Wood Research at the University of Sopron – Physical-mechanical Properties

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Abstract. This study series shows research fields and results in wood science of the University of Sopron, Hungary. In this paper, we review several studies regarding the physical-mechanical properties of wood, including some properties of Turkey oak grown in different stands, showing that it should be planted among other species in same stand to achieve optimal wood quality. Research in the field of the firewood plantations has shown that it is necessary to choose the right species of poplars, in a given area. Paulownia and some invasive species grow rapidly, so they have great potential as raw materials and there are significant differences between paulownia varieties. Based on their densities, box elder, tree of heaven and green ash can be substituted for the noble species. Basswood can be well impregnated with paraffin, making it a good choice for pencils. Low-quality noble oak logs have the potential to be used in structural elements as lamellae, improving the yield and decreasing the loss in the wood industry. Black locust, sessile oak, beech, poplar, larch and spruce were subjected to different mechanical test methods at different moisture contents. Their properties decreased with increasing moisture content between 12% moisture content and FSP for all six wood species, but the ratio of changes varied, depending both on the measurement method and on the species.

1 Introduction

The University of Sopron in Hungary deals extensively with the proper management of trees and wood from both scientific and practical perspectives. The Faculty of Forestry is the only institution in Hungary that trains, among others, forest engineers and nature conservation engineers, while the Faculty of Wood Engineering and Creative Industries trains, among others, engineers for the wood industry, specialists in the creative industry, and product designers. The former Institute of Wood Science, now part of the Institute of Basic Sciences, deals with the properties and modification possibilities of wood. The following scientific publications are good examples: [1–17]. This study presents the activities and some of our important results we have carried out in recent years to present research regarding the wood industry. We believe that the work we do is globally important. This article covers density, modulus of rupture and modulus of elasticity results for Turkey oak grown in both mixed-species and pure-species stands; energetical utilization research of plantation wood;

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characterization of paulownia wood and some invasive wood species; impregnation of basswood with paraffin; potential uses of low-quality oak; and compares mechanical properties of wood at different moisture contents.

1.1 The influence of stand composition on the selected properties of Turkey oak (*Quercus cerris* L.)

Global forests are under pressure to produce adequate timber to meet the increasing demand for wood and wood products. Matching forest resources to consumer demand has always been complex and of a great concern. This situation gives relevance the concept of sustainability, which can only be achieved through a robust system of forest management. Studies have predicted that global timber consumption will increase by at least 40% between 2005 and 2030 [18–20]. Meanwhile deforestation and forest degradation are still global threats and contribute to about 15% of global warming. More frequent and severe droughts have been predicted for our future climate with expected repercussion on the resilience of forest ecosystems [21–23]. Timber trade regulations and loud environmental concerns are likely to shift the supply of wood from natural forests to plantation timber. Turkey oak species are categorized as drought tolerant and are under-utilized in Hungary. Potentially, Turkey oak can be a promising species for the Hungarian industry because of the predicted climate change. However, the effect of tree species composition on wood quality is limited for Turkey oak. Such information is needed for effective decision making in forest operations. Wood density is an important trait that indicates several other wood properties, as well as the quality of the given species.

The demand for wood as a raw material is increasing and this trend also reflected in research directions. There is a growing demand for rapidly growing tree species that yield large amounts of timber quickly, and their growth characteristics are just as important as the properties of the wood itself. New varieties may also be important within the energy sector as their yields per hectare and their heating value together determine their energy yield. Furthermore, the broader utilization of existing resources is facilitated by the application of existing species in new areas.

1.2 Utilization of wood in the energy field

Biologically renewable energy sources are increasingly significant as a result of ongoing rearrangements within the energy sector. Forest plantations, including those recognized by the Kyoto Protocol as resources to reduce greenhouse gas emissions [24], belong to this category. Rapidly growing tree species such as poplar, willow, and black locust are particularly important for firewood plantations because of their high biomass production and excellent sprouting ability. These short rotation plantations can generate significant quantities of wood as a renewable energy source in a relatively short time period. To make full use of suitable land for establishing plantations, it is essential to select the most appropriate tree species or varieties based on local conditions. However, several factors must be considered when making these selections.

1.3 Characteristics of paulownia (*Paulownia* spp.) wood

There is a growing demand for fast-growing tree species to fill the gap in the wood trade between supply and demand. Prominent representatives among these are several varieties of Paulownia trees, which belong to the fastest growing tree species in the world, but also have one of the lowest densities, with a significant portion of pith. Interest in Paulownia trees has significantly increased across Europe in recent decades. However, the available scientific

publications do not provide a complete view of the wood characteristics of this tree species. For different cultivated varieties, reference is primarily made to the characteristics of the basic species. Among the characteristics of wood, density is the most crucial for determining its usability. Knowledge of density predicts its strength properties [25].

1.4 Characteristics of invasive wood species

The spread and habitat-transforming effects of invasive plant species cause significant environmental problems worldwide [26]. Efforts to combat invasive tree species are being made globally, but necessary basic information for their wood utilization is less known to the processing industry. The most critical characteristic for the usability of wood is its density, from which we can make inferences to its strength properties. The literature on invasiveness has rapidly expanded over the past decades, but it does not typically delve into the wood properties of individual species. Knowledge of of densities is one of the most crucial attributes for the industrial use of tree species for wood, paper, and energy. Density is closely linked to the quality parameters of end-use, such as cellulose yield and the strength of building materials [27]. To position the densities of the three invasive tree species in relation to other tree species, it is advisable to compare the results within the same genus but of greater significance tree species.

1.5 Impregnation of basswood (*Tilia argentea*) for use in pencil manufacturing

There are special requirements concerning raw materials for pencils. They include a uniform structure, relatively small differences between earlywood and latewood density, straight grain and a lack of defects, especially knots. As a consequence, there are a relatively small number of species suitable for pencil manufacturing. The technology also requires relatively large cross-sections and pith-free lumber for producing the lamellae used for pencil manufacturing. Therefore, the raw material base available for pencil manufacturing is restricted, and there is a competition amongst pencil producers for raw materials. Basswood is homogenous and smooth in texture, making its mechanical processing and surface treatment trouble-free. Timing is essential when applying paraffin treatment to basswood for pencil manufacturing.

1.6 Visual assessment of boards made from low-quality noble oak (*Quercus* spp.) logs and the use of noble oak lamellae produced from low-quality timber

In this study, we tested the quality of timber derived from low-quality oak logs. Our main objective was to determine the amount of defect-free lamellae that can be obtained from logs that do not reach category II of the current Hungarian standard (MSZ 45 [28]).

Currently, lower quality hardwood lamellae (including knots, sapwood, etc.) are rarely used for structural purposes. Their most common use is for energy purposes, although a reassessment of their use, based on habits and traditional practices, could allow their higher value recovery, improving plant performance and profits, partly reducing the shortage of timber and contributing to more environmentally friendly operations.

1.7 Comparison of selected mechanical properties of six wood species at different moisture contents

The properties of wood are the result of several factors. The structure of annual rings and the resulting inhomogeneity, the porosity, the moisture content (*MC*) and many other factors influence wood properties.

Water can be found in wood in three states: liquid water (free water) and water vapor in cell lumina; water bound in cell walls (bound water); and crystallized water linked to the chemical components of wood. The fiber-saturation point (*FSP*) is the *MC*, when all the cavities of the cell wall are saturated with water, but no free water is in the cell lumen (Molnár 2004). *FSP* is at about 30% *MC*, depends on the wood species. The mechanical properties of wood change a lot below the *FSP*. The aim of this study was to determine the differences of tensile strength, bending strength, compressive strength and Brinell hardness between 12% *MC* and *FSP*.

2 Materials and methods

2.1 The influence of stand composition on the selected properties of Turkey oak

A total of 12 Turkey oak (*Quercus cerris* L.) trees were harvested from Vas County in Hungary. 7 trees from pure-species stand and 5 trees from a mixed species stand. The selected trees were at least 67 years old. Samples prepared for testing, according to standards, were taken from breast-height level with consideration for both sapwood and heartwood to cover possible variability within trees. The moisture content of the test samples was 12% after a conditioning at normal climate (20 °C and 65% RH).

2.2 Utilization of wood in the energy field

This study included three-year-old clones of three different hybrid poplar (*Populus*) varieties ('Erti', 'I-214', 'Kopeczky') from two distinct growing areas (Borjád and Sárvár). After assessing yields and heating values, the expected heating values per hectare were determined.

2.3 Impregnation of basswood for use in pencil industry

The experimental basswood samples were impregnated with paraffin emulsion at a net *MC* of 7%, using three different methods. The applied vacuum and pressure parameters were the same in all three cases.

2.4 Producing high added value structural timber from lamellae waste

100 pieces of small oak specimens (*Quercus* spp.; 22 × 50 × 424 mm) remaining as by-products of an industrial production were subjected to both non-destructive and bending tests. The analysis of the non-destructive tests showed that the method used does not provide reliable results due to the small specimen sizes and is therefore presented for information only. The requirements of standard EN 408: 2010 + A1 [29] were followed for bending tests because it deals both with structural solid and glued-laminated timber and the end-use of small-size lamellae may be in load-bearing structures. The bending tests were performed on an Instron 4208 (Instron Corporation, USA) universal material testing machine.

2.5 Comparison of selected mechanical properties of six wood species at different moisture contents

For the tests, the most commonly used Hungarian hardwood and softwood species were selected: black locust (*Robinia pseudocacia*), sessile oak (*Quercus petraea*), beech (*Fagus sylvatica*), poplar (*Populus* spp.), larch (*Larix decidua*) and spruce (*Picea abies*). The porosity and density of the samples were divided into three categories:

- high density (>700 kg/m^3): black locust, beech
- medium density (550-700 kg/m^3): oak, larch
- low density (<550 kg/m^3): poplar, spruce.

Tensile strength tests were done according to standard ISO13061-06 [30]. Bending tests followed the specifications of ISO13061-03 [31]. Compression tests were carried out according to ISO13061-17 [32] standard. Brinell-Mörath hardness tests were done as it is shown in the standard MSZ 6786-11 [33].

3 Results and discussion

3.1 The influence of stand composition on the selected properties of Turkey oak

ANOVA analysis showed that there was a statistically significant difference between turkey oaks grown in mixed and pure species stands for the three wood properties (basic density; modulus of rupture; modulus of elasticity). The outputs in Figure 1 compare the effect of stand composition on basic density, modulus of rupture and modulus of elasticity, respectively.

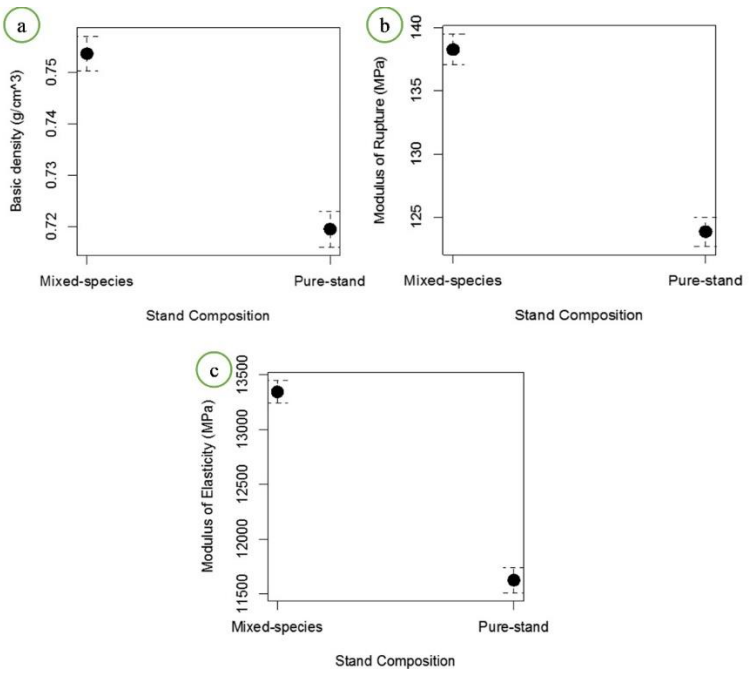

Fig. 1. Basic density (a), modulus of rupture (b) and modulus of elasticity (c) for Turkey oak from mixed- and pure-species stands from Vas County, Hungary.

This study indicates that plantation wood from Turkey oak exhibit traits suitable construction purposes. However, to guarantee superior qualities, Turkey oak should be planted among other species in same stand.

3.2 Utilization of wood in the energy field

Based on the results of the research, there is no significant difference in the lower heating values (LHV) of different varieties when projected on weight, and the quality of the growing site does not have a substantial impact within the same variety (Figure 2). However, from the perspective of yields, the quality of the growing site is important. Energy yield is determined by these two components, and the result can be greatly modified by the proper variety selection in a given area, where nearly twice the yield can be achieved.

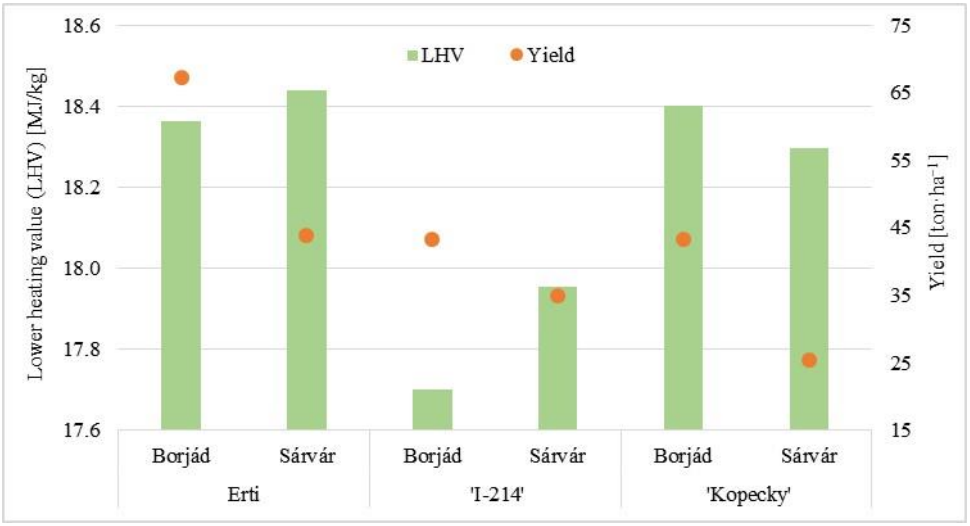

Fig. 2. The heating value and yield of hybrid poplars.

3.3 Characteristics of paulownia wood

The base species *Paulownia tomentosa*, as well as the *Paulownia* Clone in vitro 112 and *Paulownia tomentosa* Robust4 variants studied so far, all exhibit very low densities (Figure 3). However, there can be significant differences between individual varieties, is important for industrial utilization. In the low density of the wood, the strength properties of paulownia are also moderate.

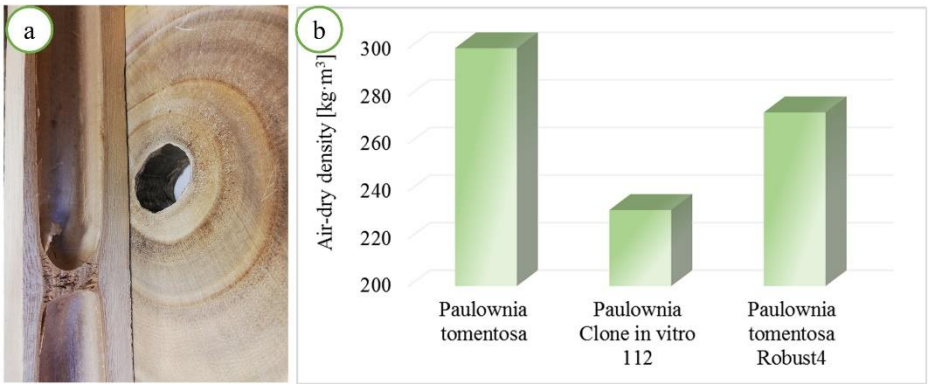

Fig. 3. The wood of Paulownia (a) and the air-dry densities of paulownia species (b).

3.4 Characteristics of invasive wood species

To position the densities of these three invasive tree species in relation to other tree species, it is advisable to compare the results within the same genus but of species which have greater significance in the industry and wood science. The densities of these three invasive tree species are well separated from each other (Figure 4). The lowest value is the box elder (*Acer negundo*), followed by the two ring-porous species, the tree of heaven (*Ailanthus altissima*), and the green ash (*Fraxinus pennsylvanica*) in sequence. The air-dry density of the green ash is similar to that of the common ash, but the box elder's density may be significantly lower than that of sycamore.

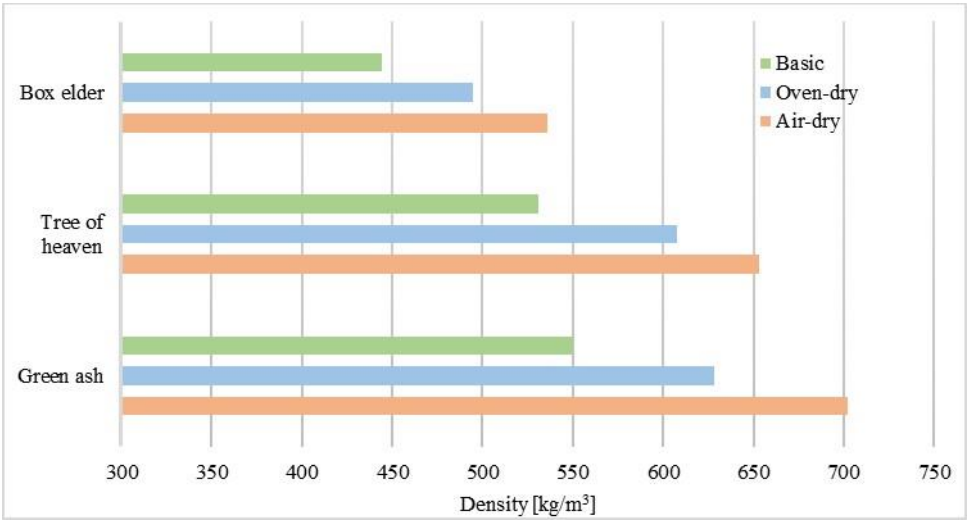

Fig. 4. Different density values of the examined invasive tree species.

3.5 Impregnation of basswood for use in pencil manufacturing

The experimental results suggest that the lower the wood density, the greater the amount of paraffin is taken up (Figure 5). At around 400 kg/m^3 wood density, the wood can take up nearly twice its original weight in paraffin, while at around 500 kg/m^3 density, it can only

uptake less than half. There is no significant difference in impregnation quality among the three different impregnation methods applied, described in Figure 5.

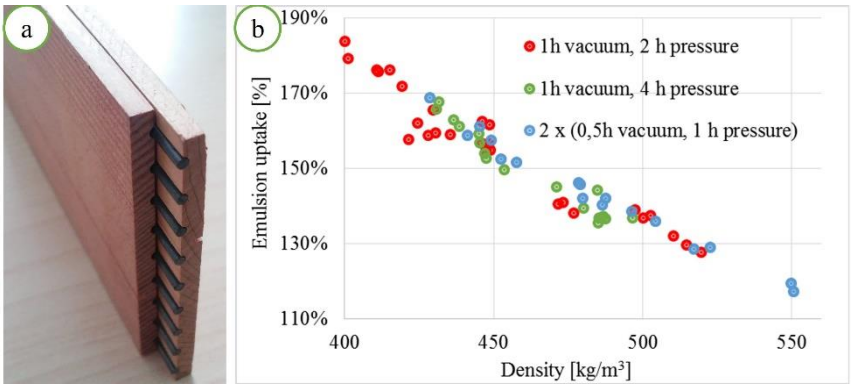

Fig. 5. Impregnated pencil raw material (a) and the relationship between the density and emulsion uptake (b).

3.6 Visual assessment of boards made from low-quality oak logs

Out of 50 boards with a surface area of approximately 60 m^2, 11 m^2 of lamella surface could be extracted, which represents an extraction rate of 18%. The survey was carried out with the lamellae widths and lengths in use today, with the largest proportion of lamellae being the middle size, 50 mm wide. This is definitely advantageous from a value-added point of view. Three quarters of the assortment was between 0.25 and 0.5 metres long, i.e. belonging to the short lamella section. All these results were due to the presence of a significant number of wood defects which limited the extraction of first grade lamellae: mainly sound and dead knots, slope of grain, sapwood, fissures and biotic damages. Given that the subsequent use of these small-sized lamellae seems possible mainly in glued-laminated wood supports, it is likely that lower quality lamellae (contain small knots, and sapwood, etc.) could be used as well, which would highly increase the yield. This requires further research, analysis and related mechanical testing.

3.7 Production possibilities of high added value structural timber from lamellae waste

The average lamellae density (712.6 ± 72.5 kg/m^3) was within the published values, despite the wood defects, but a density test alone cannot be used for classification. The relationships between density and both static and dynamic modulus of elasticity of the specimens were good (R^2 = 56.4% and 51.3%, respectively). There was a good linear relationship between static and dynamic modulus of elasticity, too (R^2 = 57.5%). The best correlation was between the deflection measured in the elastic range and bending strength (R^2 = 62.8%). These lamellae may be used mainly to produce glued-laminated timber, which would allow part of the wood nowadays used as firewood to be sold as a very high value-added product. This idea is supported by the classification obtained according to standard for structural timber EN 338 [34]: this sample set belongs to strength class D35 and it is particularly suitable for further processing. Visual grading criteria have also been defined to visually pre-grade our sample set currently being taken out of industrial production. By doing this, 20% of the specimens were declared as unusable and the classification of the remaining sample set is significantly improved as strength class D45. Comparing our average results with those of

the clear samples, they are very similar, meaning that there is a large amount of additional wood available for further industrial use. Taking into account our results, it is likely that a significant amount of the industrial timber residues could be used for lamellae, including for glued laminated structural applications. Of course, several other products could also be made by finger jointing, panelling, etc. In this way, a higher proportion of timber could be utilized in the wood industry, which creates the potential for more profitable management and better compliance with societal requirements.

3.8 Comparison of selected mechanical properties of six wood species at different moisture contents

Tensile strengths at 12% *MC* are well above the average values of the literature, except for oak and poplar. As example, the tensile strength can be as high as 245 MPa for spruce and 180 MPa for beech and oak. The loss of strength due to the increasing *MC* is 56.8 MPa (38%) for spruce, 18.6 MPa (16%) for larch, 55.5 MPa (26%) for black locust, 35.1 MPa (31%) for oak, 50.6 MPa (28%) for beech and 8.3 MPa (7%) for poplar.

The bending strength results of spruce, black locust and poplar exceed the mean values, while larch is much lower compared to the results of Molnár [35]. With increasing moisture content between 12% and *FSP*, bending strength decreases by 41.4 MPa (45%) for spruce, 51 MPa (52%) for larch, 56.1 MPa (39%) for black locust, 38.8 (36%) for oak, 62.8 MPa (55%) for beech and 42 MPa (49%) for poplar.

The compression strength showed a significant average reduction of 60% with the change in *MC* between 12% and *FSP*. The compression strength of spruce and poplar samples exceed the average values, while the remaining wood species remain below that. The minimum values given by Molnár [35], were always achieved.

The hardness of the wood species was tested in all three anatomical directions. The reduction of hardness with increasing *MC* is shown in Table 1.

Table 1. Changes of Brinell-Mörath hardness in different anatomical directions between 12% moisture content and fiber saturation point of different wood species.

Direction	***Black locust***	***Oak***	***Beech***	***Poplar***	***Larch***	***Spruce***
Longitudinal	41%	48%	11%	28%	33%	19%
Radial	4%	35%	7%	41%	30%	29%
Tangential	8%	43%	3%	37%	17%	20%

4 Conclusions

This paper summarizes the results of several studies, including density, modulus of rupture and modulus of elasticity for Turkey oak grown in both mixed-species and pure-species stands; energetical utilization research of plantation wood; characterization of paulownia wood and some invasive wood species; basswood impregnation possibilities with paraffin; potential uses of low-quality oak; mechanical properties compared at different moisture contents. Our purpose was to show research activities at the University of Sopron, regarding the physical-mechanical wood properties.

Turkey oak, as a wood species possibly spread in the near future in Hungary, has should be planted among other species in same stand to achieve optimal wood quality. This was evidenced by all examined properties: density, modulus of rupture and modulus of elasticity.

From the perspective of yields, the quality of the growing site does play a significant influencing role in energy-wood plantations. Nearly twice the yield can be achieved by the proper variety selection in a given area using poplar clones (*Populus*).

Paulownia belongs to the fastest-growing tree species, thus, it have a great industrial potential despite that it has a very low density, with a significant pith portion. After the examination of densities, it can be stated that there can be significant differences between individual varieties.

The study of invasives is important because their rapid spread could provide industry with a significant amount of timber in the future. By determining the density, important strength and other properties can be estimated. The air-dry densities of the 3 species studied are 536 kg/m^3 for box elder, 653 kg/m^3 for tree of heaven and 702 kg/m^3 for green ash.

The raw material base of pencil manufacturing is rather restricted. Basswood (*Tilia argentea*) is homogenous and smooth in texture, making its mechanical processing and surface treatment trouble-free. Our tests have shown that the impregnation capability of lower density linden is significantly better.

Only 18% of the low quality noble oak (*Quercus* spp.) boards can be used for defect-free lamella production. Taking into account the lower quality lamellae, their tests have shown that they can be used for the production of high-quality glued-laminated timber production with strength classes above D35.

Black locust (*Robinia pseudocacia*), sessile oak (*Quercus petraea*), beech (*Fagus sylvatica*), poplar (*Populus*), larch (*Larix decidua*) and spruce (*Picea abies*) were subjected to different test methods. Tensile strength, bending strength, compressive strength and hardness of the air-dry samples correlate well with the data from the literature. This confirms the correctness of our measurements. The examined properties consequently decreased with increasing moisture content between 12% moisture content and *FSP* for all six wood species, but the ratio of changes was various, depending both on the measurement method and on the species. The selected sample groups represented different groups of wood species, thus, these different sample groups will become better comparable.

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References

1. M. Báder, and R. Németh, Moisture-dependent mechanical properties of longitudinally compressed wood, *Eur. J. Wood Prod.* **77** (2019) 1009–1019. doi:10.1007/s00107-019-01448-1.
2. M. Bak, F. Molnár, R. Rákosa, Z. Németh, and R. Németh, Dimensional stabilization of wood by microporous silica aerogel using in-situ polymerization, *Wood Sci Technol*. **56** (2022) 1353–1375. doi:10.1007/s00226-022-01412-y.
3. F. Fodor, and M. Bak, Studying the Wettability and Bonding Properties of Acetylated Hornbeam Wood Using PVAc and PUR Adhesives, *Materials*. **16** (2023) 2046. doi:10.3390/ma16052046.
4. A. Ghavidel, A. Jorbandian, M. Bak, J. Gelbrich, J.J. Morrell, I. Sandu, and R. Hosseinpourpia, Degradation assessment of archaeological oak (*Quercus* spp.) buried under oxygen-limited condition, *Holzforschung*. **77** (2023) 198–207. doi:10.1515/hf-2022-0168.
5. F. Horváth, M. Bak, and M. Báder, Faanyagok gombaállóságának változása rostirányú tömörítést és további modifikációs eljárásokat követően, *Gradus*. **8** (2021) 59–65. doi:10.47833/2021.2.ENG.003.

6. M. Báder, and R. Németh, A review of wood compression along the grain—After the 100th anniversary of pleating, *Forests*. **14** (2023) 763. doi:10.3390/f14040763.
7. M. Bak, D. Takács, R. Rákosa, Z.I. Németh, and R. Németh, One-Step Process for the Fabrication of Hydrophobic and Dimensional Stable Wood Using Functionalized Silica Nanoparticles, *Forests*. **14** (2023) 651. doi:10.3390/f14030651.
8. Z.A. Köbölkuti, K. Cseke, A. Benke, M. Báder, A. Borovics, and R. Németh, Allelic variation in candidate genes associated with wood properties of cultivated poplars (Populus), *BioFut*. **70** (2019) 286–294. doi:10.1556/019.70.2019.32.
9. F. Fodor, M. Bak, A. Bidló, B. Bolodár-Varga, and R. Németh, Biological Durability of Acetylated Hornbeam Wood with Soil Contact in Hungary, *Forests*. **13** (2022) 1003. doi:10.3390/f13071003.
10. M. Báder, R. Németh, Á. Vörös, Z. Tóth, and A. Novotni, The effect of agroforestry farming on wood quality and timber industry and its supportation by Horizon 2020, *Agroforest Syst*. **97** (2023) 587–603. doi:10.1007/s10457-023-00812-8.
11. M. Bak, F. Molnár, and R. Németh, Improvement of dimensional stability of wood by silica nanoparticles, *Wood Material Science & Engineering*. **14** (2019) 48–58. doi:10.1080/17480272.2018.1528568.
12. F. Fodor, M. Bak, and R. Németh, Photostability of Oil-Coated and Stain-Coated Acetylated Hornbeam Wood against Natural Weather and Artificial Aging, *Coatings*. **12** (2022) 817. doi:10.3390/coatings12060817.
13. M. Báder, R. Németh, J. Sandak, and A. Sandak, FTIR analysis of chemical changes in wood induced by steaming and longitudinal compression, *Cellulose*. **27** (2020) 6811–6829. doi:10.1007/s10570-020-03131-8.
14. K. Cseke, Z.A. Köbölkuti, A. Benke, A. Rumi, M. Báder, A. Borovics, and R. Németh, Nemesnyár klónok faanyagtani jellemzőkhöz köthető génjeinek genetikai változatossága, *Erdészettudományi Közlemények*. **10** (2020) 5–16. doi:10.17164/EK.2020.001.
15. É. Lublóy, D.T. Mészáros, L.G. Takács, Z. Cimer, and H. Norbert, Examination of the fire performance of wood materials treated with different precautions, *J Therm Anal Calorim*. **148** (2023) 4129–4140. doi:10.1007/s10973-023-12050-2.
16. M. Bak, and R. Németh, Effect of different nanoparticle treatments on the decay resistance of wood, *BioResources*. **13** (2018) 7886–7899.
17. M. Báder, R. Németh, and J. Konnerth, Micromechanical properties of longitudinally compressed wood, *Eur J Wood Prod*. **77** (2019) 11. doi:10.1007/s00107-019-01392-0.
18. FAO, State of the World's Forests 2009, Rome, Italy, 2009.
19. F. Steierer, Current wood resources availability and demands national and regional wood resource balances EU/EFTA countries, United Nations, Geneva, Switzerland, 2010.
20. UNECE-FAO, FAO: The European Forest Sector Outlook Study II 2010-2030, United Nations, United Nations Economic Commission for Europe, Food and Agriculture Organization of the United Nations, Geneva, 2011.
21. P.R.J. Shukla, R. Skea, K. Diemen, Ø. Calvin, F. Christophersen, and J. Creutzig, eds., Meeting report of the intergovernmental panel on climate change expert meeting on mitigation sustainability and climate stabilization scenarios, in: IPCC Working Group III Technical Support Unit, London, UK, Imperial College London, 2017.

22. M. Hanewinkel, D. Cullmann, M.J. Schelhaas, G.J. Nabuurs, and N.E. Zimmermann, Climate change may cause severe loss in economic value of European forestland, *Nat. Clim. Chang*. **3** (2013) 204-207,. doi:10.1038/nclimate1687.
23. V. Altieri, S. Franco, F. Lombardi, P.A. Marziliano, G. Menguzzato, and P. Porto, The role of silvicultural systems and forest types in preventing soil erosion processes in mountain forests: A methodological approach using cesium-137 measurements, *J. Soils Sediments*. **18** (2018) 1-10,. doi:10.1007/s11368-018-1957-8.
24. K. Updegraff, M.J. Baughman, and S.J. Taff, Environmental benefits of cropland conversion to Hybrid poplar: economic and policy considerations, *Biomass Bioenergy*. **27** (2004) 411–428. doi:DOI:10.1016/j.biombioe.2004.05.002.
25. M. Kiaei, Radial variation in wood static bending of naturally and plantation grown alder stems, *Cellulose Chem. Technol*. **47** (2013) 339–344.
26. G. Ónodi, Az idegenhonos, illetve inváziós fafajok élőhelyformáló hatásai, *Erdészettudományi Közlemények*. **6** (2016) 101–113. doi:10.17164/EK.2016.008.
27. C. Harvald, and P.O. Olesen, The variation of the basic density within the juvenile wood of Sitka spruce (Picea sitchensis,) Scand, *J. For. Res*. **2** (1987) 525–53. doi:10.1080/02827588709382488.
28. MSZ 45:2022 Fűrészrönk. Követelmények és megjelölés (Sawlogs. Requirements and marking)., 2022.
29. EN 408:2010+A1:2012: Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties, 2012.
30. ISO 13061-06: Physical and mechanical properties of wood - Test methods for small clear wood specimens - Part 06: Determination of ultimate tensile stress parallel to grain, 2014.
31. ISO 13061-03: Physical and mechanical properties of wood - Test methods for small clear wood specimens - Part 03: Determination of ultimate strength in static bending, 2014.
32. ISO 13061-17: Physical and mechanical properties of wood - Test methods for small clear wood specimens - Part 17: Determination of ultimate stress in compression parallel to grain, 2017.
33. MSZ 6786-11: Test methods for wood materials. Determination of hardness, 1982.
34. EN 338:2016 Structural timber. Strength classes, 2016.
35. S. Molnár, Knowledge of wood (Faanyagismeret), Mezőgazdasági Szaktudás Kiadó, Budapest, Hungary, 2004.