaction with current work and contribute to the goodness of the model (the greater R-squared). The said first factors are formed by three or more variables. The other factors also explain this variable but in a smaller percentage. It should be noted that the hierarchy established in the PCA analysis is basically maintained in the stepwise regression, so that factor 1 (motivation-personal development) is consolidated as the first group of variables of greater relevance in the explanation of job satisfaction.

Based on this study, it can be concluded that behavioral patterns about job satisfaction in logging, wood, and paper industries, are very similar to the Spanish set and that job satisfaction is extremely important.

Previous literature considered that job satisfaction had a positive correlation with job performance. As a consequence, firms and institutions should try to improve the satisfaction of their workforce. Thus, workers need to be motivated to improve their satisfaction.

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The Effects of Press Method and Coating Material Differences on the Properties of Medium Density Fiberboard

Utjecaj metode prešanja i materijala za oblaganje na svojstva MDF ploča

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ABSTRACT • *This article deals with the effects of press method and coating material differences on some properties of medium density fiberboard (MDF) covered with PVC, which has an important place in furniture production materials. For this purpose, test samples were prepared from MDF with 18 mm thickness covered with high gloss (HG) and matt PVC using wrapping and membrane press methods. Apart from affecting the values of water absorption of HG covered samples and the values of thickness swelling of samples processed by membrane press, the test results showed a statistically significant effect of the pressing method and coating material on water absorption, thickness swelling, modulus of elasticity, bending strength and adhesion strength values in all other tests. At the same time, it was determined that samples covered with HG material received less water, while MDF samples covered with matt material had a low thickness swelling. Also, modulus of elasticity of the samples covered with matt material was much higher and adhesion strength of the HG covered samples was much better.*

Key words: *MDF, wrapping method, membrane method, high gloss PVC, mat PVC*

SAŽETAK • *U radu je prikazano istraživanje utjecaja različitih metoda prešanja i materijala za oblaganje na neka svojstva ploča vlaknatica srednje gustoće (MDF ploča) obloženih PVC folijom, koje imaju važno mjesto među materijalima za proizvodnju namještaja. Za tu su svrhu uz pomoć preše za oblaganje profila i membranske preše pripremljeni uzorci za ispitivanje izrađeni od MDF ploča debljine 18 mm i obloženi mat PVC folijom i PVC folijom visokog sjaja (HG). Osim za vrijednosti upijanja vode uzoraka obloženih PVC folijom visokog sjaja i vrijednosti debljinskog bubrenja uzoraka obloženih uz pomoć membranske preše, rezultati ispitivanja pokazali su statistički značajan utjecaj metoda prešanja i materijala za oblaganje na upijanje vode, debljinsko bubrenje, modul elastičnosti, čvrstoću savijanja i čvrstoću prianjanja u svim ostalim testovima. Ujedno je utvrđeno da su MDF uzorci obloženi HG folijom upili manju količinu vode, dok su MDF uzorci obloženi mat PVC folijom imali manje debljinsko bubrenje. Također, uzorci obloženi mat PVC folijom imali su mnogo veći modul elastičnosti, ali je čvrstoća prianjanja uzoraka obloženih HG folijom bila mnogo bolja.*

Ključne riječi: *MDF, metoda oblaganja profila, membranska metoda, PVC folija visokog sjaja, mat PVC folija*

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1 INTRODUCTION
1. UVOD

In recent years, forests have been increasingly disappearing and the quality lumbers obtained from trees and used in plywood and veneer industry are decreasing. Quality trees are decreasing while prices are increasing. Poor quality wood can be used in MDF production (Akgül and Çamlıbel, 2006).

Medium density fiberboard (MDF) panels are extensively used in furniture industry. MDF and other panel boards are produced as flat and homogenous surface. The panels have pointed surfaces with coating materials. These coated panels are used in laboratories paneling, kitchen furniture, and other industrial product applications. The performance of the coated panels is based on the type of the coating material and the quality of wood-based panel (Sparkes, 1993; Hoag, 1992).

Wood-based panels may be exposed to many destructive factors such as fungi, humidity, low and high environmental temperatures. To reduce the damage caused by these factors, wood based panels are coated with different materials and different coating methods according to conditions of use (Bozkurt and Göker, 1986; İstek *et al*., 2012).

Surface coating of composite boards (chipboard, MDF, plywood, etc.) is especially important to increase the aesthetic value and strength properties. In fact, the panels are coated to widen the range of application and improve their strength characteristics (Thoemen *et al*. 2010; İstek *et al*. 2010). Coating process can improve the surface quality of panels as well as color properties (Nemli, 2000). Performance of panel surface during the coating process is assessed by characteristics of wood species and manufacturing method (Cassens and Feist, 1991; Richter *et al*., 1995).

The aim of this study is to reveal the changes in MDF properties coated with different PVC folios by using membrane and wrapping press by different press methods.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

2.1 Material used in tests
2.1. Materijal uzoraka

Medium density fiberboards (MDF), with 18 mm thickness covered with 0.50 mm high gloss (HG) and 0.40 mm matt PVC (MT) using wrapping and membrane press methods in accordance with related standards, were used as a test material. HG and matt PVC grammage was 0.697 gr/cm^2 and 0.512 gr/cm^2, respectively.

2.2 Press methods used in experiments
2.2. Metode prešanja

Two methods used for coating the test specimens are briefly described below.

Wrapping press method (WP): With this method, straight and milled surfaces could be covered up to 0.15µm-0.50µm high gloss and matt PVC materials. Generally, hot-melt glues with double component polyurethane based are used as adhesive. Covering process within the wrapping method is carried out in this way. Firstly, glue melted in pressure tanks at 120-140ºC is spread on the back of the PVC, after being filtered. Later, with the help of the pressure, glued PVCs are adhered on the panel surface that comes from the coating machine feed track.

Membrane press method (MP): Generally, this method is used for covering MDFs. Firstly, single component polyurethane based glue is spread twice on MDF surface, and then dried. Later, the press process is carried out at the temperature of 55-80^{o}C and at the pressure of 6-14 atm for 5-10 minutes.

2.3 Experimental tests
2.3. Provedba eksperimenta

The standards for the procedures followed in the tests are summarized in Table 1. Additionally, tests were carried out on 30 samples prepared in accordance with the standards given in Table 1.

2.4 Statistical analyzes
2.4. Statistička analiza

The Independent Samples *T*-test was performed to determine the effect of press method and coating material differences on the properties of MDF samples.

3 RESULTS AND DISCUSSIONS
3. REZULTATI I RASPRAVA

The findings obtained in the tests were analyzed by grouping the results according to coating materials and press methods. They are evaluated below.

3.1 Water absorption (WA)
3.1. Upijanje vode (WA)

The analysis results of Independent Samples *T*-test after 24 h water absorption are given in Table 2.

The analysis of *T*-test results given in Table 2 showed that, as $p>0.05$, there is no significant difference in HG covered samples depending on different press methods, whereas, since $p<0.05$, there is a significant difference in matt folio covered samples. Water absorption value after 24h was higher in MDFs covered with matt material using WP than using MP.

Table 1 Standards used in tests
Tablica 1. Standardi prema kojima je provedeno istraživanje

Experimental tests / *Provedeni eksperiment*	**Standards** / *Standardi*
Water absorption and thickness swelling / *upijanje vode i debljinsko bubrenje*	TS EN 317
Static bending strength and Elastic modulus of bending *statička* čvrstoća *savijanja i modul elastičnosti pri savijanju*	TS EN 326-1, TS EN 310
Bonding strength / č*vrstoća prianjanja*	TS EN 311

Table 2 Results of *T*-test analysis of water absorption values
Tablica 2. Rezultati analize vrijednosti upijanja vode *T*-testom

Water absorption *Upijanje vode*			**Mean** *Prosječna vrijednost* %	**Stand. deviation** *Stand. devijacija*	**Stand. Error** *Stand. pogreška*	**Coefficient of variation** *Koeficijent varijacije*	t_{value}	**Sig. (2-tailed)**
Coating material *Materijal za oblaganje*	High gloss / *visoki sjaj* (HG)	WP	11.02	0.694	0.219	6.30	0.811	0.428
		MP	10.51	1.869	0.591	17.78		
	Matt / *mat* (MT)	WP	13.23	0.766	0.242	5.79	2.682	0.015
		MP	12.36	0.861	0.272	6.97		
Press method *Metoda prešanja*	Wrapping *oblaganje profila* (WP)	HG	11.02	0.694	0.219	6.30	6.752	0.000
		MT	13.23	0.766	0.242	5.79		
	Membrane *membransko prešanje* (MP)	HG	10.51	1.869	0.591	17.78	2.879	0.013
		MT	12.36	0.861	0.272	6.97		

The same table shows that water absorption values are lower in HG covered samples (11.02 % and 10.51 %) than in matt PVC covered ones (13.23 % and 12.36 %). The reason for this difference could be the result of different adhesive and PVC folios. Coating material thickness improved water absorption values as seen in Table 2. In a study conducted on particleboards, Nemli (2000) emphasized that the thickness of the coating material did not affect the water absorption values. However, these values were affected by the type of coating materials.

Considering Table 2 in terms of covering material, significant differences could be seen within the water absorption percentages at 999.9 % (p<0.001) confidence level of HG and matt PVC folios using WP and in MP covered samples at 95 % (p<0.05) confidence level. Özdemir *et al*. (1999) determined that the particle board surfaces coated with varnished veneer, lacquer coating, continuous pressure laminate, high pressure laminate and polyvinylchloride coating materials resulted in a significant decrease in water absorption ratios.

3.2 Thickness swelling (*TS*)
3.2. Debljinsko bubrenje (*TS*)

Results of the statistical analysis of thickness swelling values obtained in the experiments aimed at finding the differences of press methods and covering materials within the MDF samples, 18 mm thick and covered with PVC folios, are given in Table 3.

According to Independent Samples T-test given in Table 3, different press methods significantly affect the material's thickness swelling percentages of high gloss covered fiberboards at a confidence level of p<0.001. Likewise also, different press methods resulted in a significant difference in thickness swelling values of the MDF samples covered with matt material at a confidence interval of p<0.01. In both covering processes, it was observed that samples covered with MP had a low thickness swelling.

By using WP, the difference in thickness swelling between the samples covered with HG and matt materials were found to be statically significant at a (p<0.001) level. On the other hand, as (p>0.05), the relation between thickness swelling percentages of the samples covered with membrane press were considered non-significant, as seen in Table 3. In his article, Akkılıç (1998) also determined that there was no difference between the oak veneer and laminate veneer samples after 24-hour soaking. In the same study, it is stated that the thickness swelling values of the samples covered with the finished folio are very high and even close to the results of raw samples.

Besides, it was also determined that samples covered with matt PVC (0.99 % and 0.88 %) had a lower thickness swelling than the HG covered samples (1.86 % and 0.90 %) after 24h according to Table 3. Moreover, Nemli (2000) noted that particleboard surfaces coated with lacquer paint, melamine-impregnated pa-

Table 3 Results of thickness swelling measurements after 24 h
Tablica 3. Rezultati mjerenja debljinskog bubrenja nakon 24 sata

Thickness swelling *Debljinsko bubrenje*			**Mean** *Prosječna vrijednost* %	**Stand. deviation** *Stand. devijacija*	**Stand. Error** *Stand. pogreška*	**Coefficient of variation** *Koeficijent varijacije*	t_{value}	**Sig. (2-tailed)**
Coating material *Materijal za oblaganje*	High gloss / *visoki sjaj* (HG)	WP	1.86	0.045	0.014	2.40	24.713	0.000
		MP	0.90	0.114	0.036	12.58		
	Matt / *mat* (MT)	WP	0.99	0.080	0.025	8.10	2.969	0.008
		MP	0.88	0.087	0.028	9.94		
Press method *Metoda prešanja*	Wrapping / *oblaganje profila* (WP)	HG	1.86	0.045	0.014	2.40	29.758	0.000
		MT	0.99	0.080	0.025	8.10		
	Membrane *membransko prešanje* (MP)	HG	0.90	0.114	0.036	12.58	0.496	0.626
		MT	0.88	0.087	0.028	9.94		

pers, veneer sheets and roller laminates resulted in a significant decrease in the thickness swelling values after 24 hour soaking.

3.3 Modulus of elasticity (*MOE*) and static bending strength (*STS*)
3.3. Modul elastičnosti (*MOE*) i statička čvrstoća savijanja (*STS*)

Data obtained by tests for modulus of elasticity and static bending strength of samples covered with high gloss and matt materials using two different press methods are given in Table 4.

As seen in Table 4, different press methods significantly ($p<0.001$) affect the elastic modulus of MDF samples covered with HG material. The same result is applicable to the samples covered with matt PVC material. Table 4 shows that the elastic modulus values of the MDFs are higher when pressed with MP than with other methods. This difference in elastic modulus values are probably the result of the PVC thickness. Nemli (2000) noted that coating the particleboards with different materials increased the bending strength and modulus of elasticity, and that the coating material thickness did not affect the results. Likewise, Table 4 shows that there is a significant difference between HG and matt covering materials at a confidence level of ($p<0.001$) between the elastic modulus values for both press methods applied. At the same time, the table shows that samples covered with MP have a high elastic modulus. Yet, it has been calculated that samples covered with PVC folios have a higher elastic modulus than the samples covered with HG. This difference in values could be derived from the press method, because matt PVC is coated on one side, while HG PVC is double-side coated.

On the other hand, Table 4 also shows that different press methods have a significant effect on the static bending strength of the fiberboard covered with both HG and matt materials at a confidence level of 999.9 % ($p<0.001$). In elastic modulus tests, while covered samples using MP reach a high bending strength, samples covered with matt covering materials using WP were calculated to have a higher (41.5 N/mm^2) bending strength. Statistical data presented in Table 4, obtained from the Independent Sample T-test applied on the bending strength values calculated in both WP and MP, showed a significant effect on the strength values of different covering materials at a confidence interval of $p<0.001$. Similarly, Akkılıç (1998) stated that there are statistical differences between the bending strength values of particleboard coated with finished folio, oak veneer and laminate materials.

Contrary to the elastic modulus, bending strength of the samples covered with matt folios using WP was higher than when using MP. Likewise, the average bending strength (43.7 N/mm^2) measured in samples covered with HG material using MP were calculated to be higher than when using the other method. Özdemir (1996) determined that particleboard coated with PVC had higher bending strength than the uncoated particleboard.

3.4 Bonding strength (*BS*)
3.4. Čvrstoća prianjanja (*BS*)

The analysis of bonding strength values obtained from the tests and calculations is presented in Table 5.

The results of *T*-test analysis given in Table 5 reveal that there are significant differences ($p<0.001$) in the bonding strength depending on the press method (WP and MP) used for covering samples with HG and matt PVCs. At the same time, bonding strength values of MDFs covered with both materials were higher when WP was used. This result may be caused by the application technique and the type of adhesive used.

As it is known, in most uses of this type of material, distinction can be made between the bonding strength and other properties. For this reason, accord-

Table 4 Results analysis of modulus of elasticity and static bending strength values
Tablica 4. Analiza rezultata mjerenja modula elastičnosti i statičke čvrstoće savijanja

Tests *Veličina*	**Parameters** *Svojstva*			**Mean** *Prosječna vrijednost* N/mm^2	**Stand. deviation** *Stand. devijacija*	**Stand. Error** *Stand. pogreška*	**Coefficient of variation** *Koeficijent varijacije*	t_{value}	**Sig. (2-tailed)**
Modulus of elasticity *Modul elastičnosti*	Coating material	HG	WP	3573.2	77.27	13.548	2.16	18.156	0.000
			MP	4023.6	13.55	4.284	0.34		
		MT	WP	3938.1	28.45	8.961	0.72	32.705	0.000
			MP	4302.5	20.94	6.623	0.49		
	Press method	WP	HG	3573.2	77.27	13.548	2.16	14.016	0.000
			MT	3938.1	28.45	8.961	0.72		
		MP	HG	4023.6	13.55	4.284	0.34	35.353	0.000
			MT	4302.5	20.94	6.623	0.49		
Bending strength *Čvrstoća savijanja*	Coating material	HG	WP	37.6	1.022	0.323	2.72	18.320	0.000
			MP	43.7	0.275	0.087	0.63		
		MT	WP	41.5	1.314	0.415	3.17	11.745	0.000
			MP	35.9	0.713	0.226	1.99		
	Press method	WP	HG	37.6	1.022	0.323	2.72	7.447	0.000
			MT	41.5	1.314	0.415	3.17		
		MP	HG	43.7	0.275	0.087	0.63	32.122	0.000
			MT	35.9	0.713	0.226	1.99		

Table 5 Independent Samples *T*-test analysis of bonding strength values
Tablica 5. Rezultati analize vrijednosti čvrstoće prianjanja *T*-testom

Bonding strength Čvrstoća *prianjanja*			**Mean** *Prosječna vrijednost* N/mm²	**Stand. deviation** *Stand. devijacija*	**Stand. Error** *Stand. pogreška*	**Coefficient of variation** *Koeficijent varijacije*	t_{value}	**Sig. (2-tailed)**
Coating material *Materijal za oblaganje*	High gloss / *visoki sjaj* (HG)	WP	2.09	0.145	0.046	6.95	4.972	0.000
		MP	1.80	0.113	0.036	6.27		
	Matt / *mat* (MT)	WP	1.16	0.066	0.021	5.64	5.698	0.000
		MP	0.96	0.095	0.030	9.91		
Press method *Metoda prešanja*	Wrapping *oblaganje profila* (WP)	HG	2.09	0.145	0.046	6.95	18.368	0.000
		MT	1.16	0.066	0.021	5.64		
	Membrane *membransko prešanje* (MP)	HG	1.80	0.113	0.036	6.27	18.145	0.000
		MT	0.96	0.095	0.030	9.91		

ing to Table 5, the choice of WP could contribute to obtaining better results.

On the other hand, when Table 5 is evaluated taking into consideration the covering material difference, it can be seen that the covering material difference has a significant effect on MDF test sample bonding strength at a confidence interval of 999.9 %. At the same time, it could be said that bonding strength values (2.09 %, 1.80 %) of the samples covered with HG using WP are better than matt covered samples using MP (1.16 %, 0.96 %). This improvement can be explained by the difference in coating material thicknesses. In a study, Kılıç (2006) researched the quality of bonding strength of beech, pine and oak veneers adhered to surfaces of flat pressed particleboard, medium density fiberboard and oriented strand board with polyvinyl acetate, urea-formaldehyde and contact adhesive. As a result of the tests, the highest bonding strength was obtained from the combination of radial cross-section beech veneer, oriented strand particleboard and urea-formaldehyde adhesive, whereas the lowest strength was obtained from the combination of tangential beech veneer, fiberboard and contact adhesive.

4 CONCLUSION
4. ZAKLJUČAK

The aim of this study was to research the difference of some properties of MDF samples, which are the key input of forest products sector, using two different press methods with high gloss and matt PVC folios. The conclusions of this study could be summed up as below.

Except for the HG covered samples, water absorption percentages were determined to be statistically affected by the press method and covering material difference in other samples. At the same time, samples covered with HG material absorbed less water.

In determining the difference of the covering material based on thickness swelling values, an insignificant effect was observed in membrane press covered samples, while there were significant differences in other samples. MDF samples covered with matt material showed a lower thickness swelling than the others.

Tests showed that both the press method difference and the covering material difference had a significant effect on elastic modulus, bonding strength and static bending strength at ($p<0.001$) level.

Besides, the values of elastic modulus of the samples covered with matt material were higher than the values of HG covered samples, while bonding strength of the HG covered samples was better than that of the matt covered samples. Considering the static bending strength, it was determined that the difference of the covering material did not have a similar effect on both strengths.

For this reason, when selecting the coating material to be adhered to board surfaces, due to different adhesion properties of HG and mat coatings, it is necessary to consider the characteristics, quality, surface condition of the board and properties of the environment.

A survey of the literature also reveals that so far few studies have been focusing on press methods. For this reason discussion has not been adequately included. This topic definitely requires further research.

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Nesogordonia papaverifera (A. Chev.) R. Capuron

NAZIVI

Nesogordonia papaverifera Capuron naziv je drva botaničke vrste iz porodice *Sterculiaceae*. Trgovački su nazivi te vrste kotibé (Njemačka, Francuska), danta (Velika Britanija, Gana, Nigerija), senhungo (Angola), ahia, baka (Njemačka), olborbora (Gabon), akuama, apru, epro (Gana), ovoué (Kamerun), tsanya (Kongo), otutu (Nigerija).

NALAZIŠTE

Stabla *Nesogordonia papaverifera* R. Capuron rastu u zapadnoj Africi. Područja rasprostranjenosti tog drveća jesu Obala Bjelokosti, Gana, Nigerija, Kamerun, Gabon, Kongo, Angola. Ponajprije raste u području tropskih poluzimzelenih i zimzelenih kišnih šuma, ali i unutar nizinskih tropskih kišnih šuma.

STABLO

Naraste od 25 do 30 m, dužina debla mu je 20 m, prsni promjer od 0,6 do 0,8 (1,0) m. Deblo je pravilnoga, cilindričnog oblika. Vanjska je kora drveta ispucana, siva do crvenkastosiva. Debljina kore je od 1 do 2,5 cm.

DRVO

Makroskopska obilježja

Drvo je rastresito porozno. Bjeljika i srževina međusobno se razlikuju bojom. Srževina je crvenosmeđa, katkad i ljubičastocrvena, a s vremenom potamni. Bjeljika je svjetlosmeđa do crvenkasta.

Tekstura drva je fina, jednolična i dekorativna. Žica drva je ravna ili usukana. Sirovo je drvo aromatičnog mirisa. Granica goda nije uvijek uočljiva. Pore i drvni traci vidljivi su povećalom .

Mikroskopska obilježja

Traheje su raspoređene pojedinačno, u paru i radijalno. Promjer traheja je 40...75...100 mikrometara, a gustoća 29...37...42 na 1 mm^2 poprečnog presjeka. Volumni udio traheja iznosi 18...26 %. Traheje srži ispunjene su smeđim sržnim tvarima. Raspored aksijalnog parenhima je aparatrahealno ljestvičast i katni. Volumni udio aksijalnog parenhima kreće se u rasponu od 20...28 %. Staničje drvnih trakova je homogeno do slabo heterogeno, visine 250...300 mikrometara, širine 15...25...35 mikrometara, odnosno 1...2...3 stanice. Gustoća drvnih trakova je 5 – 8 po milimetru poprečnog presjeka. Volumni udio drvnih trakova iznosi od 18 do 21 %. Aksijalni parenhim i parenhim drvnih trakova često su ispunjeni kristalima. Drvna su vlakanca libriformska, a dugačka su 700...850...1300 mikrometara. Debljina staničnih stijenki vlakanaca je 2,2...2,9...3,5 mikrometara, a promjer lumena 4,0...11,0...16,0 mikrometara. Volumni udio vlakanaca je od 33 do 36 %.

Fizička svojstva

Gustoća standardno suhog drva, ρ_o	660...720...770 kg/m^3
Gustoća prosušenog drva, ρ_{12-15}	680...760...830 kg/m^3
Gustoća sirovog drva, ρ_s	900...950...1050 kg/m^3
Poroznost	oko 52 %
Radijalno utezanje, β_r	5,0...5,6...6,2 %
Tangentno utezanje, β_t	7,0...8,0...9,4 %
Volumno utezanje, β_v	12,2...13,8...15,9 %

Mehanička svojstva

Čvrstoća na tlak	46...63...76 MPa
Čvrstoća na vlak, paralelno s vlakancima	6,5...14...17 MPa
Čvrstoća na savijanje	11...15,5...23,6 MPa
Tvrdoća prema Brinelu, paralelno s vlakancima	55...73...92 MPa
Tvrdoća prema Brinelu, okomito na vlakanca	23...36...46 MPa
Modul elastičnosti	8,0...13,5 GPa

TEHNOLOŠKA SVOJSTVA

Obradivost

Drvo se dobro strojno obrađuje. Lako se ljušti, pili, blanja, brusi, buši i politira. Prije bušenja drvo je potrebno predbušiti. Obrada ručnim alatima je otežana.

Sušenje

Drvo se dobro i polako suši. Za vrijeme sušenja rijetko dolazi do vitoperenja ili kolapsa.

Trajnost i zaštita

Prema normi HRN 350-2, 2005, srž drva srednje je otporna na gljive truležnice (razred otpornosti 3) i srednje otporna na napad termita (razred otpornosti M). Srž je slabo permeabilna (razred 3 – 4). Prema normama, može se upotrebljavati u uvjetima koji odgovaraju razredu opasnosti 2 (u unutarnjim uvjetima i vani, ali natkriveno). Drvo koje je povremeno izloženo vanjskim utjecajima potrebno je na odgovarajući način zaštititi, dok se trajno izlaganje promjenjivim vanjskim utjecajima ne preporučuje.

Uporaba

Drvo vrste *Nesogordonia papaverifera* upotrebljava se za izradu ljuštenih furnira i furnirskih ploča, unutarnjega skupocjenog namještaja, drvenih podova, stolarije i stubišta, drvenih predmeta, držala za alate, glazbenih instrumenata i u modelarstvu.

Sirovina

Drvo se na tržištu pojavljuje u obliku trupaca i piljenica različitih dimenzija.

Napomena

Drvu vrste *Nesogordonia papaverifera* (A. Chev.) R. Capuron zasad ne prijeti nestanak (nije na popisu ugroženih vrsta drva CITES – Convention on International Trade in Endangered Species). Drvo sličnih svojstava imaju i vrste *Cistanthera leplaei* Verm., C. Spp, *Pentace burmanica* Kurz, *Staudtia gabonensis* Warb., *Tarrietia utilis* Sprague, T. Spp.

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Merhar, M.; Gornik Bučar, D.: The Influence of Radial Slots on Dynamic Stability of Thermally Stressed Circular Saw Blade, No. 4, pp. 341-349.

UDK: 630*824.23 Screws

doi:10.5552/drind.2017.1630
Perçin, O.; Şadiye Yasar, Ş.; Altunok, M.; Uzun, O.: Determination of Screw Withdrawal Resistance of Some Heat-Treated Wood Species, No.1, pp. 61-68.

UDK: 630*824.328 Urea resin; 630*863.215 Board forming and pressing

doi:10.5552/drind.2017.1640
Salem, M. Z. M.; Böhm, M.; Nasser, R. A.: Measuring the Formaldehyde Content from Different Types of Oriented Strand Board Manufactured with Different Thicknesses and Glued with Different Resins, No. 2, pp. 173-178.

UDK: 630*831.5 Posts. Stakes. Paling. Fences and gates; 674.031.632.224.2 *Fagus sylvatica* L.

doi:10.5552/drind.2017.1703
Detvaj, J.; Janovčíková, P.: Efficient Exploitation of Beech Wood by Production of an Atypical Structural Element - a Hollow Wooden Post, No. 3, pp. 261-266.

UDK: 630*829.2 Types of finishes; 630*835.1 Recreational goods (Toys, models, sporting goods)

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Wulf, F.; Sanne, M.; Pfriem, A.: Coatings for Use on Wooden Bicycle Frames – Applicability, Test Methods and Artificial Weathering Results, No. 4, pp. 281-289.

UDK: 630*832.281.2 Products. For use in construction plywood; 630*832.282.7 Mechanical properties

doi:10.5552/drind.2017.1634
Jakimovska Popovska, V.; Iliev, B.; Zlateski, G.: Impact of Veneer Layouts on Plywood Tensile Strength, No. 2, pp. 153-161.

UDK: 630*833.01 Building components and fittings; general

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Wieruszewski, M: Cross Laminated Timber (CLT) as an Alternative Form of Construction Wood, No. 4, pp. 359-367.

UDK: 630*834 Shingles. Cooperage. Packing containers (Manufacture and use)

doi:10.5552/drind.2017.1644
Andreolli, M.; Corradetti, D.; Cremonini, C.; Negro, F.; Piazza, M.; Zanuttini; R.: Italian Standard UNI 9151 – a New Approach to the Design of Industrial Wood Packaging, No. 3, pp. 267-273.

UDK: 630*841.3 Preservatives ; 630*.841.4 Preserving processes; 674.031.623.234 Poplar species grown in Europe; 674.031.951.62 Genus *Paulownia*

doi:10.5552/drind.2017.1701
Rasouli, D.; Bahmani, M.; Humar, M.: Impregnability of Paulownia and Populus Wood with Copper Based Preservatives, No. 3, pp. 211-218.

UDK: 630*847 Drying (seasoning); 630*813.25 Complex phenolics (e.g., tanins and other polymeric phenolics); 674.031.632.154.2 Genus *Alnus*. *Alnus glutinosa* Hill. Syn A. communis

doi:10.5552/drind.2017.1649
Klarić, M.; Pervan, S.; Biošić, M.: Influence of Lyophilisation and Oven-Drying on Extraction Yield of Oregonin from European Black Alder (*Alnus glutinosa* (L.) Gaertn.) Bark, No. 3, pp. 205-210.

UDK: 630*861.02 Wood chips; 630*863.212 Particle drying; 674.032.13 Spruce, *Picea excelsa*; 674.031.632.22 Genus *Fagus* ; 674.031.623.22 Genus *Salix*;

doi:10.5552/drind.2017.1602
Górnicki, K.; Kaleta, A.; Bryś, A.; Winiczenk, R.: Modelling of Drying Curves of Spruce, Beech,Willow and Alder Particles, No.1, pp. 11-16.

UDK: 630* 861.232 Particleboard; 630*812 Physical and mechanical properties

doi:10.5552/drind.2017.1631
Rangavar, H.: Wood-Cement Board Reinforced with Steel Nets and Woven Hemp Yarns: Physical and Mechanical Properties, No. 2, pp. 121-128.

UDK: 630*861.311 Kraft (sulfate); 674.032.475.4; 674.031623.234.2 *Populus tremula* L.

doi:10.5552/drind.2017.1723
Ayben, K. P.; Gülsoy, S. K.; Pranovich, A.: Influence of Some Boron Compounds on Kraft Pulping of European Black Pine and European Aspen, No. 4, pp. 323-332.

UDK: 630*863.2 Boards formed of mixed paricles (including sawdust fibers). Resin-bonded mouldings; 630*812.7 Mechanical strength properties: general

doi:10.5552/drind.2017.1521
Plenzler, R.; Ludwiczak-Niewiadomska, L.; Strzelecki, P.: Elastic and Strength Properties of OSB Layers, No.1, pp. 3-9.

UDK: 630*863.319 Fiberboards (including fiber boards laminated with other materials, e.g. veneer, chipboard, paper). Resin-bonded fibre mouldings ; 630*864.26 Celulose and regenerated cellulose derivates. Analyses

doi:10.5552/drind.2017.1709
Sozen, E.; Aydemir, D.; Zor, M: The Effects of Lignocellulosic Fillers on Mechanical, Morphological and Thermal Properties of Wood Polymer Composites, No. 3, pp. 195-204.

UDK: 630*875.2 With no recovery of by-products

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Kazimierski, P.; Kardas, D.: Influence of Temperature on Composition of Wood Pyrolysis Products, No. 4, pp. 307-313.

UDK: 630*945 Advisory, services, publicity, propaganda, education, training research

Šefc, B.: Scientists and their carier, Iva Ištok defended doctoral thesys, No. 1, pp. 81-82.

Jambreković, V.: In memoriam prof. dr. sc. Vladimir Bruči, No. 1, pp. 83-84.

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