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The Effect of Different Relative Humidity Conditions on Mechanical Properties of Historical Fir Wood Under the Influence of Natural Aging

Utjecaj relativne vlažnosti zraka na mehanička svojstva ostarjelog drva jele izloženoga prirodnom starenju

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ABSTRACT • *Wood undergoes degradation and aging due to various physical and biological factors throughout its lifespan. Among these factors, environmental conditions such as relative humidity, temperature, rainfall, and UV radiation play a crucial role in the physical, chemical, and biological deterioration of wood. In this study, the effects of relative humidity on the density, bending strength, and compressive strength of wood were investigated. Fir beam elements from a traditional wooden structure, estimated to be approximately 150 years old, and freshly cut fir wood specimens were tested under relative humidity conditions of (30 ± 5) %, (65 ± 5) %, (85 ± 5) %, and (95 ± 5) % at a temperature of (20 ± 2) °C. A one-way ANOVA analysis was conducted to evaluate the effects and interactions of different relative humidity conditions on density, bending strength, and compressive strength for both naturally aged fir and freshly cut fir specimens. The results indicate that naturally aged fir wood exhibits greater stability in terms of density; however, strength loss is more pronounced under high relative humidity conditions. These findings suggest that natural aging has a significant impact on the preservation of wooden structures with historical and cultural value and contribute to a better understanding of such structures.*

KEYWORDS: *fir; natural aging; relative humidity; historical wood*

SAŽETAK • *Drvo je tijekom svoga životnog vijeka zbog raznih fizičkih i bioloških čimbenika podložno razgradnji i starenju. Među tim čimbenicima odlučujući utjecaj na fizičko, kemijsko i biološko propadanje drva imaju relativna vlažnost zraka, temperatura, padaline i UV zračenje. U ovom su istraživanju ispitivani učinci relativne vlažnosti zraka na gustoću drva, čvrstoću na savijanje i čvrstoću na tlak. Elementi jelovih greda iz tradicionalne drvene konstrukcije, približne procijenjene starosti od 150 godina, i uzorci svježe posječene jelovine ispitani su pri relativnoj vlažnosti zraka 30 ± 5 %; 65 ± 5 %; 85 ± 5 % i 95 ± 5 % te pri temperaturi 20 ± 2 °C. Provedena je jednosmjerna*

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ANOVA analiza kako bi se procijenili učinci i interakcije različitih uvjeta relativne vlažnosti zraka na gustoću, čvrstoću na savijanje i čvrstoću na tlak prirodno ostarjelih i svježe posječenih uzoraka jelovine. Rezultati su pokazali da prirodno ostarjela jelovina pokazuje veću stabilnost u smislu gustoće, međutim, njezin gubitak čvrstoće u uvjetima visoke relativne vlažnosti zraka veći je od gubitka čvrstoće uzoraka svježe posječenog drva. Ti rezultati sugeriraju da prirodno starenje znatno utječe na očuvanje drvenih konstrukcija povijesne i kulturne vrijednosti te pridonose boljem razumijevanju tih konstrukcija.

KLJUČNE RIJEČI: *jelovina; prirodno starenje; relativna vlažnost; ostarjelo drvo*

1 INTRODUCTION
1. UVOD

Wood is a natural polymer primarily composed of cellulose, hemicellulose, and lignin. These components provide structural support to the living tree and confer a certain degree of resistance against microorganisms. Due to the partially crystalline nature of cellulose in wood, it exhibits some resistance to microbial attack. Additionally, lignin, which consists of phenylpropane units, functions as a heterogeneous polymer and offers considerable resistance to certain decay fungi (Scheffer and Morrell, 1998).

Wood is a natural material and, like many other natural materials found in nature, it is hygroscopic, meaning it absorbs moisture from its surroundings. The moisture interaction between wood and the surrounding atmosphere varies depending on the relative humidity and temperature of the air, as well as the existing moisture content in the wood (Glass and Zelinka, 2021). From a materials science perspective, the relative humidity range between 0 % and approximately 95 - 98 % is generally referred to as the *"hygroscopic moisture range"*, whereas humidity levels exceeding this threshold are termed the *"over-hygroscopic moisture range"*. The dominant mechanisms of moisture absorption in wood behave differently within these two ranges. In the hygroscopic range, water primarily binds to the hydrogen bonds in the cell walls. In the over-hygroscopic range, water uptake predominantly occurs through capillary condensation within macro voids, such as cell lumina and pit chambers, external to the cell walls. This over-hygroscopic range is also the moisture level at which fungal decay in wood occurs (Fredriksson, 2019).

The moisture content in wood has a significant impact on its performance, influencing important material properties such as resistance to degradation, mechanical properties, and dimensional stability (Thybring and Fredriksson, 2021). In the short term, moisture in wood often leads to surface deterioration, which can be mitigated by protective coatings such as varnish, lacquer, or paint (Glass and Zelinka, 2021). However, the long-term effects of moisture fluctuations become more pronounced, particularly in humid and warm regions where atmospheric moisture levels are high. For instance, prolonged exposure to varying relative humidity reduces the long-term strength of wood elements under load. Additionally, it exacerbates creep effects, leading to excessive deformation, cracking, or premature failure (Wang *et al*., 2021).

Many physical environmental conditions, such as relative humidity, not only play a role in the degradation of wood but also influence its aging mechanisms. The aging process in wood begins when a tree is felled. In the absence of microbial influence, changes in the chemical components of wood occur very slowly and are dependent on environmental conditions (Fengel, 1991). On the other hand, Aydın and Aydın (2020) noted that the degradation period is not only dependent on the type and conditions of the environment, such as the wood contact with soil, but also on the region location, the material position, and the wood species. Various studies in the literature have examined the material properties, general behavior, and condition of wood under the influence of different physical factors (such as sunlight, temperature, and humidity) during natural aging. One such study was conducted by Matsuo *et al*. (2011). In this study, the color properties of wood samples exposed to natural aging effects and those subjected to temperatures between 90 °C and 180 °C were compared. The study concluded that natural aging causes a slow and slight oxidation of wood color, while thermal treatment accelerates the color changes occurring during aging. Popescu *et al*. (2009) used X-ray photoelectron spectroscopy (XPS) to analyze wood samples from different-aged and stored linden trees. The study analyzed the chemical changes on the surfaces of six-year-old, undamaged wood and degraded wood samples approximately 150, 180, and 250 years old using the XPS method. The study found that the surface of the 150-year-old wood samples (early aging stage) exhibited significant chemical changes, with the highest ratio of carbon atoms and the lowest ratio of oxygen atoms during this aging stage. Zhang *et al*. (2024) studied and compared the moisture content (MC), density, compressive strength parallel to grain (CSPG), conventional static bending strength (BS), modulus of elasticity in static bending (MOE-BS), shear strength parallel to grain (SSPG), compressive strength perpendicular to the grain (CSEG), chemical composition, and microstructure of both new and old wood samples from five different tree species in restored buildings. The study concluded that significant changes were observed in the physical and mechanical properties of wood subjected to natural aging. However, the extent of these changes was found to vary depending on the wood species, initial properties, storage conditions, and environmental factors. In a study conducted by Topaloglu (2023), changes in the properties of wood from two façade elements of a traditional building approximately 100 years old were examined during the natural aging process. FTIR analysis in the study revealed that the cellulose and lignin on the surface of aged wood had degraded over time. It was found that the moisture content and density values of the aged wood were lower than those of the new wood samples, and the water absorption rate of the aged wood increased with the natural aging process. Liu *et al*. (2019) investigated the effects of sunlight and artificial light sources on wood subjected to outdoor conditions by exposing three different wood species to natural sunlight for 733 days and artificial xenon light for 180 hours. The study found that wood exposed to artificial xenon light showed more severe aging compared to wood exposed to natural sunlight. Additionally, the aging process under artificial xenon light was approximately 30 times faster than natural aging. Cavalli *et al*. (2016) reviewed the differences in the mechanical properties of wood elements of different ages through literature analysis and examined the research findings. Additionally, based on their analysis, they provided recommendations for future studies. While studies in the literature have focused on changes in material properties of wood elements under the influence of factors such as sunlight and temperature, as previously discussed, there are also studies on the material properties of naturally aged wood under different relative humidity conditions. One such study, conducted by Gereke *et al*. (2011), investigated the behavioral differences between new and naturally aged wood. The study concluded that similarities in moisture behavior were observed between the old and new wood samples. Han *et al*. (2023) explored the effects of natural aging on the moisture sorption behavior of structural components of a historic wooden building in China. In this study, three experimental groups were formed: naturally aged, decayed wood samples; aged, sound wood samples; and reference wood samples. The results showed that the naturally aged decayed wood samples were more hygroscopic than the aged sound wood samples, and both of these samples were more hygroscopic than the reference wood samples. Additionally, the hemicellulose and lignin contents of the samples were found to change with the aging of the wood. Xin *et al*. (2024) investigated the effects of environmental factors on natural aging and the aging mechanism of larch (*Larix principis-rupprechtii Mayr*) timber. Experimental studies were conducted on 130 samples of larch timber processed from the outer wood (sapwood) region to examine the effects of ultraviolet (UV) irradiation time and drying-wetting (D-W) cycles on the color, physical, and mechanical properties of timber samples. The study concluded that the timber color was significantly affected by UV irradiation and D-W cycle aging. During the D-W cycle, the density and bending properties of the timber decreased significantly, while the effect of UV irradiation was found to be weak. Žlahtič-Zupanc *et al*. (2018) prepared samples from European oak (*Quercus robur / Q. petraea*), sweet chestnut (*Castanea sativa*), European larch (*Larix decidua*), Scots pine (*Pinus sylvestris*) heartwood and sapwood, Norway spruce (*Picea abies*), and beech (*Fagus sylvatica*) trees and investigated the moisture behavior of wood under outdoor conditions. Two different sample groups were prepared for the study. Small samples were exposed to natural outdoor conditions for 9, 18, and 27 months and then analyzed in the laboratory using various methods (contact angle, short- and long-term water absorption, and water vapor absorption). Large samples were also placed outdoors in a single layer and equipped with moisture monitoring sensors for 18 months. The results showed that exposure to natural outdoor conditions could change the wood performance with respect to water, and this change was more pronounced in thermally modified wood, where a decrease in moisture performance was observed.

Recent studies in the literature have focused on the physical and mechanical properties of wood materials under the influence of natural aging. However, there are few studies in the literature that compare the changes in the physical and mechanical properties of wood used in traditional structures and naturally aged wood with freshly cut wood under different relative humidity conditions. The aim of this study is to determine the effect of the natural aging process on the physical and mechanical properties of fir wood. In this context, the changes and differences in the mechanical properties of wood obtained from fir trees used as structural materials in historical buildings, which have undergone natural aging, and freshly cut fir wood were examined under specific standards and different environmental relative humidity conditions. By comparing naturally aged fir and freshly cut fir samples, the changes in fundamental properties such as density, bending strength, and compressive strength of the material under different relative humidity conditions were analyzed. ANOVA analysis was used in the study to determine statistically significant differences. The findings identified the behavior and performance changes of the fir wood from a historical building, approximately 150 years old, under different environmental relative humidity conditions. The results of this study provide important insights, especially in terms of the long-term durability and safety of historical wooden structures and objects. Furthermore, by analyzing the material behavior of fir wood under different environmental relative humidity conditions, it is believed that this study will fill an important gap in the literature regarding conservation and restoration works.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The wood material used in this study was obtained from the load-bearing wooden beam of a traditional wooden structure, estimated to be approximately 150 years old, located in Ankara, Türkiye, and currently undergoing restoration. The building consists of a basement, ground floor, first floor, and second floor, and it was constructed using the traditional wooden frame technique with adobe infill between the wooden frames (Survey Report, 2021). Over time, the wooden elements in the building have deteriorated due to environmental effects, leading to color changes, dimensional changes, decay, and cross-sectional losses in the wood. Specifically, these effects have been more pronounced in the load-bearing wooden posts and beams in the basement, which are more exposed to moisture, and in the wooden frame wall structure located on the facade of the building (Figure 1). Due to the decision to proceed with reconstruction of the building, a load-bearing wooden beam, approximately 70 mm × 100 mm × 1200 mm in size, was taken from the damaged, deteriorated, and unusable first-floor ceiling beams and examined in the experimental study. Upon examining the cross-section of the historical wooden sample, it was observed that it mostly consisted of juvenile wood and exhibited numerous nail joint holes, cracks, and biologically induced degradation.

For comparison in the study, a piece of freshly cut solid timber of the same species, with a high juvenile wood ratio, was selected and supplied from the sawmill.

2.1 Wood identification and determination of anatomical properties
2.1. Identifikacija drva i određivanje njegovih anatomskih svojstava

To initially identify the wood species of the sample obtained from the historic structure, samples of dimensions 10 mm × 10 mm × 10 mm were taken. The samples were boiled in pure water until they sank to the bottom to soften the wood tissue and allow the air within the tissue to escape, preparing them for sectioning. The samples were then stored in a mixture of alcohol, glycerin, and pure water in a 1/1/1 ratio until they were ready to be sectioned. To prevent fungal contamination, a small amount of phenolic acid was added to the mixture (Gerçek, 2011; Merev, 1998). Then, sections were obtained in three different orientations – transverse, radial, and tangential – using a Reichert sliding microtome at a thickness of 15-20 microns. The obtained sections were bleached in sodium hypochlorite for 5-10 minutes and then washed with pure water. Prior to staining, 1-2 drops of acetic acid were added to the environment for pH balancing, and after waiting for 1-2 minutes, the samples were washed again with pure water. After these processes, the sections were stained in 50 % safranin 0 for 5 minutes. Once the staining was complete, the sections were transferred to a 50 % alcohol-water mixture. Standard preparation techniques were applied to the sections, and permanent preparations were made in glycerin gela-

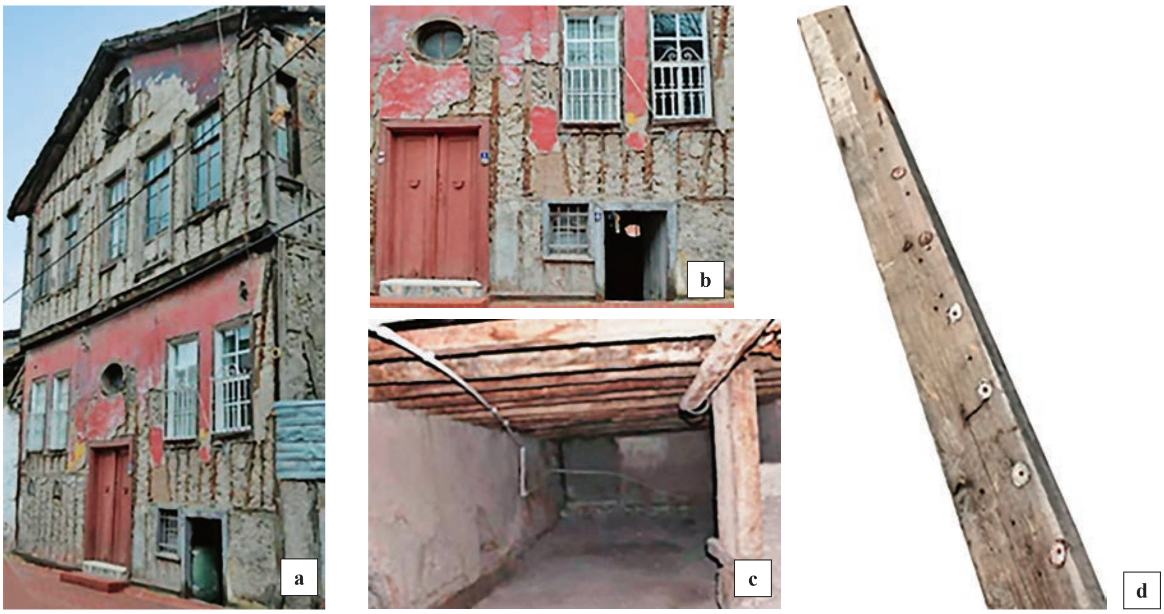

Figure 1 Traditional wooden structure selected for the experimental study (Survey Report, 2021): a) adobe infill between the wooden frame system, b) color and dimensional changes in wooden elements of the ground floor, c) color changes and decay in wooden elements of the basement, d) wooden beam sample taken for the experimental study

Slika 1. Tradicionalna drvena građevina odabrana za eksperimentalno istraživanje (izvješće o istraživanju, 2021.): a) ispuna od ćerpiča između sustava drvenih okvira, b) promjene boje i dimenzija drvenih elemenata prizemlja, c) promjene boje i propadanje drvenih elemenata podruma, d) uzorak drvene grede uzet za eksperimentalno istraživanje tin (Ives, 2001). The microphotographs of the permanent preparations of the wood samples were taken with the help of a digital camera attached to an Olympus BX50 research microscope and analyzed using BAB Bs200ProPlus Image Processing and Analysis Software (Bab, 2000). The obtained photographs were compared with wood atlases and reference preparations. As a result of these comparisons, the original wood species and genus of the samples taken from the historic structure were determined.

2.2 Density, bending, and compression tests
2.2. Ispitivanje gustoće, čvrstoće na savijanje i čvrstoće na tlak

After the wood samples obtained from the historical structure and freshly cut wood were prepared to appropriate test dimensions, they were conditioned in a climate chamber (Figure 2) at (20 ± 2) °C. Initially, the samples were kept at (30 ± 5) % relative humidity (RH) until they reached equilibrium moisture content, followed by conditioning at relative humidity values of (65 ± 5) %, (85 ± 5) %, and (95 ± 5) %, respectively, until equilibrium moisture content was reached (Figure 2). Once the samples achieved the desired equilibrium moisture content at the specified conditions, density, bending, and compression tests were performed separately for each moisture group (Table 1). Due to the limited number of test samples obtained from the historical structure, additional samples of the same quantity and dimensions were prepared from freshly cut wood for comparison.

2.2.1 Determination of densities at different relative humidity values
2.2.1. Određivanje gustoće uzoraka drva pri različitim vrijednostima relativne vlažnosti zraka

The density test was conducted in accordance with ISO 13061-2 standard. Samples measuring 20 mm × 20 mm × 30 mm were cut from the wood material obtained from both the historical building and the freshly cut wood. For each test group, 10 prepared samples were initially conditioned in a climate chamber at (20 ± 2) °C and a relative humidity of (30 ± 5) % until they reached equilibrium moisture content. Once the samples reached equilibrium moisture content, their weights were quickly measured using a precise scale, and the cross-sectional dimensions were recorded. This procedure allowed the calculation of the sample density at (20 ± 2) °C and (30 ± 5) % relative humidity. The same test sample was subsequently used for relative humidity values of (65 ± 5) %, (85 ± 5) %, and (95±5) %, and the samples were conditioned in the

Figure 2 Conditioning of the prepared test samples in the climate chamber
Slika 2. Kondicioniranje pripremljenih ispitnih uzoraka u klimatizacijskoj komori

Table 1 Experimental work plan
Tablica 1. Plan istraživanja

Experimental group *Vrsta uzoraka*		Experimental tests *Ispitivani parametri*	Specimen dimensions, mm *Dimenzije uzoraka, mm*	Number of specimens *Broj uzoraka*				Total number of specimens *Ukupan broj uzoraka*
				30 % RH	65 % RH	85 % RH	95 % RH	
1	Historical wood *ostarjelo drvo*	Density / *gustoća*	20×20×30	10	10	10	10	10*
		Bending *čvrstoća na savijanje*	20×20×330	5	5	5	5	20
		Compression *čvrstoća na tlak*	20×20×30	8	8	8	8	32
2	New wood (Control group) *svježe posječeno drvo (kontrolni uzorci)*	Density / *gustoća*	20×20×30	10	10	10	10	10*
		Bending *čvrstoća na savijanje*	20×20×330	5	5	5	5	20
		Compression *čvrstoća na tlak*	20×20×30	8	8	8	8	32

* In the density test, the same sample was used for the relevant relative humidity values
* *U ispitivanju gustoće upotrijebljen je isti uzorak za ispitivanje pri različitim relativnim vlažnostima zraka.*

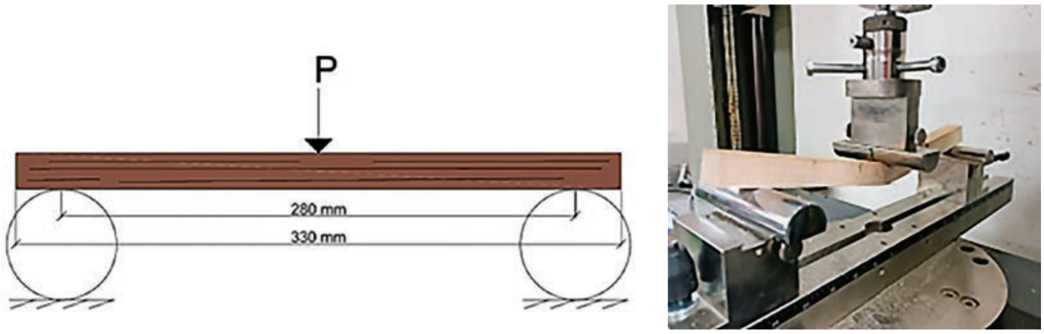

Figure 3 Bending test: left – experimental setup, right – application of bending test
Slika 3. Ispitivanje čvrstoće na savijanje: lijevo – eksperimentalni postav, desno – prikaz ispitivanja

climate chamber. After the sample reached equilibrium moisture content in the climate chamber at (20 ± 2) °C and relative humidity values of (65 ± 5) %, (85 ± 5) %, and (95 ± 5) %, the density was recalculated for each of the relevant humidity values.

2.2.2 Determination of bending resistance at different relative humidity values
2.2.2. Određivanje čvrstoće na savijanje pri različitim vrijednostima relativne vlažnosti zraka

The bending strength determination test was conducted in accordance with ISO 13061-3 standard (Figure 3). Five samples of 20 mm × 20 mm × 330 mm were cut and prepared from both the historical structure and newly cut wood. The prepared samples were conditioned at (20 ± 2) °C and (30 ± 5) % relative humidity until they reached constant mass in a climate chamber. Once these conditions were met, the samples were placed between two parallel cylindrical supports. A force was applied to the test samples at a constant speed from a single point on the top during the experiment. Upon completion of this process, an additional set of five specimens was prepared, and the same procedures were systematically conducted under relative humidity conditions of (65 ± 5) %, (85 ± 5) %, and (95 ± 5) %, with the bending strengths recorded accordingly.

2.2.3 Determination of compressive strength at different relative humidity values
2.2.3. Određivanje čvrstoće na tlak pri različitim vrijednostima relativne vlažnosti zraka

The compressive strength test was conducted in accordance with ISO 13061-17 standard (Figure 4). Samples measuring 20 mm × 20 mm × 30 mm were prepared from the wood material obtained from both the historical building and freshly cut wood, with eight samples of each. The prepared samples were first conditioned in a climate chamber at a temperature of (20 ± 2) °C and a relative humidity of (30 ± 5) % until they reached equilibrium moisture content. Afterward, the samples were removed from the climate chamber and subjected to a compressive strength test parallel to the fibers. Upon completion of this process, an additional set of eight specimens was prepared, and the same procedures were systematically conducted under relative humidity conditions of (65 ± 5) %, (85 ± 5) %, and (9 ± 5) %, with the compression strengths recorded accordingly.

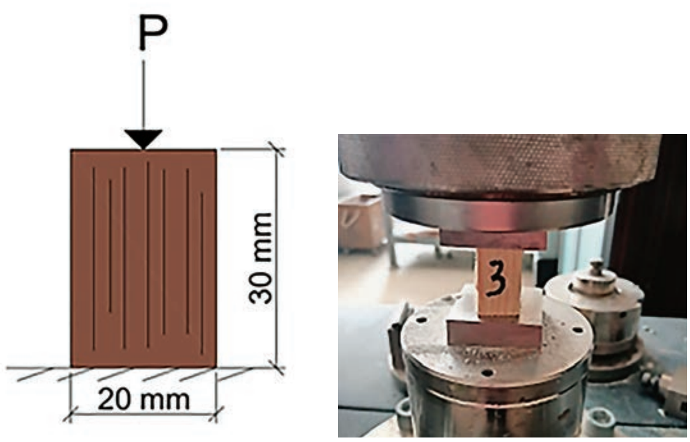

Figure 4 Compression test: left – experimental setup, right – application of compression test
Slika 4. Ispitivanje čvrstoće na tlak: lijevo – eksperimentalni postav, desno – prikaz ispitivanja

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

As a result of the species identification test conducted on the original wood samples, it was determined that the original wood samples belong to the *Abies* sp. (fir) genus. For comparison purposes, a control group consisting of newly cut, solid, and juvenile wood-rich (juvenile wood) *Abies* sp. (Fir) wood was selected for both original and solid naturally aged *Abies* sp. wood. Anatomical cross-sectional images of the original historical *Abies* sp. (fir) sample are shown in Figure 5.

Figure 6 shows the density distributions of naturally aged solid fir wood and freshly cut solid fir wood under different relative humidity conditions, presented as whisker plot graphs. In addition, one-way ANOVA was applied to determine the statistically significant differences in the density, bending strength, and compressive strength values of naturally aged fir wood and new solid fir samples under different relative humidity conditions. The results are shown in Table 2. The ANOVA results indicated significant differences between the groups in both the new ($F = 7.908$, $p < 0.001$) and naturally aged ($F = 7.336$, $p = 0.001$) fir samples. According to the Duncan test results, the samples at the 65 % relative humidity level were significantly different from the other groups. These results suggest that the interaction between relative humidity and the aging process of fir wood may vary, and that naturally aged fir wood may exhibit a more stable structure in terms of density at lower relative humidity levels. Upon examining Figure 6, the median density of naturally aged fir samples was generally higher than that of new fir wood. This was only different at the 65 % relative humidity level, where the median density of the new fir samples was considerably higher than all other samples. On the other hand, the generally higher density of naturally aged fir wood compared to new solid fir wood indicates that the aging process has a positive effect on the density of fir wood and leads to an increase in density. This result was also observed in the work of Zhang *et al*. (2024) on camphor tree (*Cinnamomum camphora*) and catalpa (*Catalpa ovata*) species, where wood density increased with aging. However, in the same study, the opposite result was found for Chinese arborvitae (*Platycladus orientalis*), red maple (*Acer palmatum*), and Scots pine (*Pinus sylvestris*), where density decreased with increased aging. Similarly, Unver *et al*.

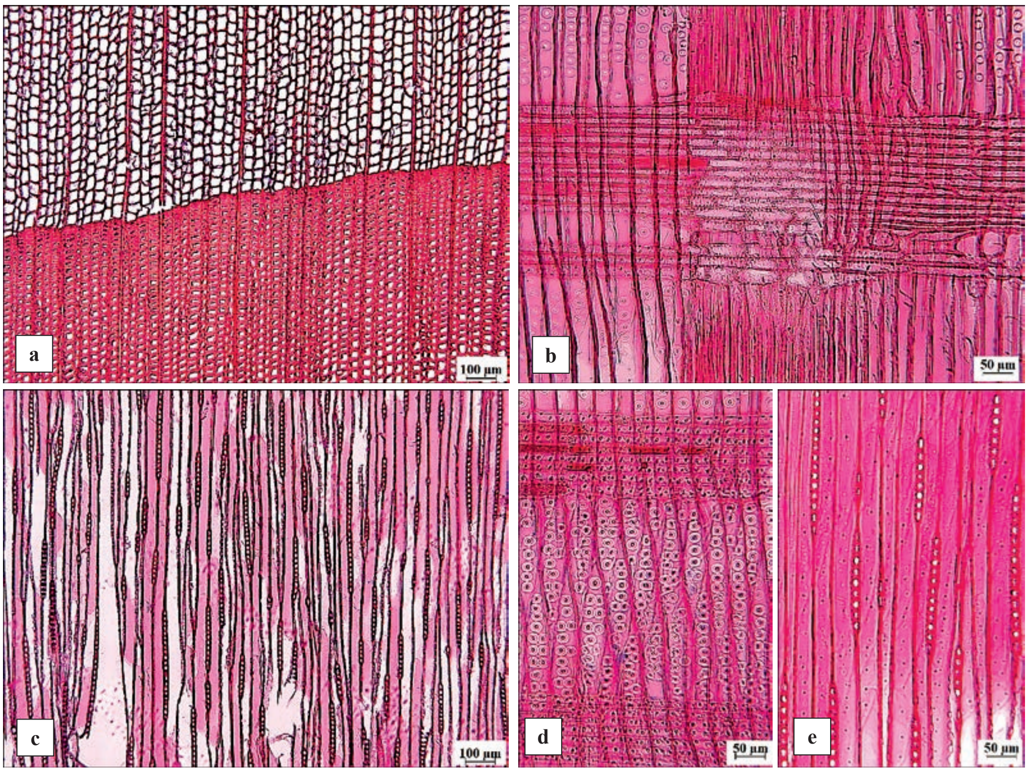

Figure 5 *Abies* sp. (Fir) wood: a) Transverse section showing distinct growth rings, and gradual transition from earlywood to latewood; b) Radial section showing homogeneous rays, and crystals present in the marginal and submarginal ray cells; c) Tangential section showing exclusively uniseriate rays; d) Radial section showing uniseriate and biseriate pits on tracheid radial wall; e) Tangential section showing small pits on tracheid tangential walls

Slika 5. Drvo jele (*Abies* sp.): a) poprečni presjek s jasnim godovima i postupnim prijelazom iz ranoga u kasno drvo; b) radijalni presjek koji prikazuje homogene trakove i kristale u marginalnim i submarginalnim stanicama trakova; c) tangentni presjek koji prikazuje isključivo jednostruke trakove; d) radijalni presjek koji prikazuje jednostruke i dvostruke jažice na radijalnoj stijenci traheide; e) tangentni presjek koji prikazuje male jažice na tangentnim stijenkama traheida

Table 2 ANOVA analysis and Duncan test groups for density, bending strength, and compressive strength values under different relative humidity conditions
Tablica 2. ANOVA analiza i grupe Duncanova testa za vrijednosti gustoće, čvrstoće na savijanje i *čvrstoće na tlak* pri različitim uvjetima relativne vlažnosti zraka

Tests *Ispitivanje*	**Relative humidity** *Relativna vlažnost zraka*	**New sample Mean ± SD** *Svježe posječeno drvo; srednja vrijednost + standardna devijacija*	**Duncan (new)** *Duncanov test (novi)*	**Old sample Mean ± SD** *Ostarjelo drvo; srednja vrijednost + standardna devijacija*	**Duncan (old)** *Duncanov test (stari)*	***F* value (new)** *F-vrijednost (novi test)*	***p* value (new)** *p-vrijednost (novi test)*	***F* value (old)** *F-vrijednost (stari test)*	***p* value (old)** *p-vrijednost (stari test)*
Density, g/cm³ *gustoća,* g/cm³	30 %	0.4430 ± 0.0247	a*	0.4524 ± 0.0144	a	7 908	0.000	7 336	0.001
	65 %	0.4903 ± 0.0235	b	0.4575 ± 0.0127	ab				
	85 %	0.4530 ± 0.0221	a	0.4696 ± 0.0143	bc				
	95 %	0.4614 ± 0.0211	a	0.4785 ± 0.0137	c				
Compression strength, N/mm² *čvrstoća na tlak,* N/mm²	30 %	50.64 ± 4.09	d	52.33 ± 1.27	d	143 939	0.000	263 433	0.000
	65 %	44.39 ± 3.74	c	36.66 ± 2.07	c				
	85 %	32.04 ± 2.87	b	31.98 ± 1.69	b				
	95 %	20.49 ± 0.92	a	25.45 ± 2.67	a				
Bending strength, N/mm² *čvrstoća na savijanje,* N/mm²	30 %	86.10 ± 8.20	b	90.10 ± 8.55	d	23 153	0.000	29 445	0.000
	65 %	82.18 ± 6.35	b	80.24 ± 7.04	c				
	85 %	57.44 ± 7.34	a	64.86 ± 7.37	b				
	95 %	55.98 ± 7.60	a	49.50 ± 6.16	a				

*Groups with the same letter do not show a statistically significant difference between them ($p < 0.05$). SD – Standard deviation. / *Među grupama označenim istim slovom nema statistički značajne razlike (p < 0,05). SD – standardna devijacija.*

(2024) noted a tendency for density reduction in naturally aged Scots pine (*Pinus sylvestris L.*) and unbarked oak (*Quercus petraea L.*), but an increase in density was observed when these woods were treated with tannin. When examining the graph in Figure 6, the interquartile range (IQR) of the naturally aged fir samples was narrower, and their density distribution was more homogeneous. In contrast, the density distribution of new solid fir samples was wider. This suggests that with aging, the density values of fir wood in different samples tend to converge. Furthermore, when looking at the graph as a whole, it is evident that the density of the naturally aged fir samples significantly increased with the rise in relative humidity. This result was more inconsistent for the new solid fir samples.

Figure 7 displays the bending strength behavior of naturally aged and freshly cut fir samples under different relative humidity conditions on a whisker plot graph. With the increase in relative humidity, both the naturally aged fir samples and the freshly cut fir samples exhibited a decrease in bending strength. This can be explained by the increase in the water content of the wood up to the fiber saturation point, leading to a reduction in bending resistance (Küch, 1943; cited in Berkel, 1970). The trend of decreasing bending strength median values with increasing relative humidity for both groups indicates that the mechanical properties of fir samples are adversely affected by increased relative humidity. Similarly, ANOVA analysis revealed significant differences in bending strength for both the new fir ($F = 23.153$, $p < 0.001$) and naturally aged fir samples ($F = 29.445$, $p < 0.001$). For new fir samples, bending strength was measured as 86.10 N/mm² at 30 % relative humidity, dropping to 55.98 N/mm² at 95 % relative humidity. Similarly, for the naturally aged fir samples, the bending strength at 30 % relative humidity was 90.10 N/mm², which decreased to 49.50 N/mm² at 95 % relative humidity. The naturally aged fir wood generally exhibited higher bending strength compared to newly cut fir wood, but it was found to be more sensitive to increases in ambient relative humidity (Table 2). Furthermore, as seen in Figure 7, the median bending strength for the naturally aged fir samples was generally higher than that of the newly cut fir samples under different relative humidity conditions. The only exception was at 65 % relative humidity, where the bending strength of both the naturally aged fir and newly cut fir samples was similar, and at 95 % relative humidity, where the naturally aged fir sample had lower strength. The higher bending strength of the naturally aged fir samples under varying relative humidity conditions indicates that aging strengthens the bending strength of fir wood. However, Kranitz *et al*. (2016) reported the opposite result, stating that aging weakens the flexibility and strength properties of wood, especially reducing the plastic deformation capacity. In a study by Sonderegger *et al*. (2015), the bending strength of naturally aged spruce trees (120-150 years old) was higher than that of new spruce trees. However, the bending strength of fir samples aged 120-150 years was lower than that of newly cut fir. This contradictory result in the historical fir wood was emphasized by Sonderegger *et al*. (2015), who argued that the key factor influencing the bending strength was the wood density, rather than the tree age.

Another notable aspect in the graph is that, although the trend of bending strength reduction due to the increase in ambient relative humidity is similar for both groups, the loss of bending strength at each relative humidity increase stage is more pronounced in the naturally aged fir wood samples. In particular, at 95 % relative humidity, the reduction in bending strength

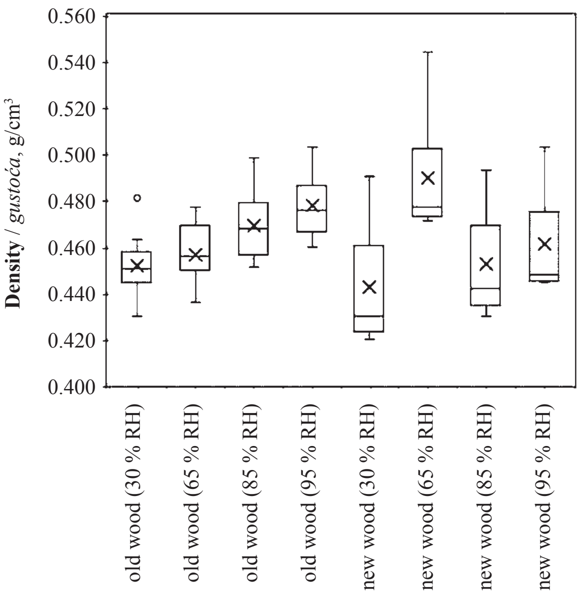

Figure 6 Whisker box plot graph of density values of naturally aged fir wood and new fir wood at different relative humidity levels
Slika 6. Kutijasti dijagram vrijednosti gustoće uzoraka prirodno ostarjele i svježe posječene jelovine pri različitim relativnim vlažnostima zraka

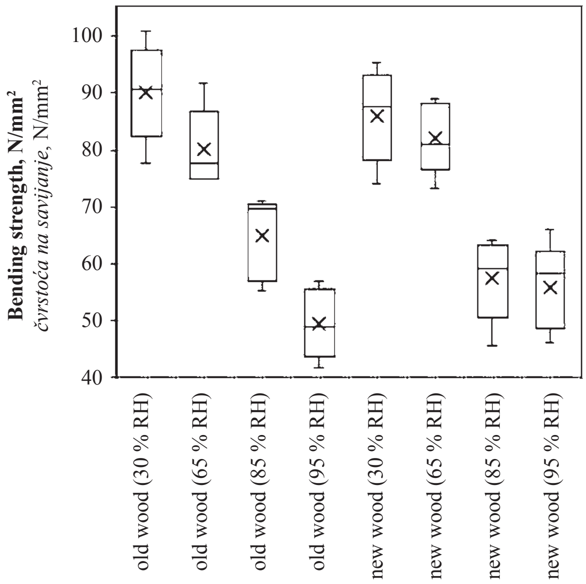

Figure 7 Whisker box plot graph of bending strength values of naturally aged fir wood and new fir wood at different relative humidity levels
Slika 7. Kutijasti dijagram vrijednosti čvrstoće na savijanje uzoraka prirodno ostarjele i svježe posječene jelovine pri različitim relativnim vlažnostima zraka

loss is notably higher for the naturally aged fir wood samples. This result can be explained by the deterioration and aging of wood due to various environmental (weathering) or biological factors (fungi, bacteria, insects, marine borers) (Unger *et al*., 2001). Specifically, the mechanical strength loss in deteriorated and damaged wood is particularly attributed to the degradation of hemicellulose and the loss of sugars in hemicellulose (Nilsson and Rowell, 2012).

Figure 8 shows the whisker plot graph of the compression strength of naturally aged and new fir wood samples under different environmental relative humidity conditions. In general, as the relative humidity increased, both the naturally aged fir samples and the new solid fir samples exhibited a decrease in compression strength. High environmental relative humidity negatively affected the compression strength of fir samples in both groups, leading to a decline. Similarly, ANOVA analysis revealed statistically significant differences in compression strength between both new ($F = 143.939$, $p < 0.001$) and aged ($F = 263.433$, $p < 0.001$) samples, depending on the relative humidity level (Table 2). In both groups, as the relative humidity increased, a noticeable decrease in compression strength was observed. For new solid fir samples, the compression strength at 30 % relative humidity was 50.64 N/mm², whereas at 95 % relative humidity, it decreased to 20.49 N/mm². Similarly, for the naturally aged fir samples, the compression strength was 52.32 N/mm² at 30 % relative humidity, dropping to 25.45 N/mm² at 95 % relative humidity. This indicates a reduction in mechanical strength due to the water uptake of

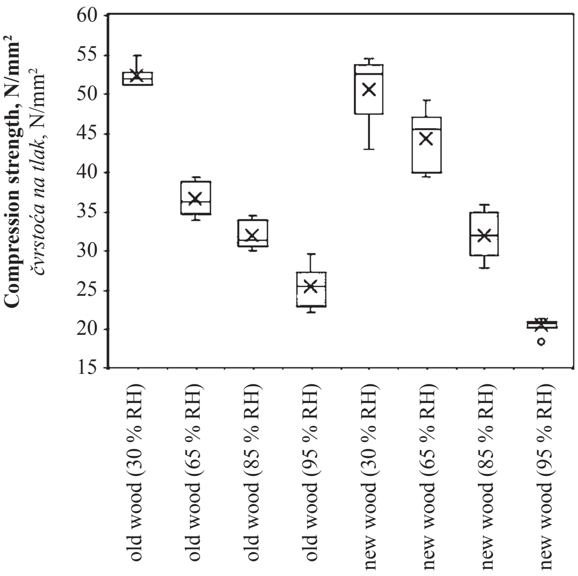

Figure 8 Whisker box plot graph of compression strength values of naturally aged fir wood and new fir wood at different relative humidity levels
Slika 8. Kutijasti dijagram vrijednosti **čvrstoće na** tlak uzoraka prirodno ostarjele i svježe posječene jelovine pri različitim relativnim vlažnostima zraka

the wood. However, when examining the graph in Figure 8, it can be observed that the interquartile range (IQR) for the naturally aged fir samples is narrower. This suggests that the compression strength values in the longitudinal direction of naturally aged fir samples are more consistent and closer to one another. Another point is that the compression strength median for naturally aged fir samples is generally lower than that of the new solid fir samples. A similar result has been reported by Xin *et al*. (2022), where aging negatively affected mechanical properties. On the other hand, Attar-Hassan (1976) observed the opposite result, indicating a 7 % increase in crushing strength and a decrease in the compression proportional limit as a result of aging. This indicates that, while the load-bearing capacity of wood increases with aging, the elastic limit decreases. In another study, Erdhardt *et al*. (1996) mentioned that aging caused only minimal changes in mechanical properties depending on the age of the tree and varying environmental relative humidity conditions. Another important point shown in the graph in Figure 8 is that for the 30 % relative humidity condition, the compression strength values for both groups are similar. However, for the 95 % relative humidity condition, the compression strength of the new fir samples was noticeably lower than that of the naturally aged fir samples. The significant decrease in the compression strength of new solid fir samples under high relative humidity conditions suggests that naturally aged wood is less affected by high relative humidity in terms of compression strength.

4 CONCLUSIONS
4. ZAKLJUČAK

The results obtained in this study can be summarized as follows:

With the increase in relative humidity, the density of the naturally aged fir samples showed a significant increase. This result was more inconsistent for the new solid fir samples.

As the relative humidity increased, both the naturally aged fir wood samples and the new solid fir wood samples exhibited a tendency for a decrease in bending strength. However, the highest bending strength was obtained for both experimental groups at the relative humidity of 30 %.

With the increase in relative humidity, both the naturally aged fir samples and the new fir samples showed a tendency for a decrease in compression strength. At high relative humidity (95 % RH), the compression strength of both groups was negatively affected, resulting in the lowest compression strength values.

Statistically significant differences in terms of density, bending, and compression strengths were found based on different relative humidity levels through ANOVA analysis. It was determined that the naturally aged fir wood was more stable in terms of density, while the loss of strength became more pronounced under high relative humidity conditions.

In conclusion, when evaluated under different relative humidity conditions, the fir wood subjected to natural aging generally demonstrated superior performance in terms of density and bending strength compared to the new fir wood. However, in terms of compression strength, it was determined that the naturally aged fir wood exhibited lower strength than the new fir wood across different relative humidity levels.

In general, the natural aging process causes significant and noticeable changes in the physical and mechanical properties of wood materials. To more comprehensively and thoroughly examine these changes, it is considered essential to take into account environmental and mechanical factors, such as temperature fluctuations, humidity conditions, and load history, as highlighted by Froıdevaux *et al*. (2012). In this context, understanding the natural aging process of wood, commonly used in traditional historical buildings, is of great importance for the preservation and maintenance of wooden cultural heritage. In this study, evaluations were conducted solely on fir trees (*Abies* sp.) grown in Ankara, Turkey; however, conducting similar studies on various tree species from different regions is believed to broaden the scope of the findings.

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