Gradus Vol 11, No 3 (2024)
ISSN 2064-8014

COMPARITIVE STUDY OF DIFFERENT HORNBEAMS (CARPINUS BETULUS L.)

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https://doi.org/10.47833/2024.3.ENG.014

Keywords:
Bending strength,
Brinell-Mörath hardness,
Density,
Modulus of elasticity,
Wear resistance.

Article history:
Received 8 July 2024
Revised 5. November 2024.
Accepted 10. November 2024

Abstract

The industrial application of hornbeam is significantly hindered by its fluted growth, mainly due to the poor output of the sawmill. Our study seeks to enhance the understanding of wood science and the wood business by examining the physical-mechanical characteristics of cylindrical and fluted hornbeams, while considering various site factors. Hornbeam has a notable density, rendering its manufacturing process challenging, yet, it excels in producing durable and resistant wooden components. Currently, cylindrical or almost cylindrical hornbeam logs may be found in Hungarian forests. However, there is little information on their timber quality and general characteristics. Research indicates that cylindrical hornbeams exhibit better properties compared to fluted-growth hornbeams. This is supported by findings such as higher density, with cylindrical hornbeams having an average density that is 4.38% greater. Additionally, the Brinell-Mörath hardness of cylindrical hornbeams is on average 12.61% higher.

1 Introduction

The hornbeam (*Carpinus betulus* L.), often found in European woods, has a crucial role in forestry and the wood industry [7]. Hornbeam wood has a conventional growth pattern characterized by fluted and twisted features, which significantly impacts the quantity and ease of working with the timber [10]. Nevertheless, there are also hornbeam logs that are cylindrical or nearly cylindrical in shape, and their wood qualities are not as well understood. However, these logs show interesting traits for industrial applications [13]. Prior studies on hornbeam have mostly concentrated on the wood's physical and mechanical characteristics, as well as its ecological and economic importance [14]. However, these research have not thoroughly investigated the many forms of the trunk.

The objective of this research is to conduct a comprehensive comparison between cylindrical and fluted-growth hornbeams. The main aim of the research is to examine the impact of different trunk forms of hornbeam on the physical and mechanical characteristics of the wood. Additionally, the study seeks to enhance our understanding of the importance of certain growth shapes, which might have practical advantages for the industry. The ultimate objective is to enhance the forestry output of cylindrical hornbeam, so bolstering the domestic wood sector via the provision of superior grade timber in the long run. We have performed investigations on the essential material characteristics, including density, swelling, bending modulus of elasticity (*MoE*), and modulus of rupture (*MoR*). During the assessment of the outcomes, particular emphasis is placed on attributes that are essential for industrial processing. This study enhances our comprehension of hornbeam species and the optimization of their industrial use. It aids in the sustainable management of hornbeam forests and has the potential to enhance the quality of timber and perhaps veneer manufacturing.

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2 Materials and methods

Throughout the study, hornbeam logs were acquired from several forestry districts in Hungary. The Szombathelyi Forestry and Nyírerdő Nyírség Forestry produced both cylindrical and fluted-growth specimens, while a cylindrical hornbeam wood was acquired only from Zala County. The existing sample approach did not differentiate between young and mature wood but excluded pith and juvenile wood. All of the specimens were defect-free sound wood pieces. The primary objective of the study was to compare the forms of cylindrical and fluted-growth trunks, and this analysis was conducted in relation to existing textual data. This method enables a concentrated analysis of the structural and morphological disparities in the wood. The code designations for the analyzed samples are categorized based on the provider, origin, and growth shape, as shown in (*Table 1*).

Table 1. Sample marking and origin

Specimen	Location	Shape of log	Code
Nyírerdő Forestry	Baktalórántháza 10/A	fluted-growth	Nyírség-1
Nyírerdő Forestry	Baktalórántháza 10/A	cylindrical	Nyírség-2
Szombathelyi Forestry.	Hegyhátszentmárton 5/a	cylindrical	Vas-1
Szombathelyi Forestry	Hegyhátszentmárton 5/a	cylindrical	Vas-2
Szombathelyi Forestry	Hegyhátszentmárton 5/a	fluted-growth	Vas-3
Zala Country	Pusztaederics 21D	cylindrical	Zala

2.1 Determination of physical and mechanical properties

The analysis of the physical attributes of the hornbeam samples encompasses two crucial factors: density and swelling. The density measurement relies on the completely dry condition, which may fluctuate depending on the relative moisture content (*MC*) of the wood [12]. The swelling measurement assesses the changes in dimensions caused by differences in moisture content of wood, as established by the ISO 13061-15:2017 [5] standard. We used 15 specimens for each sample measuring 20×20×30 mm (*Tangential×Radial×Longitudinal; T×R×L*) as prescribed by the requirements for the evaluation.

The mechanical tests were conducted to ascertain the hardness, bending strength, and impact bending strength. The hardness measurement was performed using the Brinell-Mörath test protocol, which is generally accepted. The test was done in accordance with the Hungarian standard MSZ 6786-11:1982 [11]. The dimensions of the 15 specimens per sample were 50×50×50 mm (*T×R×L),* and it was conditioned to reach the moisture content equilibrium under normal circumstances (20 °C and 65% relative humidity). The standard specifies that Hornbeam, a very dense wood species, requires a load of 1000 N for a period of 30 seconds. Experiments were conducted on the anatomical directions of end-grain, radial, and tangential. Equation 1 was used to ascertain the hardness (H_B).

$$H_B = \frac{2 \cdot F}{D \cdot \pi \cdot (\mathrm{D} - \sqrt{D^2 - d^2})} \tag{1}$$

where:
F – applied force: 1000 N,
D – diameter of the steel ball: 10 mm,
d – average diameter of the indentation.

We chose the three-point bending test to determine the bending strength, since it allows for easier comparison with various types of wood. The ISO 13061-03:2014 [2] standard was implemented. Simultaneously, the Modulus of Elasticity (*MoE*) was calculated using the ISO 13061-04:2014 [3] standard. This included measuring the deflection at the center of the specimen while a progressively rising transverse force was applied for 15 specimens per sample. The load was incrementally raised till failure in order to ascertain the bending strength. Significant emphasis was placed on the testing pace, since the observed mechanical characteristics are highly influenced by the test time. Wood and other polymeric materials exhibit more plasticity at lower rates due to their strength and elasticity. At elevated speeds, as a result of the accelerated accumulation of stress and increased load, the specimen exhibits reduced deformation prior to fracture.

Charpy impact bending tests were performed in accordance with the ISO 13061-10:2017 [4] standard. For the testing, we used altogether 90 specimens that were 20×20×300 mm (*T*×*R*×*L*) in size and free from any defects. These specimens were subjected to a controlled environment of 20 °C temperature and 65% relative humidity. The Charpy impact tester was used to conduct the impact bending strength testing. The pendulum and the supports had a radius of curvature of 15 mm, and the distance between the supports was 240 mm. The specimens were positioned symmetrically on the supports along the radial surface of the wood. The energy absorption was quantified with a precision of 1 Joule. The results obtained from each testing methods were standardized to a *MC* of 12% (σ_{12}). For natural wood, the following conversion formula is applied [1] (Eq. 2):

$$\sigma_{12} = \sigma_u[1 + \alpha(u - 12)] \tag{2}$$

where: σ_u– the strength value of the tested specimen at a moisture content of *u*,
u – moisture content,
α – strength change per 1.0% change in moisture content within the fibre saturation point:
$\alpha_{\sigma h}$= 0.04 (bending strength),
α_{Eh}= 0.02 (bending modulus of elasticity),
$\alpha_{\sigma \ddot{u}h}$= 0.02 (impact bending strength),
$\alpha_{\mathrm{Hb\ (end-grain)}}$= 0.035 (hardness in the end-grain direction),
$\alpha_{\mathrm{Hb\ (side)}}$ = 0.025 (hardness in the longitudinal direction).

The wear resistance of wood was assessed by measuring the ability of its surface layers to withstand abrasive forces, which are often caused by friction. The assessment was performed using the Taber abrasion technique, in accordance with the Hungarian MSZ 6786-14:1982 [11] standard. The specimens had dimensions of 100×100×10 mm (*T*×*R*×*L*) and had a centrally located hole with a diameter of 10 mm. The 10 specimens per sample were subjected to abrasion using a Taber abrasion machine, applying a load of 1000 g for 400 rotations, using sandpaper with a grain level of 40. Before measuring, the specimens were conditioned. The specimens were measured with a precision of 0.1 mm for their dimensions and 0.001 g for their mass. The thickness was measured at four specific sites, located 24 mm inward from the corners, and the resulting average value was calculated. The outcomes were assessed by considering the decrease in thickness using formula (Eq. 3):

$$R_v = \frac{V_0 - V_1}{4} \quad \text{[mm/100 rev.]} \tag{3}$$

where: V_0 – the thickness of the specimen before the test (mm),
V_1 – the thickness of the specimen after abrasion (mm).

The wear resistance is determined by calculating the arithmetic mean of the test results of specimens with the same cross-sectional direction. The calculation of wear resistance based on mass loss is determined using Eq. 4:

$$R_g = \frac{g_0 - g_1}{4} \quad \text{[mm/100 rev.]} \tag{4}$$

where: g_0 – average thickness of the specimen before the test (mm),
g_1 – average thickness of the specimen after abrasion (mm).

3 Results and discussion

During the evaluation of hardness tests, we observed that the values in different anatomical directions followed the trends reported in the literature. The fluted-growth group from Nyírség exhibited 11.43% lower hardness in the radial direction compared to the tangential direction. The results of our other groups correlated in the radial and tangential directions; therefore, these directions are not detailed separately and are presented together. The results obtained during the examination are shown in (*Figure 1*) The specimens from Zala County showed 3.47% higher hardness in the longitudinal direction compared to the average taken from the literature. Additionally, the fluted-stemmed individual from Szombathely, which also exhibited outstanding hardness, showed 8.76% higher hardness in the end-grain direction. There is no significant difference in side hardness between the cylindrical hornbeams from Zala and Szombathely. The fluted samples from Szombathely (Vas-3) differ from these groups, showing a significant difference in side hardness compared to the other groups. It is only 20.31% lower than in the longitudinal direction. In addition, its end-grain hardness is slightly higher than that of the cylindrical samples grown in the same location. The specimens from the Nyírség logs have an average hardness that is 45.23% lower in the end-grain direction and 38.24% lower in the side direction compared to the average of the other groups. The prominent differences can be attributed to the quality of the growing site and other growth factors.

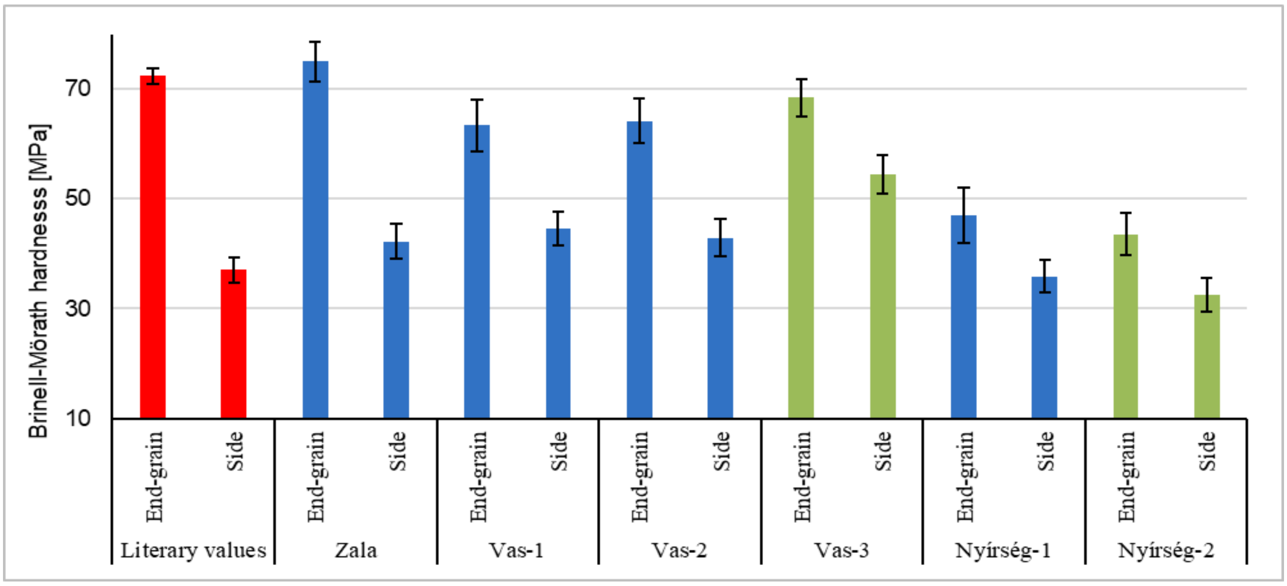

Figure 1: Brinell-Mörath hardness of hornbeam wood from different locations, markings are in Table 1. Cylindrical log shape is marked by blue colour, fluted-growth logs are marked by green

In the bending strength tests, it was generally observed that the greatest deformation before specimen failure required the application of the highest force. The specimens maintained a nearly constant slope from 10% to 40% of the maximum force. This phase lasted up to an average load of 1300 N, with the specimens reaching their maximum bending strength at 2975 N. The obtained bending strength and modulus of elasticity in bending were also compared to average values found in the literature, calculated from the values listed in (*Table 2*).

Table 2. Literary values of hornbeam. Abbreviations: MoR - modulus of rupture; MoE - modulus of elasticity

Author	*MoR* [MPa]	*MoE [GPa]*
Molnár [9]	58.0-160.0-200.0	7.00-16.20-17.70
Kiaei [6]	140.9-153.5	14.70-14.76
Meier [8]	110.4-112.4	11.68-12.10

Thus, the average Modulus of Rupture (*MoR*) was determined to be 122.88 MPa, and the Modulus of Elasticity (*MoE*) was determined to be 12.99 GPa. The results obtained during the analysis are shown in (*Figure 2*), where the groups derived from logs of different shapes are visually distinguished by colors.

The samples exhibited no abnormalities that could affect the test results. Based on the measurements, we can state that none of the groups reached the values reported in the literature. However, the raw material from the Zala logs showed somewhat higher bending strength compared to the other groups. The difference between the cylindrical and fluted-growth specimens from Vas County was negligible, less than 0.5%.

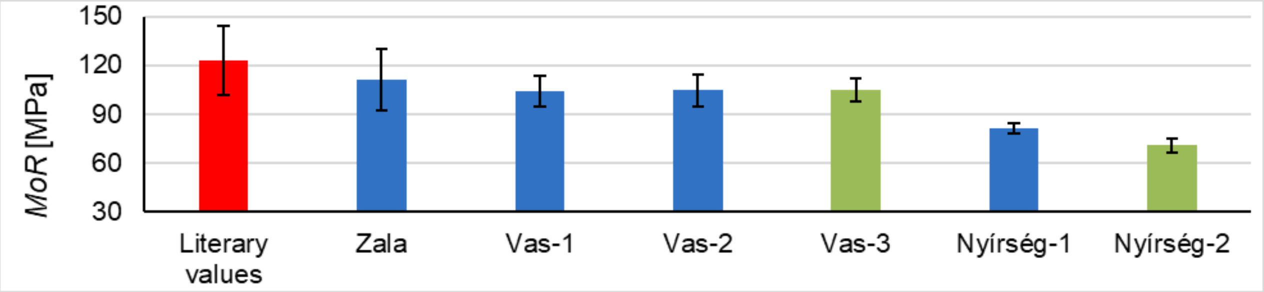

Figure 2: Modulus of rupture (MoR) of hornbeam wood from different locations, markings are in Table 1. Cylindrical log shape is marked by blue colour, fluted-growth logs are marked by green

In contrast, the wood from Nyírerdő exhibited significant differences compared to the other samples. For fluted-growth logs, the Modulus of Rupture (*MoR*) was 33.25% lower, and for cylindrical logs, it was 23.42% lower than the average *MoR* of the other samples. Even after filtering out the outliers, the overall results did not change significantly. No errors were observed during the measurements, and the standard deviation of the final results indicates that the specimens within each sample exhibited similar values. The significantly weaker results are likely due to the specific growing conditions of the site. Further analyses will be necessary to better understand why these samples differ so markedly from the others. (*Figure 3*) shows the Modulus of Elasticity (*MoE*), where a similar trend can be observed for both Nyírerdő samples. For the cylindrical hornbeam, the *MoE* is 21.64% lower, and for fluted-growth hornbeam, it is 37.71% lower compared to the averages of the other samples. A significant difference is also noticeable for the cylindrical hornbeam from Szombathely, where the *MoE* of the Vas-1 sample is statistically significantly higher. The other two samples from Vas have the same *MoE* as the sample from Zala. An uncertainty of the results is indicated by the larger difference between the two cylindrical samples from Vas than between the fluted and the cylindrical samples. Additionally, in this case, the measured values are still below the average values reported in the literature.

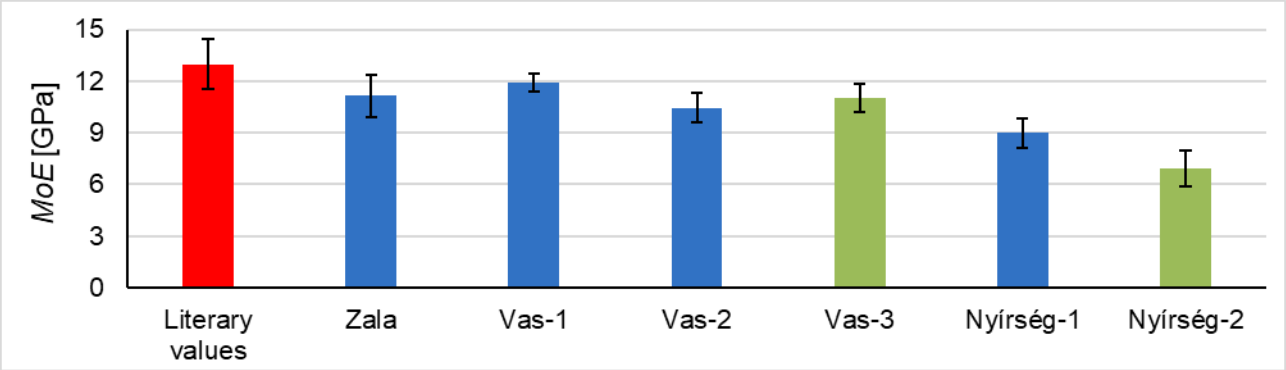

Figure 3: Modulus of elasticity (MoE) of hornbeam wood from different locations, markings are in Table 1. Cylindrical log shape is marked by blue colour, fluted-growth logs are marked by purple

The results of the impact bending strength tests are presented in *(Table 3)*. The cylindrical sample from Szombathely (Vas-1) exhibited outstanding values in the impact bending tests, showing nearly 80% higher impact bending strength than the other samples. The fluted-growth sample from Nyírerdő correlates well with the fluted-growth sample from Szombathely (Vas-3) and the literature values as well.

Table 3. Charpy impact bending test results of hornbeam from different locations, markings are in Table 1

Sample	Impact bending strength [MPa]	Standard deviation [MPa]
Literary values	98.00	16.61
Zala	84.43	7.03
Vas-1	179.52	10.74
Vas-2	116.90	11.40
Vas-3	95.82	19.28
Nyírség-1	119.40	16.75
Nyírség-2	96.51	12.02

The Nyírség-1 and Nyírség-2 samples also correlate with each other, but the Zala sample is 26.86% lower than the former and 29.29% lower than the latter. Compared to the fluted-growth samples (Nyírség-2 and Vas-3), Zala sample has 15.52% and 11.89% lower strength values, respectively. In the impact bending tests, the cylindrical samples showed better results than the fluted-growth samples, except for the specimens from Zala. Nonetheless, the impact bending strength results align well with the *MoE* presented in (*Figure 3*). In summary, the fluted-growth samples can be considered as dynamically good even when the Vas-1 cylindrical sample is an outlier.

The data obtained from the wear resistance measurements are shown in (*Figure 4)*. The specimens from each measured group achieved the "highly wear-resistant" classification defined by the MSZ-6786/14-82 [11] standard, both in the radial and tangential directions.

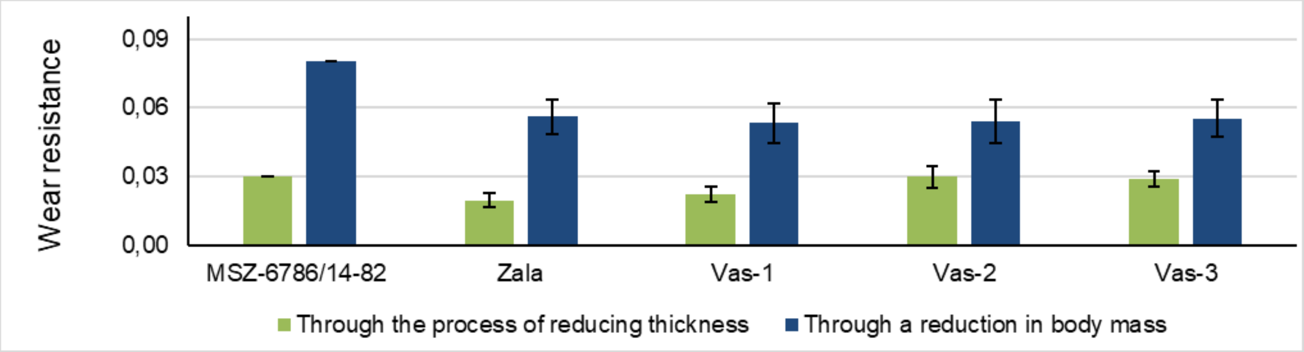

Figure 4. The wear resistance is determined by the decrease in thickness and the mass loss

Figure 4 demonstrates a strong correlation between the indications derived from mass loss. Nevertheless, the indications derived from thickness reduction reveal a variation of around 30% for the Zala and Vas-2 groups. The wear indices of the groups, represented as percentages, are shown in (*Table 4*). The wear resistance by the decrease in thickness of Vas-3 sample is similar to Vas-2 sample and clearly poorer than Vas-1 sample. This indicates that not only the shape of the log matters. But still the samples of the cylindrical trunks from Zala and Vas were the best in this respect.

Table 4. Test piece wear index, expressed as a percentage (t=%)

Zala	0,3
Vas-1	0,2
Vas-2	0,3
Vas-3	0,2

The swelling of the different hornbeam samples is shown in (*Figure 4*), in terms of volumetric (*V*), tangential (*T*), and radial (*R*) directions. It is evident that all six samples follow the trends obtained from the literature averages [8;10].

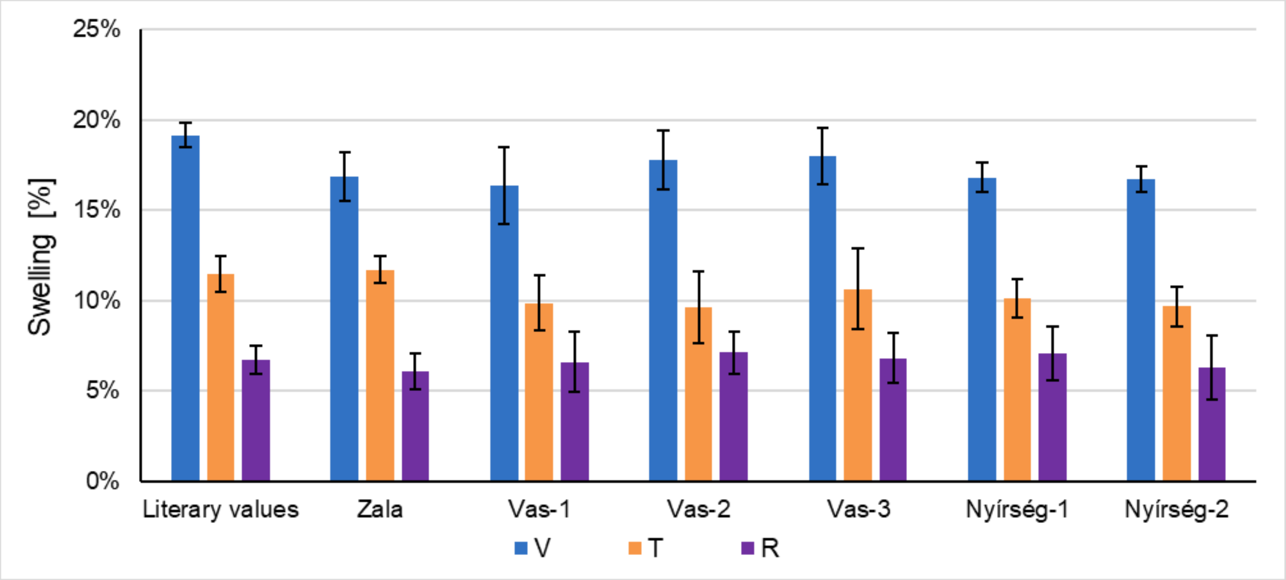

Figure 4: Swelling of hornbeam wood from different locations, markings are in Table 1. Blue columns represent volumetric, yellows tangential and purples radial swelling

The swelling measurements yielded highest values of 17.74% for volumetric swelling, 11.47% for tangential swelling, and 7.13% for radial swelling. The volumetric swelling values of both samples from Nyírerdő exhibited a strong correlation, comparable to the Zala and Szombathely Vas-1 samples. The samples labelled as Vas-2 and Vas-3 had greater volumetric swelling, showing larger difference between the two cylindrical samples from Vas than between the fluted and the cylindrical samples. In the tangential direction, the Z-H-1 sample exceeded the literature values (11.68%) and was on average 1.5% higher compared to the other samples. The Zala sample exhibited distinctiveness in the radial direction compared to the other samples. The result is 6.11%, which is lower than the values of the Nyírerdő and Zala samples. The densities of the cylindrical and fluted-growth samples are shown in (*Table 4*). Under the conditions of 20 °C and 65% relative humidity, the density values varied from 678 to 763 kg/m³. There were no notable disparities seen between the logs from Szombathely and Zala. However, the logs from Nyírerdő had a density that was 8-10% lower than the logs from West Hungary. This accounts for the diminished mechanical outcomes seen in the Nyírerdő samples. It should be noted that the cylindrical samples from Vas had averagely 3.1% higher values compared to Vas-3, but none of them differed significantly from the Zala sample.

Table 4. Densities [kg/m^3] of fluted-growth and cylindrical hornbeams, markings are in Table 1

Sample	Literary values	Zala	Vas-1	Vas-2	Vas-3	Nyírség-1	Nyírség-2
Average	774	742	753	763	735	692	678
Min.	735	691	712	713	679	658	645
Max	790	787	803	805	783	711	708
Deviance	22.47	19.61	25.64	27.05	26.92	15.93	17.04
Variance	2.90%	2.64%	3.41%	3.55%	3.66%	2.30%	2.51%

4 Conclusion

This study determined that the trunk shape of hornbeam *(Carpinus betulus L.)* has a significant impact on its physical and mechanical properties. The test results showed that cylindrical hornbeam possesses better average impact strength (27.91%), modulus of elasticity (18.25%) and modulus of rupture (14.01%) than the fluted-growth hornbeams, which are advantageous for industrial use. Of course, growing site is also important for quality. The wood from Zala achieved the best results or was among the best in most tests, as an example 75 MPa Brinell-Mörath hardness and 110 MPa *MoR.* In contrast, the logs from Nyírség have an average Brinell-Mörath hardness that is 45.23% lower in the end-grain direction and 38.24% lower in the side direction compared to the average of the other groups. Both woods from Nyírség performed worse in most of the tests, which is likely the effect of the poorer growing conditions. Exceptions are the dynamic test and the swelling, where similar results were obtained. The swelling measurements yielded highest values of 17.74% for volumetric swelling, 11.47% for tangential swelling, and 7.13% for radial swelling. In the wear resistance test, all specimens performed well and achieved the classification "highly wear-resistant".

Our observations highlight that selective breeding of cylindrical-growth hornbeam or the application of appropriate forestry practices in specific growth sites can improve the industrial applicability of hornbeam wood in the distant future. Further research is needed to gain a deeper understanding of the influencing factors. Additionally, sampling locations should be expanded, as the research results suggest that the growth sites greatly influence individual strength values, sometimes resulting in stronger or denser wood structures.

After evaluating the outcomes, we may potentially determine the suitable growth parameters by using the correlations. This will allow foresters to cultivate premium timber that can be more effectively exploited, especially in the face of climatic fluctuations.

5 Acknowledgment

Supported by the ÚNKP-23-2-III-SOE-163 New National Excellence Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund. We express our thanks to Imre Horváth for the specimen preparation.

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