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ORIGINAL PAPER

The changes occurring in oak *Quercus robur* L. wood as a result of long-term immersion in freshwater of hydrotechnical objects

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ABSTRACT

Oak *Quercus robur* wood is characterized by high durability and resistance to variable weather conditions. It is a heavy, hard material (II hardness class according to Brinell) that is easily split and elastic. As a material, oak wood is easy to process mechanically. Due to these characteristics, oak wood is a valuable resource widely used in construction, including water-related objects. The research material used in this study was oak wood obtained from the sluice gate of the dam in Czaniec. The dam was built in 1958, and the oak elements of the sluice gate were also constructed that year. The studied material was exposed to extremely variable environmental conditions until 2020, being periodically submerged in water and also outside the aquatic environment. In this study, the strength of oak wood was analyzed through bending and compression tests using a Shimadzu AG-XV strength testing machine. Additionally, the chemical properties were examined through elemental analysis using an LECO CHN628 + S analyzer and thermogravimetric analysis on a Mettler Toledo TGA/DSC3 apparatus. The average density of the tested material in an absolutely dry state was 639 kg/m^3, with a calorific value of 18.39 MJ/kg. The cellulose content was 43%, hemicellulose 21%, lignin 29%, water 6%, and resin and ash 1%. The tested wood exhibited a bending strength of 76.00 MPa and a compression strength of 60.77 MPa along the fibers. The wood meets the required standards for structural wood according to ISO PN-EN 338:2016-06, with a class of D50. Despite the challenging conditions and the long period of storage, the tested oak wood still retains properties similar to recently obtained oak wood.

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KEY WORDS

calorific value, elemental composition, wood density

Introduction

Oak wood is a valuable industrial material known for its durability and resistance to atmospheric conditions. With its aesthetic qualities, it is heavy, hard, easy to split and flexible. Physical properties according to Krzysik's six-grade scale, oak is a moderately heavy wood (class III) (Galewski and Korzeniowski, 1958; Krzysik, 1974; Kozakiewicz *et al*., 2012). The average density for the air-dry state (for wood with a moisture content of approximately 12%) is 660 to 740 kg/m^3 (Galewski and Korzeniowski, 1958; Krzysik 1974; Szymański *et al*. 2013). The wood in question has a fibre saturation point moisture content of 24% and average shrinkage values. According to Mo-nin's fraction class, oak belongs to the medium shrinkage class. The anisotropy of shrinkage has an average value of more than 2.0. The high density of the wood is associated with high mechanical properties, especially as it is a straight-fibre wood. For example, the average compressive strength is approx. 65 MPa and the static bending strength is approx. 88 MPa. The wood has an average modulus of elasticity of up to 11.0 GPa and a fairly high hardness. Oak heartwood is resistant to being saturated with wood preservatives. However, this is not necessary due to its high natural durability. According to EN 350-2:2000, the durability of heartwood against fungi on a five-point scale is 2, which means durable wood. The sapwood is not durable and is a waste in many applications (Galewski and Korzeniowski, 1958; Krzysik, 1974; Kozakiewicz *et al*., 2012).

Oak wood has long been associated with nobility, elegance, longevity and luxury (Galewski and Korzeniowski, 1958; Krzysik, 1974; Kozakiewicz *et al*., 2012). Due to its properties, oak wood is widely used in many branches of woodworking, including: interior joinery (floors, cladding, parquets, panels and mouldings), exterior joinery (production of chipboard and veneers), hydraulic engineering (bridge and quay piles, bridges, sluices), coopering and cooperage, railway sleepers or light underground structures (Wasilewski and Stelmach, 2014; Szymczak-Graczyk and Bykowski, 2023).

Regarding water and drainage construction, there is a significant variation in the durability of oak *Quercus robur* L. wood. The longest durability of freshly cut oak wood is observed when it is covered with peat or peaty soil with a slightly acidic pH. Oak wood undergoes significant degradation in permeable sandy soils, which experience significant fluctuations in moisture and temperature (Dziamski,1989; Broda and Mazela, 2014). The aquatic environment directly affects the appearance of oak wood. Wood exposed to water undergoes various changes, as water initiates the bacterial decomposition of sugars in the wood, causing it to darken and gradually change color (Surmiński, 2000; Krajewski and Witomski, 2016). Gray decay, hydrolytic decay, mineralization, and leaching of non-structural substances progress (Szczepaniak, 2002). Water filling the wood cells maintains their shape. Removing water leads to the collapse of weak cell walls in wood, and re-soaking does not restore the original state. The durability of oak wood is lower in seawater compared to freshwater, as seawater saturates the wood with salt compounds. The alternating immersion and emergence from water are the most detrimental to the strength of wooden elements (Szymczak-Graczyk, 2021; Szymczak-Graczyk and Bykowski, 2023).

In the Middle Ages, timber was deliberately submerged in ports to relieve stress and was known as 'Venetian Wood'. In the past, various types of wood, such as beech, oak sycamore, ash, and spruce, were submerged in water, which could be traded on long-distance routes from Egypt

to Venice. In the water, the wood was heavily exposed to the activity of microaerophilic bacteria that fed on wood substances. These bacteria were so active that the water in the lake turned black and emitted a strong odor. Venice wood, used in old instruments, does not transmit light when held against a lamp, unlike in new instruments. Due to the loss of sugars, wood becomes not only lighter and denser but also much more resilient (Krajewski and Witomski, 2016). Oak wood submerged in water for at least several decades darkens to nearly black. Even a short period of time in a water environment is enough to initiate permineralization of the wood (Galewski and Korzeniowski, 1958; Krzysik, 1974). Over time, submerged oak wood loses its specific weight, hardness, and strength. However, its shrinkage and susceptibility to desorption cracks increase. Several studies have shown that as wood ages, it tends to become harder due to the increase in lignin content and the decrease in cellulose amount, resulting in a denser and more compact structure (Mathot and Benoist, 1994; Liu *et al*., 2005; Kránitz *et al*., 2016). Understanding the changes in mechanical, physical, and chemical properties of wood due to the exposure to water is essential for determining the material's further usefulness, optimal maintenance of wooden structures, and conservation methods for wooden hydrotechnical objects (Szymanowski, 1953; Dziamski, 1989; Broda and Mazela, 2014). The aim of this study was to investigate the properties of pin oak wood harvested from the dam and compare it with fresh oak wood to illustrate the changes that occur in oak wood when it is exposed to extremely variable conditions over time.

Materials and methods

The research material consisted of oak obtained from the sluice gate of the dam in Czaniec (Poland, Silesian Voivodeship, Bielsko County, Porąbka municipality: 49.810157, 19.207669). The dam was built in 1958, and it was in the same year that the oak elements of the sluice gate under investigation were created. The studied material was used in extremely variable environmental conditions until 2020 (periodically fully submerged in water and exposed outside the water environment). We were the first in Poland to carry out this research, and the first in Europe. This is due to the uniqueness of the material, which can only .The material was obtained during maintenance work on the dam. The dam had to be emptied of water during the extraction of the material to ensure the safety of the people maintaining the aforementioned facility. It was assumed that pedunculate oak wood is the only native species used in hydrotechnical structures in Poland. The classification of the sampled pedunculate oak material is confirmed by microscopic and macroscopic features of the wood structure.

Three oak wood beams measuring 0.25×0.14×0.5 m were sampled from the dam for the research, from which the test samples were made A total of forty samples were prepared from each beam for each type of analysis that is, forty replicates were made for each analysis. Besides, for the analysis of elemental composition, samples were divided according to their location in the dam. One beam was taken from the marginal part of the dam while two beams were taken from the middle part. Due to the statistically normal distribution of the samples, the properties of the test material were determined as the average of the total.

Wood density. The density of the wood in a dry state was determined based on the PN-EN 384:2010 standard. 40 samples were taken from each beam, whose external dimensions (length, width, height) were measured using an electronic caliper AOS ABSOLUTE Digimatic Standard 150 mm (MITUTOYO Corp., Kawasaki, Japan) with an accuracy of ±0.02 mm. The weight was determined using an analytical balance Excellence METTLER TOLEDO (Mettler Toledo, Columbus, Ohio, USA) with an accuracy of ±0.01 g.

Thermogravimetry analysis (TGA), elemental composition, combustion heat, and calorific value. Thermogravimetry analyses (TGA) were conducted using the TGA/DSC3 instrument (Mettler Toledo, Columbus, Ohio, USA/Switzerland) at the Central Mining Institute (GIG) in Katowice, Poland. The thermogravimetric method was employed by Zawadzki *et al.* (2013), Tyutkowa *et al.* (2017), and Işleyen and Kesik (2021), among others. The temperature inside the device was increased by 1°C per hour, from approximately 22 to 600 ±1°C. Based on the obtained data, the combustion values of hemicellulose, cellulose, and lignin were determined and read, and the percentage shares of these compounds were calculated (Mathot and Benoist, 1994; Liu *et al.*, 2005; Mahut *et al.*, 2007). For all samples, proximate and elemental composition, as well as calorific values were determined. Moisture and ash contents were determined in LECO TGA701 thermogravimetric analyzer (LECO Corporation, USA) at 105°C and 550°C respectively (Piętka *et al.*, 2019; Tamelová *et al.*, 2022; Gendek *et al.*, 2023; Malaťák *et al.*, 2023;).

Carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) contents were measured using a LECO CHN628 + S analyzer (LECO Corporation, USA) by combustion analysis. LECO flour standards were used for calibration of the instrument. The sulfur content for all samples was below the calibration range, *i.e.* 0.02% wt. Oxygen (O) content was calculated as a difference. The analysis results were converted to dry state according to ISO 16993:2015 (Piętka *et al.*, 2019; Tamelová *et al.*, 2022; Gendek *et al.*, 2023; Malaťák *et al.*, 2023) .

LECO AC600 bomb calorimeter (LECO Corporation, USA) was used for the determination of higher heating value (HHV – Qvad dry). The lower heating value (LHV – Qnet dry) was converted according to ISO 1928: 2009. A detailed measurement procedure is described in the publication by Zawadzki (2013), Piętka *et al.* (2019), Tamelová *et al.* (2022), Gendek *et al.* (2023), Malaťák *et al.* (2023).

Wood strength in static bending and compression. Wood samples were prepared according to the ISO 3129:2019 standard. From the obtained research material, 40 samples with dimensions of 20×20×300 mm were prepared for determining the strength of wood in static bending, and samples with dimensions of 20×20×30 mm were prepared for determining the strength of wood in compression. The external dimensions were measured using an electronic caliper AOS ABSOLUTE Digimatic Standard with an accuracy of ±0.1 mm.

The strength in static bending was determined according to the ISO 13061-3:2014 standard, and the strength in compression was determined according to the ISO 13061-17:2017 standard. The research procedures and mathematical formulas were described, among others, by Hirashima *et al.* (2021).

The Shimadzu AG-XV universal testing machine (Shimadzu, Tokyo, Japan) was used for the experiments. During the measurements, the control software recorded the force during the bending (Fg) and compression (Fc) of the sample with an accuracy of ±0.1 N, as well as the displacement with an accuracy of ±0.01mm. The testing speed was set to ensure sample failure in static bending and compression occurred within 90 ±30 seconds from the start of loading. Based on the recorded data, the software determined the maximum bending (σg) and compression (σc) stresses, as well as the modulus of elasticity in bending (εg) and compression (εc).

Wood shrinkage. Wood swelling is an increase in its linear dimensions and volume as a result of an increase in the bound (hygroscopic) water content of the wood. Wood swells in the hygroscopic humidity range of 0-30%, *i.e.* from the absolutely dry state to the point of fibre saturation (Prażmo, 1999; Szczuka and Żurowski, 1999).

Wood shrinkage is the opposite of swelling and involves a decrease in dimension (linear and volumetric) due to a decrease in the bound water content of bound water. Wood with a moisture content of more than 30 per cent will only give up free water during drying. Wood with a moisture content higher than 30% only gives up free water during drying, which results in a gradual decrease in the wood mass without any change in its dimensions. Release of bound (hygroscopic) water occurs during shrinkage of the wood from the saturation point of the fibres (30%) to an air-dry state (about 6%). The non-homogeneous anatomical structure of wood is the reason for the non-uniform shrinkage or swelling of the wood at cross-sections – in the tangential direction and along the fibres, the shrinkage along the (Prażmo, 1999; Szczuka and Żurowski, 1999). For the purposes of this study, wood shrinkage was measured in three sections (tangential, radial and longitudinal).

STATISTICAL ANALYSES. The statistical analysis of the results was performed using Statistica 13.3 software (TIBCO, 2017). To determine the differences between means and homogeneous groups, analysis of variance (ANOVA) tests and *post-hoc* multiple comparisons tests were conducted at a confidence level $\alpha \leq 0.05$ (Tukey HSD test; variable MC [%]).

Results

The initial water moisture content of the samples used for the study ranged from 6.46% to 6.7%. The density of the tested dry wood was 639 kg/m^3.The tangential shrinkage in the tested samples ranged from 7% to 12%, which is within the normal range. In comparison to freshly harvested wood, the colour of oak wood extracted from the water reservoir showed initial signs of turning grey. Microscopic comparison between fresh wood and the extracted wood revealed the beginning of the silicification process. Figure 2 illustrates the microscopic structure of fresh oak wood and oak wood extracted from the water reservoir.

The obtained results of the TGA analysis are presented in Table 1. The hemicellulose content in the tested samples averaged 21%. The cellulose content ranged from 43%, slightly below the value for fresh oak wood. The lignin content was 29%, higher than the value for fresh oak wood. An average amount of 7% of the remaining components was also observed.

The results of elemental composition, ash content, combustion heat, and calorific value of the oak wood presented in Table 2. The ash content for the tested samples ranged from 0.76 to 0.92%. The carbon content ranged from 50.40% to 51.01% while the hydrogen content ranged from 5.68% to 5.75%. The nitrogen content in the samples was lower than that of oak *Quercus*

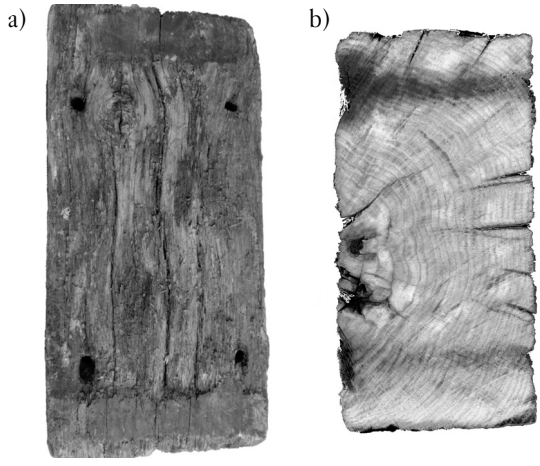

Fig. 1.
An example view of a single wooden beam obtained for the study
a – general view, b – cross-section

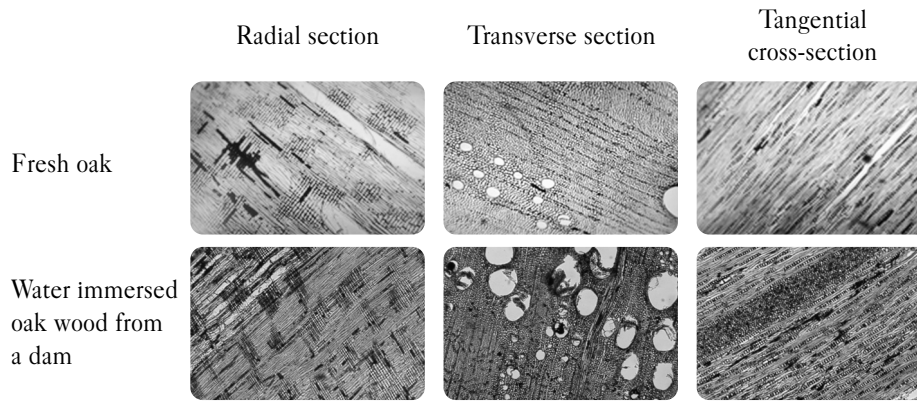

Fig. 2.
Example view of the microscopic structure of oak *Quercus robur* wood from the water reservoir: radial, tangential, and transverse sections

Table 1.
TGA analysis of oak *Quercus robur* wood obtained from water dam elements in %

	Hemicellulose [%]	Cellulose [%]	Lignin [%]	Other components [%]
Oak wood (Galewski and Korzeniowski, 1958)	21.5 (±4.0)	45.6 (±0.7)	25.8 (±2.3)	10.5 (±6.5)
Oak wood from a dam	21 (±2.2)	43 (±1.8)	29 (±0.9)	7 (±1.4)

Table 2.
Results of elemental analysis of a dry state series of oak *Quercus robur* wood samples obtained from a water dam

	Ash_{dry}	C_{dry}	H_{dry}	N_{dry} [%]	S_{dry}*	O_{dry}**	$Q_{vad\ dry}$	$Q_{net\ dry}$**
Oak *Quercus robur* (Galewski and Korzeniowski, 1958)		49.32 (±0.8)	5.78 (±0.32)	0.39 (±0.11)	<0.02	44.5 (±0.5)		18.4
Oak *Quercus robur* from a dam Reservoir bank	0.76a,b (±0.05)	51.01a,c (±0.21)	5.68c (±0.03)	0.22a (±0.03)	<0.02	42.33	19.63b (±0.01)	18.39
Oak *Quercus robur* from a dam Center of a dam	0.92a,b,c (±0.14)	50.40b (±0.05)	5.75d (±0.03)	0.16a (±0.05)	<0.02	42.77	19.48b (±0.13)	18.22

Note: *Values below the measurement error were omitted in calculations; **Calculated values; a, b, c, d – identical letters next to values represent homogeneous groups of means, significant differences for $p<0.05$ with $\alpha \leq 0.05$

robur wood reported in literature data, averaging from 0.16% to 0.22%. Sulfur content was below 0.02% in all samples, and the oxygen content was determined to be an average of 42.55%. The combustion heat value in all tested groups was below 20 MJ·kg^{-1}, and the calculated calorific value averaged 18.30 MJ·kg^{-1}. Oak wood according to literature has a slightly higher calorific value (Cavalli *et al*., 2016).

Although ANOVA analysis indicated statistically significant differences between the means in carbon and hydrogen elements of investigated oak wood, as well as ash content, the measured combustion heat values did not show significant differences between the material origins and were classified into one homogeneous group.

The results of maximum bending and compressive stresses of wood, as well as the modulus of elasticity, presented in Table 3. The timber tested showed a flexural strength of 79.51 MPA and a compressive strength of 60.77 MPA along the fibres.

Table 3.

Results of bending and compressive stresses, as well as modulus of elasticity of oak *Quercus robur* wood obtained from a water dam

σγ MPa	εγ GPa	σχ MPa	εχ GPa
79.51 (±1.17)	6.74 (±0.64)	60.77 (±0,52)	1.451 (±0.74)

Note: homogeneous groups of means for $\alpha \leq 0.05$

Based on the ANOVA analysis, it can be concluded that the analyzed material from the Dam showed no significant differences between the wood samples. Compared to fresh wood, it differed significantly obtaining a bending strength value lower by 15% on average. In the case of compression along the fibers, the strength of wood from the Dam was higher by 29% on average. ANOVA analysis showed that the mean values were not significantly different and that they belonged to one homogeneous subset ($p>0.05$).

Discussion

Wood elements exposed to water conditions undergo deterioration (biodegradation) (Onusseit, 2006; Krajewski and Witomski, 2016). Significant changes occurring in wood exposed to the aquatic environment include progressive gray decay of wood, permineralization with the progressing process of silicification, and leaching of non-structural substances (Krzysik, 1974; Broda and Mazela, 2014). In wood subjected to water conditions, a significant decrease in specific weight and a reduction in properties such as hardness and strength are observed. However, shrinkage and susceptibility to desorption cracking increase. Wood with signs of depreciation due to partial or complete degradation of hemicellulose, cellulose, and lignin may have significantly lower industrial value than fresh wood (Szczepaniak, 2002; Liu *et al*., 2005; Krajewski *et al*., 2019). An important factor influencing the durability of oak wood in hydrotechnical structures is the inability to conserve the wood. Petroleum-based substances, fungicides, and preservatives have a negative impact on organisms living in water. Oak wood contains tannins, which react with iron salts present in the water. This phenomenon is manifested by a gradual change in color, ranging from gray-black to black (Galewski and Korzeniowski, 1958; Broda and Mazela, 2014). According to the authors of publications on black oak, the first signs of transformation of European oak into black oak can be observed in the aquatic environment after about 60 years (Krzysik, 1974).

The calculated density of the tested groups of oak wood in a dry state after nearly 70 years of use in a hydrotechnical object was within the range of 639 kg/m^3. This value was lower by 3.5-14% compared to the density reported in the literature (approximately 660-740 kg/m^3) for unused wood (Galewski and Korzeniowski, 1958; Krzysik, 1974; Kozakiewicz *et al*., 2012; Szymański *et al*., 2013). Strength testing of wood requires considering many factors, among which the anatomical direction is essential, as wood is an anisotropic material with non-uniform and variable structure. Healthy oak wood exhibits an average longitudinal compressive strength of approximately 47 MPa, and a static bending strength of 93 MPa. All analysed samples showed bending strength values below (79.51 ±1.17), and compressive strength values along the fibers above (60.77 ±0.52), as specified in the ISO standard PN-EN 338:2016-06. Analysis of the content of individual chemical compounds revealed relatively small differences in the tested samples (Galewski and Korzeniowski, 1958; Kozakiewicz *et al*., 2012; Szymczak-Graczyk, 2021). Due to energy considerations, a relatively high carbon content of over 50% is favorable. Despite the

passage of time, the density of the tested material in a dry state remained at 639 kg/m^3, corresponding to the characteristic density of construction hardwood in the D50 strength class. The strength parameters of the wood meet the requirements of structural wood standards described in the ISO standard PN-EN 338:2016-06, for bending depending on the sample, for class D75 and higher, and for compression for all classes. Therefore, such wood can be reused for construction purposes.

Conclusions

The examined oak elements obtained from the Czaniec Dam, compared to freshly harvested wood, show initial signs of changes in the macro and microstructure of the wood. The wood has grayed, with a decrease in density of up to 14% in the tested material. Elemental studies of wood composition highlighted a slight increase in the proportion of lignin and a decrease in cellulose, which directly translates into an increase in the proportion of carbon by an average of 2% and a decrease in the proportion of oxygen by an average of 4.5%. The prepared microscopic slides revealed the beginnings of silicification. The analyzed material exhibited a decrease in static bending strength by an average of 17% and an increase in longitudinal compression strength by an average of 29%. The analysed oak material showed no significant differences in terms of calorific properties. Despite the changes that occurred in the tested material, the examined oak wood still meets the standards of structural timber ISO PN-EN 338:2016-06, for bending depending on the sample for class D75 and higher, and for compression for all classes.

Autors' contributions

M.B.G. – conceptualization, methodology, formal analysis, material collection, statistical analyses, investigation, preparation of material for analysis, writing – original draft preparation; R.R. – conceptualization, methodology, formal analysis, material collection, statistical analyses, investigation, preparation of material for analysis; A.G. – statistical analyses, formal analysis, conceptualization, methodology, writing – original draft preparation; M.A. – statistical analyses, formal analysis, conceptualization, methodology, writing – original draft preparation; B.T. – elemental analyses, conceptualization, methodology, manuscript review and editing; J.M. – elemental analyses, conceptualization, methodology, manuscript review and editing; K.M. – conceptualization, methodology, material collection, manuscript review and editing; B.B. – conceptualization, methodology, material collection, manuscript review and editing; R.W. – conceptualization, methodology, manuscript review and editing; Ł.M. – preparation of material for analysis, strength analyses of wood;

Conflict of interest

The authors declare no conflict of interest.

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STRESZCZENIE

Zmiany zachodzące w drewnie dębowym wskutek długotrwałego zanurzenia w słodkowodnych obiektach hydrotechnicznych

Drewno dębowe charakteryzuje się dużą trwałością i odpornością na zmienne warunki atmosferyczne, jest materiałem ciężkim, twardym (II klasa twardości wg Brinella), łatwo łupliwym i elastycznym oraz łatwym w obróbce mechanicznej. Jest więc ono cennym surowcem o szerokim zastosowaniu w budownictwie, również wodnym. Materiałem badawczym był dąb pozyskany ze śluzy zapory w Czańcu. Została ona wybudowana w 1958 r., wtedy też powstały elementy dębowe śluzy. Badany materiał był użytkowany do 2020 r. w skrajnie zmiennych warunkach środowiskowych: czasowo całkowicie zanurzony w wodzie i poza środowiskiem wodnym (poglądowy materiał badawczy przedstawiono na rycinie 1). W ramach pracy przeprowadzono badania wytrzymałości drewna na zginanie i ściskanie przy użyciu maszyny wytrzymałościowej Shimadzu model AG-XV, a także właściwości chemicznych poprzez badania elementarne wykonane analizatorem LECO CHN628+S oraz termograwimetryczne na aparacie TGA/DSC3 firmy Mettler Toledo. Na rycinie 2 przedstawiono obraz mikroskopowej budowy drewna dębowego świeżego oraz pozyskanego z zapory wodnej. W porównaniu do drewna świeżo pozyskanego drewno wydobyte z czaszy zbiornika wodnego wykazuje pierwsze oznaki zmiany barwy na szarą, a porównanie mikroskopowe uwidacznia początek procesu krzemionkowania. Wyniki analizy TGA przedstawiono w tabeli 1. Zawartość hemicelulozy w badanych próbkach wynosiła średnio 21%. Procentowa ilość celulozy mieściła się w granicy od 43%, tzn. nieznacznie poniżej wartości dla drewna dębowego świeżego. Zawartość ligniny wynosiła 29% – powyżej wartości dla drewna dębowego świeżego. Średnia ilość pozostałych składników wynosiła 7%. Skład elementarny, zawartość popiołu, ciepło

spalania i wartość opałową drewna przedstawiono w tabeli 2. Zawartość popiołu dla badanych próbek wynosiła 0,76-0,92%, a zawartość węgla 50,40-51,01%. Wodór występował w ilości 5,68--5,75%. Zawartość azotu w próbkach była niższa niż w drewnie dębowym z danych literaturowych i wynosiła średnio 0,16-0,22%. Siarka stanowiła poniżej 0,02% we wszystkich próbkach, a zawartość tlenu określono na średnio 42,55%. Wyniki maksymalnych naprężeń przy zginaniu i ściskaniu statycznym drewna oraz modułów sprężystości podano w tabeli 3. Zdrowe drewno dębowe wykazuje średnią wytrzymałość na ściskanie podłużne ok. 47 MPa, natomiast na zginanie statyczne 93 MPa. Wszystkie analizowane próbki wykazują parametry na zginanie statyczne poniżej wartości określonych w normie ISO PN-EN 338:2016-06 – 79,51 ±1,17, natomiast na ściskanie wzdłuż włókien powyżej wartości tej normy – 60,77 ±0,52. Wartość ciepła spalania we wszystkich badanych grupach wynosiła poniżej 20 $MJ \cdot kg^{-1}$, a obliczona wartość opałowa średnio 18,30 $MJ \cdot kg^{-1}$. Drewno dębowe ma wg literatury nieznacznie wyższą wartość opałową. Spełnia ono wymagane dla drewna konstrukcyjnego normy ISO PN-EN 338:2016-06 klasa D50. Pomimo trudnych warunków i długiego okresu przechowywania badanego surowca ma on właściwości zbliżone do niedawno pozyskanego drewna dębowego.