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Comparison of fluted-growth and cylindrical hornbeam logs from Hungarian forests

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ABSTRACT
Hornbeam (*Carpinus betulus* L.) logs are typically noted for their fluted and twisted growth, which results in growth rings that are polygonal and faceted rather than round. This type of growth has a negative impact on their industrial use, primarily because of the low sawmill yield. Hornbeam has a high density, making it difficult to manufacture, yet it is extremely good for hard and wear-resistant wood parts. Today, however, cylindrical or almost cylindrical hornbeam logs can be found in Hungarian forests, although little information is available on their timber and overall features. Some research (drying characteristics, surface tension, chipping parameters, varnish adhesion, etc.) suggest that cylindrical hornbeams have better properties than fluted-growth hornbeams, as the density of the cylindricals are averagely 4.38% higher, and Brinell-Mörath hardness is on average 12.61% higher. By investigating some physical-mechanical properties between cylindrical and fluted hornbeams, taking into account some site influences, our research aims to improve the knowledge of wood science and wood industry. Once the results have been evaluated, we may be able to select the appropriate growing parameters using the correlations. This will enable foresters to grow high-quality logs that can be utilized much better even in the changing climate.

INTRODUCTION
The hornbeam (*Carpinus betulus* L.), typically found in European forests, holds significant importance in forestry and the wood industry (Majer 1968). Hornbeam wood grow traditionally fluted and twisted, which considerably affects the yield of timber and its workability (Molnár 2002). However, cylindrical or nearly cylindrical hornbeam logs also occur, whose wood properties are less well known but possess promising characteristics for industrial use (Solymos 1993). Previous research on hornbeam has mainly focused on the physical and mechanical properties of the wood, as well as its ecological and economic significance (Szalacsi 2015; Veres 2013). These studies, however, have not extensively examined the different trunk shapes. The aim of this study is to compare cylindrical and fluted-growth hornbeams in detail. The primary objective of the research is to investigate how the trunk shapes of hornbeam affect the physical and mechanical properties of the wood and to expand our knowledge of the significance of these two growth shapes, which could be beneficial for the industry. The long-term goal is to promote the forestry production of cylindrical hornbeam, which may support the domestic wood industry by providing higher quality timber in the distant future. We have conducted examinations of the most critical material properties, such as density, swelling, bending modulus of elasticity (*MoE*) and modulus of rupture (*MoR*). During the evaluation of the results, special attention is given to characteristics that are crucial for industrial processing. This research contributes to a better understanding of the hornbeam species and the optimization of its industrial utilization, assists in the sustainable management of hornbeam stands, and can improve the quality of wood in timber and maybe in veneer production.

MATERIALS AND METHODS
During the research, hornbeam logs were obtained from different forestry regions of Hungary. Both cylindrical and fluted-growth specimens were provided by Szombathelyi Forestry and Nyírerdő Nyírség Forestry, while only cylindrical hornbeam log was sourced from Zala County. The current sampling strategy did not distinguish between juvenile and heartwood, the exclusive aim of the research was the comparative analysis of cylindrical and fluted-growth trunk shapes, evaluated in the context of literary

data. This approach allows a focused examination of the structural and morphological differences in the wood. The various code designations for the studied samples, according to provider, origin, and growth shape, are presented in Table 1.

Table 1: Sample marking and origin

Specimen	Location	Shape of log	Code
Nyírerdő Forestry	Baktalórántháza 10/A	fluted-growth	N-H-5
Nyírerdő Forestry	Baktalórántháza 10/A	cylindrical	N-H-6
Szombathelyi Forestry.	Hegyhátszentmárton 5/a	cylindrical	S-H-14
Szombathelyi Forestry	Hegyhátszentmárton 5/a	cylindrical	S-H-16
Szombathelyi Forestry	Hegyhátszentmárton 5/a	fluted-growth	S-H-15
Zala Country	Pusztaederics 21D	cylindrical	Z-H-1

Determination of physical and mechanical properties

The examination of physical characteristics of the hornbeam samples involves two critical parameters: density and swelling. The density determination is based on the absolutely dry state, which can vary depending on the relative moisture content (*MC*) of the wood (Rónyai 2021). The measurement of swelling evaluates the dimensional changes related to the *MC* variations of wood, determined according to the ISO 13061-15 (2017) standard. For the examination, we used specimens of 20×20×30 mm (*Tangential×Radial×Longitudinal; T×R×L*) as specified in the standards.

The mechanical tests focused on determining hardness, bending strength, and impact bending strength. The hardness measurement was conducted following the widely recognized Brinell-Mörath test procedure, adhering to the Hungarian standard MSZ 6786-11 (1982). The specimen dimensions were 50×50×50 mm ($T×R×L$), conditioned to equilibrium *MC* at normal conditions (20 °C and 65% relative humidity). Hornbeam, being a very hard wood species, required a load of 1000 N, with a load duration of 30 seconds as specified in the standard. Tests were performed on the end-grain, radial, and tangential anatomical directions. Eq. 1 was used to determine hardness (H_B).

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

where:

F – applied force: 1000 N,

D – diameter of the steel ball: 10 mm,

d – average diameter of the indentation.

For the measurement of bending strength, we selected the three-point bending test, ensuring easier comparability with other wood species. The ISO 13061-03 (2014) standard was applied. At the same time, the *MoE* was determined following the ISO 13061-04 (2014) standard, where the deflection as a result of gradually increasing transverse load was measured at the centre of the specimen. The load was then gradually increased until failure to determine the bending strength. Special attention was paid to the rate of the tests, as the measured mechanical properties strongly depend on the duration of the test. Strength and elasticity are factors where wood and other polymeric materials tend to behave more plastically at lower rates. At higher rates, due to the faster build-up of stress and greater load, the specimen deforms less before breaking.

Charpy impact bending tests were conducted according to the ISO 13061-10 (2017) standard. For these tests, we also used failure-free specimens of 20×20×300 mm ($T×R×L$), which were conditioned at 20 °C and 65% relative humidity. The impact bending strength tests were performed using a Charpy impact tester. The radius of curvature for the pendulum and the supports was 15 mm, and the distance between the supports was 240 mm. The specimens were symmetrically placed on the supports on the radial surface of the wood. The absorbed energy was measured with an accuracy of 1 J.

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 (Báder and Németh 2019) (Eq. 2):

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

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),
$\alpha_{\sigma üh}$= 0.02 (impact bending strength),
$\alpha_{Hb\ (end-grain)}$= 0.035 (hardness in the longitudinal direction),
$\alpha_{Hb\ (side)}$= 0.025 (hardness in the transverse directions).

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 sample from Nyírerdő exhibited 11.43% lower hardness in the radial direction compared to the tangential direction. The results of the other samples 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. In Figures 1-3 the different log shapes are visually distinguished by different colours. The specimens from Zala showed 3.47% higher hardness in the longitudinal direction compared to the average taken from the literature. Additionally, the fluted-growth sample 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 (S-H-15) differ from these samples, showing a significant difference in side hardness compared to the other samples. It is only 20.31% lower than in the longitudinal direction. The specimens from the Nyírerdő 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 samples. The prominent differences can be attributed to the quality of the growing site and other growth factors.

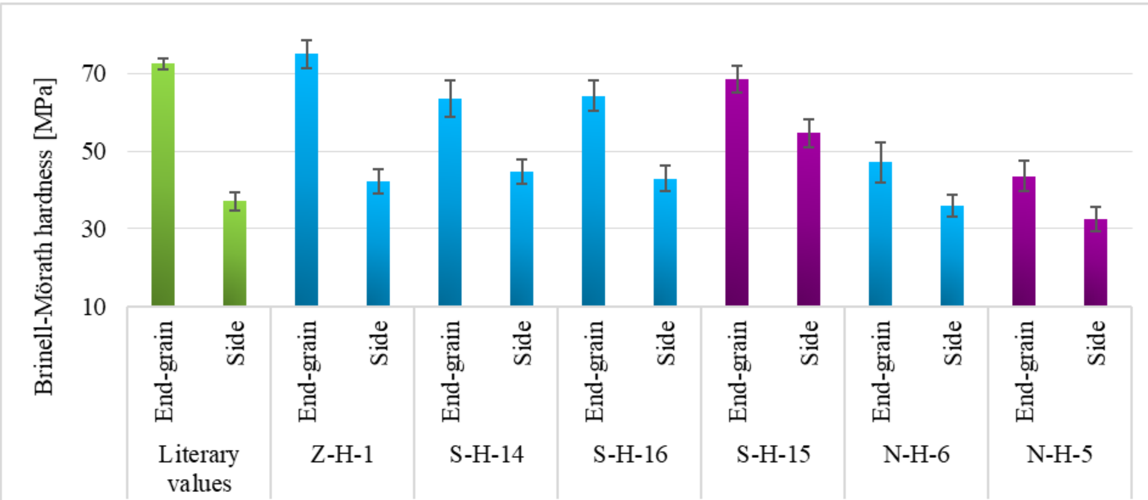

Figure 1: Brinell-Mörath hardness of hornbeam wood from different locations, markings are in Table 1. Cylindrical log shape is marked by blue colour, fluted-growth logs are marked by purple

In the bending tests, specimen failure occurred at the highest force, that means the moment of the greatest deformation. The specimens maintained a nearly constant slope from 5% to 50% of the maximum force. This phase lasted up to an average load of 1300 N, with the specimens reaching their maximum bending strength averagely at 2975 N. The obtained *MoR* and *MoE* were also compared to average values found in the literature, calculated from the values in Table 2.
Thus, the average *MoR* of the literature was determined to be 122.88 MPa, and the *MoE* was determined to be 12.99 GPa. Our test results are shown in Figure 2. The specimens exhibited no abnormalities that could affect the test results. Based on the measurements, we can state that none of the samples reached the values reported in the literature. However, wood from Zala showed somewhat higher *MoR* compared

to the other samples. The difference between the cylindrical and fluted-growth samples from Szombathely was negligible, less than 0.5%.

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

Author	***MoR* [MPa]**	***MoE* [GPa]**
Molnár (2004)	58.0–160.0–200.0	7.00-16.20–17.70
Majid (2019)	140.9–153.5	14.70–14.76
Meier (2024)	110.4–112.4	11.68–12.10

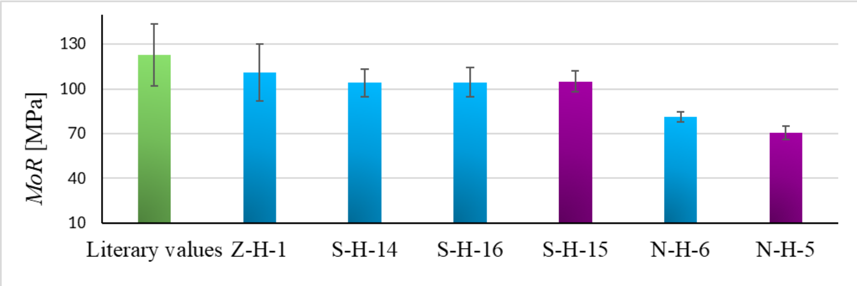

Figure 2: Modulus of rupture (MoR) of hornbeam wood from different locations, markings are in Table 1. Cylindrical log shape is marked by blue colour, fluted-growth logs are marked by purple

In contrast, the wood from Nyírerdő exhibited drastic differences compared to the other samples. For fluted-growth logs, the *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. There were no errors 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 needed to better understand why these samples differ so highly from the others. Figure 3 shows the *MoE*, where a similar trend can be observed on 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 S-H-14 sample is statistically significantly higher. Additionally, in this case, the measured values are still below the average values reported in the literature.

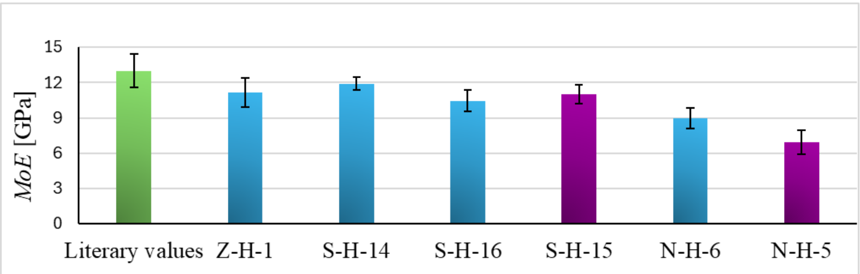

Figure 3: Modulus of elasticity (MoE) of hornbeam wood from different locations, markings are in Table 1. Cylindrical log shape is marked by blue colour, fluted-growth logs are marked by purple

The results of the impact bending strength tests are presented in Table 3. The cylindrical sample from Szombathely (S-H-14) 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 samples from Szombathely (S-H-15) and the literature values as well. The N-H-5 and S-H-16 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 (N-H-6 and S-H-15), 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.

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
Z-H-1	84.43	7.03
S-H-14	179.52	10.74
S-H-16	116.90	11.40
S-H-15	95.82	19.28
N-H-5	119.40	16.75
N-H-6	96.51	12.02

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 (Molnár and Bariska 2002; Meier 2024).

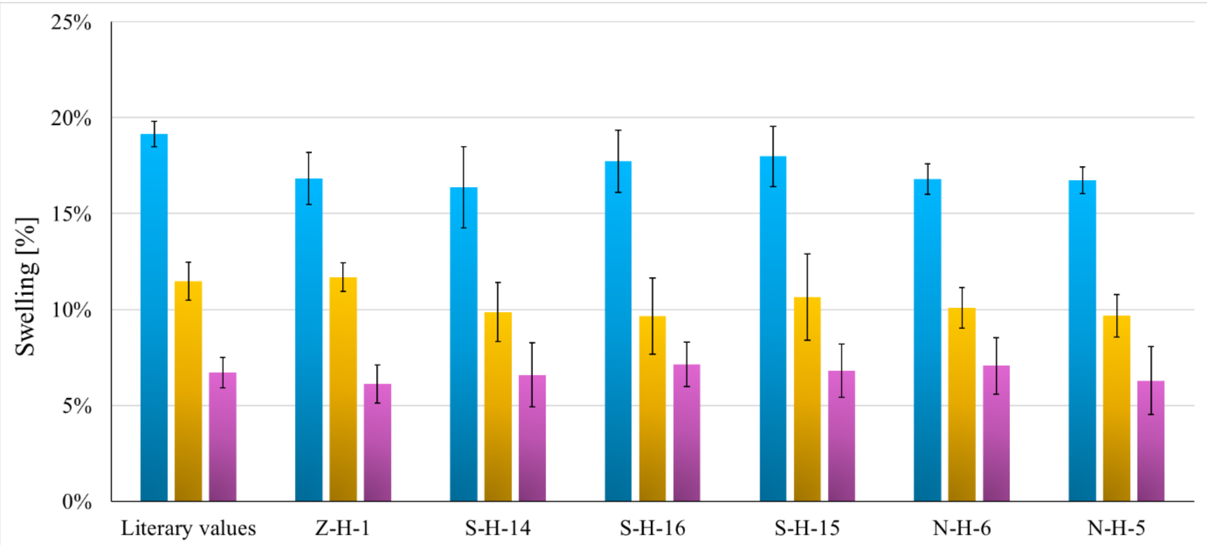

Figure 4: Swelling of hornbeam wood from different locations, markings are in Table 1. Blue columns represent volumetric, yellows tangential and purples radial swelling

In the swelling measurements, the maximum values were 17.74% for volumetric, 11.47% for tangential, and 7.13% for radial directions. The volumetric swelling values for both samples from Nyírerdő correlated with each other, similar to the Zala and Szombathely S-H-14 samples. The S-H-14 and S-H-16 samples exhibited higher volumetric swelling. 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. In the radial direction, the Z-H-1 sample stood out from the others. It has a value of 6.11%, which is lower compared to the Nyírerdő and Zala samples.

The densities for the cylindrical and fluted-growth samples are presented in Table 4. Conditioned at 20 °C and 65% relative humidity, the density values ranged between 678 and 763 kg/m³. No significant differences were found between the logs from Szombathely and Zala, but the logs from Nyírerdő had 8-10% lower density compared to the logs from West Hungary. This explains the weaker mechanical results of the Nyírerdő samples.

Table 4: Densities [kg/m³] of fluted-growth and cylindrical hornbeams, markings are in Table 1

Sample	Literary values	Z-H-1	S-H-14	S-H-16	S-H-15	N-H-5	N-H-6
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%

CONCLUSIONS

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. These 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. For future studies, we have already started the fungal resistance tests of these samples, as well as conducted wear resistance and water permeability tests. It will be important to get to know some important anatomical, genetic, and fungal resistance differences between cylindrical and fluted hornbeams as well, to improve the knowledge of wood science and wood industry.

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