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PHYSICAL AND MECHANICAL PROPERTIES OF SUBFOSSIL OAK (*Quercus*, SP.) WOOD

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Abstract

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The paper deals with the examination of physical and mechanical properties of subfossil wood of oak (*Quercus*, sp.). The issue of establishing physical and mechanical properties of subfossil oak wood has not yet been addressed in the area of the Czech Republic. The main objective is to find out what changes to subfossil wood properties have occurred in comparison with recent wood. For these purposes, samples from three locations were taken (gravel pit Tovačov – district Přerov, gravel pit Kostomlátky – district Nymburk, and the Bečva basin near Osek nad Bečvou). All of the selected properties were tested in compliance with relevant valid Czech technical norms (ČSN). The results provide us with a realistic picture of the properties of wood that has been deposited under the ground in very specific conditions for thousands of years. With regard to density, the results do not show any definite changes. The dimensions of subfossil wood are approximately doubled in comparison with recent wood. On the other hand, there is an obvious decrease in mechanical properties. The paper also offers the results of dendrochronological or radiocarbon dating of the trunks.

subfossil wood, physical and mechanical properties, oak, locations

Subfossil wood is unfossilized wood which has been deposited in rivers, swamps or moraine sediments for hundreds or thousands of years (Kaennel, Schweingruber; 1995). In former literature, subfossil oak (*Quercus*, sp.) trunks are referred to as "black oak" because of their colour (Kalicki, Krąpiec; 1995). The change of the wood shade into black is caused by ferric components dissolved in water reacting with tannins present in oak. The intensity of the shade is primarily determined by the time for which the wood has been deposited and the nature of sediments. Besides the changes of the shade, there are also changes in physical and mechanical properties (Govorčin, Sinković; 1995). The oak is the most frequent species existing in subfossil form, but to a smaller extent there are also pine, elm, maple, poplar, beech, ash and alder (Dvorská, Vít; 2002).

Subfossil trunks are remnants of bottomland forests, i.e. forests with high level of groundwater and with cyclical flooding. This formerly common biotope is disappearing due to the rising extent of watercourse regulation. In the Czech Republic, it is to be found mainly in alluvial plains of large lowplain rivers; in Bohemia, this is the Labe, in Moravia, mainly the Dyje and the Morava Rivers (Hrib et al., 2004).

Oak forests started appearing on the banks of central European rivers about 10,000 years ago, it means at the beginning of the Holocene (Becker, 1982; Leuschner et al., 1986). However, the process in which the trunks were deposited is disputable. Most often it is considered that banks were eroded in meanders or during large floods (Kalicki, Krąpiec; 1995). The fallen trees then soaked up water and settled in deposited layers of channel alluvium under the water surface (Krąpiec, 1996). The trunks were gradually hidden beneath the accretion on the slip-off slope during the channel migration (Kalicki, Krąpiec; 1995). The slip-off slope is the relatively gentle slope at the inner edge of a meander. That is why subfossil oak trunks are often found in gravel pits when deposited sand and gravel is mined (Krąpiec, 1996).

The lifespan of riverside oaks which grew on river banks during the Holocene is relatively short – 95% of the trees only have 150–400 growth rings. This fact is associated to the frequency of the above mentioned floods. Regular floods, especially those with floating ice which appeared in spring, often damaged the forests on river banks (Becker, 1993).

When examining physical and mechanical properties of subfossil wood, it is necessary to establish its age so that the change of properties can be assessed in relation to time. The age of wood is usually found out by the dendrochronological analysis. In the Czech Republic, this is a common method used for dating of wooden finds. To be able to date them there has to be a standard chronology available. The standard chronology is created for each tree species individually by gradual overlapping of growth ring sequences towards the past (Rybníček, 2004). If the standard chronology for the particular species and the particular areas is not sufficiently long, dating is not possible and another way to establish the age has to be found. In such cases, the radiocarbon method is used; the method establishes the age of the organic material on the basis of the proportion of stable and unstable carbon (http://c14.arch.ox.ac.uk).

The topic of this paper is unique within the Czech Republic. So far subfossil trunks have only been subjected to dendrochronological dating and they were used for the purpose of extending the standard oak chronology towards the past. No research has been conducted in the Czech Republic concerning the properties of subfossil oak. Abroad, Govorčin and Sinković (1995), Horský and Reinprecht (1986), Wagenführ (2000) or Bednar and Fengel (1974) dealt with the issue of subfossil wood properties.

SUBFOSSIL WOOD PROPERTIES

During the time subfossil wood is deposited in the specific conditions, a number of complicated physical and chemical processes occur. These finally result in its fossilization (Habětín, Knobloch; 1981). When these processes are in progress, the wood chemical as well as morphological structure change, which is naturally reflected in its properties (Reinprecht et al., 1988). Wood properties are affected by many factors, the most important of them being probably its chemical composition (Požgaj, 1997). As regards the chemical composition, subfossil wood differs from recent wood by a considerably lower proportion of hemicelluloses. This is caused by the fact they are easily eluted in humid environment (Bednar, Fengel, 1974; Govorčin, Sinković, 1995; Wagenführ, 2000). Therefore, when wood is deposited in the soil and water affects it, some substances are removed and carbonate of lime and silica sediment on the wood surface (Govorčin, Sinković; 1995). For examinations we have chosen: density, dimensional changes – swelling and shrinking, modulus of elasticity and compression strength parallel to the grain, and hardness.

PHYSICAL PROPERTIES

Density is of the greatest information relevance, especially with moisture of 12% and 0%, as it affects all the other physical and mechanical properties of wood to a considerable extent. The density of wood is defined as its weight per unit volume. Generally, we can say the higher density, the higher values of some physical and mechanical properties (Požgaj, 1997; Gryc, Horáček, 2007). When the measured density of subfossil oak wood is compared with recent wood, the values are more or less the same, or slightly rising (Reinprecht et al., 1988; Govorčin, Sinković, 1995). A more considerable increase in density is to be found in surface layers where a higher degree of petrifaction can be assumed and not even the influence of chemical changes can be ruled out, e.g. cellulose crystal lattice thickening and different morphology (Horský, Reinprecht, 1986).

Wood shrinkage is a process during which the linear dimensions, the area or the volume are reduced as a consequence of a loss of bound water (Požgaj, 1997). With regard to dimensional changes, there are considerable differences found when the values of recent and subfossil wood are compared. Wagenführ, 2000; Reinprecht et al., 1988 and Govorčin, Sinković, 1995 present approximately twofold percentage of subfossil oak shrinkage vis-à-vis recent oak, and this is also related to a high number of cracks.

MECHANICAL PROPERTIES

Generally, mechanical properties of subfossil oak wood are lower than the properties of recent oak (Govorčin, Sinković; 1995). One of the most significant mechanical properties is compression strength parallel to the grain. Compression parallel to the grain is the basic way of applying stress – the pressure is applied in the direction of the main anatomical elements of wood. Deformation takes form of the material shortening (Matovič, 1993). Compression strength parallel to the grain of subfossil oak corresponds to about 70–80%, in some cases even 50% of the strength of recent oak (Bednar, Fengel, 1974; Horský, Reinprecht, 1986). The modulus of elasticity of subfossil oak in compression decreases even more than its strength (Horský, Reinprecht; 1986).

Because, as far as subfossil wood is concerned, the process of silicification, which means the replacement of wood cell structure by minerals, is involved, it is interesting to focus on wood hardness (Carrión, 2003). The hardness is the ability of wood to resist indentation of another object into its structure. There are two tests used for establishing the hardness of wood: Brinell hardness test and Janka hardness test. When using the Brinell test a steel ball is forced into the wood using a fixed force and then the indentation diameter is measured with the Brinell magnifier. Janka hardness test uses a tool with a tip of 11.284 mm steel ball, which is forced into the wood. Then the hardness is calculated as the force necessary to indent the ball to half of its diameter per the area of indentation, which is 100 mm^2 (Požgaj, 1997). The professional literature states that the values of subfossil oak hardness are lower even though the cell structure was replaced by harder minerals.

MATERIALS AND METHODS

Description of locations

Oak (*Quercus*, sp.) samples were taken from three locations; one of them was a river bank, two were gravel pits.

The first location was the bed of the Bečva River, near Osek nad Bečvou. The village is located in the Přerov district, about 10 km to the east of Přerov (GPS coordinates: N49 29.841 E17 31.241, 217 m ASL). The trunk which was sampled for property examination was deposited in gravel about 2.5 m under the surface of the plain. The gravel was grey yellow and consisted of semi-rounded stones of 3–5 cm, exceptionally up to 10 cm (oral report provided by ing. J. Vít).

Two trunks were taken from gravel pit Tovačov. The gravel pit is located about 12 km to the west of Přerov (GPS coordinates: N 49°24'26,4", E 017°17'46,9", 201 m ASL). The pit excavates gravel using dredges from about 10 m deep.

The last location is a gravel pit between the villages of Kostomlátky and Doubrava, located 5 km to the west of Nymburk (GPS coordinates: N 50°09´57.7", E 014°58´07.3", 182 m ASL). The pit lies on the Labe River.

Wood density

Wood density is defined as weight per unit volume with specific moisture (Požgaj, 1997). The density was found out in compliance with ČSN 49 0108. For the actual measuring, we used testing samples of 20 × 20 mm in transversal dimensions and 25 ± 5 mm in length. Their weight was taken with accuracy of 0.01 g and dimensions with accuracy of 0.1 mm. The density of each sample with specific moisture was calculated using the following formula (Matovič, 1993):

$$\rho_0 = \frac{m_0}{V_0} [\text{kg.m}^{-3}], \quad (1)$$

where:

m_0 is weight with 0% moisture

V_0 is volume with 0% moisture.

Dimensional changes

Wood shrinking is a process when wood dimensions are reduced as a consequence of a loss of bound water (Požgaj, 1997). Shrinkage of subfossil wood was found out in compliance with ČSN 49 0128. For the actual testing, we used testing samples of 20 × 20 mm in transversal dimensions and 30 mm in length. The previously measured samples were dried in the temperature of 103 ± 2°C until the moisture content was 0% and then weighed again. The content of moisture in a sample is 0% when there is no weight difference greater than 0.02 g between two processes of weighing within the interval of 2 hours. The obtained results were used to calculate the shrinkage of subfossil wood using the following formula (ČSN 49 0128):

$$\beta_{i\max} = \frac{i_{iw1} - i_{iw2}}{i_{iw1}} \cdot 100[\%], \quad (2)$$

where:

i_{iw1} – dimensions of a dried sample V, R, T, L

i_{iw2} – dimensions of a sample with 0% moisture V, R, T, L.

Swelling is the ability of wood to expand its dimensions by accepting bound water (Požgaj, 1997). Swelling of subfossil wood was found out in compliance with ČSN 49 0126. The same samples were used for the testing of swelling as for the testing of shrinking. The samples with 0% moisture obtained in the process of shrinkage measuring were used for the measuring of swelling. The samples that had cracked during drying were not included. The samples previously measured were drenched in distilled water with the temperature of 20 ± 2 °C until their dimensions were stable. Then they were measured again. Swelling was calculated using the following general formula:

$$\alpha_{i\max} = \frac{i_{\max} - i_0}{i_0} \cdot 100[\%], \quad (3)$$

where:

i_{max} – dimensions of a sample drenched in the water for 7 days V, R, T, L

i_0 – dimensions of a sample with 0% moisture V, R, T, L.

Mechanical properties

Mechanical properties were examined for normalized moisture of 12%.

Compression strength parallel to the grain

The compression strength parallel to the grain was examined in compliance with ČSN 49 0110. Using ZWICK Z050 universal testing device pressure was applied to conditioned samples with the dimensions of 20 × 20 × 30 mm evenly at constant speed. The compression strength parallel to the grain was expressed in MPa following this formula (ČSN 49 0110):

$$\sigma_p = \frac{F_{\max}}{a \cdot b} [\text{MPa}], \quad (4)$$

where:

F_{max} is maximum load

a, b are transversal dimensions of the sample.

Results were rounded off to the nearest 0.5 MPa.

Static hardness

The static hardness of wood was examined using Janka method in compliance with ČSN 49 0136.

We used conditioned samples with the dimensions of 50 × 50 × 50 mm and ZWICK Z050 universal testing device. A steel ball (an indenter) with the radius of 5.64 mm was forced into the depth of 5.64 mm, which created an indented area of 1 cm². The force necessary for indenting the ball directly provides the hardness per 1 cm², which was converted to MPa. As we assumed the material will be more fragile, we only forced the ball into the half depth – 2.82 mm. Then the static hardness is to be calculated using this formula (Matovič 1993):

$$HJ = 4\,F / (3 \cdot \pi \cdot r^2)\ [\text{MPa}], \quad (5)$$

where:
F is the force necessary for ball indentation
r is the radius of the indenter.

RESULTS

Sampling was carried out in 3 locations during 2008. Samples were taken from a selected trunk in each location and then testing samples were made for the purpose of examining the selected physical and mechanical properties.

Wood density

Tab. I shows the subfossil wood density in the individual locations and the density of subfossil and recent wood as presented by various authors. The samples from Osek nad Bečvou correspond to the density of recent wood. However, there is a considerable difference in the samples from Tovačov, where the density is about 100 kg.m⁻³ lower and it decreases with age. On the contrary, the density of the sample from Kostomlátky achieves quite high values. Further, tab. I shows that generally the density does not decrease with age but that its value depends on the location, the conditions of deposition, and also the degree of degradation.

Dimensional changes

Tab. II shows the values obtained through the measuring of subfossil oak shrinkage. In the second part of the table the values of shrinkage of subfossil and recent oak of different age as presented by various authors are provided for comparison. It is obvious that the percentages of shrinking are quite high and the differences between locations are not very significant. Only sample 19 from Tovačov shows considerably lower values than the other samples. Generally, we can conclude that the values

I: *Density of subfossil and recent oak wood ($\bar{x}$ – arithmetic mean, s – standard deviation, v – coefficient of variation, n – number of samples)*

Location	Age of samples	Statistics	Density of samples with 0% moisture (kg.m⁻³)
Kostomlátky – Doubrava	165 BC–241 AD	$\bar{x}$	746
		s	53.37
		v	7.15
		n	73
Tovačov (sample No.19)	265–50 BC	$\bar{x}$	575
		s	39.94
		v	6.95
		n	158
Osek nad Bečvou	945–405 BC	$\bar{x}$	669
		s	37.94
		v	5.67
		n	133
Tovačov (sample No.6)	2490–2190 BC	$\bar{x}$	529
		s	19.02
		v	3.60
		n	186
Source	**Age of samples**	**Moisture (%)**	**Density (kg.m⁻³)**
Požgaj (1997)	recent	12.30	696.0
Tsoumis (1991)	recent	12.00	690.0
Noack (1963)	recent	0.00	670.0
Vavrčík et al. (2008)	recent	0.00	618.2
Rowell, Barbour (1990)	1050 AD	0.00	660.0
Reinprecht, Kúdela, Čunderlík (1988)	731 ± 150 AD	0.00	631.0
Govorčin, Sinković (1995)	about 2050 BC	11.56	735.4
Bednar, Fengel (1974)	6550 BC	0.00	650.0
Horský, Reinprecht (1986)	6200 BC	0.00	725.0
Rowell, Barbour (1990)	6550 BC	0.00	650.0
Wagenführ (2000)	subfossil – age not provided	12.00	665.0

II: *Values of subfossil oak shrinkage ($\bar{x}$ –arithmetic mean, s – standard deviation, v – coefficient of variation, n – number of samples)*

Location	Age of samples	Statistics	Longitudinal shrinking (%)	Tangential shrinking (%)	Radial shrinking (%)	Volumetric shrinking (%)
Kostomlátky – Doubrava	165 BC–241 AD	$\bar{x}$	0.91	14.41	10.36	23.97
		s	0.23	1.76	1.46	1.89
		v	25.18	12.22	14.05	7.87
		n	73	73	73	73
Tovačov (sample No.19)	265–50 BC	$\bar{x}$	0.41	11.79	6.54	17.86
		s	0.21	3.36	1.40	4.06
		v	52.66	28.46	21.41	22.75
		n	158	158	158	158
Osek nad Bečvou	945–405 BC	$\bar{x}$	0.46	15.32	8.36	22.74
		s	0.23	2.82	1.08	3.17
		v	50.54	18.38	12.88	13.93
		n	133	133	133	133
Tovačov (sample No.6)	2490–2190 BC	$\bar{x}$	0.88	15.89	7.43	22.83
		s	0.61	1.31	0.79	1.21
		v	69.30	8.22	10.57	5.28
		n	186	186	186	186
Source	**Age of samples**	**Statistics**	**Longitudinal shrinking (%)**	**Tangential shrinking (%)**	**Radial shrinking (%)**	**Volumetric shrinking (%)**
Tsoumis (1991)	recent	$\bar{x}$	0.40	7.80	4.00	12.20
Požgaj (1997)	recent	$\bar{x}$	–	–	–	13.70
Vavrčík et al. (2008)	recent	$\bar{x}$	–	8.40	4.70	13.00
Rowell, Barbour (1990)	1380 AD	$\bar{x}$	–	20.00	9.50	–
Reinprecht, Kúdela, Čunderlík (1988)	731 ± 150 AD	$\bar{x}$	–	–	–	26.50
Govorčin, Sinković (1995)	about 2050 BC	$\bar{x}$	1.09	17.22	9.37	25.79
Horský, Reinprecht (1986)	6200 BC	$\bar{x}$	–	–	–	31.60
Wagenführ (2000)	subfossil – age not provided	$\bar{x}$	0.50	11.90	8.00	20.40

correspond to the values presented in professional literature. Compared with recent wood, the values of subfossil wood are approximately twofold.

As far as the swelling of subfossil wood is concerned (Tab. III), we can see the conclusion is the same as in the case of shrinking. The values of swelling are similar to the values of shrinking.

III: *Values of subfossil oak swelling ($\bar{x}$–arithmetic mean, s – standard deviation, v – coefficient of variation, n – number of samples)*

Location	Age of samples	Statistics	Longitudinal swelling (%)	Tangential swelling (%)	Radial swelling (%)	Volumetric swelling (%)
Kostomlátky – Doubrava	165 BC–241 AD	$\bar{x}$	1.28	17.08	11.93	32.71
		s	0.30	2.37	1.75	2.85
		v	23.33	13.90	14.68	8.71
		n	73	73	73	73
Tovačov (sample No.19)	265–50 BC	$\bar{x}$	0.46	13.75	6.62	21.85
		s	0.20	2.89	0.91	3.68
		v	42.60	21.00	13.78	16.85
		n	158	158	158	158
Osek nad Bečvou	945–405 BC	$\bar{x}$	0.86	14.93	8.46	25.72
		s	0.39	1.65	0.75	2.24
		v	45.18	11.06	8.92	8.71
		n	52	52	52	52
Tovačov (sample No.6)	2490–2190 BC	$\bar{x}$	0.67	11.23	5.95	18.64
		s	0.26	0.97	0.66	0.92
		v	38.34	8.65	11.02	4.95
		n	56	56	56	56

Source	Age of samples	Statistics	Longitudinal swelling (%)	Tangential swelling (%)	Radial swelling (%)	Volumetric swelling (%)
Rowell, Barbour (1990)	recent	$\bar{x}$	0.60	7.90	4.60	–
Rowell, Barbour (1990)	1150 AD	$\bar{x}$	1.00	15.10	8.10	–
Rowell, Barbour (1990)	850 AD	$\bar{x}$	1.20	13.80	9.30	–
Rowell, Barbour (1990)	2750 BC	$\bar{x}$	1.00	12.30	5.90	–
Horský, Reinprecht (1986)	6200 BC	$\bar{x}$	–	18.19	10.04	31.08

IV: *Values of compression strength parallel to the grain of subfossil oak ($\bar{x}$–arithmetic mean, s – standard deviation, v – coefficient of variation, n – number of samples, AD – air-dry)*

Location	Age of samples	Density of samples with 0% moisture (kg.m^{-3})	Wood moisture (%)	Statistics	Compression strength (MPa)	Modulus of elasticity (MPa)
Kostomlátky – Doubrava	165 BC–241 AD	746	12	$\bar{x}$ s v n	39.19 3.06 7.81 73	8577 4616.66 53.83 73
Tovačov (sample No.19)	265–50 BC	575	12	$\bar{x}$ s v n	33.33 3.82 11.46 46	4178 1414.89 33.87 46
Osek nad Bečvou	945–405 BC	669	12	$\bar{x}$ s v n	39.58 3.49 8.82 110	9384 3421.55 36.46 110
Tovačov (sample No. 6)	2490–2190 BC	529	12	$\bar{x}$ s v n	29.30 1.69 5.77 161	4408 1815.90 41.19 161

Source	Age of samples	Density of samples with 0% moisture (kg.m^{-3})	Wood moisture (%)	Statistics	Compression strength (MPa)	Modulus of elasticity (MPa)
Tsoumis (1991)	recent	–	12.00	$\bar{x}$	43.0	–
Noack (1963)	recent	–	12.00	$\bar{x}$	57.0	–
Matovič (1993)	recent	–	12.00	$\bar{x}$	57.5	–
Požgaj (1997)	recent	–	12.00	$\bar{x}$	59.8	–
Lavers (1993)	recent	–	12.00	$\bar{x}$	51.6	–
Vavrčík et al. (2008)	recent	–	12.00	$\bar{x}$	53.9	–
Rowell, Barbour (1990)	800 BP	–	AD	$\bar{x}$	45.7	–
Reinprecht, Kúdela, Čunderlík (1988)	731 ± 150 AD	–	10.00	$\bar{x}$	50.7	–
Govorčin, Sinković (1995)	about 2050 BC	–	10.94	$\bar{x}$	46.2	–
Rowell, Barbour (1990)	2750 BC	–	AD	$\bar{x}$	38.5	–
Bednar, Fengel (1974)	6550 BC	–	12.00	$\bar{x}$	44.9	–
Horský, Reinprecht (1986)	6200 BC	–	10.00	$\bar{x}$	60.0	–
Rowell, Barbour (1990)	6550 BC	–	AD	$\bar{x}$	44.9	–
Wagenführ (2000)	subfossil – age not provided	–	12.00	$\bar{x}$	38.0	–

The differences between the resulting means of swelling and shrinking are only due to the definition and mathematical expression of the process.

Compression strength parallel to the grain

Tab. IV presents average values of the compression strength parallel to the grain of subfossil oak wood from the examined locations and the results presented in literature. The strength does not exceed the limit of 40 MPa and the modulus of elasticity does not exceed the limit of 9500 MPa; these values can be considered relatively low, especially when compared with the same properties in recent wood. Further, the table shows that neither of these properties is in direct proportion to the density or the age of wood. This leads us to the conclusion that the strength and the elasticity are definitely affected by another factor as well.

Static hardness

The resulting average values of the static hardness of subfossil oak in all directions and values presented in literature are provided in Tab. V. In contrast to the other properties, there are no results for Osek nad Bečvou as the amount of material was not sufficient for the testing samples to be made. The hardness in the longitudinal direction exceeds 40 MPa, whereas the hardness in the transversal directions is about half of the value. Furthermore, it is slightly higher in the radial direction than in the tangential direction. The range of values of hardness in the transversal directions is quite wide in dependence on the density and the age of the wood – between approximately 19 MPa and 34 MPa.

DISCUSSION

The aim of the study was to examine selected physical and mechanical properties of subfossil oak (*Quercus*, sp.) wood and to compare the obtained results with the data presented in literature on subfossil and recent oak. The attention in the Czech Republic has always been focused on the use of subfossil oak from the dendrochronological perspective and nobody so far has dealt with its physical and mechanical properties. Therefore, this is the first research into this issue in the Czech Republic.

Besides the basic indicator of density, the selected physical properties include the dimensional changes of wood, i.e. shrinking and swelling. Regarding mechanical properties, the attention focused on the compression strength parallel to the grain, as this is a relatively frequent way of stressing wooden elements (piles, columns, etc.). Further, the hardness of wood was examined in all the three anatomical directions. The hardness was selected for the purpose of assessing the influence of assumed silicification in subfossil wood on this property.

The results of wood density presented in Tab. I show that there are considerable differences between individual locations. While the density of the sample from Osek nad Bečvou approximates the values of recent wood, where the density is

V: *Values of subfossil oak static hardness as tested using Janka method ($\bar{x}$–arithmetic mean, s – standard deviation, v – coefficient of variation, n – number of samples)*

Location	Age of samples	Density of samples with 0% moisture (kg.m^{-3})	Wood moisture (%)	Statistics	Longitudinal direction (MPa)	Radial direction (MPa)	Tangential direction (MPa)
Kostomlátky – Doubrava	165 BC–241 AD	746	12	$\bar{x}$	52.4	33.5	27.2
				s	8.80	8.67	6.66
				v	16.79	25.89	24.51
				n	52	52	52
Tovačov (sample No. 19)	265–50 BC	575	12	$\bar{x}$	42.8	27.3	20.6
				s	7.90	7.51	4.49
				v	18.44	27.50	21.75
				n	43	43	43
Tovačov (sample No. 6)	2490–2190 BC	529	12	$\bar{x}$	41.6	22.3	19.1
				s	3.19	2.11	1.98
				v	7.68	9.47	10.34
				n	46	46	46
Source	**Age of samples**	**Density of samples with 0% moisture (kg.m^{-3})**	**Wood moisture (%)**	**Statistics**	**Longitudinal direction (MPa)**	**Radial direction (MPa)**	**Tangential direction (MPa)**
Matovič (1993); cited from Ugolev (1975)	recent	–	12.00	$\bar{x}$	67.5	56.0	49.0
Wagenführ (2000)	subfossil – age not provided	–	12.00	$\bar{x}$	44.0	23.0	
Horský, Reinprecht (1986)	6200 BC	–		$\bar{x}$	35.21	10.42	10.94

around 620–670 kg.m^{-3} with 0% moisture, the density of the sample from Kostomlátky, the youngest of the explored samples, significantly exceeds 700 kg.m^{-3}. Such a high density is also presented by e.g. Horský and Reinprecht (1986) for a sample from 6550 BC. A contrasting trend can be seen in the samples from gravel pit Tovačov, where the density is about 100 up to 200 kg.m^{-3} lower than in the remaining locations or than is presented by Wagenführ, 2000; Bednar, Fengel, 1974 or Govorčin, Sinković, 1995. As the results show, these lower values of the density of samples from Tovačov considerably affect the results of the other examined properties.

The average values of shrinking and swelling of samples from Osek nad Bečvou, Tovačov and Kostlomlátky (Tab. II, Tab. III) do not differ much, although e.g. the sample from Kostomlátky dates from 165 BC–241 AD and sample 6 from Tovačov from 2490–2190 BC, i.e. the latter is approximately 2000 years older. Therefore, we can conclude that shrinking and swelling of subfossil oak does not change with time. When compared with the data presented in literature, our results show that the dimensional changes are twice as high as those of recent oak wood. The only exception is the values of longitudinal shrinking of Osek nad Bečvou samples (0.46 %), which reach the values of shrinking of recent oak or values similar to Wagenführ 2000, where, however, the age is not presented. In contrast to the values of shrinking, the results of wood swelling in some cases vary to a great extent, especially in samples from Tovačov and in volumetric dimensional changes of samples from Kostomlátky, although swelling and shrinking are reversible processes. However, as we can learn from literature on the topic, the differing values of swelling and shrinking are only caused by the definition and mathematical expression of the processes.

The compression strength parallel to the grain is presented in literature to range between 70 and 80% of the strength of recent oak. Horský, Reinprecht (1986) state that the strength can even drop to 50% of recent oak. The resulting values of strength of the samples from Osek nad Bečvou 39.58 MPa and Kostomlátky 39.19 MPa (Tab. IV) confirm the theory. The values are comparable with results of subfossil oak presented by e.g. Wagenführ 2000. On the other hand, the strength of the Tovačov samples is considerably lower (30.33 MPa and 29.30 MPa), reaching about 55% of the strength of recent oak. As has been mentioned above, the lower strength of these samples has been influenced to a great extent by their lower density. Due to the fact, we cannot unfortunately establish to what extent the higher age of these samples influences their lower strength.

Wood hardness was tested using Janka method. Two samples of a different age from Tovačov and a sample from Kostomlátky were used to test the hardness. The sample from Osek nad Bečvou was not tested for hardness as the material was not sufficient to produce testing samples of demanded dimensions. The averages of the resulting values of Tovačov samples are around 42 MPa in the longitudinal direction, 22–27 MPa in the radial direction and around 20 MPa in the tangential direction (Tab. V). On the other hand, the Kostomlátky sample achieves much higher values even with respect to its higher density. The hardness of wood is 52.4 MPa in the longitudinal direction, 33.5 MPa in the radial direction and 27.2 MPa in the tangential direction. The lower hardness in the tangential direction in comparison with the radial direction can be explained by the orientation of pith rays in the wood. The results show that the hardness is lower in comparison with recent wood (Tab. V), but also that there is a greater difference between the hardness in the longitudinal and the transversal directions. The hardness in transversal directions of subfossil wood amounts to about 45–65% of the hardness in the longitudinal direction, whereas the hardness in transversal directions of recent wood amounts to about 70–80% of the hardness in the longitudinal direction.

The outcome of the research is that the properties of subfossil oak wood in comparison with recent wood are quite different. The density is highly variable, the dimensional changes are considerably higher and mechanical properties are approximately 20–50% lower. There are more possible explanations for the changes of properties. One of the theories is a biological degradation of wood which causes the decomposition of wood structure, and thus the change of properties (Klaassen, 2008). Another theory can be based on the difference of the compositions of subfossil and recent oak wood. As stated by Wagenführ 2000 and Bednar, Fengel 1974 the proportion of hemicelluloses in subfossil wood is much lower, which is caused by the fact they are easily eluted from wood when laid in humid environment in the long term. As hemicelluloses form the binding component between cellulose and lignin, when they are eluted, these bonds of wood are disturbed. With dimensional changes there is free space for water molecules; with mechanical stress the wood has a lower resistance due to the violated structure.

It is hard to assess the influence of age on the properties of the samples as the samples from Tovačov are considerably different from all the others in all their parameters. However, if we consider the samples from Tovačov separately from the samples from Kostomlátky and Osek nad Bečvou, it is possible to use the data in Tab. I and state that with the increasing age the wood density decreases. The same dependence is valid for the other examined properties because all of them are considerably affected by the density. However, to confirm or reject this theory it will be necessary to analyse many other samples from various locations.

In the future it is expected that more samples of subfossil oak will be taken, their physical and mechanical properties will be tested and they will be dated. Further, it is advisable to focus the attention on the chemical analysis of subfossil wood which would better reveal, confirm or reject the above mentioned theories on the changes of wood properties.

SUMMARY

The objective was to explore selected physical and mechanical properties of subfossil oak (*Quercus*, sp.) wood and to compare the results with recent oak. For the purposes of this work, the following properties were chosen: physical – density, shrinkage, and swelling; mechanical – compression strength parallel to the grain and hardness. Further, the age of the samples was established using radiocarbon dating. The results are presented in Tab. VI.

VI: *Measured values of selected physical and mechanical properties of subfossil oak*

Wood property		Tovačov (sample No. 19)	Osek nad Bečvou	Tovačov (sample No. 6)	Kostomlátky – Doubrava
Age		265–50 BC	945–405 BC	2490–2190 BC	165 BC–241 AD
Density (kg.m^{-3}) with 0 % moisture		575	669	529	746
Shrinking (%)	Longitudinal	0.41	0.46	0.88	0.91
	Radial	6.54	8.36	7.43	10.36
	Tangential	11.79	15.32	15.89	14.41
	Volumetric	17.86	22.74	22.83	23.97
Swelling (%)	Longitudinal	0.46	0.86	0.67	1.28
	Radial	6.62	8.46	5.95	11.93
	Tangential	13.75	14.93	11.23	17.08
	Volumetric	21.85	25.72	18.64	32.71
Compression strength parallel to the grain (MPa)		33.33	39.58	29.3	39.19
Modulus of elasticity (MPa)		4178	9384	4408	8577
Hardness (MPa)	Longitudinal direction	42.8	–	41.6	52.4
	Radial direction	27.3	–	22.3	33.5
	Tangential direction	20.6	–	19.1	27.2

On the basis of the results, we can conclude that the values, with minor variations, correspond to the values provided in professional literature about subfossil oak. The dimensional changes of subfossil oak wood reach approximately twofold values when compared to recent wood. On the other hand, mechanical properties – compression strength parallel to the grain and hardness – make about 50–80 % of the values of recent oak.

SOUHRN

Fyzikální a mechanické vlastnosti subfosilního dubového dřeva

Cílem práce bylo stanovení vybraných fyzikálních a mechanických vlastností subfosilního dubového (*Quercus*, sp.) dřeva a porovnání výsledků s recentním dubem. Pro účely této práce byly vybrány z fyzikálních vlastností – hustota, sesychání a bobtnání, z mechanických vlastností – pevnost v tlaku ve směru vláken a tvrdost. Dále bylo u vzorků zjištěno i jejich stáří radiokarbonovou metodou. Výsledné hodnoty jsou přehledně prezentovány v Tab. VI.

Z výsledků vyplývá, že hodnoty s drobnými odchylkami odpovídají hodnotám, které uvádí o subfosilním dubovém dřevě literatura. Rozměrové změny subfosilního dubového dřeva dosahují přibližně dvojnásobných hodnot, než je tomu u recentního dřeva. Naproti tomu mechanické vlastnosti – pevnost v tlaku ve směru vláken a tvrdost dřeva – odpovídají přibližně 50–80% hodnotám recentního dubového dřeva.

subfosilní kmeny, fyzikální a mechanické vlastnosti, dub

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VII: *Tabulka naměřených hodnot vybraných fyzikálních a mechanických vlastností subfosilního dubu*

Vlastnost dřeva		Tovačov (Vz. 19)	Osek nad Bečvou	Tovačov (Vz. 6)	Kostomlátky – Doubrava
Stáří vzorků		265–50 BC	945–405 BC	2490–2190 BC	165 BC–241 AD
Hustota dřeva (kg.m^{-3}) při vlhkosti 0 %		575	669	529	746
Sesychání (%)	Podélné	0,41	0,46	0,88	0,91
	Radiální	6,54	8,36	7,43	10,36
	Tangenciální	11,79	15,32	15,89	14,41
	Objemové	17,86	22,74	22,83	23,97
Bobtnání (%)	Podélné	0,46	0,86	0,67	1,28
	Radiální	6,62	8,46	5,95	11,93
	Tangenciální	13,75	14,93	11,23	17,08
	Objemové	21,85	25,72	18,64	32,71
Pevnost dřeva v tlaku ve směru vláken (MPa)		33,33	39,58	29,3	39,19
Modul pružnosti (MPa)		4178	9384	4408	8577
Tvrdost dřeva (MPa)	Podélný směr	42,8	–	41,6	52,4
	Radiální směr	27,3	–	22,3	33,5
	Tangenciální směr	20,6	–	19,1	27,2

REFERENCES

BEDNAR, H., FENGEL, D., 1974: Physikalische, chemische und strukturelle Eigenschaften von regentem und subfossilem Eichenholz. *Holz als Roh- und Werkstoff*, 32, p. 99–107.

CARRIÓN, J. S., 2003: *Evolución vegetal*. Murcia: DM, 497 p. ISBN 84 8425 335 X.

DVORSKÁ, J., VÍT, J., 2002: Dendrochronologické a radiometrické zpracování subfosilních kmenů z Mohelnice. In: *8. Kvartér 2002*. Brno, in Anonymus (ed.). p. 22–25.

GOVORČIN, S., SINKOVIĆ, T., 1995: Some physical and mechanical properties of the Bednja abonos. *Drvna–Industrija*, Vol. 46, No. 1, p. 9–14. ISSN 0012-6772

GRYC, V., HORÁČEK, P., 2007: The Variability of Spruce (Picea abies /L./ Karst.) Wood Density with Present Reaction Wood. *Journal of forest science*, Vol. 53, No. 3, p. 129–137. ISSN 1212-4834

HABĚTÍN, V., KNOBLOCH, E, 1981: *Kapesní atlas zkamenělin*. Praha: Státní pedagogické nakladatelství, 288 p.

HORÁČEK, P., 2001: *Fyzikální a mechanické vlastnosti dřeva I*. Brno: Mendelova zemědělská a lesnická univerzita v Brně. 128 p. ISBN 80–7157–347–7

HORSKÝ, D., REINPRECHT, L., 1986: *Štúdia subfosílneho dubového dreva*. Zvolen: Vysoká škola lesnícka a drevárska. 70 p.

HRIB, M., KORDIOVSKÝ, E., BUČEK, A., 2004: *Lužní les v Dyjsko-moravské nivě*. Břeclav, Moravia-press. 591 p. ISBN 80-86181-68-5

KAENNEL, M., SCHWEINGRUBER, F., 1995: *Multingual Glossary of Dendrochronology: Terms and Definitions in English, German, French, Spanish, Italian, Portuguese and Russian*. Birmensdorf, Swiss Federal Institute for Forest, Snow and Landscape Research. Berne, Stuttgart, Vienna: Paul Haupt Publisher. 467 p. ISBN 3–258–05259–X

KALICKI, T., KRĄPIEC, M., 1995: Problems of dating alluvium using buried subfossil tree trunks: lessons from the “black oaks” of the Pistula Halley, Central Europe. *The Holocene*, Vol. 5, No. 2, p. 243–250. ISSN 0959-6836

KLAASSEN R. K. W. M., 2008: Bacterial decay in wooden foundation piles: patterns and causes. A study on historical pile foundations in the Netherlands. *International Biodeterioration and Biodegradation*, Vol. 61, No. 1, p. 45–60.

KRĄPIEC, M., 1996: Subfossil oak chronology (474 BC – AD 1529) from Southern Poland. In *Tree Rings, Environment and Humanity*. J.S. Dean, D.M. Meko a T.W. Swetnam. Tucson, Arizona: Radicarbon, p. 813–819.

LAVERS, G. M., 1993: *The strength properties of timber*. 3. edition. Watford, Garston: Building Research Establishment. 60 p. ISBN 0 85125 562 0

MATOVIČ, A., 1993: *Fyzikální a mechanické vlastnosti dřeva a materiálů na bázi dřeva*. 1. edition. Brno: Vysoká škola zemědělská v Brně. 212 p. ISBN 80–7157–086–9

NOACK, D., 1963: Vergleichende Untersuchungen über physikalische und technologische Eigenschaften des Kern- und Splintholzes der mitteleuropäschen Eiche. *Holz Roh- Werkstoff*, 21, p. 108–122.

POŽGAJ, A., CHOVANEC, D., KURJATKO, S., BABIAK, M., 1997: *Struktura a vlastnosti dreva*. 2. edi-

tion. Bratislava: Príroda, a. s. 488 p. ISBN 80–07–00960–4
REINPRECHT, L., KÚDELA, J., ČUNDERLÍK, I., 1988: Vlastnosti subfosílneho dubového dreva z oblasti Zelená voda. *Drevársky výskum*, 117, p. 79–90.
ROWELL, R. M., BARBOUR, R. J., 1990: *Archaeological Wood: Properties, Chemistry, and Preservation*. Oxford University press. 473 p. ISBN-13: 9780841216235
RYBNÍČEK, M., 2004: Dendrochronologická analýza krovu kostela Nanebevzetí Panny Marie a sv. Ondřeje ve Starém Hobzí, *Acta universitatis agriculturae Mendelianae Brunensis*, LII, No. 5, 155–168 p.
TSOUMIS, G., 1991: *Science and Technology of Wood: Structure, Properties, Utilization*. Chapman & Hall. 494 p. ISBN-10: 0442239858.
VARČÍK, H., GRYC, V., RYBNÍČEK, M., 2008: *Variabilita vybraných fyzikálních a mechanických vlastností dřeva dubu letního. Vliv věku, poloměru kmene a výšky*. 1. edition. Kostelec nad Černými lesy: Lesnická práce, s. r. o. 52 ps. ISBN 978-80-87154-18-2.
WAGENFÜHR, R., 2000: *Holzatlas*. 5. edition. München: Fachbuchverlag Leipzig im Carl Hanser Verlag. 707 p. ISBN 3-446-21390-2.
ČSN 49 0103. Drevo. Zisťovanie vlhkosti pri fyzikálnych a mechanických skúškach. 1979
ČSN 49 0108. Drevo. Zisťovanie hustoty. 1993
ČSN 49 0110. Medza pevnosti v tlaku v smere vlákien. ÚNM Praha 1980.
ČSN 49 0111. Metóda zisťovania modulu pružnosti v tlaku pozdĺž vlákien. ÚNM Praha 1992.
ČSN 49 0126. Skúšky vlastností rastlého dreva. Metóda zisťovania napúčavosti 1988
ČSN 49 0128. Skúšky vlastností rastlého dreva. Metóda zisťovania zosýchavosti 1988
ČSN 49 0136. Drevo. Metóda zisťovania tvrdosti podľa Janky, 1983
http://c14.arch.ox.ac.uk/embed.php?File=dating.html, poslední úpravy verze 4.4.2009 (www stránky), [cit. 2009-04-16]

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