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Experimental Investigation on the Material Properties of Historical Chestnut and Elm Structural Timbers

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Abstract

Aim of study: This study aims to experimentally investigate the changes in the physical and mechanical properties of wood elements from two tree species, used as load-bearing structures 150 years ago and exposed to similar environmental conditions, due to natural aging over time.

Area of study: A historical wooden building in rural Giresun, Türkiye, was selected.

Material and method: Species identification tests were performed on the samples, followed by density, hardness, bending, and compression tests according to relevant standards.

Main results: In this study, chestnut and elm wood samples exposed to identical physical conditions and comparable biological degradation were examined. The experimental findings revealed that the reductions in compressive and bending strengths were nearly equivalent for both species. For comparative purposes, data from sound chestnut and elm wood collected from the same region were employed as the control group.

Research highlights: It is evident that chestnut and elm species are frequently used together in registered and protected structures in the region, and that elm, in particular, occurs in small groups within Turkish forests and is regarded as a valuable wood species. Since chestnut exhibits mechanical properties similar to those of elm as a result of natural aging, it is proposed that chestnut may be used as a substitute for elm in regional restoration practices when necessary.

Keywords: Historical Wood, Chestnut Wood, Elm Wood, Mechanical Properties

Tarihi Kestane ve Karaağaç Yapısal Ahşap Elemanlarının Malzeme Özelliklerinin Deneysel Olarak İncelenmesi

Öz

Çalışmanın amacı: Bu çalışma, 150 yıl önce taşıyıcı yapı elemanı olarak kullanılan ve benzer çevresel koşullara maruz kalan iki ağaç türüne ait odun elemanlarının, zamanla doğal yaşlanma süreçlerinin etkisiyle fiziksel ve mekanik özelliklerinde meydana gelen değişiklikleri deneysel olarak incelemeyi amaçlamaktadır.

Çalışma alanı: Giresun'un kırsal bölgesindeki tarihi bir ahşap yapı seçilmiştir.

Materyal ve yöntem: Örnekler üzerinde tür tespiti yapılmış, ardından ilgili standartlara göre yoğunluk, sertlik, eğilme ve basınç testleri uygulanmıştır.

Temel sonuçlar: Çalışmada, aynı fiziksel koşullar altında olan ve benzer biyolojik hasara maruz kalan kestane ve karağaç odunu örnekleri karşılaştırılmıştır. Deneysel sonuçlar, her iki türün basınç ve eğilme dayanımlarındaki azalmanın neredeyse aynı olduğunu göstermiştir. Aynı bölgeden alınan sağlam kestane ve karaağaç odunu verileri, karşılaştırma için kontrol grubu olarak kullanılmıştır.

Araştırma vurguları: Bölgedeki tescilli ve korunan yapılarda kestane ve karaağaç türlerinin sıklıkla birlikte kullanıldığını ve özellikle karaağaç türünün Türkiyedeki ormanlarda küçük gruplar halinde yayıldığını ve değerli bir odun türü olduğunu göstermektedir. Kestane türünün doğal yaşlanma etkisi sonucunda karaağaç türü ile benzer mekanik özellikler sunmasından dolayı bölgedeki restorasyonlarda karaağaç yerine gerektiği durumlarda kullanılabileceği önerilmektedir.

Anahtar Kelimeler: Tarihi Ahşap, Kestane, Karaağaç, Mekanik Özellikler

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Introduction

Structurally, wood exhibits numerous differences even without the aid of optical tools. In addition to the differences between two distinct types, namely "*hardwood*" and "*softwood*" species, there are also variations within the same species due to structural features such as sapwood, heartwood, growth rings, etc. The primary reason for these differences is the variability in the wood's texture, which changes based on growth and development (Fengel & Wegener, 1989). When examined at the micro level, differences still exist between softwood and hardwood. Both the components that make up the cell and the functions of these components are significantly different (Kettunen, 2006). At the cellular and tissue level, wood consists of different types of cells, and the volumetric ratios of these cells vary depending on the species of the tree. Softwoods are composed of more than 90% tracheids, and the diameter and wall function of these tracheids vary. At this point, wide-diameter, thin-walled tracheids facilitate water transport and form the *"earlywood"* portion of the wood. Narrow-diameter, thick-walled tracheids provide mechanical strength to the wood and form the *"latewood"* portion (Sjostrom, 1993; Chen et al., 2020). On the other hand, when examining the cellular structure of hardwoods, it is evident that they evolved later in the evolutionary process and have more specialized cell types. Vessels are involved in water transport, while fibers provide mechanical strength. This differentiation has provided hardwoods with advantages over softwoods in many climatic regions. The lumen of tracheids, vessels, and fibers, which are hollow structures, vary in diameter and size. The hierarchical porous structure of wood is formed by micrometer-sized pits that cross the cell walls and nanometer-scale pores within the cell walls (Chen et al., 2020). The cell wall of tracheids consists of various layers formed by the alignment of numerous fine cellulose microfibrils that spiral around the cell lumen in each layer. These microfibrils are embedded in a more flexible and water-sensitive matrix made of amorphous lignin and hemicelluloses. Moreover, the average angle of the microfibrils relative to the cell axis influences the axial stiffness and dimensional stability of the wood, which are important properties of the wood (Huang et al., 2003). In summary, regarding the microstructure of softwood and hardwood, the key difference is that hardwoods possess a characteristic cell type called the vessel element (or pore), while softwoods do not have these cells (Wiedenhoeft, 2010). (Figure 1).

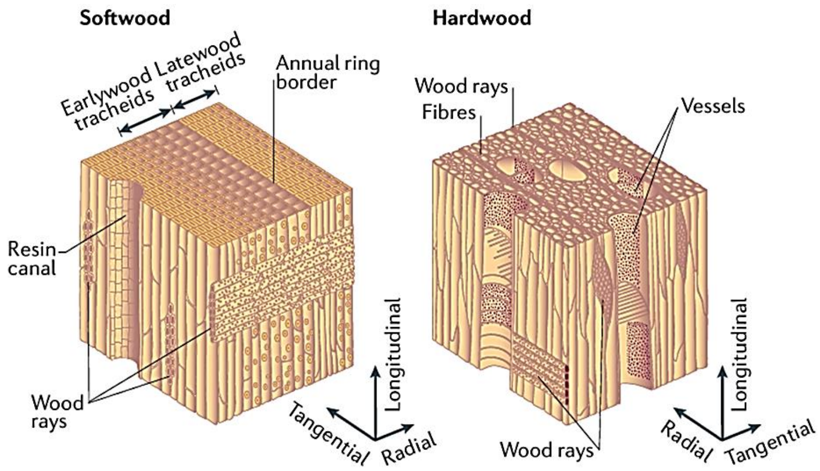


Figure 1. Cellular structure of softwood and hardwood at the micro level (Chen et al., 2020)

Wood is an anisotropic for material structure. Therefore, its physical and mechanical properties vary according to the longitudinal, tangential, and radial growth directions. The mechanical properties of wood differ from one another depending on both the moisture content and the direction of growth. While the moisture content in wood is below the fiber saturation point, significant changes are observed in the mechanical traits of wood.

The mechanical properties change to a limited extent when the moisture content exceeds the fiber saturation point. Compressive strength increases as the moisture content in wood decreases, especially in a direction parallel to the fibers (Rowell, 2005). The rate of moisture in wood is also significant for the existence of biological organisms that damage wood. Although the phrase *"dry wood does not rot"* is accurate as a general principle, the importance of moisture in wood has been demonstrated in a study conducted in China. In the related study, ten-thousand-year-old wood removed from graves was in a dry state throughout the period and remained in the same form from the date it was first used (Rowell & Barbour 1990; Rowell, 2005).

On the other hand, termites, which are known to attack dry wood, attack wood by bringing their moisture to it. Of the other biological creatures that attack wood, white rotting fungi need the least amount of water to attack, while brown ones need more. Of all these fungi, soft rotting fungi need the highest amount of water content. However, they all require moisture at or near the fiber saturation point to cause damage to wood (Rowell, 2005). Moreover, wood rotting fungi invade distinct parts of the wood, so their destruction differs. The brown rotting fungus invades the cellulose of the wood and leaves the lignin. Therefore, because of their invasion, a brown tone appears on the surface of the wood, and the wood loses almost all its structural strength. On the contrary, white rotting fungi invade the wood by consuming both cellulose and lignin, leaving a soft, fibrous texture on the surface of the wood (For example, “*the Coriolus (Polystictus) versicolor"* fungus) (Richardson, 1993).

The type of wood used in the construction of wooden buildings varies depending on the region where the building is located. Among these materials, chestnut and elm have been among the most preferred materials in historical wooden structures as load-bearing wooden building elements. It is safe to state that this is primarily due to the widespread distribution of chestnut and elm species in the region where the structures are located and since these species have great hardness and medium weight for macroscopic characteristics as mentioned in As et al. (2001). In this context, in the study on the strength of a chestnut tree by Thaler et al. (2014), it was mentioned that the heartwood of *Castanea sativa* is one of the most resistant commercial tree species in Europe. In their study investigating the strength of *Castanea sativa*, they claimed that the ring width and weather conditions (outdoor use) did not affect its strength. They added that none of the fungi used in the experiment could decompose the heartwood of *Castanea sativa* and that the fungicidal and mechanical properties of the 35-year-old *Castanea sativa* species, which was one of the experimental groups in the study, still did not deteriorate within the specified time. Topaloglu et al. (2021) examined the changes in the physical and mechanical properties of the historical chestnut tree belonging to different age groups over time. They found no change in the anatomical structure of the relevant samples. However, they mentioned that hemicelluloses were degraded on the surfaces of almost all samples and that the lignin structure changed. They added that the mechanical properties of the samples were in good condition when compared to the current chestnut samples. In another study on the mechanical properties of chestnut wood, Romagnoli *et al.* (2014) found that when the width of the growth rings on the chestnut wood increased from ≤ 2 mm to ≥ 7 mm, compressive strength decreased by 19.5%, while modulus of rupture (MOR) decreased by 22.8%. Additionally, they stated that as the age of the tree increased (as expressed as a chronological class), there might be a decrease in the specific gravity, MOR, and compressive strength in general. In a study by Kus Sahin et al. (2020), natural weathering processes that softwood and hardwood species underwent under outdoor conditions for 12 months were investigated, and hardwood species were found to have greater hardness values (Shore D hardness) than softwood species, which was expected. Furthermore, the highest values were seen in the oak (73), beech (70), cherry (68), chestnut (65) and basswood (47) species, respectively, over a period of 12 months. Similarly, in the study on the strength of the elm species by Han et al. (2019), the nanomechanical and topochemical changes of the wooden construction elements of the elm species in a historical building under the effect of natural ageing were examined. Consequently, they said that the elm morphologically deteriorated near the outer surface, and the lignin and carbohydrate significantly decreased on the outer part of the wooden beams. However, they mentioned that natural ageing did not pose an issue for the safety of historical buildings but could prepare an environment suitable for the formation and exacerbation of biological deterioration-damaging wood. In another study by Mania et al. (2020), the effect of the change in fibre deflection angle on mechanical properties was investigated through different wood species. In the study, they stated that among the species selected, the elm species showed a decrease of only 38 % in its strength compared to the almost linear fibre arrangement and that this rate was higher in other species. In the study by Ghavidel et al. (2020) on the archaeological European white elm (*Ulmus laevis*), Kürschner-Hoffer cellulose, chlorite holocellulose analyses/α-cellulose, and hemicellulose content in freshly cut wood were higher than those of the archaeological wood. However, they said the amount of lignin in archaeological elm was higher than that of the freshly cut wood. As a result of the study, it was concluded that the bacterial degradation of archaeological elm caused a decrease in chlorite holocellulose content and hence, an increase in the percentage of lignin.

In a study by Ramage et al. (2017), it was mentioned that chestnut and elm species were quite successful mechanically, physically, and structurally compared to most tree species. The present study revealed that the strength of decay by fungi in chestnut and elm species was relatively high and that the resistance to water ingress of the relevant tree species was extremely high (BS EN 1994; Ramage et al., 2017).

The aim of this study was to investigate the differences and changes in the material properties, including density, hardness, bending, and compressive strength, because of the mechanical and biological impacts to which different types of wooden-bearing elements in a historical wooden structure were exposed. In this context, the physical and mechanical properties of chestnut and elm species, which were obtained from a historical wooden structure and had various mechanical and biological damage, and the intact/perfect chestnut and elm species, which were selected from the literature as the control group and spread in the relevant region, were compared.

Material and Methods

Within the scope of the experimental study, nine wooden samples were taken from a traditional wooden building known to be approximately 150 years old and located in Çavuşoğlu Village at Giresun, Türkiye. Samples were assigned GC code numbers based on the location from where they were obtained (Çavuşoğlu, Giresun) (Table 1). Initially, visual inspection analysis of the existing damage was conducted on the samples. In this context, the width, length, and depth of the damage in the samples were recorded. Damages were primarily mechanical and biological issues spread over the samples (Table 1).

Table 1. Table of visual inspection analysis performed on samples

9 Wooden Samples	Code/Damage Type/Photograph		
	GC1-Mechanical damage	GC2-Mechanical damage	GC3-Mechanical damage
			
	GC4-Mechanical and biological damage	GC5-Mechanical damage	GC6-Mechanical and biological damage
			
	GC7-Mechanical and biological damage	GC8-Mechanical damage	GC9-Mechanical damage
			

After the visual inspection analysis, experimental samples were prepared by cutting one piece of 10 mm x 10 mm x 10 mm, three pieces of 50 mm x 50 mm x 50 mm, three pieces of 50 mm x 50 mm x 150 mm, and three pieces of 50 mm x 50 mm x 300 mm from each sample. Samples measuring 10 mm x 10 mm x 10 mm were reserved for the species identification test, while those measuring 50 mm x 50 mm x 50 mm were reserved for density and hardness tests. Additionally, samples measuring 50 mm x 50 mm x 150 mm were reserved for bending and 50 mm x 50 mm x 300 mm for compression tests.

Samples measuring 10 mm x 10 mm x 10 mm were boiled in distilled water for easier sectioning in the species' identification experiment. Thus, the air in the wood tissues was allowed to escape and soften. Then, the boiled samples were kept within an alcohol/glycerin/pure water mixture in a 1 : 1 : 1 ratio until they were sectioned. Phenic acid was added to the mixture against the fungal effects that might occur (Gerçek, 2011 & Merev, 1998). When the samples became suitable for sectioning, they were sectioned in three directions: transversal, radial, and tangential, with the help of the *"Reichert"* slide microtome. The sections obtained were soaked in sodium hypochlorite for 5-10 min and then washed with distilled water. Before painting the sections, 1-2 drops of acetic acid were added to the medium to balance the pH. After 1-2 min, it was rewashed with distilled water. After all these procedures, the sections were kept in 50 % saffron for 5 min. The sections whose dyeing process was completed were transferred into a 50% alcohol-water mixture. Standard preparation procedures were performed on the sections, and experimental materials were transformed into permanent preparations in glycerin gelatin (Ives, 2001). Microphotographs of permanent preparations obtained from wood samples were taken with the help of a digital camera connected to an Olympus BX50 research microscope as well as Bap Image Processing and Analysis Software (Bab, 2000). The photographs were then compared with wood atlases and comparison preparations. As a result of the comparisons, it was determined to which tree species or genus the samples belonged.

Air-dry and oven-dry densities of the test samples were determined according to the ISO 13061-2 (ISO 2014) standard. After the density determinations of the samples were completed, a hardness test was performed on the same samples (Figure 2). The experimental study was carried out in accordance with the BS EN 1534 (BS EN 2020) standard. In this context, the force was applied to the samples with a steel sphere with a 10 mm diameter. As a result of the force applied, a circular trace was formed on the sample surfaces by the steel sphere. The resulting circular trace was measured from two different directions with the help of a caliper. In the test, two different hardness measurements were performed parallel and perpendicular to the fibers.

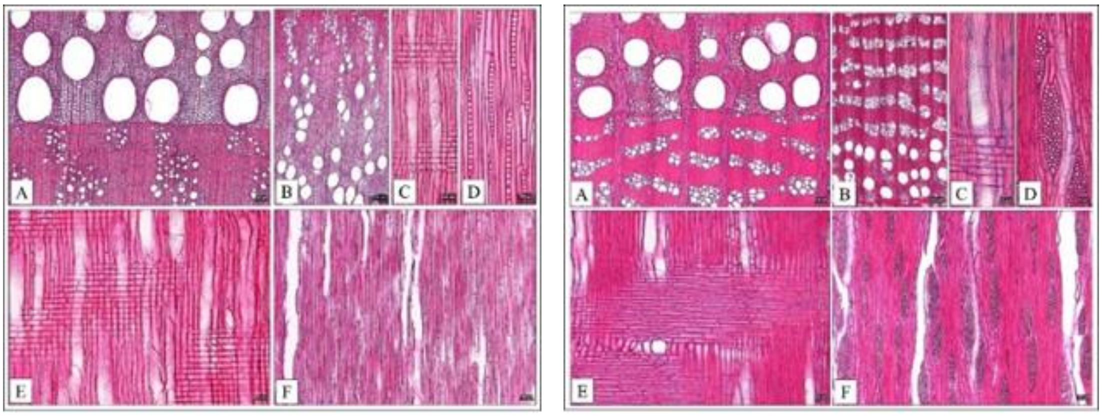
For the bending test, samples with the dimensions of 50 mm x 50 mm x 150 mm were subjected to a bending test in a direction perpendicular to the fibers and in accordance with the ISO 13061-3 (ISO 2014) standard. The section size was set at 50 mm to measure the bending strength, since the samples in the test phase were too rotten. The sample length mentioned in the relevant standard was not met, and a sample size measuring as much as three times the size of the transversal sample section was decided upon to achieve an adequate number of samples for the experimental phase, which was specific to the present study. To perform the test, the samples were at a relative humidity of 65 ± 5 % and a temperature of 20 ± 2 ºC, by considering the relevant standard that indicated constant mass weight. The samples were placed in the middle of two parallel and cylindrical supports by providing these conditions. The force was applied to the experimental samples from a single point from the top with a constant velocity throughout the test (Figure 2). The bending strengths of the samples were recorded at the end of the test.

For the compression test, samples prepared in the dimensions of 50 mm x 50 mm x 300 mm were subjected to compression in a direction parallel to the fibers (Figure 2). The test was performed according to the BS EN 408:2010+A1:2012 (BS EN 2012) standard. The experimental samples were loaded using loading heads whose centers would overlap or by applying a compression force that did not allow bending. The fracture pattern of each experimental sample and the differences in the fracture region were recorded. The compressive strengths of the samples parallel to the fibers were recorded at the end of the test.

Figure 2. Mechanical tests applied to the specimens, from left to right: brinell hardness test, three-point bending test and compression test parallel to the grain

Results and Discussion

The microscopic images of the samples were examined in the experiment for species identification. Consequently, it was found that the samples coded GC1, GC2, GC3, GC4, GC5, GC6, and GC9 belonged to the Chestnut species *(Castanea sativa Mill.,)*, and the samples coded GC7 and GC8 belonged to the Elm species *(Ulmus sp.,)* (Figure 3).



a b

Figure 3. Microscopic images of the samples: a) anatomical characteristics of the Castanea sativa Mill., taxon: a - *CS; ringed wood with tracheid, distinct annual ring border, b- CS; "Y" shaped tracheid groups in the latewood zone, c-RS; simple perforation table, e- *RS; homocellular medullary ray parenchyma consisting of squamous cells, d,f- *TS; Uniserial homocellular medullary rays *CS; Cross section, RS; radial section, TS; tangential section, (---) scale; 250µm (b), 100µm (a,f), 50µm (c,d,e), b) anatomical characteristics of the Ulmus sp., taxon; a,b - *CS; ringed wood with tracheid, latewood tracheids grouped in a zig-zag shaped field in the tangential direction, distinct annual ring border, c-RS; simple perforation table, spiral thickening in latewood tracheids e- *RS; homocellular medullary ray parenchyma consisting of squamous cells, d,f- *TS; multiserial and uniserial homocellular medullary rays *CS; Cross section, RS; radial section, TS; tangential section, (---) measurement scale; 250 µm (b), 100 µm (a,f), 50 µm (d,e), 25 µm (c)

The experimental study selected studies from the literature containing the physical and mechanical values of intact/perfect chestnut and elm species as the control group. In addition, attention was paid to the fact that the experimental studies selected from the literature included intact/perfect chestnut and elm species that spread in the relevant region. In this context, the data of the relevant study, including the results of the physical and mechanical properties of the intact/perfect chestnut, which was previously examined by Ay & Şahin (2002a,b) and obtained from the relevant region, were selected as the chestnut species' control group. However, the only study in the literature containing the physical and mechanicalproperties of the elm species, widespread in Türkiye, was compiled and examined only by As et al. (2001). In this context, the physical and mechanical properties of "*Ulmus montana"* in the related study by As *et al.* were selected as the control group (Table 2). A limited number of small-sized samples were obtained for the experimental phase, which was one of the limitations of the study, since the samples of the experimental group were authentic wooden elements from the historical wooden building in the region. Of nine authentic wooden samples obtained from the historical wooden building, seven were chestnut species and two were elm. Within the experimental study, air-dry density as well as oven-dry density, brinell hardness values, and bending and compressive strengths of the samples from both groups were compared. Efforts were made to select at least three samples for each experimental method for the historical chestnut and elm samples within the experimental study, which could not be achieved due to the elm samples being too small (Table 2).

Table 2. Physical traits of the study and control samples within the experimental study

Group	Sample	Species	Damage Status	Experimental Study	Number of Samples	Sample Dimension (mm)
Experimental Group 1	Historical wood	Chestnut	Biological and mechanical damages	Density test	11	50×50×50
				Hardness test	11	50×50×50
				Bending test	12	50×50×150
				Compression test	9	50×50×300
Control Group 1 Relevant reference: (Ay & Şahin, 2002a,b)	New wood	Chestnut	Intact	*	*	*
Experimental Group 2	Historical wood	Elm	Biological and mechanical damages	Density test	2	50×50×50
				Hardness test	2	50×50×50
				Bending test	2	50×50×150
				Compression test	2	50×50×300
Control Group 2 Relevant reference: (As et al. 2001)	New wood	Elm	Intact	*	*	*

*Samples of the control group were not experimentally studied since they were selected from the relevant study in the literature.

As a result of the density tests performed on the samples, the density of the historical chestnut samples was determined to be higher than that of the new chestnut samples (Figure 4). This ratio was approximately 10 % higher for air-dry density and approximately 9 % higher for oven-dry density. This result was the opposite in the historical elm sample (Figure 5). As a result of the density tests performed on the elm species, the density of the historical elm samples was lower than that of the new elm samples. This result was approximately 3 % lower in air-dry density value and approximately 2 % lower in oven-dry density. This result can be explained by the fact that as the age of the deciduous trees increases, the density is lower due to the formation of lighter wood from the trunk to the periphery, as mentioned by Berkel (1970). However, this result was not observed in chestnut, a deciduous tree species. Regarding the subject, when the studies in the literature in which historical woods with a certain useful life were compared with new wood, it was concluded that the density value did not change due to the natural ageing impact on the wood. The density values of old and new wood were close (Machado et al., 2019). A similar result was obtained from a density test conducted on wood elements of Castanea sativa species with service lives of 88, 113, and 120 years, taken from the "*Zeytinlik"* district, Giresun/Türkiye, by Topaloğlu et al. (2021). In the relevant study, the air-dry density of the old wood samples was found to be between 0.5 g/cm³ and 0.58 g/cm³, and the oven-dry density ranged from 0.47 g/cm³ to 0.54 g/cm³. The density values of wood samples taken from the rafter, roof ridge, and column pillar were found to be the same and/or close to the values of the recent wood. In addition to these findings, in another study conducted by Topaloğlu (2023), density tests performed on approximately 100-year-old chestnut samples taken from the "*Zeytinlik"* neighborhood in Giresun, Türkiye, revealed that the density of the historical chestnut samples was lower than that of the recent chestnut samples. Considering these data, it is observed that the density values of the historical chestnut samples are higher than those of the new ones, whereas the density values of the historical elm samples are lower. This finding is consistent with the data reported in the literature.

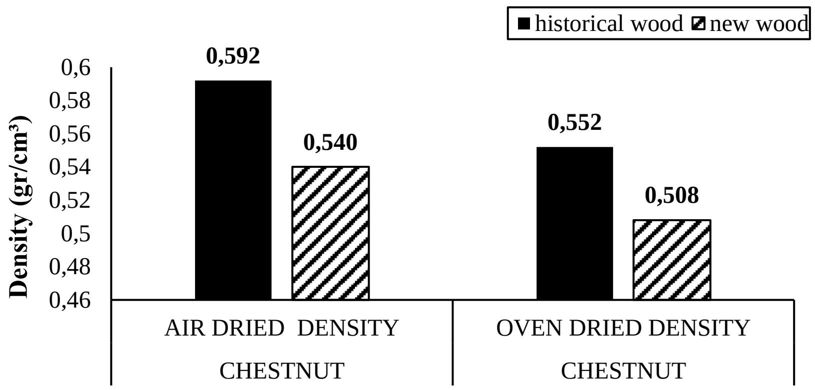


Figure 4. Results of the density tests on chestnut species

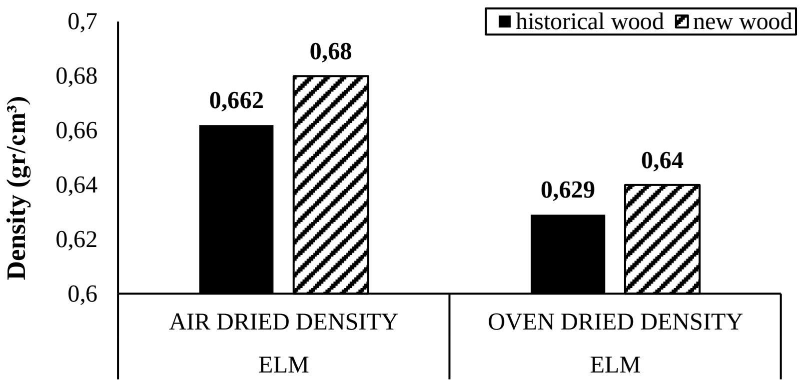


Figure 5. Results of the density tests on elm species

As a result of the hardness test, while the Brinell hardness test result of the historical chestnut was very close to that of the new chestnut in a direction parallel to the fibers, it was approximately 26 % higher for the historical than the new chestnut in a direction perpendicular to the fibers (Figure 6). In the formation of this result, it is thought that the hardness changes depending on the structure of the wood on the relevant surface, and by considering the Brinell hardness measurement, it is a measurement of the surface hardness of the wood. The samples subjected to the experiment do not rot, especially in a direction perpendicular to the fibers, as stated by Berkel (1970). In this context, it was supported through the Brinell hardness test that a superficial rotting observed in historical chestnut samples, when viewed from the outside, was observed primarily in a direction perpendicular to the fibers. However, when the results of mechanical experiments are examined, it can be concluded that the samples are rotten from the inside rather than the outside. In particular, the bending strength of the historical chestnut samples was 57 % less than the new chestnut, and the compressive strength was 40% less than the new chestnut (Figure 6). The severe decrease in the bending strength of the samples was more significant than the compressive strength. As Eriç (2016) mentioned, the increase in the lignin content of wood as it ages can be due to the transformation of wood into a more rigid and fragile material. Another approach is that since the historical samples are not only under the effect of natural ageing but also have biological damage, both the bending and compressive strengths of the materials were very low due to rotting in the internal structures of the materials. When examined through the density values of the materials, the bending and compressive strengths of the historical chestnut samples with high density, as shown in Figure 4, were very low. Contrary to this result, as mentioned by Berkel (1970), the bending strength in wood was expected to result in a linear increase depending on the density. At this point, although an increase in the mechanical traits of the historical chestnut samples is expected due to an increase in the lignin ratio as the wood ages, as mentioned by Eriç (2016), or due to an increase in the density of the wood as referred by Berkel (1970), it is concluded that damaging biological agents may internally damage the wooden materials. Moreover, it is supported by experimental studies that severe losses occur in cellulose and hemicellulose, which are responsible for the bending strength of wood, and lignin, which is responsible for compressive strength, due to biological destruction (Berkel, 1970).

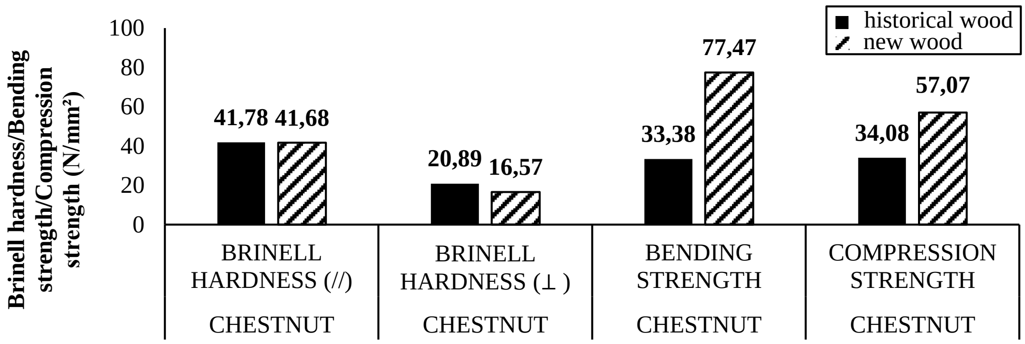


Figure 6. Results of the hardness, bending, and compression tests on the chestnut species

As a result of the hardness test on the elm samples, it was found that the Brinell hardness values of the historical elm samples were lower than that of the new elm samples for both fiber directions (Figure 7). This result is in parallel with the density experiment when Figure 5 is examined. In this context, it can be mentioned that there was superficial rotting observed when the historical elm samples were viewed from the outside. However, the Brinell hardness values of the historical elm samples were measured as approximately 28 % less in a direction parallel to the fibers and 38 % less in a direction perpendicular to the fibers compared to the new elm samples. These results show that in the historical elm samples, the materials were superficially, but heavily damaged, from the inside and outside.

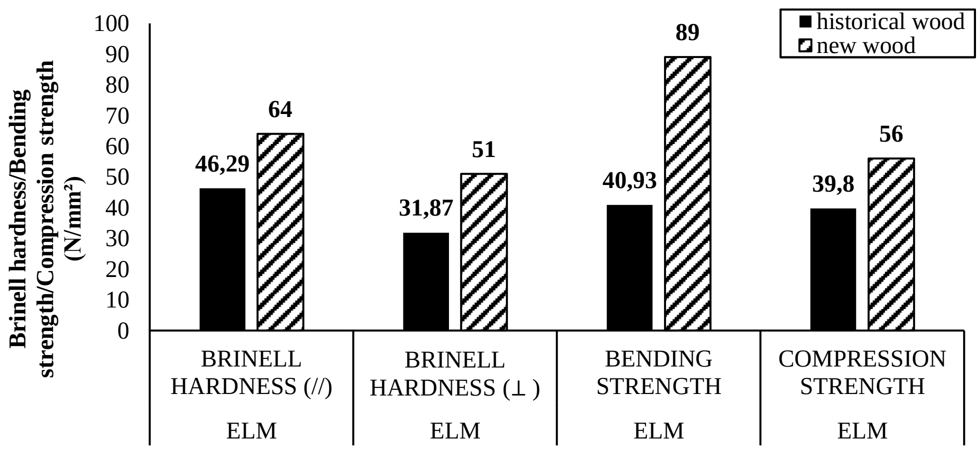


Figure 7. Results of the hardness, bending, and compression tests on the elm species

When the bending and compressive strength graphs in Figure 7 were examined, the historical elm samples showed a loss of approximately 54 % in bending and 29 % in compressive strength compared to the new elm samples. This loss in the mechanical properties of the materials is thought to result from severe damage to the material, as demonstrated by the density and hardness experiments. A similar approach is present in the study by Cavalli et al. (2016). In their study, Cavalli et al. (2016) concluded that the bending strength and bending stiffness behavior of wooden materials either remained at the same values over time or a decrease was observed if it was very serious. However, they stated that the severe decrease in the bending strength of wood materials after many years was not directly related to the ageing of the wood but might occur due to the result of approaches related to the use of wood, such as the duration of load, the protection of the wood, and the dismantling damages. In addition to this approach, as in the historical elm samples used in the experiment, the loss of strength in biologically damaged wood is thought to be due to the degradation of cellulose and hemicelluloses, as stated by Witomski et al. (2016).

Another point that drew attention when the graphs in the experimental study were examined was that the results of the loss in strength of the historical chestnut and elm species were close to one another. While the loss in bending strength of the historical chestnut samples was 57 % less than the new chestnut, this value was 54 % less in the historical elm samples compared to the new elm. Similarly, the loss in compressive strength of the historical chestnut samples was 40 % less than the new wood, while this value was 29 % less in the historical elm samples compared to the new wood. Considering the data mentioned above, the change in the mechanical properties of two different deciduous tree species, which were in the same structure and had the same service life and damage type, resulted in harmony with one another. However, the greater decrease in compressive strength of historical chestnut compared to the historical elm species suggests, based on Berkel's (1970) findings that lignin provides compressive strength to wood, that the lignin content in historical Anatolian chestnut may have decreased to a greater extent.

Figures 8 and 9 show the correlation graphs between density-bending strength and density-compressive strength, respectively, for the historical chestnut samples. When Figure 8 is examined, a strong linear relationship ($R^2 = 0.8169$) is found between air-dry density and bending strength in the historical chestnut samples. Similarly, a moderate linear relationship ($R^2 = 0.762$) is observed between oven-dry density and bending strength. These results indicate that as the density increases in the historical chestnut samples, there is a corresponding increase in bending strength.

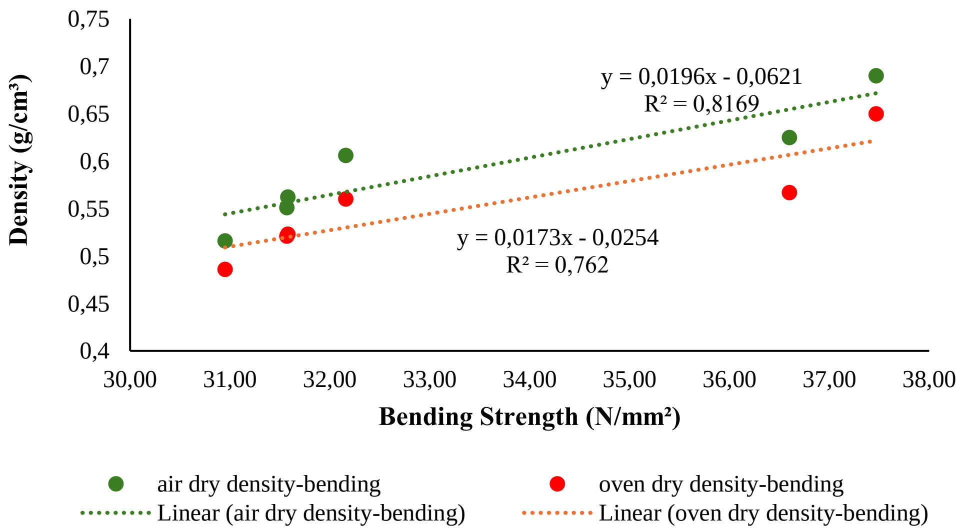


Figure 8. The correlation analysis for the density-bending strength of historical chestnut samples

The strong linear relationship between density and bending strength obtained from the historical chestnut samples is not observed in the density-compressive strength correlations when Figure 9 is examined. The correlation results for air-dried density-compressive strength ($R^2 = 0.1124$) and oven-dried density-compressive strength ($R^2 = 0.0269$) show that no linear relationship could be established. These results indicate that the increase in density is not related to an increase in compressive strength for the historical chestnut samples.

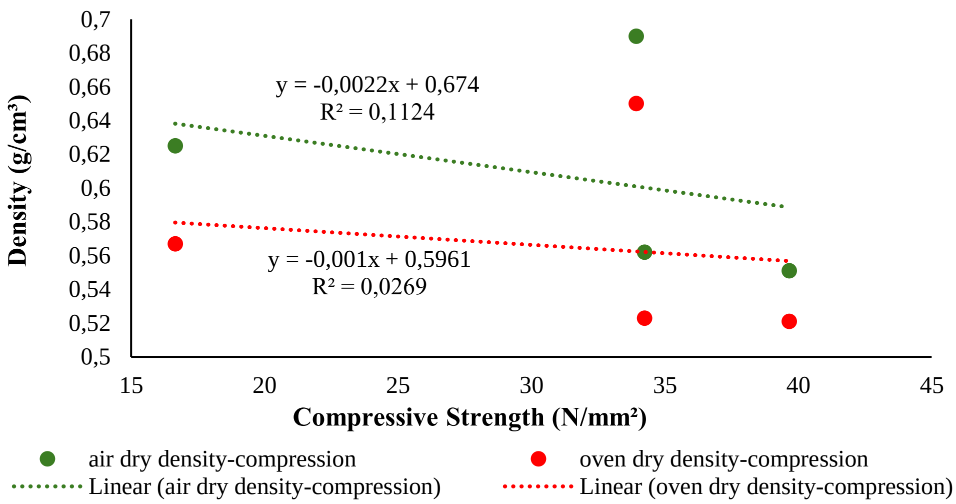


Figure 9. The correlation analysis for the density-compressive strength of historical chestnut samples

Conclusions

Within the scope of the study, the changes in the physical and mechanical traits of the load-bearing wooden elements from the chestnut and elm species of the same age, taken from a historical wooden building (under the same physical conditions), arising from exposure to the same type of biological damage, were investigated. In this context, historical wooden elements were selected from the relevant sources in the literature and compared with the physical and mechanical properties of the same intact/perfect chestnut and elm species from the relevant region. As a result of the density experiments carried out in the study, the historical chestnut samples had a slightly higher density compared to the new chestnut samples. Conversely, the historical elm samples had a lower density than the new elm samples by a small margin. It was concluded that the density in the experimental study, as mentioned in the literature, did not change due to natural ageing but changed depending on the porosity rate in the structure of the historical wood and the damage in the structure. As a result of the hardness experiment in the study, the historical chestnut had a hardness value close to the new chestnut. Accordingly, since the hardness experiment measured the hardness on the surface of wood, it was concluded that the historical chestnuts were relatively rigid. However, the historic elm had a lower hardness value than the new elm. This result arose from damage on the surface of the historical elm species. As understood from the mechanical experimental results of the study, both wood species had relatively low strength values compared to the new woods. Historical chestnut yielded approximately 57 % less bending and 40 % less compressive strength than new chestnut. This result led to the conclusion that the historical chestnut rotted excessively from the inside and that the cellulose, hemicellulose, and lignin that provided mechanical strength to the wood were excessively destroyed by damaging biological agents. Similarly, the historic elm had approximately 54% less bending and 29% less compressive strength than the new elm. At this point, it was concluded that the loss of cellulose and hemicellulose, which provided bending strength, was more common in historical elm wood. When all experimental results were evaluated, the difference in the bending strength of the woods belonging to different deciduous tree species was very close (57 % and 54 %) until the present-day. However, it was concluded that the loss of compressive strength over time in two different species was not relatively close to one another (40 % and 29 %), which arose from the high amount of damage to the element (the loss of lignin was higher). The relevant data experimentally show that these two species, especially the elm species, which are generally used together in the registered and conserved buildings in the region, spread in scattered and few groups in the forests of Türkiye and its wood is very valuable (Akkemik, 1995). Therefore, the restorations to be made in the relevant region could use the chestnut instead of Elm species, when necessary, since it provides the similar mechanical properties.

Ethics Committee Approval

N/A

Peer-review

Externally peer-reviewed.

Author Contributions

Conceptualization: M.A.K.A., O.S.D.; Investigation: M.A.K.A., O.S.D.; Material and Methodology: M.A.K.A., O.S.D.; Supervision: O.S.D.; Visualization: M.A.K.A.; Writing-Original Draft: M.A.K.A.; Writing-review & Editing: M.A.K.A., O.S.D. All authors have read and agreed to the published version of manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

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