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Mechanical properties of sapwood versus heartwood, in three different oak species

Gustoća i mehanička svojstva drva bjeljike hrasta u usporedbi s drvom srži

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ABSTRACT • *The aim of this study was to investigate the main mechanical properties of sapwood and heartwood in white and red oaks. Samples of wood were taken from 26 oak beams prepared to be used for railway sleepers, of which 62 % were from white oak (either Quercus petraea or Q. robur) and 38 % from red oak group, represented by Q. cerris. For both oak groups, the following parameters were determined: the density, bending strength, modulus of elasticity (MOE), compression strength and Brinell hardness of sapwood and heartwood. Multiple analyses were done to compare the properties of sapwood and heartwood, as well as the properties of white vs. red oaks. The results revealed no significant differences between sapwood and heartwood properties but statistically significant differences were found between the properties of white and red oaks. The research results contradict the common opinion of users that the mechanical properties of sapwood are inferior to those of heartwood. Investigations revealed that Q. cerris had even better mechanical properties than Q. robur or Q. petraea, which also contradicts the common opinion that its mechanical properties are inferior to those of white oaks. The results help to understand better wood variability for optimal selection of timber for constructions.*

Key words: *oak, Quercus, sapwood, heartwood, mechanical properties, density, bending strength, modulus of elasticity, Brinell hardness*

SAŽETAK • *Cilj ovog istraživanja bio je ispitati osnovna mehanička svojstva drva bjeljike i srži bijeloga i crvenog hrasta. Uzorci su uzeti od 26 hrastovih greda spremnih za izradu željezničkih pragova, od čega je 62 % greda od bijelog hrasta (Quercus petraea ili Q. robur), a 38 % od skupine crvenih hrastova, čiji je predstavnik Q. cerris. Za drvo bjeljike i drvo srži obiju skupina hrasta određena je gustoća, čvrstoća na savijanje, modul elastičnosti (MOE), tlačna čvrstoća i tvrdoća prema Brinellu. Napravljene su višestruke analize radi usporedbe svojstava bjeljike i srži, kao i usporedbe svojstava drva bijelih i crvenih hrastova. Rezultati su pokazali da nema značajne razlike između svojstava drva bjeljike i srži, ali statistički značajne razlike pokazale su se između svojstava drva bijeloga i crvenog hrasta. Rezultati istraživanja proturječe uvriježenome mišljenju korisnika da su mehanička svojstva bijeljike lošija od mehaničkih svojstava drva srži. Istraživanja su pokazala da drvo Q. cerris ima čak i bolja mehanička svojstva nego drvo Q. robur i Q. petraea, što je također suprotno ustaljenom mišljenju da su njegova svojstva lošija od svojstava drva bijelog hrasta. Rezultati će pridonijeti boljem razumijevanju varijabilnosti svojstava drva i optimalnom izboru drva za gradnju.*

Ključne riječi: *hrast, Quercus, bjeljika, srž, svojstva, gustoća, čvrstoća na savijanje, modul elastičnosti, tvrdoća prema Brinellu*

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1 INTRODUCTION
1. UVOD

Oak is one of the most important and widely used sources of structural timber in Europe. However, its properties have high variability for several reasons. Firstly, the genus oak *(Quercus)* contains numerous tree species (Mabberley, 1987) that cannot be easily differentiated based on wood structure. Trade timber can therefore contain more than one wood species under the same commercial name. Another source of variation is the cellular wood structure, with compact cell walls and void cell lumina, which directly affects wood density, as one of the most relevant wood properties. In ring porous oaks, the density is related to the earlywood/latewood proportion, whereby wood with narrower annual rings and a high proportion of earlywood usually has lower density than wood with wider rings and a lower proportion of earlywood (Kollmann and Cote, 1968).

Most European oaks are ring-porous species and can be assigned to white or red oak groups (Richter and Dallwitz, 2000). The main representatives of white oaks are the widely used sessile (*Quercus petraea*) and pedunculate oak (*Qercus robur*). Turkey oak (*Quercus cerris*), which belongs to red oaks, is less frequent. It grows and is mainly used in southern and south-eastern Europe (Richter and Dallwitz, 2000).

Oak wood, among other uses, is still largely used for the production of railway sleepers. The required wood properties for railway sleepers and similar products are defined by EN 13145 (2012). This standard recommends wood species, quality requirements, origin, manufacturing conditions, forms, dimensions and tolerances, as well as the durability and preservation of wood sleepers and bearers for use in railway tracks. According to EN 13145 (2012), wood for sleepers and bearers must have a natural or conferred durability allowing its use in hazard class 4 as defined in EN 335-1 (2006). According to EN 350-2 (1994), solid wood to be used in hazard class 4 must conform to natural durability class 1 or 2. Wood with natural durability of classes 3, 4 or 5 or containing non-durable sound sapwood must be treated to achieve a conferred durability, which allows its use in hazard class 4. The longevity of class 2 species may also be increased by treatment as recommended by EN 13145 (2012). Deviations from the procedures described above must be agreed between the customer and supplier.

Oaks are also among wood species recommended for railway sleepers. They are termed European oaks and include the following species: *Quercus robur* (pedunculate oak*), Q. petraea* (sessile oak) and *Q. pubescens* (pubescent oak). According to the standards, the presence of sapwood is permitted when sound (EN 13145, 2012).

In Slovenia, as a part of the railway sleepers market of the European Union, customers expect oak timber in trade to contain mainly heartwood of white oaks, *Quercus robur* and *Q. petraea*. They often claim that the mechanical properties of red oak, *Quercus cerris,* which also grows in the region, are inferior to those of both white oaks. They also avoid using sapwood, due to the belief that the mechanical properties of sapwood are inferior to those of heartwood. However, published information to support or reject such opinions is scarce or lacking. Standard literature that provides information on oak wood properties mainly reports on heartwood properties of *Quercus robur* and *Q. petraea* (Esau, 1965; Grosser and Teetz, 1987; Richter and Oelker, 2001; Wagenführ, 1996; Anonymus, 2012), while information on the properties of *Quercus cerris* and, particularly, oak sapwood is scarce (Ayobi *et al.*, 2011).

When lumber or other products are cut from the stem, the characteristics of these fibrous cells and their arrangement affect wood properties such as strength and shrinkage, as well as the grain pattern (Miller, 1989). The formation of heartwood is a natural aging process (Bosshard, 1968); development of sapwood into heartwood takes place in a relatively narrow transition zone, perhaps only the width of one or two growth increments (Wilson and White, 1986; Bamber and Fukazawa, 1985). Sapwood is involved in the transport of water and minerals from the roots and due to their function sapwood cells contain more water and lack the deposits of darkly staining chemical substances commonly found in heartwood. Many of these differences between sapwood and heartwood are chemical; in some cases heartwood substances impregnate cell walls, in others they can also be found in the cell lumina. The amount of starch in parenchyma cells declines in older sapwood and is completely metabolized when sapwood is transformed to heartwood (Hillis, 1987; Shigo and Hillis, 1973; Magel *et al.*, 1994; Taylor *et al.*, 2002). The death of parenchyma cells occurs as a consequence of the accumulation of toxic excretory products of metabolism (Zimmermann and Brown, 1971). Such excretions are trans-located through parenchyma cells towards the centre of the tree (pith), around which the cylinder of heartwood is formed and gradually expanded (Tsoumis, 1991).

Numerous studies have stressed that toxic heartwood compounds seem to function mostly in the exclusion of pathogens from the wood and may help wood to resist fungi, boring insects and bacteria and so increase its natural durability of wood (Hillis, 1987; Mabberley, 1987; Kollmann and Cote, 1968). In addition to differences in colour, sapwood and heartwood often differ considerably in regard to wood durability, whereas possible differences in other properties are rarely reported.

The aim of the present study was to identify oak wood (white oaks vs. red oak) in randomly collected material from a timber yard, and to determine the density and selected mechanical properties, separately for sapwood and heartwood and separately for white and red oaks. We tested the hypotheses that the mechanical properties of red oak *Quercus cerris* are inferior to those of white oaks (*Quercus robur* and *Q. petraea*) and that the mechanical properties of sapwood are inferior to those of heartwood.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

2.1 Wood samples
2.1. Drvni uzorci

In a timber yard, we randomly selected 26 oak beams from freshly cut trees, originating from various sites in Slovenia. We then prepared clear, oriented samples of sapwood and heartwood. The heartwood samples were taken from the outer parts of the heartwood so that they contained only adult wood; innermost juvenile wood was not included.

After pre-cutting, the samples were seasoned to moisture content (MC) of approximately 15 % and then conditioned at relative air humidity (φ) 65 % and temperature (T) 20 °C.

Moisture equilibrated samples were cut to final dimensions as required by the standards used to determine mechanical properties (conditions of φ=65 % and T=20 °C).

2.2 Wood identification
2.2. Identifikacija drva

The cross-sections of all samples were polished. They were inspected under a microscope for the dimensions and appearance of latewood vessels. Large, solitary and thick-walled latewood vessels indicated the red oak group, which is mainly represented by Turkey oak (*Quercus cerris*). Very small, thin-walled latewood vessels occurring in multiples indicated white oaks, in the area mainly represented by pedunculate oak (*Quercus robur*) or sessile oak (*Quercus petraea*), on the assumption that these two oaks cannot be accurately differentiated in terms of their wood anatomy (Richter and Dallwitz, 2000).

2.3 Density
2.3. Gustoća

The oven-dry density was calculated according to ISO 3131 (1975a) and was based on the oven dry mass and volume:

$$\rho_0 = \frac{m_0}{V_0} \tag{1}$$

Where

ρ_0 is the oven-dry density, kg/ m^3
m_0 is the mass of the oven dried sample, kg
V_0 is the volume of the oven dried sample, m^3.

The samples were oven-dried at 103±2 °C and afterwards the volume was defined using a Breuil volume meter (Kollmann and Cote, 1968).

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

The bending strength and modulus of elasticity were determined in agreement with ISO 3133 (1975c), using a Zwick-100 testing machine. The dimensions of the samples were 20 mm x 20 mm x 300 mm, with the longest dimension in the axial direction. The distance between the points of suspension was 280 mm. The velocity of force loading was set such that every test was finished within 90±30 seconds. Bending strengths (σ_B) in N/mm^2 were calculated for each sample as follows:

$$\sigma_B = \frac{3 \cdot P_{max} \cdot l}{2 \cdot b \cdot h^2} \tag{2}$$

Where:

P_{max} is the breaking load, N;
l is the distance between the centres of the supports, mm;
b is the width of the test piece, mm;
h is the height of the test piece, mm.

and modulus of elasticity in bending (*MOE*) in MPa:

$$MOE = \frac{l^3 \cdot m}{4 \cdot b \cdot h^3} \tag{3}$$

Where

m is the gradient (i.e., slope) of the initial straight-line portion of the load deflection curve:

$$m = \frac{P}{D}, \quad \text{N/mm} \tag{4}$$

where D is the deflection of the centre of the beam at load P.

2.5 Compression strength
2.5. Tlačna čvrstoća

Compression strength tests were done as specified by ISO 3132 (1975b). The dimensions of oriented samples were 20 x 20 mm in cross section and 40 mm in the axial direction. The velocity of loading was set so that every test was finished within 90±30 seconds, using a Zwick-100 testing machine. Finally, the compression strength was calculated (σ_c) for each of the sapwood and heartwood samples

$$\sigma_C = \frac{P}{a \cdot l} \tag{5}$$

Where

σ_c is the compression strength, MPa (N/mm^2)
P is the load, in N, corresponding to the proportional limit in compression perpendicular to the grain (conventional ultimate strength);
a is the thickness of the piece, mm;
l is the width of the piece, mm.

2.6 Brinell hardness
2.6. Tvrdoća prema Brinellu

Sapwood and heartwood hardness were measured according to EN 1534 (2000) on a Zwick-100 testing machine. The Brinell method was used, with a steel ball 10±0.01 mm in diameter and 1000 N of force loading. The tests were done so that 1000 N of force was reached in 15±3 s and this constant force was subsequently maintained for another 25±5 s. Brinell hardness was calculated from the depth of the ball impress and expressed in N/mm^2: End-hardness and side-hardness were defined (Kollmann and Cote, 1968). For end-hardness, loading was performed in an axial direction (parallel to the grain) and the steel-ball was impressed on the cross-section of wood. In case of side-hardness, loading was performed in a tangential direction (perpendicular to the grain) with the ball impression on the radial surface of the wood. The tests were performed separately for sapwood and heartwood.

$$HB = \frac{2 \cdot F}{\pi \cdot D \cdot \left[D - \left(D^2 - d^2 \right)^{\frac{1}{2}} \right]} \tag{6}$$

Where
π is the ″pi″ factor (≈3,14);
F is the nominal force, N;
D is the diameter of the ball, mm;
d is the diameter of the residual indentation, mm.

2.7 Statistical analyses
2.7. Statističke analize

Statistical analyses of datasets were done with Microsoft Excel and Statgraphics Plus (version 5.1) computer software. Data were analyzed by ANOVA (analysis of variance). When the differences between analyzed groups were found to be significant, multiple range tests (95% LSD method) were used to determine the differences between means at a 95.0% confidence level.

3 RESULTS
3. REZULTATI

3.1 Wood identification
3.1. Identifikacija drva

Wood anatomical examination (Fig. 1) revealed that the samples originated from 16 white oak (*Q. robur* or *Q. petrea*) and 10 red oak (*Q. cerris*) beams. Differentiation of very small, thin walled latewood vessels grouped in multiples in white oaks and of large, solitary and thick-walled latewood vessels in red oaks is shown in Figure 1. In both white and red oaks, earlywood vessels in heartwood were filled with tyloses.

3.2 Density
3.2. Gustoća

Statistical values for the oven-dry density of 70 sapwood and 46 heartwood samples divided into white and red oak groups are presented in Figure 2. Oven-dry densities were in the range as reported in the literature (Table 11). On average, white oak sapwood has the

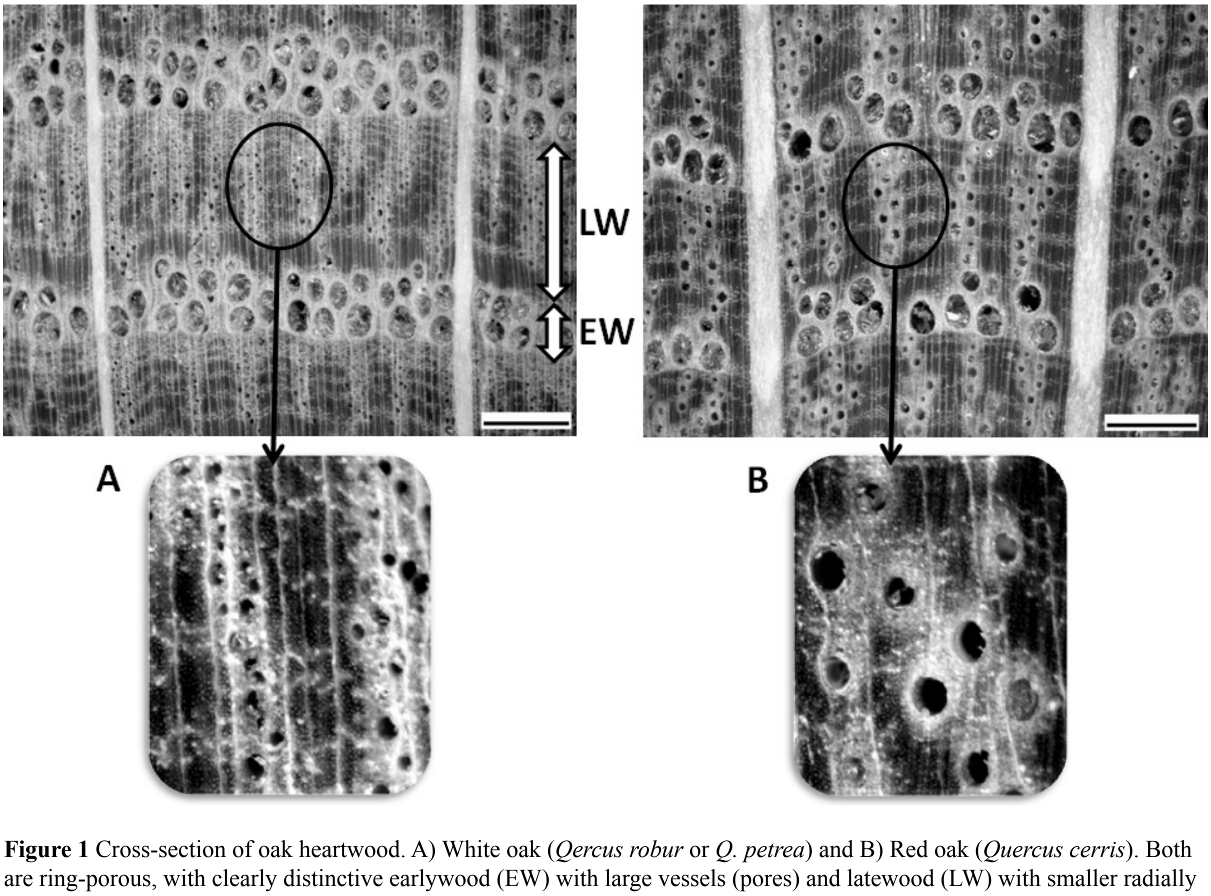

Figure 1 Cross-section of oak heartwood. A) White oak (*Qercus robur* or *Q. petrea*) and B) Red oak (*Quercus cerris*). Both are ring-porous, with clearly distinctive earlywood (EW) with large vessels (pores) and latewood (LW) with smaller radially oriented vessels. Red oaks have fewer, more solitary, and thicker walled latewood vessels (B) than white oaks (A). Scale bars: 1 mm

Slika 1. Poprečni presjek srži drva hrasta. A) bijeli hrast (*Qercus robur* ili *Q. petrea*), B) crveni hrast (*Quercus cerris*). Oba su prstenasto porozna, s jasno odvojenim ranim drvom (EW) velikih traheja (pora) i kasnim drvom (LW) manjih, radijalno orijentiranih traheja. Kasno drvo crvenih hrastova ima manje, više međusobno udaljene traheje debljih stijenki (B) nego drvo bijelog hrasta (A). Oznaka skale: 1mm

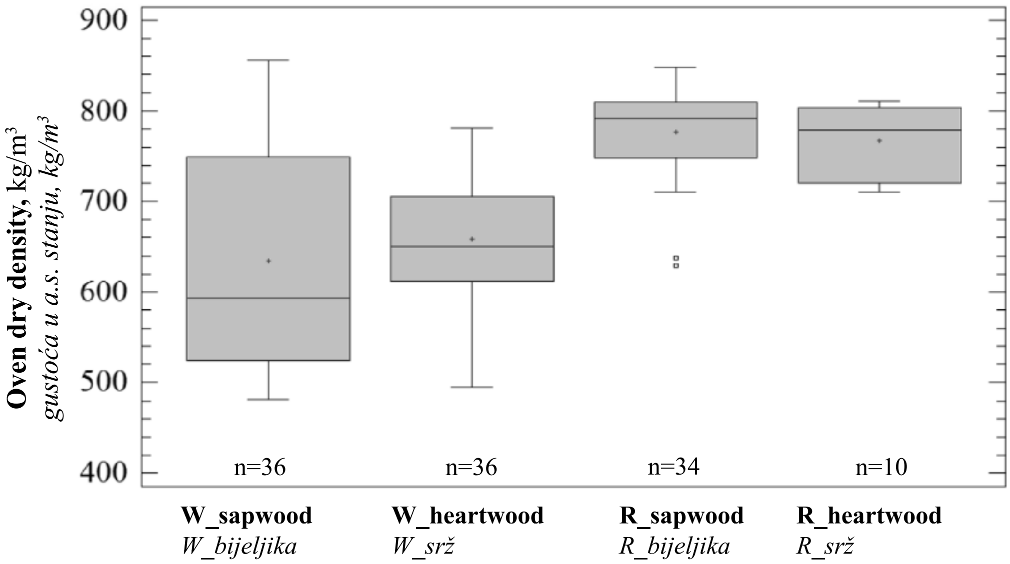

Figure 2 Oven-dry densities of white oak and red oak sapwood and heartwood. W_sapwood - white oak sapwood, W_heartwood - white oak heartwood, R_sapwood – red oak sapwood and R_heartwood - red oak heartwood; *n* – number of samples
Slika 2. Gustoća apsolutno suhog drva bjeljike i srži bijeloga i crvenog hrasta. W_sapwood – bjeljika bijelog hrasta, W_heartwood – srž bijelog hrasta, R_sapwood – bijeljika crvenog hrasta i R_heartwood – srž crvenog hrasta; *n* – broj uzoraka

lowest (634.1 kg/m^3) and red oak sapwood has the highest (767.3 kg/m^3) oven-dry density.

According to ANOVA (Table 1), differences between the densities of white and red oak groups were found to be significant (F = 20.88, P<0.05). The multiple range test (95 % LSD method) (Table 2) showed that the differences between sapwood and heartwood within white and red oak groups were not statistically significant.

The results confirm that the density of ring porous woods is mainly dependent on growth ring structure and its variability and less on structural and chemical changes as a result of heartwood formation processes (Tsoumis, 1991).

Table 1 ANOVA indicating the comparison of oven-dry densities of sapwood and heartwood at W_: white oak and R_: red oak
Tablica 1. ANOVA analiza za usporedbu gustoće u standardno suhom stanju drva bjeljike i srži bijeloga (W) i crvenog (R) hrasta

Source / *izvor*	***SS***	***DF***	***MS***	***F*-Ratio** *F-omjer*	***P*-Value*** *P-vrijednost**
Between groups *između skupina*	459573	3	153191	20.88	0.0000
Within groups *unutar skupina*	821563	112	7335.39		
Total (Corr.) *ukupno*	1.28114E6	115			

*P<0.05; *SS* - sum of squares, *DF* - degrees of freedom, *MS* - mean square / *P<0.05; SS – zbroj kvadrata; DF – stupanj slobode; MS - srednja vrijednost kvadrata*

3.3 Bending strength and modulus of elasticity (MOE)
3.3. Čvrstoća na savijanje i modul elastičnosti (*MOE*)

The bending strength and *MOE* were defined for 70 sapwood samples (white oak: 36; red oak: 34) and 46 heartwood samples (white oak: 36; red oak: 10). The bending strength and MOE of sapwood and heartwood were compared separately for white and red oak groups (Figure 3 and 4).

Table 2 Multiple range tests (95% LSD method) of sapwood and heartwood oven-dry densities of W_: white oak and R_: red oak
Tablica 2. Višestruka (95% LSD metoda) usporedba gustoće u standardno suhom stanju drva bjeljike i srži bijeloga (W) i crvenog hrasta (R)

	Count *Broj*	**Mean** *Srednja vrijednost*	**Homog. Groups** *Homogene skupine*
W_sapwood *W_bjeljika*	36	634.1	X
W_heartwood *W_srž*	36	658.3	X
R_sapwood *R_bjeljika*	34	776.4	X
R_heartwood *R_srž*	10	767.3	X

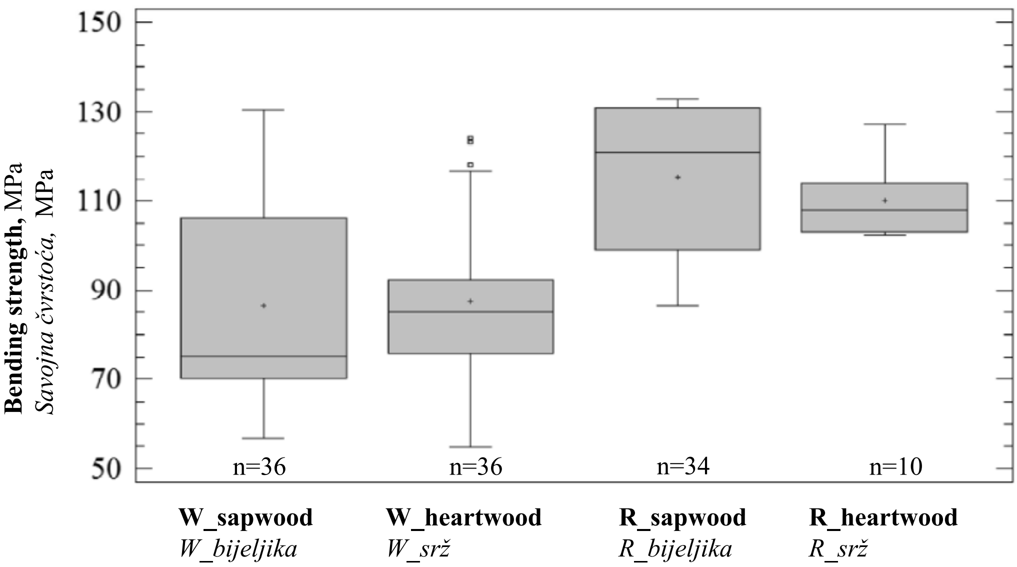

Figure 3 Bending strength of sapwood and heartwood samples. W_sapwood - white oak sapwood, W_heartwood - white oak heartwood, R_sapwood – red oak sapwood and R_heartwood - red oak heartwood; *n* – number of samples
Slika 3. Čvrstoća na savijanje drva bjeljike i srži bijeloga i crvenog hrasta. W_sapwood – bjeljika bijelog hrasta, W_heartwood – srž bijelog hrasta, R_sapwood – bjeljika crvenog hrasta i R_heartwood – srž crvenog hrasta; *n* – broj uzoraka

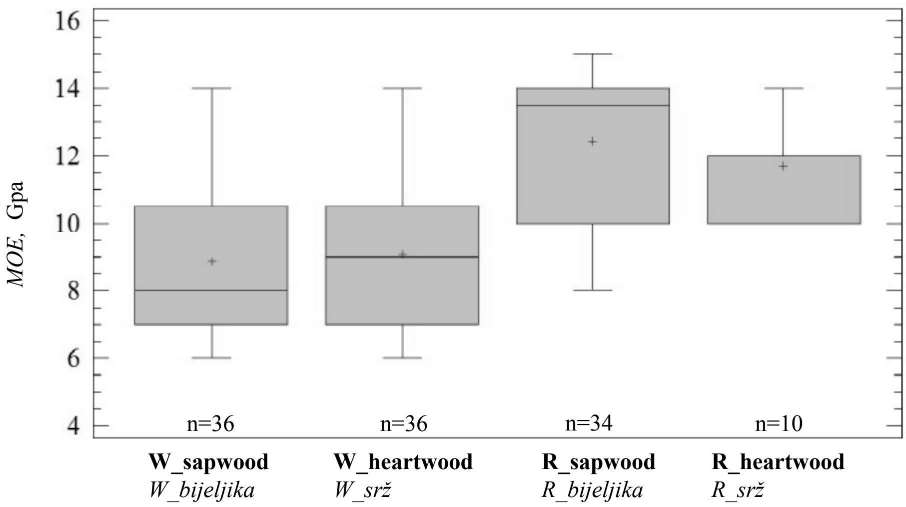

Figure 4 Modulus of elasticity (*MOE*) of sapwood and heartwood samples. W_sapwood - white oak sapwood, W_heartwood - white oak heartwood, R_sapwood – red oak sapwood and R_heartwood - red oak heartwood; *n* – number of samples
Slika 4. Modul elastičnosti (*MOE*) drva bjeljike i srži bijeloga i crvenog hrasta. W_sapwood – bjeljika bijelog hrasta, W_heartwood – srž bijelog hrasta, R_sapwood – bjeljika crvenog hrasta i R_heartwood – srž crvenog hrasta; *n* – broj uzoraka

Table 3 ANOVA for comparison of bending strength of sapwood and heartwood for W_: white oak and R_: red oak
Tablica 3. ANOVA analiza za usporedbu čvrstoće na savijanje drva bjeljike i srži bijeloga (W) i crvenog (R) hrasta

Source / *Izvor*	***SS***	***DF***	***MS***	***F*-Ratio** *F-omjer*	***P*-Value*** *P-vrijednost**
Between groups *između skupina*	20322.1	3	6774.04	19.40	0.0000
Within groups *unutar skupina*	39107.2	112	349.17		
Total (Corr.) *ukupno*	59429.3	115			

*P<0.05; *SS* - sum of squares, *DF* - degrees of freedom, *MS* - mean square / *P<0.05; SS – zbroj kvadrata; DF – stupanj slobode; MS - srednja vrijednost kvadrata*

Table 4 ANOVA for comparison of modulus of elasticity (*MOE*) of sapwood and heartwood for W_: white oak and R_: red oak
Tablica 4. ANOVA analiza za usporedbu modula elastičnosti (*MOE*) drva bjeljike i srži bijeloga (W) i crvenog (R) hrasta

Source / *Izvor*	***SS***	***DF***	***MS***	***F*-Ratio** *F-omjer*	***P*-Value*** *P-vrijednost**
Between groups *između skupina*	302.6	3	100.88	19.77	0.0000
Within groups *unutar skupina*	571.5	112	5.10		
Total (Corr.) *ukupno*	874.2	115			

*P<0.05; *SS* - sum of squares, *DF* - degrees of freedom, *MS* - mean square / *P<0.05; SS – zbroj kvadrata; DF – stupanj slobode; MS - srednja vrijednost kvadrata*

According to ANOVA (Tables 3 and 4), differences between groups (white vs. red oak) were found to be significant (F = 19.40, P<0.05 and F = 19.77, P<0.05). White oak sapwood had the lowest and red oak sapwood the highest bending strength. The LSD method (Tables 5 and 6) shows that there is no statistically significant difference between the means of the sapwood and heartwood bending strengths within either white or red oak group.

Table 5 Multiple range tests (95% LSD method) of sapwood and heartwood bending strength for W_: white oak and R_: red oak
Tablica 5. Višestruka analiza (95% LSD metoda) za usporedbu čvrstoće na savijanje drva bjeljike i srži bijeloga (W) i crvenog (R) hrasta

	Count *Broj*	Mean *Srednja vrijednost*	Homog. Groups *Homogene skupine*
W_sapwood *W_bjeljika*	36	86.5	X
W_heartwood *W_srž*	36	87.4	X
R_sapwood *R_bjeljika*	34	115.3	X
R_heartwood *R_srž*	10	110.0	X

Table 6 Multiple range tests (95% LSD method) of sapwood and heartwood *MOE* for W_: white oak and R_: red oak
Tablica 6. Višestruka analiza (95% LSD metoda) s ciljem usporedbe modula elastičnosti (*MOE*) drva bjeljike i srži bijeloga (W) i crvenog (R) hrasta

	Count *Broj*	Mean *Srednja vrijednost*	Homog. Groups *Homogene skupine*
W_sapwood *W_bjeljika*	36	8.9	X
W_heartwood *W_srž*	36	9.1	X
R_sapwood *R_bjeljika*	34	12.4	X
R_heartwood *R_srž*	10	11.7	X

3.4 Compression strength
3.4. Tlačna čvrstoća

Values of compression strength (Figure 5) were within the range reported in the literature (Grosser and Teetz, 1987; Wagenführ, 1996; Anonymus, 2012; Giordano, 1976; Horvat, 1959) (Table 11).

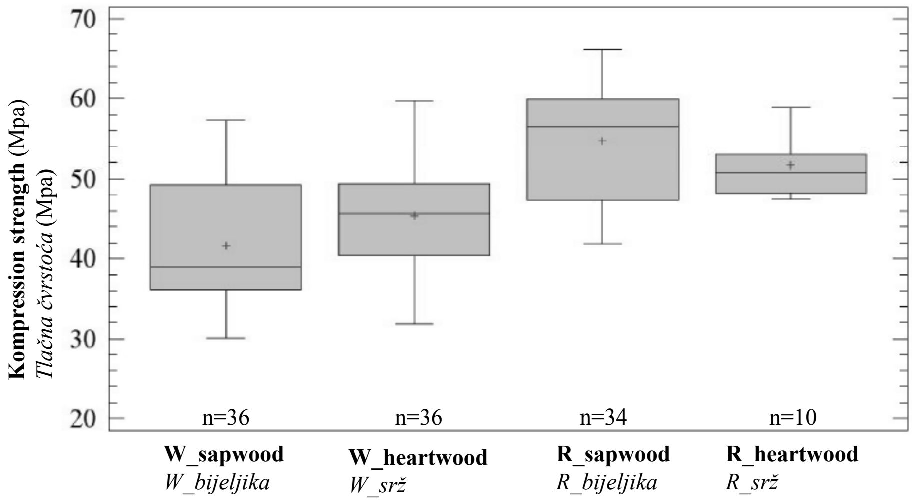

Figure 5 Compression strength of sapwood and heartwood samples. W_sapwood - white oak sapwood, W_heartwood - white oak heartwood, R_sapwood – red oak sapwood and R_heartwood - red oak heartwood; *n* – number of samples
Slika 5. Tlačna čvrstoća drva bjeljike i srži bijeloga i crvenog hrasta. W_sapwood – bjeljika bijelog hrasta, W_heartwood – srž bijelog hrasta, R_sapwood – bjeljika crvenog hrasta i R_heartwood – srž crvenog hrasta; *n* – broj uzoraka

Red oak group has higher bending strengths as well as higher *MOE*, which is in agreement with density variation. Strength also increased with increasing density, which is in agreement with reports in the literature (Tsoumis, 1991).

Table 7 ANOVA indicating the comparison of compression strength of sapwood and heartwood for W_: white oak and R_: red oak
Tablica 7. ANOVA analiza za usporedbu tlačne čvrstoće drva bjeljike i srži bijeloga (W) i crvenog (R) hrasta

Source / *Izvor*	***SS***	***DF***	***MS***	***F*-Ratio** *F-omjer*	***P*-Value*** *P-vrijednost**
Between groups *između skupina*	3382.6	3	1127.54	22.95	0.0000
Within groups *unutar skupina*	5502.0	112	49.13		
Total (Corr.) *ukupno*	8884.6	115			
**P*<0.05; *SS* - sum of squares, *DF* - degrees of freedom, *MS* - mean square / *P<0.05; SS – zbroj kvadrata; DF stupanj slobode; MS - srednja vrijednost kvadrata*					

As seen from Table 7 (ANOVA), differences between the groups were found to be significant (F = 22.95, P<0.05). The LSD test showed that white oak sapwood had the lowest and red oak sapwood the highest compression strength (Table 8) and that there is a statistically significant difference between the means of sapwood and heartwood within the white oaks group.

Table 8 Multiple range tests (95% LSD method) of sapwood and heartwood compression strength for W_: white oak and R_: red oak
Tablica 8. Višestruka analiza (95% LSD metoda) za usporedbu tlačne čvrstoće drva bjeljike i srži bijeloga (W) i crvenog (R) hrasta

	Count *Broj*	Mean *Srednja vrijednost*	Homog. Groups *Homogene skupine*
W_sapwood *W_bjeljika*	36	41.7	X
W_heartwood *W_srž*	36	45.4	X
R_sapwood *R_bjeljika*	34	54.8	X
R_heartwood *R_srž*	10	51.7	X

3.5 Brinell hardness
3.5. Tvrdoća prema Brinellu

Brinell hardness (HB) was determined for white oak samples only (Figure 6).

According to ANOVA, the P-value of the F-test was greater than 0.05, indicating no statistically significant differences between the means for Brinell hardness in any of the two tested directions (Table 9).

As seen from multiple range tests (Table 10), there are no statistically significant differences between any pair of means at a 95.0% confidence level.

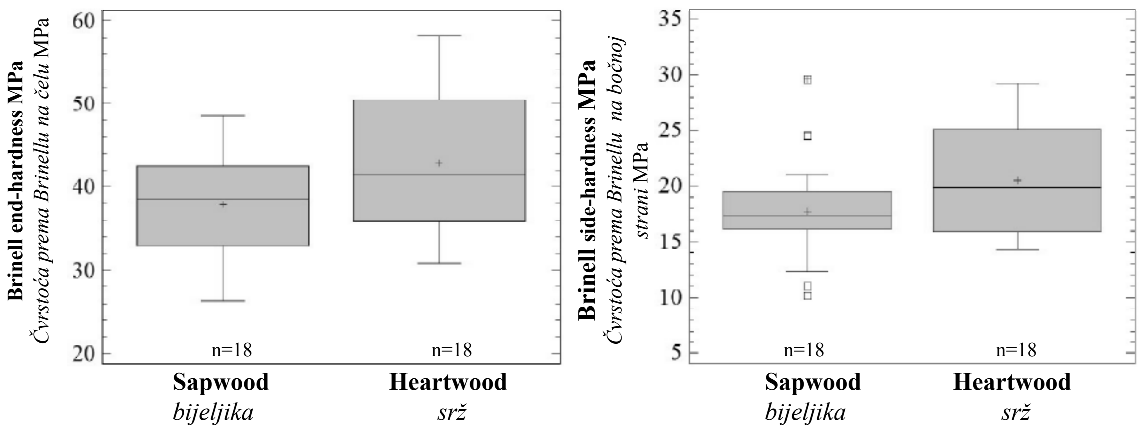

Figure 6 Brinell hardness of sapwood and heartwood samples of white oaks; left: end-hardness (impression on cross-section in an axial direction) and right: side-hardness (impression on radial surface in a tangential direction)
Slika 6. Tvrdoća prema Brinellu drva bjeljike i srži bijeloga hrasta; lijevo: tvrdoće na čelu (utiskivanje na poprečnom presjeku u aksijalnom smjeru) i desno: bočna tvrdoća (utiskivanje na radijalnom presjeku u tangencijalnom smjeru)

Table 9 ANOVA indicating the comparison of end and side Brinell hardness (HB) of sapwood and heartwood with white oak
Tablica 9. ANOVA analiza za usporedbu tvrdoće prema Brinellu na čelu i bočnoj strani uzorka od drva bjeljike i srži bijeloga hrasta

HB *Tvrdoća prema Brinellu*	Source / *Izvor*	***SS***	***DF***	***MS***	***F*-Ratio** *F-omjer*	***P*-Value*** *P-vrijednost**
End *Čelo*	Between groups *između skupina*	225.5	1	225.50	3.71	0.0623
	Within groups *unutar skupina*	2063.9	34	60.70		
Side *Bočna strana*	Between groups *između skupina*	69.4	1	69.44	3.08	0.0884
	Within groups *unutar skupina*	767.3	34	22.57		

*$P<0.05$; *SS* - sum of squares, *DF* - degrees of freedom, *MS* - mean square / *$P<0.05$; SS – zbroj kvadrata; DF – stupanj slobode; MS - srednja vrijednost kvadrata*

Table 10 Multiple range tests (95% LSD method) of end and side Brinell hardness (*HB*) for sapwood and heartwood in white oaks
Tablica 10. Višestruka analiza (95% LSD metoda) za usporedbu tvrdoće prema Brinellu (*HB*) na čelu i bočnoj strani uzorka od drva bjeljike i srži bijeloga hrasta

HB *Tvrdoća prema Brinellu*		Count *Broj*	Mean *Srednja vrijednost*	Homog. Groups *Homogene skupine*
End *Čelo*	sapwood *bjeljika*	18	38,0	X
	heartwood *srž*	18	42.9	X
Side *Bočna strana*	sapwood *bjeljika*	18	17.8	X
	heartwood *srž*	18	20.5	X

4 DISCUSSION AND CONCLUSIONS
4. RASPRAVA I ZAKLJUČCI

Our results showed that it is possible to differentiate between white and red oaks based on their wood anatomy as proposed by the literature (Richter and Dallwitz, 2000). Surprisingly, timber with the commercial name oak contained in addition to the expected white oaks *Quercus robur* and *Q. petraea,* also considerable amounts of red oak *Quercus cerris.*

Comparison of the obtained results with the data available in the literature (Table 11) shows that all obtained values varied within the ranges of the published data.

Based on our research, the hypothesis that the mechanical properties of sapwood are inferior to those of heartwood was generally rejected. In case of den-

Table 11 Comparison of the obtained results with density and mechanical properties of investigated white oaks *Quercus robur*, *Q. petrea* and red oak *Q. cerris* from the literature 1*- (Wagenführ, 1996); 2*- (Giordano, 1976); 3*- (Horvat, 1959); 4 *- (Anonymus, 2012); 5 *- (Grosser and Teetz, 1987); mark X in the table indicates missing data in the literature
Tablica 11. Usporedba dobivenih rezultata s podacima o gustoći i mehaničkim svojstvima drva bijelog hrasta *Quercus robur*, *Q. petrea* i drva crvenog hrasta *Q. cerris* iz literature 1*- (Wagenführ, 1996); 2*- (Giordano, 1976); 3*- (Horvat, 1959); 4 *- (Anonymus, 2012); 5 *- (Grosser and Teetz, 1987); oznaka X u tablici znači da u literaturi nema podataka

Oven-dry density / *Gustoća u standardno suhom stanju* kg/m3

	RESULTS		LITERATURE (heartwood)				
	sapwood	heartwood	1*	2*	3*	4*	5*
Q. robur	634	658	390 - 650 - 930	670	388 - 625 - 795	X	390 - 650 - 930
Q. petraea			390 - 650 - 930	670	465 - 662 - 837	X	390 - 650 - 930
Q. cerris	776	767	X	690	781	X	X

Bending strength / *Savojna čvrstoća* MPa

	RESULTS		LITERATURE (heartwood)				
	sapwood	heartwood	1*	2*	3*	4*	5*
Q. robur	86	87	74 - 88 - 105	53 - 108 - 153	58.8 - 92.1 - 98	60 - 110	88
Q. petraea			78 - 110 - 117	53 - 108 - 153	58.8 - 92.1 - 98	60 - 110	110
Q. cerris	115	110	X	65 - 110 - 152	X	75 - 120	X

Modulus of elasticity / *Modul elastičnosti* GPa

	RESULTS		LITERATURE (heartwood)				
	sapwood	heartwood	1*	2*	3*	4*	5*
Q. robur	8,9	9,0	10 - 11.7 - 13.2	10.6 - 12.5 - 14.6	11.5	10.5 - 14.5	11.7
Q. petraea			9.2 - 13 - 13.5	10.6 - 12.5 - 14.6	12.7	10.5 - 14.5	13
Q. cerris	12,4	11,7	X	X	X	10.2 - 15.7	X

Compression strength / *Tlačna čvrstoća* MPa

	RESULTS		LITERATURE (heartwood)				
	sapwood	heartwood	1*	2*	3*	4*	5*
Q. robur	41,6	45,4	54 - 61 - 67	29.4 - 60.8 - 84.3	51	42 - 64	61
Q. petraea			48 - 65 - 70	29.4 - 60.8 - 84.3	23.5 - 37.2 - 43.1	42 - 64	55 - 65
Q. cerris	54,8	51,6	X	36.3 - 57.4 - 83.3	57	42 - 60	X

Brinell end-hardness / *Tvrdoća prema Brinellu na čelu* MPa

	RESULTS		LITERATURE (heartwood)				
	sapwood	heartwood	1*	2*	3*	4*	5*
Q. robur	37,9	42,9	66	X	65,7	X	X
Q. petraea			66	X	41.1 - 67.7 - 97	X	X
Q. cerris	X	X	X	X	64.7 - 77.9 - 96.1	X	X

Brinell side-hardness / *Tvrdoća prema Brinellu na bočnoj strani* MPa

	RESULTS		LITERATURE (heartwood)				
	sapwood	heartwood	1*	2*	3*	4*	5*
Q. robur	17,7	20,5	34	X	X	23 - 42	X
Q. petraea			34	X	X	23 - 42	X
Q. cerris	X	X	X	X	X	22 - 35	X

sity, bending strength and MOE, compression strength and Brinell hardness, the differences between sapwood and heartwood were not significant. A significant difference was only found between the means of compression strength of sapwood and heartwood within the white oaks group. In all cases (density, bending strength, MOE, compression strength), red oak sapwood even had the highest values of all. This is, for example, in line with observations comparing the mechanical properties and extractive content in *Quercus castaneifolia* (Ayobi *et al.*, 2011) and partly in *Larix* sp. (Grabner *et al.*, 2005). The latter showed that extractive content directly affected transverse compression strength and MOE, whereas it was less pronounced in the case of axial compression strength, determined in our case. In Q. cerris mean density of sapwood found to be a little higher in sapwood than in heartwood, although the opposite was normally expected. It may happened due to relatively small size of logs used for specimens.

Our results indicate that the evaluated properties were mainly affected by wood structure. Chemical differences in terms of a higher content of heartwood extractives do not seem to affect these properties (Tsoumis, 1991).

We also rejected the hypothesis that the properties of red oak *Quercus cerris* are inferior to those of white oaks. In all cases, the properties of *Quercus cerris* had even higher values than those of white oaks.

Despite the present results, it cannot be excluded that some of the properties of *Quercus cerris* may be less favorable than those of white oaks. In Slovenia, Italy and Austria, *Quercus cerris* is often used for fuel. One of the problems is that it often has an irregular stem form. This problem may be less pronounced when using it for products such as railway sleepers. One of the differences between white oaks and *Quercus cerris* reported in the literature is natural durability. According to the EN 350-2 (1994) heartwood of *Q. robur* and *Q. petrea* has natural durability class 2 – durable, whereas heartwood of *Q. cerris* is reported to have natural durability class 3 – moderately durable. It should be noted here that natural durability, like other properties, is highly variable in oaks. Humar and co-authors (Humar *et al*., 2008) for instance, reported that the durability of heartwood in white oaks varies with wood structure; they showed that in extreme cases, white oak heartwood can even be as non-durable as beech wood (durability class 5 - not durable) (Humar *et al.*, 2008). In any case, heartwood class 2 must be treated in the case of railway sleepers to achieve a conferred durability that allows its use in hazard class 4 (EN 350-2, 1994). It should also be noted that the heartwood of all three investigated oak species is extremely difficult to be treated (treatability class 4).

Oak sapwood, as the sapwood of any wood species, is not durable (class 5) and must be treated. Fortunately, oak sapwood is easy to be treated (treatability class 1) (EN 350-2, 1994) and adequately treated sapwood can be used in hazard class 4. According to the standards for wooden railway sleeper production (EN 13145, 2012), therefore, sapwood is permitted with oak, provided that it is completely sound before the treatment is applied.

Our results showed that marketed oak timber, in addition to white oaks, also contains red oak *Q. cerris*. Despite the relatively small sample, the variability of wood properties proved to be larger within the groups (white oaks, red oaks, sapwood, and heartwood) than among the groups (white vs. red oaks, sapwood vs. heartwood). The variability of all properties is among the main disadvantages of wood as a raw material. Knowing this is the basis for optimal selection and use of timber for structural purposes.

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