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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

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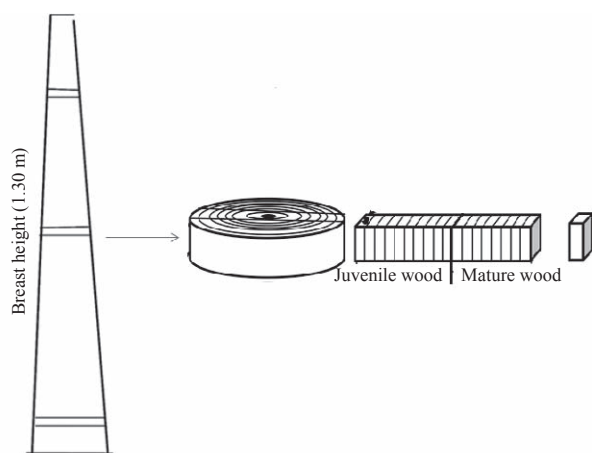
Figure 1 Sawing pattern used on each stem section for the analysis of physical and mechanical wood properties
Slika 1. Prikaz mjesta uzimanja uzoraka sa stabla za analizu fizikalnih i mehaničkih svojstava drva

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):

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

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

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

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

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/m³. 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/m³. 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/m³; 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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