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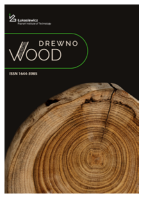

Physical Properties of Nearly Thousand-Year-Old Oak Wood Compared with Oak Wood of Different Origins From Previous Centuries and Present Times

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The aim of this study was to assess the hardness and compressive strength of oak wood from various historical contexts, including bog oak and wood from architectural structures, and to compare these properties with those of modern oak wood. Both radiocarbon and dendrochronological dating were utilized to determine the age of the wood. A total of five oak wood fragments were analyzed: bog oak, oak wood from the bell tower of the Collegiate Basilica of the Holy Spirit in Przeworsk, oak wood from the scaffolding of St. Nicholas' Church in Gniew, wood from a dismantled granary in Drawsko Pomorskie, and a sample from a water dam in Czaniec. The dating confirmed that the oak fragments varied in age, ranging from several centuries to over 900 years old. Mechanical tests using the Brinell method and compressive strength tests indicated statistically significant differences in compressive strength between the wood of bog oak and the other wood samples, which may be attributed to the long-term mineral saturation of the wood from prolonged exposure to anaerobic conditions in the bog. This mineralization likely caused a reduction in its elasticity and overall strength. In contrast, other samples, which had been exposed to varying environmental conditions such as periodic water immersion or protection from moisture, did not show significant differences in the mechanical tests. Despite these challenges, the findings suggest that compressive strength may serve as a useful indicator for estimating the age of oak wood in archaeological contexts, and particularly for assessing the influence of long-term environmental conditions on wood properties.

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Introduction

The hardness of wood is a key parameter in determining its mechanical properties, and is influenced by various factors such as the density, moisture content, and age of the wood [Kozakiewicz et al., 2012; Broda and Mazela, 2014; Cavalli et al., 2016; Mladenova and Bardarov, 2017; Gayda and Kiyko, 2023; Hivi, 2025]. The hardness of wood is known to change over time, as wood undergoes natural processes of degradation including drying, oxidation, and decomposition [Cavalli et al., 2016]. Several studies have shown that as wood ages, it tends to become harder due to the increase in lignin content and the decrease

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in cellulose, resulting in a denser and more compact structure [Kránitz et al., 2016; Dadzie et al., 2025]. One particularly fascinating area of study in this regard is the analysis of wood hardness in relation to time passed, focusing specifically on bog oak, whose age can range from hundreds to thousands of years [Kaennel and Schweingruber, 1995; Meneghello et al., 2022] or even hundreds of thousands of years [Guyette and Stambaugh, 2003]. Bog oak is also known as "Irish wood" [Mahr, 1935], and in Poland, due to its dark black color, it can be called "black oak" [Kalicki and Krąpiec, 1995]. Studies have shown that the hardness of bog oak can increase with age, as a result of various factors such as lignin concentration, mineral uptake, and structural changes during the preservation process. It was found in one study that the hardness of bog oak increased significantly with each additional century of aging, likely due to the consolidation of lignin and other cell wall components over time. The degradation of lignin in subfossil oak progressed more slowly over time than cellulose degradation. A negative correlation was found between age and the ratio of cellulose and lignin degradation; however, that relationship was statistically insignificant [Rede et al., 2022]. Furthermore, Reve et al. [2022] investigated the influence of age on the mechanical properties of bog oak and reported a gradual increase in hardness and stiffness with increasing age. The authors attributed these changes to the continued polymerization of lignin and the reduction of hemicellulose content in the cell walls of the wood. In summary, the aging process of bog oak in waterlogged environments can lead to a notable increase in hardness over time. Also, other authors have reported that the hardness of wood increases over years of aging, with a notable correlation between wood age and hardness [Chiara et al., 2022]. This increase in hardness over time has also been attributed to the gradual accumulation of extractives in the wood cell walls, which leads to a higher proportion of lignin and hemicelluloses in the wood structure. However, other research [Cavalli et al., 2016] demonstrated that the relationship between wood hardness and aging is nonlinear, with varying rates of change in hardness depending on the wood species and environmental conditions. In conclusion, the hardness of bogwood is a dynamic property that evolves over time, influenced by a combination of intrinsic and extrinsic factors. However, when ancient bog oak dries, large radial and transverse cracks occur due to the loss of wood substances, particularly cellulose [Hedges, 1990]. Understanding how wood hardness changes with time is crucial for various applications, including woodworking, construction, and the preservation of historical wooden artifacts. As a biological material, wood has a number of disadvantages, including a variable structure, and its quality depends on hereditary factors or the environment in which it grows, especially climatic conditions. Wood is hygroscopic and anisotropic, and subject to oxidation, decomposition and mineralization. The Greek philosopher Theophrastos (371–287 BC), a pioneer in wood research, stated that the quality of wood depends on the time of harvest, stronger and better-looking wood can be obtained from logs free of knots, and that the best-quality Greek wood for structural applications came from the region of Macedonia, where the wood was smooth, had a straight grain and contained resin; moreover, wood from species of juniper, chestnut, cypress, cedar, ebony and mulberry was said to be among the most resistant to biological degradation [Barboutis et al., 2019]. Understanding the factors influencing this phenomenon is crucial for the accurate assessment and utilization of this unique material in various applications, including woodworking, conservation, and archaeology. Further research is needed to explore the underlying mechanisms driving the changes in wood hardness with age and to develop predictive models for estimating wood hardness based on the age of the wood. Wood hardness is also a crucial factor in determining the quality and durability of wooden materials, with significant implications for various industrial and cultural applications [Kozakiewicz et al., 2012]. Bog oak, also known as bog-wood or bogwood, is a type of oak wood that has undergone a unique preservation process due to being submerged in peat bogs, or in water for extended periods ranging from a hundred years to centuries or millennia [Kaennel and Schweingruber, 1995]. Bog oak is well known to persist for thousands of years in riparian systems across Europe [Becker, 1993]. Bog-wood is formed from the trunks of trees that have lain in bogs or in places with bog-like conditions such as lakes, river bottoms and swamps; deprived of oxygen, the wood undergoes a process of fossilization, preserved from decay by the acidic and anaerobic bog conditions [Wasilewski and Stelmach, 2014; Krajewski, 2016; Szymczak-Graczyk and Bykowski, 2023]. The extremely low oxygen concentration in the bog protects the wood from decay, while the underlying peat provides acidic conditions where iron salts and other minerals react with the tannins in the wood, gradually giving it a distinct dark brown to almost black color [Meneghello et al., 2022]. Usually the wood is stained brown by tannins dissolved in the acidic water, while bog-wood represents the early stages in the fossilization of wood, with further stages ultimately forming jet, lignite and coal over many millions of years [Krzysik, 1975; Galewski and Korzeniowski, 1958]. Water flow and depth play a special role in the creation of bog-wood. It has been shown that the moisture conditions present in peat do not favor quick decomposition of ligno-cellulosic materials [Riggio et al., 2014; Gach et al., 2024]. Currents bind the minerals and iron in the water with tannins in the wood, naturally staining the wood in the process. This centuries-long process, often termed "maturation," turns the wood from golden-brown to completely black, while increasing its hardness [Meneghello et al., 2022] to such a degree that it can be carved only with the use of specialist cutting tools [Prażmo, 1999]. While the time necessary for the oak to transform into bog-wood varies, "maturation" commonly lasts thousands of years. Due to the ecological factors mentioned above, no two trunks can be found with the same color. Bog-wood may be formed from any tree species naturally growing near rivers, in bogs, including *Quercus* sp., *Pinus* sp., *Taxus* sp., *Taxodium* sp., and others. Bog oak, being very rare, is considered a highly valuable timber [Krajewski, 2016]. Because of its color, its hardness, and its age of sometimes as much as a thousand years, bog-wood has often been used as a material for inlaid woodwork and marquetry in place of the rarer and more expensive ebony wood [Nardi, 2006]. It is also used to create a large variety of luxury objects, and in the past was used in ecclesiastic craftsmanship [Mahr, 1935]. It has been also used for the production of small valuable objects such as jewelry, pipes and knife handles, and in the restoration of inlaid furniture [Meneghello et al., 2022].

The study of bog oak's hardness over time can offer valuable insights into the effects of natural aging and environmental factors on wood properties [Cavalli et al., 2016]. Research has shown that as bog oak undergoes the preservation process, it is subject to a series of chemical changes that can impact its hardness, density, and overall structural integrity [Szczepaniak, 2002; Krajewski, 2016]. By examining the hardness of bog oak samples at different stages of preservation, researchers can gain a deeper understanding of the mechanisms behind these changes and the potential implications for the wood's practical use in various fields. One such study investigated the changes in hardness of bog oak specimens retrieved from different archaeological sites in Europe, dating back to various historical periods, and indicated a notable increase in wood hardness with prolonged periods of immersion in bog environments, highlighting the significance of time as a critical factor in the development of bog oak's unique characteristics [Meneghello et al., 2022]. These findings underscore the importance of considering the temporal dimension in evaluating the hardness of bog oak and its implications for archaeological, conservation, and woodworking practices. In conclusion, the relationship between wood hardness and time passed in the case of bog oak presents a compelling avenue for scientific inquiry, offering valuable insights into the intricate processes underlying the preservation and transformation of wood materials over extended periods [Kránitz et al., 2016]. Further research in this field may enhance our understanding of ancient wood technologies, improve conservation strategies, and unlock novel applications for bog oak in contemporary industries. Various physical and chemical properties of subfossil wood have so far been investigated in the United States [Guyette and Stambaugh, 2003], Croatia [Sinković et al., 2009; Rede et al., 2017] and other European countries [Kubovský et al., 2020; Büyüksari et al., 2017; Kolář et al., 2014]. Given the above-mentioned findings, it was hypothesized in this work that the physical properties of oak wood originating from different periods and residing in different environmental conditions have a significant impact on the wood's hardness and compressive strength. Therefore, one of the aims of the present study was to determine the date of origin of the investigated bog-wood through both radiocarbon dating and dendrochronological methods based on determining the number of tree-rings, while the main goal of the research was to determine the hardness and compressive strength of oak wood of different ages and to compare these values with the compressive strength and hardness of oak wood obtained in modern times.

Material and methods

1. Bog oak from a gravel pit in Kłaj, Lesser Poland Voivodeship (49° 59′ 36″ N, 20° 17′ 57″ E)

The study examined a fragment of bog oak (Oak1) obtained from a tree trunk from a gravel pit in Kłaj, Lesser Poland, in 2012. The material for testing, in the form of a wood disk cut from the trunk of the bog oak, was supplied on July 14, 2022 by Mr. Sławomir Siwek, owner of the Siwek Sławomir General Construction Services Company "TIP-TOP" based in Wiśnicz Mały, Poland. The subject of detailed analysis was a dried fragment of the oak trunk butt with a dark brown color (inside the cross-section) and a gray color in its sapwood section, which was intact and light in color compared with the entire heartwood part. The fragment of wood measured 750 x 390 x 120 mm and was characterized by a double pith (Fig. 1). The wood was classified as bog oak despite lacking the characteristic dark (black) coloring (Fig. 1). Although the supplied wood fragment was obtained from a cross-section of the trunk, it did not include bark, and during the analysis no subcortical rings were observed. Despite being found in a quarry and having remained there for several decades, the wood was characterized by a distinct grain structure, original round shape, and measurable tree ring widths (Fig. 1).

2. Wood from the bell tower of the Collegiate Basilica of the Holy Spirit in Przeworsk, Podkarpackie Voivodeship (50° 03′ 27.02″ N 22° 29′ 24.67″ E)

The second oak wood (Oak2) originated from the bell tower of the Collegiate Basilica of the Holy Spirit in Przeworsk, built in 1430–1473, located on a hill in the south-eastern part of Przeworsk, and funded by Jan Tarnowski, his descendants, and the townspeople. The first mention of Przeworsk dates back to the year 1280 in the Volhynian Chronicle [Penc, 1947]. In 1393, King Władysław Jagiełło granted municipal and market rights to Przeworsk, which was associated with the establishment of a parish, erected by Bishop Jan of Lubusz, and a year later approved by Bishop Maciej of Przemyśl. The parish was entrusted to the care of the Regular Canons of the Holy Sepulcher of Jerusalem. After several decades of the parish's existence, the church of St. Catherine located at the former Little Market Square proved to be too small for the large community of Przeworsk and the surrounding villages. The Canons decided to build a church dedicated to the Holy Spirit [Ablewicz, 1995]. Construction began in 1430 and was completed in 1473. To this day, the church has retained its external Gothic-style structure. In the 17th century, a 40-meter Gothic tower was added to the church, which now serves as the bell tower [Arszyński and Mroczko, 1995]. The year 1718 saw the construction of the Chapel of the Holy Sepulcher, next to the side nave. The central feature of the church is an altar made in the Tuscan Baroque style; there is also a pulpit dating from 1713, and the oldest element of the church's furnishings is a baptismal font from 1400. In the vicinity of the church there is a single-story building constructed between 1473 and 1516 and connected by a wall from 1640, incorporating a tower from 1502, and enclosing the church. It had a defensive function: the complex survived Tatar invasions, the Swedish Deluge, and robberies. The single-story building housed the Bożogrobcy monastery, and now serves as the rectory. In 1742, the church was connected to the monastery building by a cloistered arcade [Pruncal, 2005]. Around 1785, the peak of the tower was rebuilt to its current shape, a new copper roof was added, and a few decades later, in 1845, the roof over the presbytery was lowered and the 17th-century roof tiles were replaced with iron sheeting [Kozak and Polaczek, 2009]. In the years 1908–1910, neo-Gothic porches were added to the tower on the north and south sides, and after the death of the last Bożogrobcy monk, Father Kasper Mizerski, in 1846, the monastery ceased to function, and the care of the object was taken over by diocesan priests. In 1982, Pope John Paul II elevated the church to the status of a Minor Basilica [Dziuba, 1998; Bednarz et al., 2019]. The fragment of wood had a square shape and measured 194 x 225 x 80 mm (Fig. 2). It lacked bark, and during the analysis no subcortical rings were observed. Moreover, no sapwood was detected in the cross-section (Fig. 1).

3. Wood from St. Nicholas' Church in Gniew, Pomeranian Voivodeship (53° 50′ 02″ N 18° 49′ 25″ E)

Another sample of oak wood (Oak3) originated from a wooden beam fragment from scaffolding bricked into the wall of St. Nicholas' Church in Gniew (formerly named Mewe or Gimev) in north Poland. The first document from the Catholic Church archive in Gniew is dated 1204 and concerns the foundation of a church in honor of the Archangel Michael; however, the church's officially documented history begins in 1284 with an order granting permission to build churches in the land of Gniew [Die Bau- und Kunstdenkmäler der Kreise Marienwerder… 1887]. The first construction of a church began in the mid-fourteenth century, probably on the site of an older, wooden temple that was mentioned in 1297 in the act of foundation of Gniew. The construction of the nave and the tower continued to the early 15th century, and in the second half of that century, after the Teutonic Order left the town, the tower was raised, and chapels were added to the eastern bays of the nave. Around 1557, the church was taken over by Protestants. It was returned to Catholics in 1596. In the next century the equipment was replaced with new, Baroque items [Grzyb and Strzeliński, 2008]. It is also known that masses at that time featured a band existing at the parish church, distinguished by the privilege of Jan Sobieski in 1668, which ensured its exclusive right to play at various secular ceremonies both in Gniew itself and in the villages of Gniew's eldership [Strzelecka, 1982]. At the turn of the seventeenth and eighteenth centuries, the church was affected by an unknown catastrophe, associated with fire or contemporary wars. As a result, the upper part of the tower and the vaults of the aisles were destroyed. They were rebuilt as wooden, and survived in that form until the nineteenth century. Major renovation works were probably not undertaken due to ongoing disputes with the city council in the 18th century. At the end of the century, the condition of the building was extremely poor, and renovation work took several years until 1799. In 1846 a southern porch was added, and in the years 1875–1876 a general renovation was carried out, during which vaults were made over the aisles, the upper parts of the tower were demolished, and a new 11-meter-high part with roof and neo-Gothic gables was erected. In the interwar period, the interior was renovated [Die Bau- und Kunstdenkmäler der Kreise Marienwerder… 1887]. In 1945, in the last months of World War II, artillery shells damaged the church tower and walls, and the roofs and all of the windows were destroyed. After the war, in the years 1956–1957 all necessary repairs were made and the interior was renovated [Strzelecka, 1982; Grzyb and Strzeliński, 2008]. The sample of wood investigated in this research was originally part of an oak scaffold erected during the construction of the presbytery or the plastering of its interior, and was found under aGothic painting, previously made on still damp plaster. The historical analysis of the object indicated the probable date of the painting's creation as between 1282 and the mid-14th century [Bednarz and Ptak, 2019]. The fragment of wood was triangular in shape, with a size of 167 x 125 x 65 mm and 50 mm thick (Fig. 1). The wood did not have bark, and during the analysis no subcortical rings were observed; however some sapwood was detected in the cross-section (Fig. 1).

4. Wood from a granary in Drawsko Pomorskie, West Pomeranian Voivodeship (53° 31′ 53″ N 15° 48′ 40″ E)

The next subject of detailed analysis was a fragment of a thick oak board (Oak4) measuring 290 mm x 45 mm x 100 mm. It had no bark, and no sapwood was detected in the wood cross-section (Fig. 1). The analyzed fragment of oak board originated from an old, now dismantled granary in Drawsko Pomorskie in northern Poland.

5. Wood from the Czaniec water dam in Porąbka, Silesian Voivodeship (49° 49′ 42″ N 19° 13′ 18″ E)

Detailed analysis was conducted on a fragment of oak beam (Oak5) measuring 245 mm x 130 mm x 235 mm, having no bark and no sapwood in the cross-section (Fig. 1), originating from the Czaniec water dam structure. The dam was built in 1958, and in the same year, oak elements were installed in its sluice box [Bałus et al., 2007; Jaguś, 2017; Gach et al., 2024]. The test material was exposed to extremely variable environmental conditions until 2020 (periodically fully submerged in water and exposed outside the water environment). Despite the extreme conditions to which the studied oak material was subjected, there were no significant cavities in the material that projected the macroscopic image of the wood structure (Fig. 1).

6. Hardness and compressive strength analyses

Strength tests were carried out in the Agrophysical Laboratories of the Department of Forest Utilization, Engineering, and Forestry Technology at the University of Agriculture in Kraków, using a Shimadzu Autograph AGX-V 50kN universal testing machine (Fig. 2), operated via Trapezium-X software (Shimadzu Corp. 2023). The strength of wood in compression along the fibers (CS) with reference to a 12% moisture content was tested according to the PN-79/D-04102 standard. Prior to the strength

Fig. 1. From upper left: fragment of bog oak taken from the trunk of a tree found in a gravel pit in Kłaj, Lesser Poland (Oak1), fragment of oak construction in bell tower of the Collegiate Basilica of the Holy Spirit in Przeworsk (Oak2), sample of oak from a wooden beam of scaffolding bricked into the wall of St. Nicholas' Church in Gniew (Oak3), fragment of oak structural beam from a granary in Drawsko Pomorskie (Oak4), fragment of beam from the Czaniec water dam in Porąbka (Oak5)

test, the dimensions of the cross-section of each sample were measured using a caliper with a precision of 0.05 mm. After the sample was placed on the measuring table of the machine, a pre-test was initiated, which involved automatically lowering the traverse with a force sensor at a speed of 30 mm/min until contact with the sample was made. Contact was considered to be established when the load detected was above 0.5 N. The actual test was then conducted at a speed of 3 mm/min until the force dropped by 50% compared with the maximum registered value; or if such a drop was not recorded, until the sample height decreased by 5 mm. The obtained values of compressive strength along the fibers were converted to values for wood with an absolute moisture content of 12% using the following formula:

$$CS_{12\%} = CS_{w\%}\,[1+\alpha(W-12)] \quad (1)$$

where $CS_{12\%}$ is the compressive strength at an absolute moisture content of 12%, $CS_{w\%}$ is the compressive strength at the current absolute moisture content, α is the coefficient of change in compressive strength along the fibers when the moisture content changes by 1%, and W is the current moisture content of the wood, measured immediately after the test.

The hardness of wood along the fibers was determined using the Brinell method [Brinell, 1900] based on the guidelines of the Polish standard PN-EN ISO 6506-1, 2016 [PKN, 2016]. Prior to the strength test, the dimensions of the cross-section of each sample were measured with a caliper with a precision of 0.05 mm. After the sample was placed on the measuring table of the machine, a pre-test was initiated to eliminate the resistance caused by the base spring of the indenter. The traverse with the force sensor was automatically lowered at a speed of 60 mm/min until contact with the sample was made. Contact was considered to be established when the load detected was above 3 N. The actual test was then conducted at a speed of 1 mm/min until a load of 98.1 N was reached. After reaching the specified load, it was maintained for 25 seconds. After this time, the indentation value was read from the clock indicator, and the hardness was calculated from the formula:

$$HBW = P/10\pi{\cdot}h \quad (2)$$

where HBW is the Brinell hardness (MPa) at the current moisture content of the wood, P is the load value of the indenter (N), and h is the depth of penetration of the indenter (mm).

The obtained hardness values were converted to values for wood with an absolute moisture content of 12% using the Bauschinger formula [PN-54/D-04109]:

$$H_{12} = HBW\,[1+\alpha(W-12)] \quad (3)$$

where H_{12} is the hardness of the wood at 12% moisture content, HBW is the hardness at the current moisture content, α is the coefficient of change in wood strength, and W is the absolute moisture content measured immediately after the test.

After the testing of all mechanical properties had been completed, the samples were placed in a laboratory dryer to determine the current moisture level. The drying process was carried out at a temperature of 103±2 °C and lasted for 24 hours. The absolute moisture content of the material was determined by the difference in mass before and after drying, using the formula [PN-77/D-04100:1978]:

$$W = (M_W - M_S)/M_S \cdot 100\% \quad (4)$$

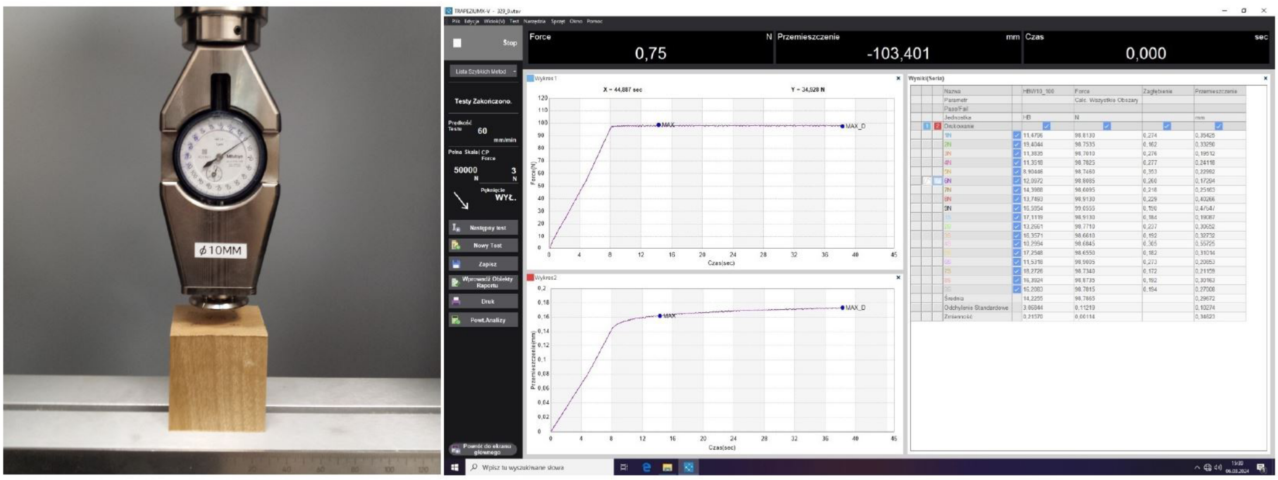

Fig. 2. Trapezium program interface and support with 10 mm steel ball showing the progress of the hardness test

where W is the absolute moisture content of the wood [%], M_W is the mass of the moist wood sample, and M_S is the mass of the absolutely dry wood sample.

The testing procedure and machine readings are illustrated by a screenshot from the Trapezium-X program (Fig. 2).

Results

1. Dating of bog oak

Using the dendrochronological method, a "floating" real sequence of tree-ring widths was created to determine the length of the oak's life and illustrate the variability of ring widths over the time. The results indicate that the oak reached at least 249 years of age. The conventional radiocarbon age of the oak wood was determined at 580±30 years [BP] (Fig. 3, Table 1).

Approximate years of formation of the external tree-rings of the examined bog-wood were determined using the radiocarbon dating method. The radiocarbon age of the oak (Oak1) from the gravel pit in Kłaj, Lesser Poland was estimated at 580±30 years before present (BP). However, considering that the wood sample for radiocarbon dating was taken from the outer part of the trunk, i.e. the area of the youngest radial growth rings (closest to the present; gray color) and that no subcortical rings were observed during the research, the age of the oldest dated ring of the bog oak, taking into account the number of rings formed by the tree, should be estimated at 871–931 years before present. A fairly long sequence containing 249 rings was confirmed in the investigated bog oak.

2. Dating of wood from the bell tower of the Collegiate Basilica of the Holy Spirit in Przeworsk

Dendrochronological dating was performed using the standard for oak constructed by Hoffsummer, which spans the years 1118–1986 [Hoffsummer, 2002]. The measurement of tree-ring widths in the oak beam (sample Oak2) showed that its chronology covered a span of 107 years and it may be classified as a relatively young oak tree. The average ring width was 1.74 mm; the highest recorded value was 3.55 mm, and the lowest 0.96 mm. Analysis of the similarity of the tree-ring chronology with the reference curve showed that the best correlation between dendroscales occurs between 1648 and 1755. The comparison indicated that the first wood ring formed in 1648 and the last in 1755. The validity of dating is evidenced by the test value TT = 1.9 ($p = 0.06$) and the correlation coefficient $r = 0.19$; N=108 ($p = 0.049$). Similarly, the accuracy of dating was confirmed by analyzing the similarity of the normalized curves, which gave the correlation coefficient $r = 0.41$; N=108 ($p < 0.001$). The accuracy of the dating was confirmed by the percentage similarity coefficient (Gleichläufigkeit value) of the millimeter curves, which took the value GLK = 0.56. The dating showed with a high probability that the oak sample from the beam construction of the bell tower dates to the beginning of the second half of the 18th century.

3. Dating of wood from St. Nicholas' Church in Gniew

In a cross-sectional slice from the oak beam, only 28 tree-rings were identified (including the oldest ones close to the core and a few latewood rings). The average

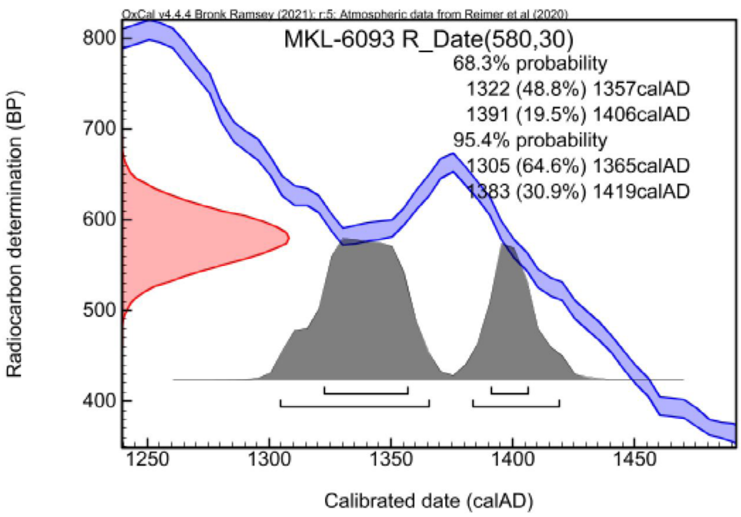

Fig. 3. Compilation of results of radiocarbon dating using the LSC technique for sample Oak1. The radiocarbon age of the youngest growth rings of the bog oak from the gravel pit area in the town of Kłaj, Lesser Poland was established at 580±30 years [BP]

ring width was 4.485 mm. The variability of ring widths was synchronized with Hoffsummer's absolute dating chronology of oak from the Ardennes–Liège area in Belgium covering the years 1118–1986 [Hoffsummer, 2002]. Due to the relatively small number of rings represented in the examined scaffolding fragment, based on a previously conducted historical analysis regarding the most probable date of the object's construction, the aforementioned reference curve was correlated with the time range of the standard chronology for the years 1118–1300. Comparative analyses indicated that the first wood ring on the beam from the wall of St. Nicholas' Church in Gniew was formed in 1191, and the last in 1219. The correctness of the dating is supported by the value of the t-Student test, TT = 2.6 ($p = 0.015$), and the correlation coefficient for the indexed data is $r = 0.47$; $N = 28$ ($p = 0.012$). In the comparison of millimeter curves, the correlation coefficient was $r = 0.56$ ($p = 0.002$) for $N = 28$. The accuracy of the dating was confirmed by the percentage similarity coefficient (Gleichläufigkeit value) of the millimeter curves, which took the value GLK = 0.68 [Bednarz and Ptak, 2019].

4. Dating of wood from the granary in Drawsko Pomorskie

Detailed dendrochronological analysis revealed the presence of 87 growth rings. The average value of radial growth was 2.380 mm, with a minimum value of 0.312 mm and a maximum value of 5.778 mm. Based on the "cross-dating" method it was estimated that the tree-rings of the oak board formed between 1667 and 1753. The correctness of the dendrochronological dating is confirmed by high correlation coefficients for normalized chronologies with the reference curve of oak from northern Poland in the time span 996–1985 [Ważny, 1986], which took values of $r = 0.40$; $N = 87$ ($p < 0.001$). Similarly, high values of Student's t-test were obtained in curve synchronization, reaching TT = 4.0; $N = 87$ ($p < 0.001$). In the comparison of millimeter curves, the correlation coefficient was $r = 0.47$ ($p < 0.001$) for $N = 87$. The accuracy of the dating was confirmed by the percentage similarity coefficient (Gleichläufigkeit value) of the millimeter curves, which took the value GLK = 0.59. The obtained statistical indicators indicate the high consistency of the course of normalized chronologies with the absolutely dated 990-year-old oak reference from northern Poland authored by Ważny [1986]. Based on this, it is concluded that the last rings preserved on the cross-section of the granary board fragment developed in the year 1753. However, considering the fact that the analyzed samples of oak wood lack sapwood, it should be suspected that the actual age of the oak wood in question is greater, and it most likely dates to the second half of the 18th century [Bednarz, 2024 – unpublished data].

5. Dating of wood from the Czaniec water dam in Porąbka

Dendrochronological dating was performed using the absolutely dated oak chronology originating from Hajnówka, Poland, created by Ważny [2019] with the year span 1720–1984. The measurement of tree-ring widths in the oak beam (sample Oak5) showed that its chronology covered a span of 46 years and it may be classified

Table 1. Result of dendrochronological and radiocarbon dating of oak wood using the crossdating method and LSC technique

No.	Wood origin description	Age [years]	Calendar time span [years]	Number of tree--rings	Laboratory sample no.
Oak1	Wood of bog oak, originated from Kłaj – gravel pit (Lesser Poland)	871-931*	1093-1153*	249	BBL-OAK1153
Oak2	Wood of oak originated from Przeworsk – bell tower of Collegiate Basilica of St. Holy Spirit (Subcarpathian Voivodeship)	269-376	1648-1755	108	BBL-OAK1755
Oak3	Wood of oak originated from Gniew – St. Nicholas' Church (Pomeranian Voivodeship)	805-833	1191-1219	28	BBL-OAK1219
Oak4	Wood of oak originated from granary in Drawsko Pomorskie (West Pomeranian Voivodeship)	271-357	1667-1753	87	BBL-OAK1753
Oak5	Wood of oak originated from The "Czaniec" water dam in Porąbka (Silesian Voivodeship)	100-145	1879-1924	46	BBL-OAK1924

* Span time estimated based on the radiocarbon dating accuracy (±30 years) and number of tree-rings determined

as a relatively young oak tree. However, sapwood was not recorded in the cross-section of the beam (Fig. 1). The average value of the ring widths was 3.679 mm; the highest recorded value was 8.871 mm, and the lowest 1.887 mm. Synchronization of the tree-ring chronology with the oak reference showed that the best correlation occurred between 1879 and 1924. The comparison thus indicated that the first ring formed in 1879 and the last in 1924. The validity of the dating is evidenced by the test value TT = 2.3 (p = 0.06) and the correlation coefficient r = 0.32; N=46 (p = 0.01). Similarly, the accuracy of dating was confirmed by analyzing the similarity of the normalized curves, which gave the correlation coefficient r = 0.35; N=46 (p = 0.017). The accuracy of the dating was confirmed by the percentage similarity coefficient (Gleichläufigkeit value) of the millimeter curves, which took the value GLK = 0.54. The dating showed with a high probability that the oak sample originating from the beam construction of the dam dates to the beginning of the second half of the 20th century.

6. Hardness and compressive strength analyses

Tests of the hardness and compressive strength of the investigated oak wood were performed on 30 wood samples cut out as cuboids with dimensions of 20 x 20 x 30 mm. A total of 150 perpendicular oak wood samples were used in the wood strength and hardness tests. The results obtained for maximum stress [N/mm^2] [MPa] and hardness [HB] [MPa] indicated the differences between the physical parameters of the analyzed oak wood in terms of minimum, average and maximum values.

The curves obtained during the compression test reveal several important characteristics of the material under investigation. The initial almost linear increase in pressure indicates the range of strength and elasticity. The end of the linear portion and the subsequent curvature of the line signal the beginning of specimen deformation; the attainment of the maximum value and the subsequent decrease indicate the end of the material's ability to maintain pressure. If the value drops to half of the maximum value, the test is then considered to be complete. If not, the test ends upon reaching a 5 mm compression path. As seen in the averaged graphs below (Fig. 4), the average compression paths for individual oaks differ, due to the varying quantity and physical characteristics of the samples, up to the moment where the maximum pressure value has dropped by half. Almost all samples from Oak3 and Oak4 maintained a load-bearing capacity above half of the maximum pressure value, indicating densification of the wood structure after the decrease from the maximum value. In the case of samples from Oak1 and Oak2, the average compression path is clearly shorter, meaning that a significant portion of the wood samples experienced a pressure drop to half of the maximum value. The samples from Oak5 largely maintained a load-bearing capacity above half of the maximum pressure value, which may be a consequence of the specific conditions (periodic immersion in water) under which the wood was kept (Table 3).

The hardness is at an average level characteristic for oak wood, that is, around 60 MPa [Bodig and Jayne, 1982], with the exception of Oak1, which exhibits a significantly lower value. This may be due to the specific conditions under which the oak wood was stored. The wood of this oak contained numerous cracks and delaminations, which is confirmed by the higher standard deviation. On the other hand, Oak5 originated from a dam, which may also have influenced the variability of the hardness test results (Table 2).

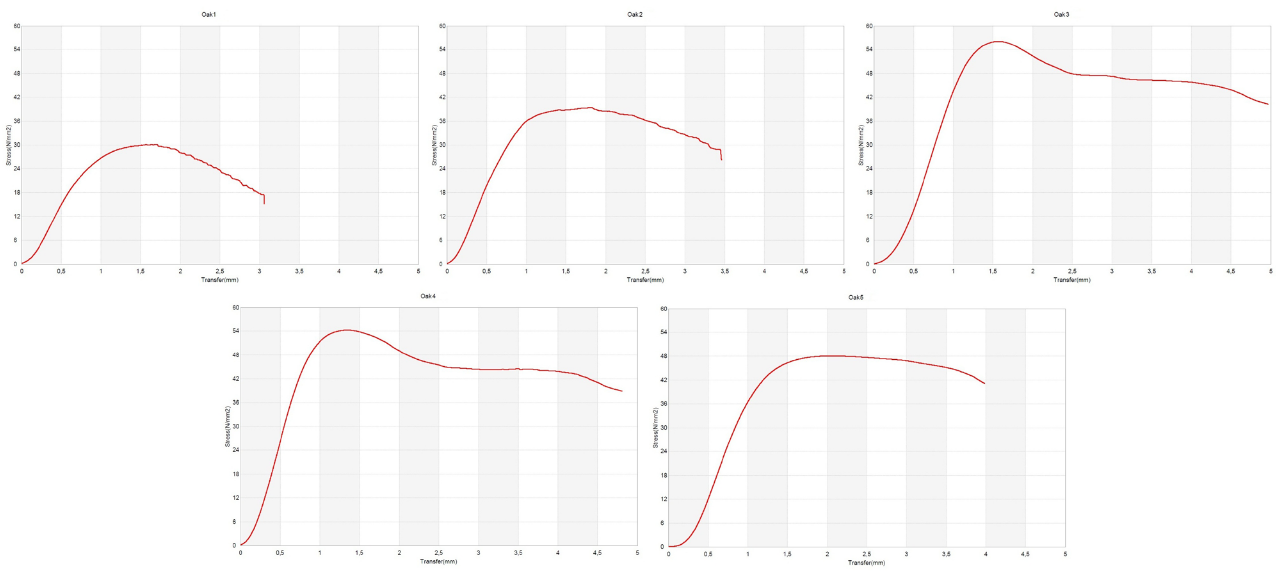

Fig. 4. Average compression test results for individual oaks, generated by the Trapezium-X program

Table. 2. Hardness test results in relation to the different origins and age of the oak wood investigated

	Hardness HB [MPa]				
	Oak1	**Oak2**	**Oak3**	**Oak4**	**Oak5**
Avarage	51.44	57.58	57.46	59.46	60.92
Standard deviation	14.17	7.44	9.55	7.33	14.99
Maximum	85.51	68.87	72.35	72.87	89.90
Minimum	28.40	47.12	44.01	46.81	35.81
Variability	0.28	0.13	0.17	0.12	0.25

Table 3. Stress test results in relation to the different origins and age of the oak wood investigated

	Maximum stress [MPa]				
	Oak1	**Oak2**	**Oak3**	**Oak4**	**Oak5**
Avarage	32.17	45.81	57.12	57.38	49.70
Standard deviation	5.85	5.56	6.65	6.00	4.21
Maximum	43.64	55.22	63.97	61.98	56.24
Minimum	18.17	36.54	44.74	40.13	41.66
Variability	0.18	0.12	0.12	0.11	0.09

Table 4. Wood's elasticity (Young's Modulus) test results in relation to the different origins and age of the oak wood investigated

	Young's modulus [MPa]				
	Oak1	**Oak2**	**Oak3**	**Oak4**	**Oak5**
Medium	1136.70	1816.15	2215.02	1984.62	1530.83
Standard deviation	351.59	716.29	705.62	380.95	537.93
Maximum	1731.44	3227.62	3109.00	2425.03	2743.99
Minimum	714.99	1031.04	1153.26	1285.21	797.85
Variability	0.31	0.39	0.32	0.19	0.35

Table 5. Deformation values as a results of compression test in relation to the different origins and age of the oak wood investigated

	Deformation [%]				
	Oak1	**Oak2**	**Oak3**	**Oak4**	**Oak5**
Medium	4.73	4.09	4.47	5.25	7.43
Standard deviation	1.46	0.95	0.90	1.01	2.30
Maximum	7.51	5.68	5.80	7.86	16.02
Minimum	2.68	2.75	3.48	3.96	4.70
Variability	0.31	0.23	0.20	0.19	0.31

The maximum stress values obtained in the compression test confirm the above observation. The pressure value for Oak1 is well below the average for this species (50–60 MPa) [Bodig and Jayne, 1982]. The consistent standard deviation values result from the fact that the contact area between the samples and the sensor during the test was larger than in the hardness test (Table 3).

The results of the compression test were used as the basis for determining the elasticity of wood (Young's modulus). In the case of the investigated oak wood samples, the results obtained correlate more clearly with the compression test results than with the hardness test results. The differences between the samples are particularly significant from a technical standpoint for Oak3, whose wood proved to be twice as elastic as the wood from Oak1 (Table 4).

The results obtained from the compression test also included deformation values, which indicate brittleness. In the tested samples, the deformation values were inversely proportional to the elasticity of the oak wood (Table 5).

7. Statistical analyses

The data obtained in the hardness and compressive strength tests were statistically analyzed. The normality of data distribution was verified with the Shapiro–Wilk test. The null hypothesis was that there is no significant departure from normality for each of the variable groups. The alternative hypothesis was that there is a significant departure from normality. The Shapiro–Wilk test was implemented using Statistica software, version 13.3 [Tibco, 2017]. The results indicated that the data for maximum pressure [N/mm^2] did not follow a normal distribution in the case of wood sample Oak4 ($p = 0.000076$, $N = 15$). Since one of the data sets for the analyzed parameters lacked normal distribution, the subsequent statistical analyses proceeded with the use of the Kruskal–Wallis method (Figs. 5–6) to test whether the samples originated from the same distribution. It was assessed whether there are statistically significant differences in the medians (or distributions) of the groups being compared [Ostertagová et al., 2014].

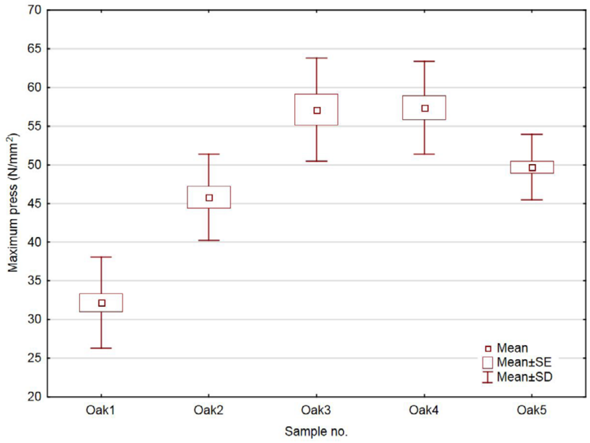

Fig. 5. Statistical differences in compressive strength between analyzed oak wood samples (Oak1–Oak5) as determined by the Kruskal–Wallis test

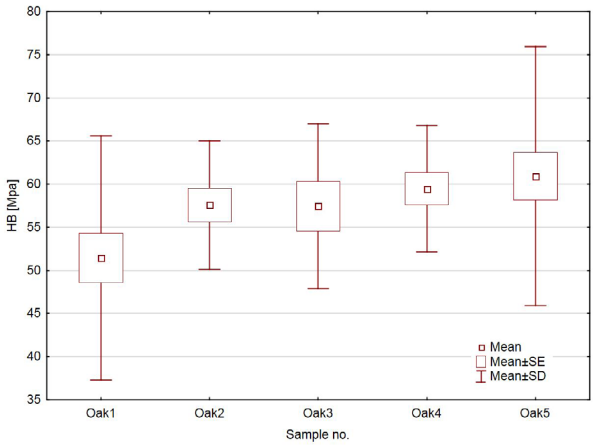

Fig. 6. Statistical differences in hardness between analyzed oak wood samples (Oak1–Oak5) determined by the Kruskal–Wallis test

It was shown that the compressive strengths of the analyzed wood samples differ statistically. Significant differences in compressive strength were observed between Oak1 and the other analyzed samples of oak wood. A similar finding was made in respect of Oak2, but without statistical differences in comparison with the compressive strength of Oak5. The compressive strengths of Oak3, Oak4 and Oak5 also differed statistically. The compressive strength of Oak4 was significantly different from that of Oak2 and Oak5, while Oak5 also differed statistically from that of Oak3 and Oak4, but did not differ from Oak2 (Fig. 5).

The data from the test of hardness of oak wood were found to follow a normal distribution, and therefore the subsequent analyses were performed with the use of parametric statistical tests, i.e. one-factor analysis of variance (ANOVA) (Fig. 6). The condition of homogeneity of variance for groups of oak wood samples originating from different environments and representing various ages was not proved (Levene's test, $p < 0.05$), and therefore the further statistical analyses were based on the Kruskal–Wallis non-parametric test. The test results did not indicate any statistical differences between values of the analyzed wood hardness parameter (Fig. 6).

Discussion

The lack of significant differences in the hardness of the tested oak wood samples of different ages is most likely due to imperfections of the test used. The Brinell hardness test was, in fact, designed and developed for the testing of homogeneous materials (metal) [Hill et al., 1989]. Therefore, it is not an ideal test for testing the hardness of wood, where the grain – associated with the different activity of the vascular cambium during the growing season in the temperate climate zone in which the oak trees originally grew – causes the cross-section of the oak trunk to have areas of different widths of earlywood (softer) and latewood (with smaller cell lumen and therefore greater hardness). Research on sessile oak has shown that sections of latewood have higher values of bending strength and modulus of elasticity than earlywood, confirming the greater hardness of latewood [Büyüksarı et al., 2017]. Unfortunately, to date, the Brinell hardness test is the only test used widely in research to assess wood hardness [Lykidis et al., 2016; Sydor et al., 2020]. Differences in compressive strength are therefore a better measure to determine changes in the physical characteristics of oak wood. The statistical differences in the compressive strength of wood are due to its different origins, Oak1 being bog oak taken from the ground, Oak2, Oak3 and Oak4 being taken from buildings, and Oak5 having been periodically immersed in water. As is well known, the age of oak wood remaining for many years in anaerobic conditions, e.g. in water, soil, peat or gravel, is closely correlated with its degree of mineral saturation [Babiński et al., 2019; Gach et al., 2024]. It appears that the environment in which wood resides is therefore crucial for its compressive strength and hardness. Aging and fossilization of wood depend on environmental conditions, with polysaccharides being more sensitive to degradation than lignin, and even extractives may survive millions of years [Fengel, 1991]. Oak wood stripped of its sapwood part, can survive for hundreds or even thousands of years, is among the most durable of all native wood species, provided that it is deprived of unlimited access to oxygen. This is because it then becomes resistant to biological erosion processes. Analyses of archaeological oak wood have shown that the heartwood is usually well-preserved, while the sapwood is significantly degraded, confirming the greater durability of the heartwood under oxygen-limited conditions [Romagnoli et al., 2018]. Hence, in many archaeological studies, oak wood is often the only evidence of human activity, along with pottery and metal ornaments, and is most often preserved to our times [Bertin et al., 2014]. The change in the color of oak wood is related to the chemical processes taking place in the wood, i.e. the reaction of tannins, phenolic compounds contained in the wood, with iron salts in water, and also to the increasing saturation of wood tissues with floating minerals over time [Dagher et al., 2022]. Assessing the degree of hardness, as well as compressive strength, therefore seems to be a good means of determining the approximate number of years for which an oak wood item or tree has been underground or underwater. The wood samples tested are not among the oldest; the bog oak (Oak1), despite having been in the ground for more than 930 years, has not undergone the black discoloration characteristic of bog oak, although beginnings of this color change can already be observed on the cross-section (gray color on the outside part of the trunk) (Fig. 1). While the definition of bog oak refers to its remaining for many years in anaerobic conditions [Schweingruber, 1990], the other wood samples, although also aged, were not permanently immersed in water, and did not lack access to oxygen; moreover, they had been protected from moisture, or were sealed in a wall (Oak3; Gniew church) or in the building structure under the roof of a granary (Oak4; Drawsko Pomorskie), while another fragment of oak wood (Oak2) came from the bell tower of the Holy Spirit Basilica in Przeworsk. The observed differences in the compressive strength of the wood samples, showing the bog oak (Oak1) to have greater strength than the other wood samples, therefore most likely result, on the one hand, from the saturation of the wood with minerals despite the fact that the wood had only been lying in the ground for 931 years, and on the other hand, from the erosion processes [Fengel, 1991] that the wood underwent when exposed to moisture and access to oxygen in the case of Oak2–Oak5. The results obtained are an important contribution to further research on the use of compression strength tests on the wood of bog oaks to simply assess their age. This is because everything indicates that there may be a close relationship between compression strength and the number of years that oak wood has remained in anaerobic conditions and in an environment that provides continuous access to water. Confirmation of the above relationship will be possible after a more detailed verification in research on bog- wood of oak with different ages of origin, where in Polish conditions bog oak can survive for thousands of years [Bednarz et al., 2019; Rakowski et al., 2023].

Conclusions

The different results obtained for the wood's resistance to compression in the present study are the result of many years of varying physical characteristics of the oak wood studied. The reasons for the statistical differences in its compressive strength should also be attributed to its different origins. Bog oak wood with an age of 931 years obtained lower compressive strength than the other wood samples. The reasons for this should be seen in the history of the wood, in particular its saturation with floating mineral parts, which most likely resulted in a loss of its elasticity. The wood was deprived of the ability to compensate for the stresses associated with sudden drying and changes its internal structure, which led to its delamination. This phenomenon is commonly noted in the case of wood of bog oaks, which, when brought to the surface and left to dry rapidly, undergoes very severe decomposition. This most likely also occurred in the case of the bog oak wood tested in our research (sample Oak1). During the preparation of the wood samples for the tests carried out in this study, the strong stratification of the annual rings and numerous cracks in the wood characterizing the Oak1 wood sample were noted. Despite the fact that the oak wood from the dam in Czaniec (Oak5), like the bog oak from Kłaj (Oak1), had been in contact with water, its immersion had not been continuous but only periodic; moreover, the wood had unlimited access to oxygen, which could have contributed to the initiation of biological erosion processes, which – as is well known – significantly impair wood's physical properties, including its strength. The remaining tested oak wood samples, due to their origin and age, did not show significant differences in compressive strength; only the compressive strength of the oak wood from Kłaj (Oak1) was statistically different from that of the wood from other locations with different ages and histories (Oak2–Oak5). There were no statistically significant differences in the hardness of the wood, the reason for which is the inadequacy of the Brinell test, which is designed for homogeneous materials. These, unfortunately, do not include wood, which is characterized in particular by the periodization of vascular cambium activity, in this case in wood originating from the temperate climate zone.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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