

..Bektaş, Tutuş, Gültekin: The Effect of Sapwood and Heartwood Differences on Mechanical...

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The Effect of Sapwood and Heartwood Differences on Mechanical Properties of Fast-Growing Tree Species

Utjecaj razlika između bjeljike i srži na mehanička svojstva drva brzorastućih vrsta

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ABSTRACT • In most uses where wood material needs impregnation or dimensional stability is essential, the properties of sapwood and heartwood should be taken into account. Also, due to the structural differences between heartwood and sapwood, differences in the strength of wood materials should be predicted. Therefore, the aim of this study was to reveal the differences between the mechanical properties of sapwood and heartwood of some important fast-growing forest trees. For this purpose, two softwoods (*Pinus sylvestris*) and (*Pinus brutia*) and two hardwoods (*Populus usbekistanica*) and (*Eucalyptus grandis*) were selected as test trees. Compression strength parallel to grain (CS \parallel), static quality value (IS), bending strength (MOR), modulus of elasticity (MOE), tensile strength perpendicular to grain (TS \perp), shearing strength parallel to grain (SS \parallel), impact bending strength (IBS), dynamic quality value (ID) and Janka hardness values (JH) of sapwood and heartwood of test trees were determined in laboratory studies. The results of the t-test analysis showed that all mentioned mechanical properties of sapwood and heartwood of test trees were separated from each other as significant, except the shear strength of Eucalyptus, dynamic quality values of red pine and Scots pine and Janka hardness value of red pine. Finally, the results of the study revealed that the differences between sapwood and heartwood strength should be taken into account when wood species are used in constructions and other sensitive areas.

Key words: mechanical properties; sapwood; heartwood; softwoods; hardwoods

SAŽETAK • U većini primjera uporabe drva u kojima je potrebna impregnacija ili je postojanost dimenzija iznimno važna treba uzeti u obzir različita svojstva drva bjeljike i srži. Usto, zbog strukturnih razlika između srži i bjeljike treba predvidjeti i razlike u njihovoj čvrstoći. Cilj je ovog istraživanja bio utvrditi razlike između mehaničkih svojstava srži i bjeljike nekih važnih brzorastućih šumskih vrsta drva. Stoga su za izradu uzoraka odabrane dvije vrste četinjača (*Pinus sylvestris* i *Pinus brutia*) i dvije vrste listača (*Populus usbekistanica* i *Eucalyptus grandis*). U laboratorijskim su uvjetima za uzorke drva četinjača i drva listača određena ova svojstva: tlačna čvrstoća paralelno s vlakancima (CS \parallel), vrijednost statičke kvalitete (IS), čvrstoća na savijanje (MOR), modul elastičnosti (MOE), vlačna čvrstoća okomito na vlakanca (TS \perp), smična čvrstoća paralelno s vlakancima (SS \parallel), čvrstoća drva na udarce (IBS), vrijednost dinamičke kvalitete (ID) i tvrdoća po Janki (JH). Rezultati usporedbe uz pomoć t-testa pokazali su da se istraživana mehanička svojstva drva bjeljike i srži znatno razlikuju, osim smične čvrstoće drva eukalipta, dinamičkih vrijednosti kvalitete drva crvenog bora i običnog bora te tvrdoće drva crvenog bora po Janki. Zaključno, rezultati studije pokazali su da je pri upotrebi drva brzorastućih

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vrsta u graditeljstvu i drugim osjetljivim područjima nužno uzeti u obzir razlike među mehaničkim svojstvima drva bjeljike i srži.

Ključne riječi: mehanička svojstva; bjeljika; srž; drvo četinjača; drvo listača

1 INTRODUCTION

1. UVOD

Wood is composed of sapwood and heartwood resulting from its anatomical structure. The above mentioned wood species differ in appearance and anatomical structure. The sapwood is generally light colored, alive and located between the heartwood and the bark. In fact, the heartwood is formed as a result of sapwood aging. Besides, the formation period of heartwood can be affected by soil, climate and habitat conditions. Tree age, place of growth and tree stand have an important impact on the width of sapwood (Bossard, 1968; Doğu, 2002). When compared with sapwood, the heartwood consisting of extractives is drier, heavier, harder and with lower fiber saturation point and lower hygroscopicity. In addition, the difference between sapwood and heartwood is entirely due to the change in chemical structure (Bozkurt and Erdin, 1997). Generally, heartwood contains more lignin and less cellulose than sapwood (Fengel and Wegener, 1989). Bertaud and Holmbom (2004) reported that heartwood has less cellulose and more lignin than sapwood and almost the same hemicellulose content.

As a result, there are differences between the sapwood and heartwood in terms of physical and mechanical properties. Therefore, physical and mechanical properties of wood should absolutely be taken into consideration when using wood. In some use areas, it is important to know the mechanical properties of sapwood and heartwood.

Cherelli *et al.* (2016) studied density measurements between sapwood and heartwood in three different trees, including eucalyptus grandis, and concluded that there was no significant difference between sapwood and heartwood densities.

In literature, there are few studies on the mechanical properties of sapwood and heartwood of trees in the world and especially in Turkey. Bal and Bektaş (2013) determined some mechanical properties of heartwood and sapwood of *E. Grandis* and found that the sapwood samples provided better mechanical properties than the heartwood samples. However, Merela and Čufar (2013) stated that there was no statistically significant difference between the mechanical properties of the sapwood and heartwood.

In a study on Japanese persimmon performed by Noda *et al.* (2002), the specific gravity, equilibrium moisture content, modulus of rupture, and modulus of elasticity of the blackened heartwood were higher than those of sapwood. Besides, Noack (1963) mentioned that there are no significant differences between the most important physical and technological properties of European oak heartwood and sapwood. The stiffness and strength of the young acacia sapwood were found to be higher than those of heartwood (Hai *et al.* 2010).

Ozalp and Hafizoglu (2008) examined the time-dependent changes in the main components of non-impregnated Scots pine (*P. sylvestris*) and red pine (*P. brutia*) sapwood and heartwood used in water cooling towers.

Moreover, Gültekin (2014) investigated the relationship between the sapwood and heartwood in terms of morphological, anatomical and physical characteristics of some conifers and broadleaf trees. The results obtained in the same study showed that there are statistically significant differences between sapwood and heartwood of most of the properties mentioned above.

In light of the above, the subject of this study is the “comparison of mechanical properties of sapwood and heartwood of Scots pine, spruce, poplar, and eucalyptus, which are Turkey’s industrial forest trees and fast-growing species”.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

The fast-growing tree species yield a minimum of ten cubic meters of wood per hectare per year at the end of the management period (Dwivedi, 1993). The species reaching a diameter value of native or indigenous species at the end of the management period, which is considered 1/3 of the management period applied for native species, are yet defined as fast-growing species (LIS, 1996).

In this study, two softwoods (Scots pine (*Pinus sylvestris* L.) and Turkish red pine (*Pinus brutia* Ten.)) and two broadleaf trees (Asian poplar wood (*Populus usbekistanica* “Afganica”) and eucalyptus (*Eucalyptus grandis*)), accepted as fast-growing species, were selected as test trees according to TS 4176. The average age of experimental trees was as follows: Scots pine - 46, Red pine - 53, Eucalyptus - 20 and poplar - 27. The altitude and slopes of wood samples were as follows: Scots pine - 1900 m and 315, Red pine - 1025 m and 64 %, Eucalyptus - 5 m and 8 % and poplar - 1250 m and 67 %.

1 m-length test specimens were taken between 2 and 4 m from the base in accordance with TS 4176 (1984). Then, the cross-sections of the specimens taken from the logs were sanded in order to identify sapwood and heartwood. In cases where the limit was not very clear, the test samples were taken at a certain distance (approximately 1 cm) from the common boundary between heartwood and sapwood, because knowing the precise boundary between sapwood and heartwood is not necessary for this study. Specimens of sapwood and heartwood were prepared separately for tests according to relevant standards and conditioned at the temperature of 20 ± 2 °C and at the relative humidity of 65 ± 5 %. Then, the mechanical tests, such as compres-

sion strength parallel to grain (including static and specific quality values), elasticity modulus, static bending strength, tensile strength perpendicular to grain, shear strength, dynamic bending strength (including dynamic quality value) and Janka hardness were performed according to TS 2595, TS 2474, TS 2478, TS 2476, TS 3459, TS 2477 and TS 2479, respectively.

As explained in TS 2595, the static and specific quality values are calculated as follows: static quality value = compression strength/(100× D_{12}); specific quality value = compression strength/(100× D_{12}^2) (where: D_{12} is air dry density (g/cm³)). Also, the dynamic quality value is determined in TS 2477 as follows: dynamic quality value = dynamic bending strength/(100× D_0^2) (where: D_0 is oven dry density (g/cm³)).

SPSS 17.0 Independent Samples T-Test was used to determine the differences between sapwood and heartwood.

3 RESULTS AND DISCUSSIONS

3. REZULTATI I RASPRAVA

Table 1 shows the values of the compression strength parallel to grain of sapwood (SW) and heartwood (HW) of the above wood species and the results of Independent Samples T-Test analysis. As can be understood from Table 1, in all wood species, the compression strength values of sapwood and heartwood

($p < 0.05$) differed significantly from each other. When the data are evaluated on the average, it can be seen that the HW values of eucalyptus (39.5 N/mm²) and red pine (65 N/mm²) are higher than SW values and lower in other wood species (26.1 and 29.7 N/mm²). On the other hand, compression strength parallel to fibers of sapwood and heartwood of *Quercus robur* and *Quercus cerris* was researched by Merela and Čufar (2013). According to the results obtained, compression strength of *Quercus robur* sapwood (41.6 N/mm²) is lower than that of heartwood (45.4 N/mm²). This result also applies to *Quercus cerris* (SW: 54.8 and HW: 51.6 N/mm²).

While the increase in density increases the compression strength, the increases in temperature, knots field, amount of resin, and humidity decrease the compression strength (Bektaş, 1997). It can be concluded that the high compression strength measured in the red pine is especially due to the high resin content in this species. Table 2 contains the data of the static quality value, which is accepted as one of the criteria for the quality related to the compression properties of the wood material (Bektaş, 1997; Bozkurt and Göker, 1996). The static quality values of sapwood of wood species shown in Table 2 were statistically ($p < 0.001$) separated from their heartwood.

Static quality values are considered to be of “medium quality” for softwoods when ranging between

Table 1 Compression strength values (I) of sapwood and heartwood of wood species

Tablica 1. Vrijednosti tlačne čvrstoće bjeljike i srži ispitivanih vrsta drva paralelno s vlakancima

| Wood species Vrsta drva | Wood type Tip drva | N | Mean Srednja vrijednost N/mm ² | SD | SE | COV % | t_{value} | Sig. (2-tailed) |
|-------------------------------|-----------------------|----|---|-------|-------|----------|-------------|--------------------|
| Eucalyptus / drvo eukalipta | SW | 48 | 37.8 | 2.295 | 0.331 | 6.07 | -2.961 | 0.041 |
| | HW | 47 | 39.5 | 5.641 | 0.823 | 14.26 | | |
| Poplar wood / drvo topole | SW | 48 | 27.4 | 1.212 | 0.175 | 4.42 | 4.099 | 0.049 |
| | HW | 48 | 26.1 | 1.848 | 0.267 | 7.08 | | |
| Red pine / drvo crvenog bora | SW | 48 | 45.1 | 2.335 | 0.337 | 5.18 | -18.255 | 0.000 |
| | HW | 48 | 65.0 | 7.209 | 1.040 | 11.09 | | |
| Scot pine / drvo običnog bora | SW | 53 | 39.3 | 7.541 | 1.036 | 19.19 | 7.055 | 0.000 |
| | HW | 44 | 29.7 | 5.382 | 0.811 | 18.10 | | |

N – Number of samples / broj uzoraka, SW – Sapwood / bjeljika, HW – Heartwood / srž, SD – Standard deviation / standardna devijacija, SE – Standard error / standardna pogreška, COV – Coefficient of variation / koeficijent varijacije

Table 2 Static quality values of sapwood and heartwood of wood species

Tablica 2. Vrijednosti statičke kvalitete bjeljike i srži ispitivanih vrsta drva

| Wood species Vrsta drva | Wood type Tip drva | N | Mean Srednja vrijednost km* | SD | SE | COV % | t_{value} | Sig. (2-tailed) |
|-------------------------------|-----------------------|----|-----------------------------------|-------|-------|----------|-------------|--------------------|
| Eucalyptus / drvo eukalipta | SW | 48 | 0.6 | 0.055 | 0.008 | 9.37 | -36.567 | 0.000 |
| | HW | 47 | 1.1 | 0.072 | 0.011 | 6.79 | | |
| Poplar wood / drvo topole | SW | 48 | 1.1 | 0.037 | 0.005 | 3.37 | 41.549 | 0.005 |
| | HW | 48 | 0.8 | 0.031 | 0.005 | 3.91 | | |
| Red pine / drvo crvenog bora | SW | 48 | 0.8 | 0.047 | 0.007 | 5.56 | -9.772 | 0.035 |
| | HW | 48 | 1.0 | 0.103 | 0.015 | 10.24 | | |
| Scot pine / drvo običnog bora | SW | 53 | 0.9 | 0.046 | 0.007 | 5.13 | 12.870 | 0.048 |
| | HW | 44 | 0.7 | 0.087 | 0.013 | 12.39 | | |

*The unit of static quality value is km (Bozkurt and Göker, 1996). / Jedinica vrijednosti statičke kvalitete je km (Bozkurt i Göker, 1996.). N – Number of samples / broj uzoraka, SW – Sapwood / bjeljika, HW – Heartwood / srž, SD – Standard deviation / standardna devijacija, SE – Standard error / standardna pogreška, COV – Coefficient of variation / koeficijent varijacije

Table 3 Specific quality values of sapwood and heartwood of wood species**Tablica 3.** Vrijednosti specifične kvalitete bjeljike i srži ispitivanih vrsta drva

| Wood species <i>Vrsta drva</i> | Wood type <i>Tip drva</i> | N | Mean <i>Srednja vrijednost</i> km* | SD | SE | COV % | <i>t</i> _{value} | Sig. (2-tailed) |
|--------------------------------------|------------------------------|----|--|-------|-------|----------|---------------------------|--------------------|
| Eucalyptus / <i>drvo eukalipta</i> | SW | 48 | 0.9 | 0.147 | 0.021 | 16.28 | -25.904 | 0.000 |
| | HW | 47 | 1.8 | 0.173 | 0.025 | 9.88 | | |
| Poplar wood / <i>drvo topole</i> | SW | 48 | 2.2 | 0.100 | 0.014 | 4.52 | 2.846 | 0.053 |
| | HW | 48 | 2.1 | 0.144 | 0.021 | 6.77 | | |
| Red pine / <i>drvo crvenog bora</i> | SW | 48 | 1.6 | 0.125 | 0.018 | 7.86 | 0.900 | 0.370 |
| | HW | 48 | 1.6 | 0.182 | 0.026 | 11.70 | | |
| Scot pine / <i>drvo običnog bora</i> | SW | 48 | 2.0 | 0.111 | 0.016 | 5.65 | 6.644 | 0.000 |
| | HW | 43 | 1.7 | 0.245 | 0.037 | 14.40 | | |

*The unit of specific quality value is km (Bozkurt and Göker, 1996). / *Jedinica vrijednosti specifične kvalitete je km (Bozkurt i Göker, 1996.).*
 N – Number of samples / *broj uzoraka*, SW – Sapwood / *bjeljika*, HW – Heartwood / *srž*, SD – Standard deviation / *standardna devijacija*, SE – Standard error / *standardna pogreška*, COV – Coefficient of variation / *koeficijent varijacije*

0.80-0.95, of “low quality” below these limits and of “good quality” above these values. Besides, it is accepted that static quality values for hardwoods are of “medium quality” in the range of 0.60-0.70, of “low quality” below these values and of “good quality” above these limits (Bozkurt and Göker, 1996; Bozkurt and Erdin 1997). According to these classifications, eucalyptus heartwood (1.1), poplar sapwood (1.1) and red pine heartwood (1.0) have “good quality” properties in terms of their compression characteristics. At the same time, except for Scots pine heartwood, the sapwood and heartwood of other wood species are considered to be of “medium quality”. Also, Scots pine heartwood (0.6) has a “low quality”.

Another “quality indicator” for wood is the specific quality value that is calculated from the relationship between compression strength and density, given in Table 3 (Bozkurt and Göker, 1996). The specific quality values calculated for each tree species and statistical analysis results are presented in Table 3.

Statistically significant differences were found in the other two species, while there was no significant difference between the specific quality values of poplar and red pine wood. In addition, as can be seen from the averages calculated in Table 3, sapwood and heartwood specific quality values showed a mixed composition in term of size and smallness.

When the bending strength values of the test specimens are evaluated according to the data given in

Table 4, it can be seen that there is a significant difference between sapwood and heartwood values at $p < 0.001$ significance level. In addition, the bending strength values (94.1 and 74.9 N/mm²) of eucalyptus and Scots pine sapwood were higher than those of heartwood (61.3 and 65.8 N/mm²). The bending strength values (48.2 and 68.5 N/mm²) of poplar and red pine sapwood were also measured as lower than those of heartwood (56.4 and 80.9 N/mm²). These results are consistent with the bending strength values of acacia wood (SW: 150.3 and HW: 132.1 N/mm²) determined by Hai *et al.* (2010).

Again, Junior and Moreschi (2003) determined the oven dry density of 0.54 g/cm³ and bending strength of 73.4 N/mm² in Loblolly pine (*Pinus taeda*) mature wood. As is known, the mature wood of a tree largely corresponds to its heartwood (Bozkurt and Erdin, 1997).

Table 5 shows the results of t-test analysis of elasticity modulus values of sapwood and heartwood of the wood species. According to t-test results, it is understood that there is a significant difference (at the level of $p < 0.001$) between the elasticity modulus values of sapwood and heartwood in all of the test specimens. On the other hand, the mutual size distribution of the elastic modulus values of sapwood and heartwood showed similarity to those of bending strength values. To be specific, the elasticity modulus of eucalyptus and Scots pine sapwood taken from the test specimens (7280.9 and 6539.3 N/mm²) was higher

Table 4 Static bending strength (MOR) values of sapwood and heartwood of wood species**Tablica 4.** Vrijednosti čvrstoće na savijanje bjeljike i srži ispitivanih vrsta drva

| Wood species <i>Vrsta drva</i> | Wood type <i>Tip drva</i> | N | Mean <i>Srednja vrijednost</i> N/mm ² | SD | SE | COV % | <i>t</i> _{value} | Sig. (2-tailed) |
|--------------------------------------|------------------------------|----|--|--------|-------|----------|---------------------------|--------------------|
| Eucalyptus / <i>drvo eukalipta</i> | SW | 35 | 94.1 | 9.234 | 1.561 | 9.81 | 12.948 | 0.000 |
| | HW | 33 | 61.3 | 11.594 | 2.018 | 18.92 | | |
| Poplar wood / <i>drvo topole</i> | SW | 42 | 48.2 | 3.211 | 0.496 | 6.67 | -9.489 | 0.000 |
| | HW | 39 | 56.4 | 4.574 | 0.732 | 8.10 | | |
| Red pine / <i>drvo crvenog bora</i> | SW | 42 | 68.5 | 10.467 | 1.615 | 15.27 | -4.165 | 0.000 |
| | HW | 34 | 80.9 | 15.259 | 2.617 | 18.87 | | |
| Scot pine / <i>drvo običnog bora</i> | SW | 32 | 74.9 | 5.541 | 0.980 | 7.40 | 4.944 | 0.000 |
| | HW | 36 | 65.8 | 8.940 | 1.490 | 13.58 | | |

N – Number of samples / *broj uzoraka*, SW – Sapwood / *bjeljika*, HW – Heartwood / *srž*, SD – Standard deviation / *standardna devijacija*, SE – Standard error / *standardna pogreška*, COV – Coefficient of variation / *koeficijent varijacije*

Table 5 Modulus of elasticity (MOE) values of sapwood and heartwood of wood species

Tablica 5. Vrijednosti modula elastičnosti bjeljike i srži ispitivanih vrsta drva

| Wood species <i>Vrsta drva</i> | Wood type <i>Tip drva</i> | <i>N</i> | Mean <i>Srednja vrijednost</i> N/mm ² | <i>SD</i> | <i>SE</i> | <i>COV</i> % | <i>t</i> _{value} | Sig. (2-tailed) |
|--------------------------------------|------------------------------|----------|--|-----------|-----------|-----------------|---------------------------|--------------------|
| Eucalyptus / <i>drvo eukalipta</i> | SW | 35 | 7280.9 | 580.35 | 98.10 | 7.97 | 13.219 | 0.000 |
| | HW | 33 | 5264.5 | 676.19 | 117.71 | 12.84 | | |
| Poplar wood / <i>drvo topole</i> | SW | 42 | 4179.1 | 293.55 | 45.30 | 7.02 | -5.046 | 0.000 |
| | HW | 39 | 4551.2 | 368.10 | 58.94 | 8.09 | | |
| Red pine / <i>drvo crvenog bora</i> | SW | 42 | 6118.0 | 1189.85 | 183.60 | 19.45 | -4.671 | 0.000 |
| | HW | 34 | 7496.8 | 1382.97 | 237.18 | 18.45 | | |
| Scot pine / <i>drvo običnog bora</i> | SW | 32 | 6539.3 | 425.63 | 75.24 | 6.51 | 10.851 | 0.000 |
| | HW | 36 | 5193.8 | 575.12 | 95.85 | 11.07 | | |

N – Number of samples / broj uzoraka, SW – Sapwood / bjeljika, HW – Heartwood / srž, *SD* – Standard deviation / standardna devijacija, *SE* – Standard error / standardna pogreška, *COV* – Coefficient of variation / koeficijent varijacije

than that of heartwood, while the elasticity modulus of poplar and red pine heartwood (4551.2 and 7496.8 N/mm²) was higher than that of sapwood. The elasticity modulus values of Acacia sapwood and heartwood were found to be 20690 and 18800 N/mm², respectively (Hai *et al.* 2010). Another study on the subject (Junior and Moreschi, 2003) reported that the modulus of elasticity of *Pinus taeda* mature wood is 10020 N/mm².

The data in Table 6 shows no difference in the shear strength of sapwood and heartwood of the test specimens prepared from eucalyptus wood. However, the shear strengths of sapwood and heartwood of poplar wood, red pine and Scots pine wood were statistically separated from each other.

Likewise, as shown in Table 6, the shear strength values (eucalyptus 9.1 N/mm², poplar 4 N/mm², Scots pine 6.3 N/mm²) of the sapwood, except those of red pine, were found to be higher than those of the heartwood (eucalyptus 8.5 N/mm², poplar 3.2 N/mm², Scots pine 4.2 N/mm²). The shear strength values of the red pine sapwood and heartwood were calculated as 4.5 N/mm² and 7.9 N/mm², respectively. This difference in red pine is likely due to factors (resin, etc.) related to anatomical structures of the specimens, especially those that increase the density of the heartwood. In a study, Bao *et al.* (2001) found that the shear strength values of the heartwood were lower than those of the sapwood. These results are consistent with the present study, except for red pine species. The shear strength of red pine sapwood and heartwood was determined by

Özkaya (2013) as 2.3 N/mm² and 2.5 N/mm², respectively. In another study, Cherelli *et al.* (2016) reported that the density results showed no statistical difference between heartwood and sapwood of *eucalyptus grandis*. Here, the absence ($p > 0.372$) of a statistically significant difference between heartwood and sapwood of eucalyptus can be explained by this determination.

According to the results of the t-test performed on the tensile strength perpendicular to fiber of sapwood and heartwood of the wood species shown in Table 7, it can be concluded that the SW and HW of the species have statistically significant differences in the confidence level $p < 0.001$.

When the values of tensile strength perpendicular to fibers are evaluated in terms of sapwood and heartwood height, the above mentioned strength values also apply here. Unlike other species, the calculated tensile strength perpendicular to fibers of red pine sapwood (3.4 N/mm²) is higher than that of heartwood (2.1 N/mm²). While the highest difference between the tensile strength of sapwood and heartwood was obtained for eucalyptus samples (1.4 N/mm²), the lowest difference was obtained for red pine (-1.3 N/mm²). The tensile strength perpendicular to fibers of the eucalyptus sapwood and heartwood were determined by Bal and Bektaş (2013) as 5.0 and 3.7 N/mm², respectively. The cellulose content of sapwood is about 1-3 % higher than that of heartwood (Bektaş, 1997; Bektaş *et al.*, 2017). As is known, this increase in cellulose content increases the tensile strength of wood material.

Table 6 Shear strength values of sapwood and heartwood of wood species

Tablica 6. Vrijednosti smične čvrstoće bjeljike i srži ispitivanih vrsta drva

| Wood species <i>Vrsta drva</i> | Wood type <i>Tip drva</i> | <i>N</i> | Mean <i>Srednja vrijednost</i> N/mm ² | <i>SD</i> | <i>SE</i> | <i>COV</i> % | <i>t</i> _{value} | Sig. (2-tailed) |
|--------------------------------------|------------------------------|----------|--|-----------|-----------|-----------------|---------------------------|--------------------|
| Eucalyptus / <i>drvo eukalipta</i> | SW | 33 | 9.1 | 2.322 | 0.404 | 25.46 | 0.901 | 0.372 |
| | HW | 22 | 8.5 | 2.360 | 0.503 | 27.64 | | |
| Poplar wood / <i>drvo topole</i> | SW | 24 | 4.0 | 0.905 | 0.185 | 22.41 | 3.680 | 0.001 |
| | HW | 24 | 3.2 | 0.592 | 0.121 | 18.34 | | |
| Red pine / <i>drvo crvenog bora</i> | SW | 32 | 4.5 | 2.145 | 0.379 | 47.77 | -5.995 | 0.000 |
| | HW | 25 | 7.9 | 2.154 | 0.431 | 27.16 | | |
| Scot pine / <i>drvo običnog bora</i> | SW | 25 | 6.3 | 3.017 | 0.603 | 47.73 | 3.533 | 0.001 |
| | HW | 37 | 4.2 | 1.645 | 0.270 | 38.96 | | |

N – Number of samples / broj uzoraka, SW – Sapwood / bjeljika, HW – Heartwood / srž, *SD* – Standard deviation / standardna devijacija, *SE* – Standard error / standardna pogreška, *COV* – Coefficient of variation / koeficijent varijacije

Table 7 Tensile strength values of sapwood and heartwood of wood species**Tablica 7.** Vrijednosti vlačne čvrstoće bjeljike i srži ispitivanih vrsta drva

| Wood species <i>Vrsta drva</i> | Wood type <i>Tip drva</i> | <i>N</i> | Mean <i>Srednja vrijednost</i> N/mm ² | <i>SD</i> | <i>SE</i> | <i>COV</i> % | <i>t</i> _{value} | Sig. (2-tailed) |
|--------------------------------------|------------------------------|----------|--|-----------|-----------|-----------------|---------------------------|--------------------|
| Eucalyptus / <i>drvo eukalipta</i> | SW | 38 | 4.4 | 0.322 | 0.052 | 7.35 | 16.820 | 0.000 |
| | HW | 43 | 3.0 | 0.419 | 0.064 | 14.09 | | |
| Poplar wood / <i>drvo topole</i> | SW | 38 | 2.2 | 0.506 | 0.082 | 23.11 | 6.154 | 0.000 |
| | HW | 37 | 1.6 | 0.299 | 0.049 | 18.74 | | |
| Red pine / <i>drvo crvenog bora</i> | SW | 46 | 2.1 | 0.559 | 0.082 | 27.51 | -8.361 | 0.000 |
| | HW | 41 | 3.4 | 0.921 | 0.144 | 27.23 | | |
| Scot pine / <i>drvo običnog bora</i> | SW | 34 | 2.5 | 0.682 | 0.117 | 27.81 | 6.179 | 0.000 |
| | HW | 44 | 1.7 | 0.433 | 0.065 | 25.99 | | |

N – Number of samples / broj uzoraka, SW – Sapwood / bjeljika, HW – Heartwood / srž, *SD* – Standard deviation / standardna devijacija, *SE* – Standard error / standardna pogreška, *COV* – Coefficient of variation / koeficijent varijacije

Table 8 shows the findings obtained as a result of experiments and analyses performed to determine the dynamic bending strength differences in sapwood and heartwood of test trees. Based on the data in the table, resulting from the t-test, it can be seen that there are significant differences between the dynamic bending strengths of sapwood and heartwood of all wood species.

The dynamic bending strengths (eucalyptus 0.085 Nm/mm², poplar wood 0.035 Nm/mm², Scots pine 0.047 Nm/mm²) of the wood species sapwood, except for red pine, were calculated as higher than those of heartwood (eucalyptus 0.042 Nm/mm², poplar wood 0.027 Nm/mm², Scots pine 0.029 Nm/mm²). In contrast to other wood species, the dynamic bending strength value (0.041 Nm/mm²) of the red pine heartwood was

measured higher than that of sapwood (0.027 Nm/mm²). The dynamic bending strength of sapwood and heartwood of eucalyptus was determined as 0.095 Nm/mm² and 0.057 Nm/mm², respectively (Bal and Bektaş 2013). These results are consistent with the dynamic bending strength values calculated for the wood specimens other than red pine. Some studies have reported that the dynamic bending strengths of *E. camedulensis* (Awan *et al.*, 2012), *E. Grandis* (Bektaş *et al.*, 2008), *P. brutia* (Bektaş *et al.*, 2008) and *P. sylvestris* (Dündar, 2005) were found to be 0.06, 0.05, 0.04 and 0.05 Nm/mm², respectively. According to these results, it can be said that the average values (eucalyptus 0.06 Nm/mm², poplar 0.03 Nm/mm², red pine 0.03 Nm/mm² and Scots pine 0.04 Nm/mm²) of dynamic bending strength of

Table 8 Dynamic (impact) bending strength values of sapwood and heartwood of wood species**Tablica 8.** Vrijednosti čvrstoće na udarce bjeljike i srži ispitivanih vrsta drva

| Wood species <i>Vrsta drva</i> | Wood type <i>Tip drva</i> | <i>N</i> | Mean <i>Srednja vrijednost</i> Nm/mm ² | <i>SD</i> | <i>SE</i> | <i>COV</i> % | <i>t</i> _{value} | Sig. (2-tailed) |
|--------------------------------------|------------------------------|----------|---|-----------|-----------|-----------------|---------------------------|--------------------|
| Eucalyptus / <i>drvo eukalipta</i> | SW | 34 | 0.085 | 0.017 | 0.003 | 19.28 | 12.781 | 0.000 |
| | HW | 32 | 0.042 | 0.010 | 0.002 | 23.46 | | |
| Poplar wood / <i>drvo topole</i> | SW | 42 | 0.035 | 0.007 | 0.001 | 20.88 | 5.367 | 0.000 |
| | HW | 39 | 0.027 | 0.005 | 0.001 | 18.74 | | |
| Red pine / <i>drvo crvenog bora</i> | SW | 43 | 0.027 | 0.009 | 0.001 | 32.07 | -4.057 | 0.000 |
| | HW | 34 | 0.041 | 0.020 | 0.004 | 49.31 | | |
| Scot pine / <i>drvo običnog bora</i> | SW | 32 | 0.047 | 0.008 | 0.002 | 17.65 | 8.116 | 0.000 |
| | HW | 33 | 0.029 | 0.009 | 0.002 | 31.60 | | |

N – Number of samples / broj uzoraka, SW – Sapwood / bjeljika, HW – Heartwood / srž, *SD* – Standard deviation / standardna devijacija, *SE* – Standard error / standardna pogreška, *COV* – Coefficient of variation / koeficijent varijacije

Table 9 Dynamic quality values of sapwood and heartwood of wood species**Tablica 9.** Vrijednosti dinamičke kvalitete bjeljike i srži ispitivanih vrsta drva

| Wood species <i>Vrsta drva</i> | Wood type <i>Tip drva</i> | <i>N</i> | Mean <i>Srednja vrijednost</i> | <i>SD</i> | Quality class <i>Klasa kvalitete</i> | <i>COV</i> % | <i>t</i> _{value} | Sig. (2-tailed) |
|--------------------------------------|------------------------------|----------|-----------------------------------|-----------|---|-----------------|---------------------------|--------------------|
| Eucalyptus / <i>drvo eukalipta</i> | SW | 34 | 2.9 | 0.601 | “good” | 20.48 | 8.207 | 0.000 |
| | HW | 32 | 1.7 | 0.592 | “fair” | 34.29 | | |
| Poplar wood / <i>drvo topole</i> | SW | 42 | 2.8 | 0.586 | “good” | 21.15 | 8.866 | 0.000 |
| | HW | 39 | 1.1 | 0.643 | “low” | 57.56 | | |
| Red pine / <i>drvo crvenog bora</i> | SW | 43 | 0.9 | 0.414 | “low” | 47.72 | -1.675 | 0.093 |
| | HW | 34 | 1.1 | 0.573 | “fair” | 54.28 | | |
| Scot pine / <i>drvo običnog bora</i> | SW | 32 | 2.1 | 0.418 | “fair” | 19.82 | 0.380 | 0.705 |
| | HW | 33 | 2.1 | 0.625 | “fair” | 30.36 | | |

N – Number of samples / broj uzoraka, SW – Sapwood / bjeljika, HW – Heartwood / srž, *SD* – Standard deviation / standardna devijacija, *SE* – Standard error / standardna pogreška, *COV* – Coefficient of variation / koeficijent varijacije

Table 10 Janka hardness value* of sapwood and heartwood of wood species
Tablica 10. Vrijednosti tvrdoće po Janki* bjeljike i srži ispitivanih vrsta drva

| Wood species <i>Vrsta drva</i> | Wood type <i>Tip drva</i> | MD | N | Mean <i>Srednja vrijednost</i> N/mm ² | SD | SE | COV % | t _{value} | Sig. (2-tailed) |
|--|------------------------------|------|----|--|-------|-------|----------|--------------------|--------------------|
| Eucalyptus <i>drvo eukalipta</i> | SW | R | 24 | 47.1 | 2.960 | - | 6.28 | 13.393 | 0.000 |
| | | T | 24 | 53.6 | 5.275 | - | 9.84 | | |
| | | L | 24 | 63.9 | 3.654 | - | 5.72 | | |
| | | AVE. | 24 | 54.9 | 2.673 | 0.546 | 4.78 | | |
| | HW | R | 35 | 27.6 | 6.246 | - | 22.61 | | |
| | | T | 35 | 35.7 | 6.195 | - | 17.37 | | |
| | | L | 35 | 52.0 | 7.506 | - | 14.44 | | |
| | | AVE. | 35 | 38.4 | 5.585 | 0.944 | 14.54 | | |
| Poplar wood <i>drvo topole</i> | SW | R | 48 | 14.0 | 1.393 | - | 9.93 | 24.448 | 0.000 |
| | | T | 48 | 11.4 | 1.789 | - | 15.68 | | |
| | | L | 48 | 24.5 | 1.367 | - | 5.57 | | |
| | | AVE. | 48 | 16.7 | 1.128 | 0.163 | 6.77 | | |
| | HW | R | 40 | 9.8 | 1.365 | - | 13.98 | | |
| | | T | 40 | 9.5 | 1.511 | - | 15.94 | | |
| | | L | 40 | 14.2 | 1.567 | - | 11.05 | | |
| | | AVE. | 40 | 11.1 | 0.955 | 0.151 | 8.57 | | |
| Red pine <i>drvo crvenog bora</i> | SW | R | 47 | 30.1 | 1.778 | - | 5.91 | 0.229 | 0.819 |
| | | T | 47 | 29.7 | 1.507 | - | 5.08 | | |
| | | L | 47 | 48.5 | 4.650 | - | 9.58 | | |
| | | AVE. | 47 | 36.1 | 1.957 | 0.285 | 36.1 | | |
| | HW | R | 42 | 32.0 | 7.262 | - | 22.72 | | |
| | | T | 42 | 35.2 | 4.795 | - | 13.63 | | |
| | | L | 42 | 40.6 | 6.006 | - | 14.79 | | |
| | | AVE. | 42 | 35.9 | 5.140 | 0.793 | 35.9 | | |
| Scots pine <i>drvo običnog bora</i> | SW | R | 39 | 26.1 | 8.186 | - | 31.38 | 15.933 | 0.000 |
| | | T | 39 | 23.2 | 3.677 | - | 15.85 | | |
| | | L | 39 | 39.2 | 3.120 | - | 7.96 | | |
| | | AVE. | 39 | 29.5 | 3.616 | 0.579 | 12.26 | | |
| | HW | R | 38 | 16.5 | 3.789 | - | 22.95 | | |
| | | T | 38 | 14.4 | 2.707 | - | 18.75 | | |
| | | L | 38 | 24.3 | 3.926 | - | 16.15 | | |
| | | AVE. | 38 | 18.4 | 2.323 | 0.377 | 12.61 | | |

* t-test analyses were based on average values / t-test temeljen je na srednjim vrijednostima, MD – Measurement directions / smjer mjerenja, N – Number of samples / broj uzoraka, SW – Sapwood / bjeljika, HW – Heartwood / srž, SD – Standard deviation / standardna devijacija, SE – Standard error / standardna pogreška, COV – Coefficient of variation / koeficijent varijacije

sapwood and heartwood given in Table 8 are consistent with the literature. The criteria and analysis results related to the dynamic quality value, which is one of the indicators of the impact quality of wood material, are given in Table 9.

In the column “quality class” given in Table 9, the dynamic quality groups based on the evaluation of wood species are as follows; eucalyptus: $ID < 1$ is “low quality”, $1 < ID < 2$ is “fair quality”, $2 < ID$ is “good quality”; poplar: $ID < 1.5$ is “low quality”, $1.5 < ID < 2.5$ is “fair quality”, $2.5 < ID$ is “good quality”; red pine and Scots pine: $ID < 1.0$ is “low quality”, $1.0 < ID < 2.5$ is “fair quality”, $2.5 < ID$ is “good quality” (Bozkurt and Göker 1996).

When the dynamic quality values of heartwood and sapwood were compared statistically, there were significant differences in eucalyptus and poplar specimens, but no meaningful difference was found between red pine and Scots pine. According to the classification of the dynamic quality values in Table 9, eucalyptus and poplar sapwood was evaluated as “good quality”,

eucalyptus, red pine and Scots pine heartwood as “fair quality” and poplar HW and red pine SW as “low quality”. Some studies by Kollmann and Cote (1968), Korkut and Güller, (2008) stated that European Hop-hornbeam has good shock quality according to dynamic quality value.

Table 10 shows the results of the statistical analysis of the hardness values calculated separately for radial (R), tangential (T), and longitudinal (L) sections in sapwood and heartwood of test trees. Considering the t-test results in the same table, it can easily be seen that there is a significant difference in $p < 0.001$ confidence level between sapwood and heartwood of other species except for red pine.

When Janka hardness values are taken into consideration, it will be understood that the sapwood hardness is higher than heartwood hardness, except for red pine wood. Here, it can be said that the obtained hardness values were well correlated with the density of the wood species. It was determined by Gültekin (2014) that sapwood densities of Scots pine, eucalyptus and

poplar were higher than those of heartwood densities, while there is an opposite relationship for red pine wood. Also, Bal and Bektaş (2013) studied the Janka hardness values of eucalyptus sapwood and heartwood on the basis of directions, in the cross section and tangential directions, and they found that the hardness of heartwood was higher than that of sapwood. In the radial direction, the hardness of sapwood was found higher.

Bektaş (1997) stated that the thickness of the cell walls, besides the density effect, increased wood hardness. Gültekin (2014) determined that the cell wall thicknesses of Scots pine, red pine and eucalyptus wood were found to be the maximum. Besides, the annual ring width is one of the factors that affects wood hardness. So, the hardness value increases as the annual ring expands in the pine trees (Örs and Keskin, 2008). Naidoo *et al.* (2010) reported that “many eucalypt species do not show distinct growth rings because cambial activity does not show a strong response to seasonal variation in climate”. Also, the same research confirmed that “*Eucalyptus grandis*, one of the most important commercial hardwood species in South Africa, is a species that does not have well-defined growth rings”.

4 CONCLUSION

4. ZAKLJUČAK

In this study, differences between the mechanical properties of sapwood and heartwood of some fast-growing forest trees (Eucalyptus, poplar, red pine and Scots pine) were investigated and the main findings are given below:

- According to t-tests analyses, it was found that the difference between the mechanical properties of sapwood and heartwood of experimental wood species was statistically significant.

- According to the results of this study, the mechanical properties of the wood species, with statistically significant differences between sapwood and heartwood, can be listed as follows: compression strength (for all trees), static quality value (for all trees), specific quality value (for all trees except for Scots pine), static bending strength (for all trees), modulus of elasticity (for all trees), shear strength (for all trees except for Eucalyptus), tensile strength (for all trees), dynamic bending strength (for all trees), dynamic quality value (for all trees except for Scots pine and red pine) and Janka hardness (for all trees except for red pine).

- Also, when comparing sapwood and heartwood, no significant difference could be determined in the shear strength of eucalyptus, dynamic quality values of red pine and Scots pine, and Janka hardness values of red pine.

- The mechanical properties of sapwood were higher than those of heartwood, except for red pine wood. It is thought that this situation with red pine is related to the resin contained in the samples.

- These differences between the mechanical properties of sapwood and heartwood should be taken

into account in the use areas that require attention, especially in wooden structures in seismic regions. However, differences in natural durability between sapwood and heartwood should also be taken into account. As known, the natural durability of sapwood is higher than that of heartwood due to its extractive content (Bozkurt and Göker, 1996).

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