CHANGES IN THE PHYSICO-MECHANICAL PROPERTIES OF PINE (*PINUS SYLVESTRIS* L.) ARCHAEOLOGICAL WOOD

Jānis Dolacis[1], **Juris Ķeviņš**[2], **Gunārs Pavlovičs**[1], **Andis Antons**[1], **Dace Cīrule**[1], **Lubov Belkova**[1] & **Uldis Spulle**[3]

[1] Latvian State Institute of Wood Chemistry, Dzerbenes iela 27, LV-1006, Riga, Latvia, dolacis@edi.lv
[2] Ltd. Inc. "KILBE" Katrīnas iela 5, Riga, LV-1045, Latvia, info.kilbe@kilbe.lv
[3] Latvian University of Agriculture, Dobeles iela 41, Jelgava, Latvia, uldis.spulle@e-koks.lv

Abstract

The object of the study was pine (*Pinus sylvestris* L.) wood that had served as marine fishing pier piles for 70 years. In this case, the piles had been driven into the sea bottom at the depth about 1.5 m; the piles' length about 2.5–3.0 m was located in the sea water, and the piles' ends, about 0.2–0.3 m in length, were located above the water in the air. The pile's part that had been at the contact of the water and the air was subjected to the major destruction, while the sub-water part and the part located in the ground were preserved well. The microscopic studies (SEM – scanning electron microscopy and OM – optical microscopy) have shown no radical distinctions in the morphology of the wood that had been located in sea water and the wood located in the ground during the service time of the piles. The results of the studies on the physico-mechanical characteristics of the wood that had been located for a long time in both the sea water and the sea ground are presented. Thus, for example, the average density (ρ_{12}) of sapwood that had been located in sea water is 455 $kg\cdot m^{-3}$, and that for the heart pith part is 473 $kg\cdot m^{-3}$, while the average density of sapwood (ρ_{12}) for the wood located in the sea bottom ground is 445 $kg\cdot m^{-3}$, and that for the heart pith is 457 $kg\cdot m^{-3}$. The density of the control wood of pine sapwood $\rho_{12} = 487$ $kg\cdot m^{-3}$, and that for the hearth pith part is 446 $kg\cdot m^{-3}$. The average compressive strength of the wood located in sea water is 48.22 MPa, and that of the wood located in the sea ground is 47.75 MPa, while the average compressive strength of wood for the control is 44.75 MPa. In the work, compressive, bending, shear, cross-cut and tensile tests were carried out.

Keywords: archaeological pine wood, physical and mechanical properties.

INTRODUCTION

Testing of the samples taken from sweepwood logs (pine, spruce, birch, aspen) has shown that, after staying in river water during 10–30 years, the strength of wood has not practically changed. Upon more long-term action of river water, the surface layer (10–15 mm thick) gradually looses the strength and starts degrading. At the same time, behind this layer, the strength remains within the standard determined for sound wood (ANONYM 2004).

If wood remains in water for a long period of time, its properties change radically. The quantitative and qualitative indices of these changes depend on the wood species. The long-term action of sea water results in a notable increase in the hardness of larch wood. In the construction of Venice, approximately 400 pieces of larch piles were driven for reinforcing the foundations of different buildings. Later, in 1827, a part of the piles was inspected. The conclusion on their strength says that the piles from larch wood, on which the underwater part of the city is based, as if has become petrified. The wood has become so hard that neither the axe nor the saw hardly take it.

The inspection of the pine piles, taken from the port constructions in the cities of Baku and Makhach-Kala has shown that their strength properties have declined by 40–70 % within the 30 years of service.

It is not possible to determine exactly the degree of the changes in sweepwood after staying in water, because its properties before the flooding are unknown. To determine the applicability of sweepwood, its testing was carried out, and the degree of deviation of the obtained data from the reference data is determined.

Upon staying in river water for up to 30 years, the strength characteristics, except those of the outer part of wood, practically do not change. Upon staying in water for a longer period of time, the wood passes to the category of fumed one. The wood of the species (oak, chestnut), containing tanning substances, passes faster to the state of fumed one. Fumed oak wood in the dry state becomes brittle and cracked. The strength and impact viscosity decrease 1.5 times and 2.0–2.5 times, respectively. In sea water, the sapwood part of wood looses the strength more readily (within a year), but the heartwood part retains the strength within longer terms.

A ship is found, which had sunk 4 centuries ago. Despite the considerable age, the ship appeared to be in a perfect state. This is explained by the fact that, in North Baltics, owing to the cold and hard water, wood

Wood Structure and Properties ´10
edited by J. Kúdela & R. Lagaňa, pp. 85–90

ISBN 978–80–968868–5–2

practically does not decay. Therefore, in the opinion of marine archaeologists, the depths of the Baltic sea may hide a variety of unique relics (http://subscribe.ru/archive/tv.news.1tv/200711/16115624.html#112324).

In the study of the oak wood of the Swedish warship „VASA", which had sunk in the harbour of Stockholm in 1628, lifted in 1956 and preserved in 1961, an important technical problem was its preservation from cracking upon drying (Bjurhager *et al.* 2010). For this purpose, polyethylene glycol was used. It is shown that, in this case, the stabilisation of the oak wood sizes, which depends to a considerable extent on the microstructure of a definite wood species, is not always reached.

In an earlier study of the same oak wood of the ship „VASA" (Ljungdahl *et al.* 2007), it has been shown that modulus of elasticity in radial direction and compressive strength decrease by 50 % in comparison with the case of whole fresh oak wood. Modulus of elasticity in the tangential direction and compressive strength also decrease by 30 % and 50 %, respectively, while the sorption isotherms of archaeological and fresh oak wood are quite similar.

Applying the methods of direct exposure mass spectroscopy (DE-MS) and pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS), it has been shown (Modugno *et al.* 2009) that a considerable loss of polysaccharides is observed in archaeological wood samples. DE-MS fingerprint mass spectra give a rapid indication of the syringyl/guaiacyl ratio and the loss of polysaccharides, as a result of degradation in a waterlogged environment. The results confirm the value of Py-GC/MS as a tool for shedding light on the chemical modifications of wood macromolecules in archaeological objects.

The construction and operation of large hydroelectric power stations of the Angara cascade in Russia: Irkutsk, Bratsk and Ust-Ilim, and the large storage ponds formed at them, resulted in adverse phenomena, namely, erosion and re-forming of the shore line of the storage ponds, the bottom and the mouth areas of the rivers, the flooding of forest tracts, the appearance of floating and sunk trees, the change of the level of ground waters, etc.

The strength characteristics of the sweepwood are below the reference data and lower than the strength of the freshly cut wood; in this case, ultimate compressive strength along the fibres for larch, pine and spruce is lower than the standard value by 37 %, 42 % and 60 %, respectively. The ultimate strength in static bending of water-logged wood is lower by 30 %, 28 % and 31 % for larch, pine and spruce, respectively (Ivanov 2008, Runova *et al.* 2001).

The chemical composition of water-logged wood (the content of cellulose, resins, fats and ash, and the substances soluble in hot water) has not changed after almost 37 years of the service of the storage ponds (Ivanov 2008, Runova *et al.* 2001).

The density of the water-logged wood practically does not change from that of the freshly cut wood and the standard data (Runova *et al.* 2001, Rasev 1977).

In pine wood that had stayed in sea water for 70 years, shrinkage decreases by about 10 % in comparison with the case of freshly cut wood (Dolacis *et al.* 2008).

MATERIALS AND METHODS

In the present study, pine (*Pinus sylvestris* L.) wood that had served as marine fishing pier piles for 70 years was investigated. In this case, the piles had been driven in the sea bottom at the depth about 1.5 m, approximately 2.5–3.0 m was present in the sea water, and the ends about 0.2–0.3 m in size were in the air. The microscopic studies (SEM-scanning electron microscopy and OM-optical microscopy have shown that no radical distinctions in the morphology of wood located in sea water and the wood located in the ground were found within the service period. The study of the anatomic parameters was carried out with a reflected light microscope MTKF-1 and a videocamera TK-C721EG (JVC Color) with the IMAGE-PRO EXPRESS – image analysis program. To determine the mechanical characteristics of wood, an universal material testing machine "Roel Zwick/Z100" was used, equipped with a computer and the software *testXpert Version 11.02* for processing the experimental data. Physical properties were investigated according to DIN and GOST standards. Moisture and density were determined according to DIN 52 183 and DIN 52 182, respectively. Swelling and shrinkage were determined according to DIN 52 184. Moisture absorbency and water absorption were determined according to GOST 16483.19-72 and GOST 16483.20-72.

Mechanical characteristics were determined in compliance with the following standards: DIN 52 185, DIN 52 186, GOST 16 483.5-73, GOST 16 483.23-73, GOST 16 483.24-73, GOST 16 483.26-73. Tensile modulus of elasticity in a fibre direction at the given moisture W was determined in compliance with GOST16 483.26-73 from the equation:

$E_w = \frac{P \times l}{a \times b \times \Delta l}$ [*Pa*], where *P* – load difference between the upper and lower proportionality ultimate stress, *N*; *l* – proportional ultimate length, *m*; *a* and *b* – sample's transverse sizes, *m*; *Δl* – average displacement value, which corresponds to the load *P*, *m*.

Compression modulus of elasticity in fibre direction at the given moisture W was determined according to GOST16 483.24-73, from the equation:

$E_w = \frac{P \times l}{a \times b \times \Delta l}$ [*Pa*], where *P* – load difference between the higher and lower proportionality ultimate stress, *N*; *l* – proportional ultimate length, *m*; *a* and *b* –

sample's transverse sizes, *m*; Δl – average displacement value, which corresponds to the load *P*, *m*.

Shearing modulus of elasticity in fibre direction at the given moisture W was determined according to GOST 16 483.5-73, from the equation:

$E_w = \frac{P \times l}{a \times b \times \Delta l}$ $[Pa]$, where P – load difference between the higher and lower proportionality ultimate stress, *N*; l – proportional ultimate length, *m*; *a* and *b* – sample's shearing sizes, *m*; Δl – average displacement value, which corresponds to the load *P*, *m*.

Impact bending strength was determined according to GOST 16 483.4-73, from the equation:

$A_W = \frac{Q}{b \times h}, J/cm^2$, where *Q* – the work done to the fracture of the sample, *J*; *b* – sample width, cm; *a* – sample height, cm.

RESULTS AND DISCUSSION

The salinity of the waters of the gulf of Riga, where the fishing pier piles under study had stayed for 70 years, is 0.35 ÷ 0.6%, and this is mostly NaCl. The acidity index pH varies in the range from 7.5 to 8.4.

The electron-microscopy images of pine wood, that had served in sea water for 70 years, do not reveal any practical distinctions from the whole pine wood (Fig. 1); crystals of sea water salts are observed only in some anatomical elements.

The average density (ρ_0) of sapwood in the oven dry state is 448 $kg \cdot m^{-3}$, but that of core is 460 $kg \cdot m^{-3}$. The density ρ_0 of the control pine wood sapwood and the heart pith part is equal to 459 $kg \cdot m^{-3}$ and 468 $kg \cdot m^{-3}$, respectively.

Tensile strength σ_t and tensile modulus of elasticity E_t for pine piles (which had been located in sea water for 70 years), in comparison with those for the control pine wood samples, are shown in Table 1.

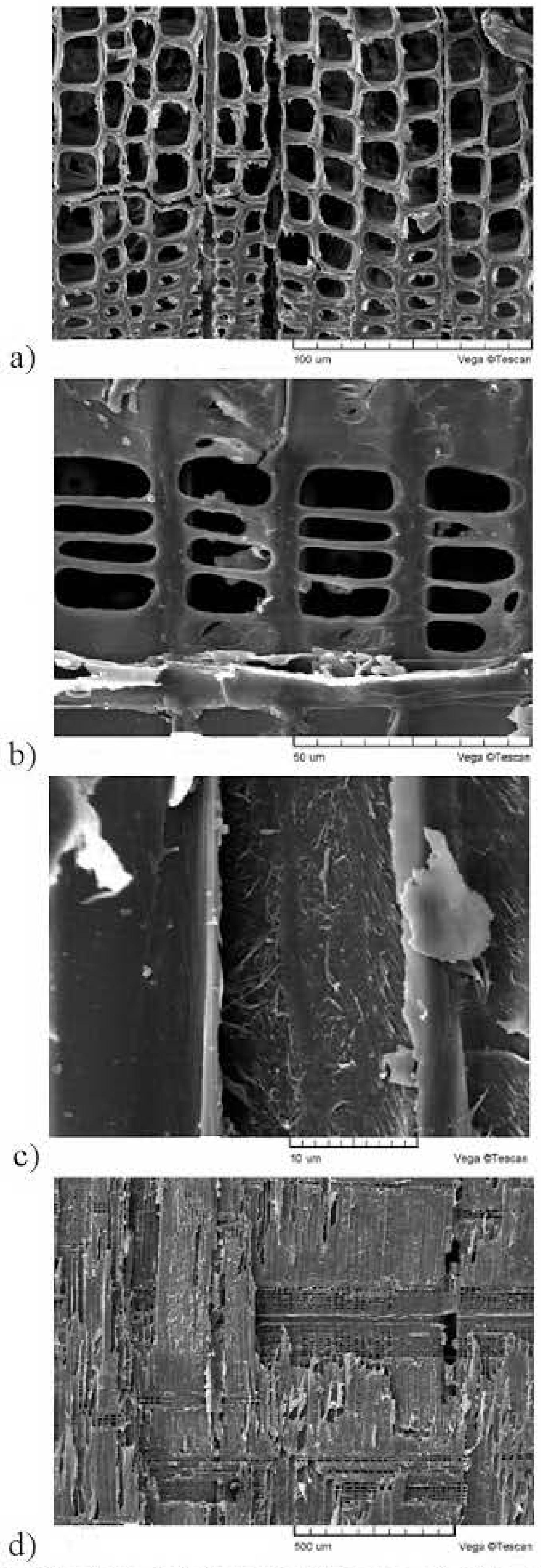

Figure 1 Electron microscopy images of pine wood: a) cross-section (1000 ×), b) radial section (3000×), c) radial section (8000×), d) radial section (200 ×).

Table 1 σ_t, E_t characteristics for pine archaeological wood and the control wood.

Wood sample	Number of samples	Density of sample ρ_{12}, $kg \cdot m^{-3}$	Tensile strength, MPa	Archaeol./ Control, ±%	E_t modulus, MPa	Archaeol./ Control, ±%
Heart – ground	10	457	104 ± 14	+12.3	2098 ± 315	–0.4
Sapwood – ground	11	445	93.0 ± 20.6	–8.8	1773 ± 240	–24.2
Heart – water	9	473	101.9 ± 18.9	+10.0	1918 ± 420	–8.9
Sapwood – water	13	455	69 ± 17.5	–32.3	1516 ± 281	–35.2
Hearth, control	28	446	92.6 ± 15.6	–	2106 ± 230	–
Sapwood, control	28	487	102.0 ± 19.5	–	2340 ± 290	–

The pine wood density distribution from the heart pith in the direction to sapwood is minor (correlation coefficient $r = 0.18$), but the correlation is essential ($r = 0.55$ and 0.92) at the trunk height $H = 25$ %, 50 % and 75 %. The correlation between shrinkage and density is high ($r \sim 0.94$) (DOLACIS *et al.* 2009).

It can bee seen that the tensile strength of heartwood for the piles, located in ground and water, is higher than that for the control wood. Modulus of elasticity for the wood located in ground is almost equal to that of the control wood (lower than by 0.4 %), but the index for the sapwood, located in ground, is lower by 8.9 % in comparison with the corresponding index of the control wood. However, the sapwood, located both in ground and water, is less durable in respect to tensile strength by 8.8 and 32.3 %, and modulus of elasticity by 24.2 and 35.2 %.

The corresponding characteristics of bending strength σ_b and modulus of elasticity in bending E_b for pine archaeological and control wood are shown in Table 2.

It can be seen that the bending characteristics σ_b and E_b for archaeological wood, both for heartwood and sapwood, are lower than the corresponding values of the control wood by 7.4 ÷ 24.6 %.

Compressive strength σ_c and modulus of elasticity in compression E_c for pine archaeological wood and the corresponding characteristics for the control wood are shown in Table 3.

As can be seen, compressive strength for archaeological wood exceeds the corresponding indices for the control wood by 2.8 ÷ 10.4 %. The same relationship is observed in the case of modulus of elasticity, except the case of pile sapwood, which had been located in ground (its index is lower by 3.4 %, in comparison with the case of the control wood).

Table 4 lists the corresponding characteristics for shear strength τ_s and shearing modulus of elasticity E_s. In this case, shear strength τ_s is lower than the corresponding indices for the control wood by 6.3 ÷ 27.4 %, but the indices of shearing modulus of elasticity E_s are higher than for the control wood by 23.1 ÷ 61.8 %. This is explained by the fact that, in the North Baltics, owing to its cold and hard water, the wood and wood material of the ships that had sunk about 4 centuries ago (Ljungdahl J., Berglund L.) are well retained.

Characteristics of ultimate strength in cutting perpendicular to grain for pine archaeological wood and the control wood are shown in Table 5.

Table 2 σ_b, E_b characteristics for pine archaeological wood and the control wood.

Wood sample	Number of samples	Density of sample ρ_{12}, kg·m^{-3}	Bending strength, MPa	Archaeol./ Control, ±%	E_b modulus, GPa	Archaeol./ Control, ±%
Core – ground	8	457	74.7 ± 5.96	–7.4	8.61 ± 0.69	–13.5
Sapwood – ground	10	445	74.9 ± 7.85	–12.5	9.14 ± 0.95	–16.7
Core – water	8	473	73.5 ± 7.66	–8.9	8.56 ± 1.23	–14.0
Sapwood – water	11	455	64.5 ± 17	–24.6	8.53 ± 1.73	–22.2
Core, control	37	446	80.7 ± 14.5	–	9. 95 ± 1.6	–
Sapwood, control	37	487	85.6 ± 12.7	–	10.97 ± 1.4	–

Table 3 Compression σ_c, E_c characteristics for pine archaeological wood and the control wood.

Wood sample	Number of samples	Density of sample ρ_{12}, kg·m^{-3}	Compressive strength σ_c,MPa	Archaeol./ Control, ±%	E_c modulus, E_c, MPa	Archaeol./ Control, ±%
Core – ground	6	457	44.4 ± 3.65	+2.8	2.078 ± 0.25	+4.9
Sapwood – ground	21	445	51.10 ± 4.03	+10.4	2.049 ± 0.23	–3.4
Core – water	12	473	46.5 ± 3.26	+7.6	2.271 ± 0.28	+14.7
Sapwood – water	7	455	50.0 ± 3.99	+8.0	2.341 ± 0.34	+10.4
Core, control	50	446	43.2 ± 5.6	–	1.98 ± 0.20	–
Sapwood, control	50	487	46.3 ± 4.8	–	2.12 ± 0.29	–

Table 4 Schear τ_s, E_s characteristics for pine archaeological wood and the control wood.

Wood sample	Number of samples	Density of sample ρ_{12}, kg·m^{-3}	Schear strength τ_s, MPa	Archaeol./ Control, ±%	E_s modulus, E_s, MPa	Archaeol./ Control, ±%
Core – ground	5	457	8.70 ± 0.56	–11.8	414 ± 48.6	+33.0
Sapwood – ground	10	445	7.91 ± 1.31	–26.7	409 ± 78.1	+27.8
Core – water	9	473	9.24 ± 0.78	–6.3	505 ± 56	+61.8
Sapwood – water	10	455	7.84 ± 0.92	–27.4	394 ± 64.4	+23.1
Core, control	30	446	9.86 ± 1.1	–	300 ± 52.3	–
Sapwood, control	30	487	10.80 ± 1.06	–	320 ± 62.8	–

Table 5 Characteristics of ultimate strength in cutting perpendicular to grain for pine archaeological wood and the control wood.

Wood sample	Number of samples	Density of sample ρ_{12}, kg·m^{-3}	Cutting strength, MPa	Archaeol./ Control, ± %
Core – ground	36	457	21.74 ± 4.41	–16.2
Sapwood – ground	39	445	25.56 ± 4.87	–9.4
Core – water	24	473	23.18 ± 2.80	–10.6
Sapwood – water	26	455	26.88 ± 4.56	–4.7
Core, control	32	446	25.94 ± 4.22	–
Sapwood, control	37	515	28.20 ± 4.13	–

Table 6 Coefficient of swelling α_{rad} in radial direction, α_{tg} in tangential direction and α_V volume for pine archaeological wood and the control wood.

Wood sample	Density of samples ρ_{12}, kg·m^{-3}	Coefficient of swelling α, %/%		
		α_{rad}	α_{tg}	α_V
Core – ground	457	3.0	8.2	11.5
Sapwood – ground	445	3.0	8.2	11.5
Core – water	473	3.4	9.1	12.8
Sapwood – water	455	3.4	9.0	12.9
Sapwood, control	507	4.1	8.7	13.0

It can be seen that the characteristics of ultimate strength in cutting perpendicular to grain for pine archaeological wood decrease by 4.7 ÷ 16.2 %.

Coefficients of swelling for archaeological and control pine wood are shown in Table 6.

As can be seen, coefficients of swelling for archaeological wood in radial direction and throughout the volume are lower than the corresponding indices of the control wood by 0.8 ÷ 26.8 %. The indices in the tangential direction for the archaeological wood located in ground are lower by 5.7 % than the corresponding indices of the control wood, but those are by 3.3 ÷ 4.4 % higher for the samples, located in water than in the case of the control wood.

CONCLUSIONS

1. For pine (*Pinus sylvestris* L.) wood, which had been located for 70 years in sea water in a marine fishing pier (the Baltic sea, the gulf of Riga), in the 2.5–3.0 m deep water and driven into the sea bottom at the depth about 1.5 m, in comparison with the control wood, the mechanical and deformation properties change selectively, i.e. from +61.8 % (shearing modulus of elasticity E_s) to – 27.4 % (schear strength, τ_s).
2. Compressive strength, σ_c in axial direction is higher by 2.8 to 10.4% than the corresponding values of the control wood.
3. A considerable decrease in mechanical characteristics is for shear strength, τ_s, (–6.3 ÷ –27.4 %), but at the same time, the greatest growth is for shearing modulus of elasticity E_s (+23.1 ÷ +61.8 %).
4. Tensile strength for heartwood, located both in ground and water, is higher than the corresponding indices of the control wood (+ 10.0 ÷ +12.3%), but for the sapwood part located in sea water and ground, tensile strength is lower than the corresponding indices of the control wood (–8.8 ÷ –32.3%).
5. Volume coefficient of swelling α for archaeological wood, in comparison with the case of control wood, is lower by –0.8 ÷ –11.5%. Hence, the form stability of this wood improves.

REFERENCES

ANONYM 2004: Changes in the properties of wood. Derevo.Ru May-June (in Russian).

BJURHAGER, I., LJUNGDAHL, J., WALLSTRÖM, L., GAMSTEDT, E. K. & BERGLUND, L. A. 2010: Towards improved understanding of PEG-impregnated waterlogged archaeological wood: A model study on recent oak. Hozforschung, 64: 243–250.

BOROVIKOV, A. M. & UGOLEV, B. N. 1989: Handbook of wood. Moscow: Lesnaja Promishlennost, 296 pp. (in Russian).

DOLACIS, J., ANTONS, A., PAVLOVIČS, G., CĪRULE, D., ALKSNE, A. & LAVNIKOVIČA, I. 2009: Relationship between the anatomical structure elements and physical properties in the trunk transverse and longitudinal direction for wood of pine (*Pinus sylvestris* L.) growing in Latvia. Annals of Warsaw University of Life Sciences – SGGW Forestry and Wood Technology, No 68: 182–185.

DOLACIS, J., BELKOVA, L., CĪRULE, D., ALKSNE, A., LAVNIKOVIČA, I., ANTONS, A. & PAVLOVIČS, G. 2008: Changes in the physical and chemical properties of pine (*Pinus sylvestris* L.) upon the prolonged presence in sea waters. Annals of Warsaw University of Life Sciences – SGGW Forestry and Wood Technology, No 63: 239–242.

GOST 16 483.24-73. Wood. Determination method of modulus of elasticity in compression along fibres (in Russian).

http://subscribe.ru/archive/tv.news.1tv/200711/16115624.html#112324;

IVANOV, V. A. 2008: Substantiation of the technology and equipment for development and processing of wood of the coastal zone and bed of storage ponds. Author's Abstract of Thesis of Doctor of Technical Sciences. St. Petersburg, 40 pp. (in Russian).

LJUNGDAHL, J. & BERGLUND, L.A. 2007: Transverse mechanical behaviour and moisture absorption of waterlogged archaeological wood from the Vasa ship. Hozforschung, 61: 279–284.

MODUGNO, F., LUCEJKO, J.J., RIBECHINI, E., COLOMBINI, M.P. & DEL RIO, J.C. 2009: Characterisation of archaeological waterlogged wood by mass spectrometric techniques. Science & Technology of Biomass Advances and Challenger. Proceedings Book. September 1–4, Villa Monasterio, Varenna (Como), Italy, pp. 27–30.

RASEV, A. I. 1977: Problems of the utilisation of sweepwood in the woodworking industry. Proceedings of the 2nd International Symposium on the Structure, Properties and Quality of Wood 96, Moscow State University of Forest , Moscow, pp. 112–115 (in Russian).

RUNOVA, E.M., SERGEJEV, A.D. & IVANOV, V.A. 2001: The properties of water-logged wood in beds of storage ponds. Moscow State University of Forest, The Journal „Lesnoj Vestnik" („Forest Bulletin"), 5: 133–137.

Acknowledgement

1. *The work is implemented in compliance with the State Research and WOOD-NET Programmes;*
2. *The co-authors are grateful to Dr. sc. ing. J. Ķeviņš, Director of SIA „KILBE", for the prepared and preserved pier pine wood pile material.*