https://doi.org/10.37045/aslh-2022-0008 *Acta Silv. Lign. Hung., Vol. 18, Nr. 2 (2022) 119–127*

Measurements of the Load-bearing Structural Aspects of Pannónia Poplar from Sites in Western Transdanubia, Hungary

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Abstract – This study summarises the test results of Pannónia poplar (*Populus* × *euramericana* cv. Pannónia) originating from three plantation sites in Győr-Moson-Sopron County in the Western Transdanubia region of Hungary: Újrónafő 11G, Győr 540B, and Kapuvár 35A. The research primarily aimed to clarify the characteristics of radial growth depending on the plantation site and to predict the selected physical and mechanical properties of the xylem. Measuring the time-of-flight (TOF) in trees was performed with a non-destructive test technique using a "Fakopp" TreeSonic device. The stress wave velocity (SWV) values calculated from TOF data are significant in estimating the dynamic modulus of elasticity (MOE) of the xylem and, therefore, in the prediction of timber suitability for structural applications. During the on-site measurements, 50 trees – as random samples from every site – were investigated to determine the diameter at breast height (DBH) and the stress wave velocity in sapwood parallel to the grain. In addition to the non-destructive measurements, the laboratory analysis of the xylem from harvested logs (three logs per site, random sample) was also performed to determine the radial growth rate and density. The one-way ANOVA results revealed significant differences in SWV values between certain plantation groups. The difference between the average values of young and old plantations is 136.8 m/s, which is a significant difference. Similar findings occurred for the middle-aged and old plantation trees. The average values of the young and the middle-aged trees can be considered the same at the 0.05 level of significance. We also established that the trees in the young (22 years old) plantation site, Újrónafő 11G, planted with the closest spacing (3 m × 4 m), had the lowest average diameter of breast height naturally and showed the highest average value of SWV. Nevertheless, the sap- and heartwood samples from this plantation site had the highest average density values in a normal climate; therefore, the highest dynamic modulus of elasticity of the xylem can be expected in logs originating from this plantation site.

***Populus* × *euramericana* cv. Pannónia / stress wave velocity / diameter at breast height / density / dynamic modulus of elasticity / load-bearing structural timber**

Kivonat – Nyugat-Dunántúli ültetvényekről származó Pannónia nyár teherviselő szerkezeti szempontok szerinti mérései. A jelen tanulmányban három, név szerint Újrónafő 11G, Győr 540B és Kapuvár 35A, nyugat-dunántúli, Győr-Moson-Sopron megyei Pannónia nyár (*Populus* × *euramericana* cv. Pannónia) ültetvénnyel kapcsolatos vizsgálati eredményeinket foglaljuk össze. Kutatómunkánkban a vizsgált ültetvényes egyedek vastagsági növekedési jellemzőinek tisztázását, valamint a fatest kiválasztott fizikai és mechanikai tulajdonságainak előrejelzését tűztük ki célul. A hang terjedési idejének (TOF) meghatározása élő fákban roncsolásmentes módon "Fakopp" TreeSonic berendezéssel történt. A TOF adatokból kiszámított hangterjedési sebesség (SWV) kiemelkedő

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jelentőséggel bír a fatest dinamikus rugalmassági modulusza (MOE) becslésében és ezáltal a szerkezeti fa minőségének előrejelzésében. A mellmagassági átmérő (DBH) valamint a szijács rostirányában történő hangterjedési sebesség meghatározása érdekében 50 véletlenszerűen kiválasztott egyed helyszíni vizsgálatára került sor. A roncsolásmentes vizsgálatok kiegészítéseként kidöntött törzsek (3 törzs ültetvényenként, szúrópróbaszerű minta) fatestének laboratóriumi analízisét is elvégeztük az évgyűrűszélesség és a sűrűség meghatározására. A one-way ANOVA eredményeink alapján jelentős különbségek mutatkoztak az SWV értékekben egyes ültetvénycsoportok között. A fiatal és idős ültetvények átlagértékei között 136,8 m/s volt az eltérés, ami szignifikáns különbség. Hasonló eredményeket tapasztaltunk a középkorú és az idős ültetvényes fák esetében is. A fiatal és a középkorú fák átlagértékei 0,05-ös szignifikancia szinten azonosnak tekinthetők. Ugyancsak megállapítottuk, hogy a fiatal (22 éves), legsűrűbb hálózatban ültetett (3 m × 4 m) és egyben legkisebb mellmagassági átmérő átlagértékkel rendelkező Újrónafő 11G ültetvény egyedei mutatták a legmagasabb SWV átlagértéket. Kiegészítésként meg kell azonban említeni, hogy ugyanezen ültetvényről származó szijács és geszt minták rendelkeztek a legmagasabb átlagértékekkel a normál klímán vett sűrűség vonatkozásában is, ezáltal a fatest legnagyobb dinamikus rugalmassági modulusza is várhatóan ennél az ültetvénynél jelezhető előre

***Populus* × *euramericana* cv. Pannónia / hangterjedési sebesség / mellmagassági átmérő / sűrűség / dinamikus rugalmassági modulusz / teherviselő szerkezeti fa**

1 INTRODUCTION

Willows and poplars belong to the same *Salicaceae* botanical family. About 40 species of the genus *Populus* exist in the northern hemisphere. Sections such as Aigerios and, partially, Leuce in Hungary (Tóth – Erdős 1988) and Aigeros, Leuce, and Tacamahaca in Austria (Nebenführ 2007) are important in forestry. The European black poplar (*Populus nigra* L.), the American black poplar (*Populus deltoides* Bartr. Ex Marsh.), and their clones (*Populus* × *euramericana*) are systematically assigned to the poplar section Aigerios. The Pannónia poplar (*Populus* × *euramericana* cv. Pannónia) is an artificial variety hybridized by Ferenc Kopeczky, a forest scientist at the Hungarian Forest Research Institute (ERTI) in Sárvár. According to Tóth and Erdős (1988), the parent trees of Pannónia poplar were *Populus deltoides* S-1-54 Belgium and *Populus nigra* Lébény 211. The rapid growth rate of Pannónia poplar is similar to variety 'I 214' (*Populus* × *euramericana* cv. 214) and can reach a density that is similar to *Populus* × *euramericana* cv. Robusta (Molnár – Bariska 2006).

Industrial poplar breeding began in Hungary in the 1920s, mainly on the Danube floodplain. Tóth and Erdős (1988) refer to the data to indicate a marked increase (more than 115,000 ha) in the total area of Poplar populations between 1949 and 1986. Thanks to its outstanding characteristics, the ‘Pannónia’ poplar variety was one of the most important planting stocks in Hungary in the 1990s (Tóth 2006). Papp and Horváth (2016) summarised the relevant scientific data, including the domestic research activities and results. Their study emphasised that although poplar research with other target species was advanced in Hungary, the number of site-specific, material scientific studies on load-bearing structural properties of Pannónia poplar are minimal.

According to Schlosser et al. (2012), many studies on replacing conifers with poplars were conducted in the 1960s and 70s, particularly in institutions such as the Wood Research Institute (Faipari Kutató Intézet) in Budapest. The physical and mechanical properties of other hybrid poplars like ‘Robusta’, ’Marilandica’ and ‘Serotina’ varieties were found to be suitable for construction purposes. The apex of contemporary research was designing and constructing an 800 m^2 hall built of poplar raw materials in Velence, Hungary in 1974, which remained in use until 2012 and retained a surprisingly sturdy wood structure.

As a raw material, Pannónia poplar has a wide range of opportunities for industrial utilisation, including furniture, cellulose, fibreboard, packaging, or matchstick production (Tóth 1996). The Institute of Wood Science, the predecessor of the Institute of Wood Technology and Technical Sciences in Sopron, analysed the Pannonia poplar samples to identify the effects of thermal modifications in dry, atmospheric air (Horváth 2008) and in vegetable oils (Bak 2012) on changes in the physical, mechanical properties and the protective effectiveness against *basidiomycetes*. These researchers also determined static compression and bending strength values (among others) of untreated small-sized samples in a normal climate. Their results were similar to the spruce data (*Picea abies L.*) in the literature, which is the most frequently used timber in roof construction in Hungary. The modulus of elasticity in three-point bending tests of samples cut out from 13-year-old Pannónia poplar trees was the same as the lower value reported for spruce in the scientific literature. The above studies investigated the xylem of juvenile wood, which cannot represent the performance of mature wood. Németh et al. (2015) called attention to the high variation of mechanical properties of different poplar hybrids from various sites and recommended timber grading before application.

Research at the University of Sopron (formerly: University of West Hungary) verified that the xylem of the first 20–22 annual rings in poplars did not show lower density than mature wood, which contradicts other wood species. Van Acker et al. (2016) pointed out that the fast-growing species will make higher production possible within both a sylvicultural and an agricultural framework. The study also suggested that poplar trees could offer the best potential alternative to softwood species for engineered wood products. Due to the lower natural durability of poplar wood species against degrading agents, the lifetime of poplar-based construction products is cardinal nowadays (Van Acker et al. 2020). Investigations into the properties of poplar wood species as a building material are increasing. Some of the investigated properties include durability against fungal decay (Horváth et al. 2012), wettability (Rábai et al. 2020, Brahmia et al. 2020), moisture-induced stresses (Mirzaei et al. 2017), fire-retarding properties (Habibzade et al. 2016), and bondability (Vilpponen et al. 2014, Wang et al. 2015, Konnerth et al. 2016).

2 MATERIALS AND METHODS

2.1 Plantation sites investigated

We performed the on-site investigations to gain information regarding the selected characteristics of the trees. *Figure 1* shows the relevant Pannónia poplar plantations sites of KAEG Zrt, which we chose for our non-destructive measurements in Győr-Moson-Sopron County in the Western Transdanubia region of Hungary. GPS coordinates determined the locations of these three plantation sites, marked with red, green and blue squares on the map.

2.2 Non-destructive measurement and laboratory measurements

During our research protocol, we performed the non-destructive studies on trees first. We used a stress wave non-destructive test technique with a "Fakopp" TreeSonic device to test the standing trees (*Figure 2*). The on-site non-destructive measurements were performed in September 2016. The moisture contents (MC_{xylem}) of the tree xylems were 150–170% and their temperatures (t_{xylem}) ranged from 15 to 20 ° C. The deviation of the SWV values along the grain caused by these two parameters is negligible at these levels (Moreno Chan et al. 2011).

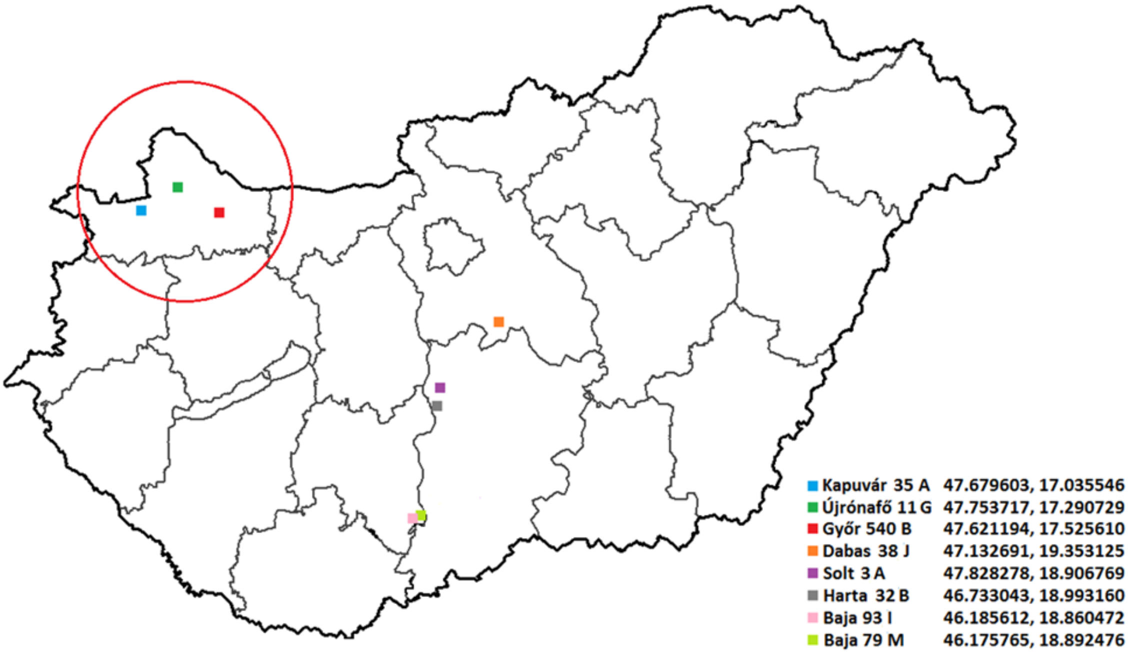

Figure 1. The relevant Pannónia poplar plantations in Győr-Moson-Sopron County (Kapuvár 35 A; Újrónafő 11 G and Győr 540 B)

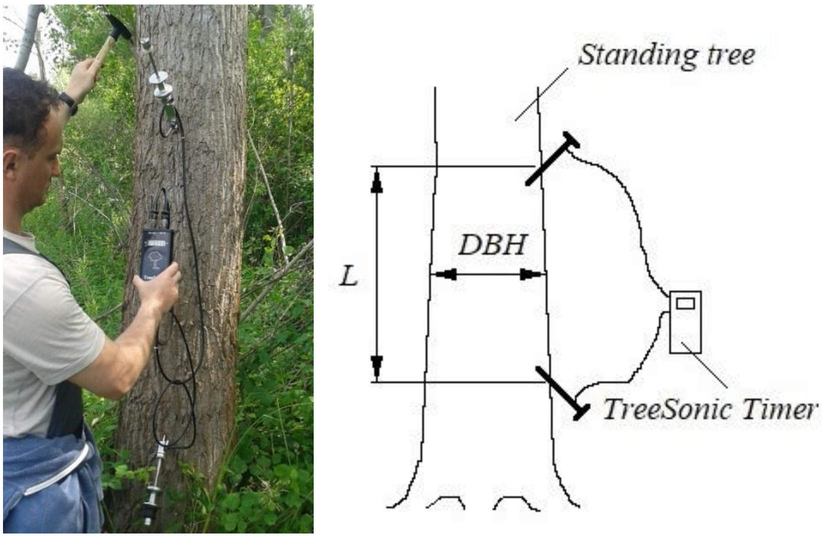

Figure 2. The time-of-flight (TOF) stress wave measurement on trees with a "Fakopp" TreeSonic device (left) and its schematic figure (right).

Fifty trees were investigated ($n_{\text{trees tested/site}}=50$) in each plantation to determine the diameter at breast height (DBH) and the stress wave velocity (SWV) in sapwood parallel to the grain. Afterwards, we performed laboratory analysis of the samples from harvested logs (three logs/plantation, random sample, $n_{logs/plantation}=3$) to determine the selected material properties. The SWS values were calculated according to the following formula:

$$\mathrm{SWV} = \frac{\mathrm{L}}{\mathrm{TOF}} \cdot 10^6 \tag{1}$$

Where:

SWV:	the longitudinal stress wave velocity along the grain in metres per second (m/s)
TOF:	the time-of-flight (wave propagation time as output of "Fakopp" TreeSonic device) in microseconds (µs)
L:	the test span in metres (m).

For the moisture content (MC) laboratory measurements and the respective density, five-five specimens ($n_{\text{sapwood samples/logs}}=5$, $n_{\text{heartwood samples/logs}}=5$, radial × tangential × longitudinal: 20 mm × 20 mm × 30 mm,) were cut out from the sapwood and heartwood as bulk samples from the logs ($n_{\text{sapwood } \textit{bulk samples}}=15$, $n_{\text{heartwood } \textit{bulk samples}}=15$). The specimens were conditioned until reaching their weight constant in a normal climate (65% relative humidity, 20 °C air temperature).

We measured the specimen size and weight with digital calliper and a digital balance, which both had a measuring accuracy down to 0.01mm and 0.01g. The values were calculated according to the following formula:

$$\rho_\mathrm{n} = \frac{m_\mathrm{n}}{l_\mathrm{n} \cdot r_\mathrm{n} \cdot t_\mathrm{n}} \cdot 10^6 \tag{2}$$

Where:

ρ_n:	sample density at normal climate (kg/m^3)
l_n:	sample size parallel to the grain at normal climate (mm)
r_n:	sample size in radial direction at normal climate (mm)
t_n:	sample size in tangential direction at normal climate (mm)
m_n:	sample weight at normal climate (g).

3 RESULTS AND DISCUSSION

In the case of KAEG Ltd., there was a considerable difference between tree ages recorded in the company registers and the plantation age determined upon the experimental felled logs ($n_{\text{logs/plantation}}=3$). Based on the annual rings of the logs, the trees were 22 years old in Újrónafő 11G plantation, 24 years old in Győr 540 B plantation, and 29 years old in Kapuvár 35A plantation.

3.1 Results of the non-destructive measurements

Table 1 presents the average tree diameter at breast height (DBH). The comparative statistical analysis in all cases was unavailable because of the significantly differing plantation ages. However, the DBH values of the Újrónafő 11G plantation – being otherwise the youngest plantation among the sites, with the closest spacing between trees (3 m ×4 m) – were naturally the lowest.

Table 1. Diameter at breast height (DBH) of the trees ($n_{\text{trees tested/site}}=50$)

DBH (cm)	Average	St. dev.	Min	Max
Újrónafő 11G (young)	21.3	3.96	15.3	30.9
Győr 540B (middle-aged)	39.5	4.17	30.9	53.2
Kapuvár 35A (old)	45.8	6.97	31.2	63.4

Table 2 presents the stress wave velocity (SWV) data in the sapwood of the standing trees. The SWV average value is highest in the young plantation (Újrónafő 11G) and lowest in the old plantation (Kapuvár 35A). The one-way ANOVA result revealed significant differences in SWV data between the different plantation groups (F(2;147)=5.859; p=0.004). The post-hoc test at the 0.05 level of significance also showed that the difference between the average values of the young and middle-aged plantation trees was not significant (21.6 m/s). The difference between the average values of the young and old plantations is 136.8 m/s, which is significantly different. A similarity can be found between the middle-aged and old plantation trees, where the difference is only 115.2 m/s.

Table 2. Stress wave velocity (SWV) along the grain in sapwood of the trees ($n_{trees\ tested}$=50, t_{xylem}=15–20 °C, MC_{xylem}=150–170%)

SWV (m/s)	Average	St. dev.	Min	Max
Újrónafő 11G (young)	4276.2	198.26	3807.1	4601.2
Győr 540B (middle-aged)	4254.6	145.96	3937.0	4601.2
Kapuvár 35A (old)	4139.4	279.01	3699.1	4854.4

3.2 Results of the laboratory measurements

The experimental logs were used to define their felling age in 2016 and to define their density. Complex statistical analysis was not recommended for the laboratory measurements because of the small sample size (three logs/plantation). However, the density values of the Újrónafő 11G young plantation were the highest in all cases. *Table 3* presents the sapwood density data at normal climate (ρ_n). Without statistical evaluation, it is evident that the data on the average sapwood density show lower differences.

Table 3. Density of the sapwood ($\rho_{n\ sapwood}$) bulk samples at normal climate ($n_{logs/plantation}$=3, $n_{samples/logs}$=5, $n_{sapwood\ bulk\ samples}$=15)

$\rho_{n\ sapwood}$ (kg/m^3)	Average	St. dev.	Min	Max
Újrónafő 11G (young)	443.7	15.84	414.0	478.3
Győr 540B (middle-aged)	427.1	27.70	337.2	483.7
Kapuvár 35A (old)	438.0	6.80	426.0	447.4

The average density values of the Újrónafő 11G heartwood samples were obviously higher than the values of samples from the other two plantations. The density values of the heartwood samples of the youngest and most densely planted trees – with the lowest DBH among the sites – exceed 500 kg/m^3 in many cases.

Table 4. The density of the heartwood ($\rho_{n\ heartwood}$) bulk samples at normal climate (n_{logs}=3, $n_{heartwood\ samples/logs}$=5, $n_{heartwood\ bulk\ samples}$=15)

$\rho_{n\ heartwood}$ (kg/m^3)	Average	St. dev.	Min	Max
Újrónafő 11G (young)	469.9	32.38	351.5	556.9
Győr 540B (middle-aged)	413.4	21.42	372.7	476.4
Kapuvár 35A (old)	395.1	28.10	363.0	442.8

3.3 The dynamic MOE expected from our results

Dynamic MOE is an important measurement for estimating stiffness in standing trees, logs, timber and small specimens. In practice, fieldwork is confined to measuring acoustic velocity, and dynamic MOE is estimated by assuming a certain value for green density (Moreno Chan et al. 2011). The relationship between the dynamic MOE, density and the SWV values of a material can be given by $E = \rho v^2$ (Divós – Bejó 2006, Moreno Chan et al. 2011).

According to the SWV values on trees and the density values of the specimens at normal climate, the average dynamic MOE of Újrónafő 11G (young) plantation is expected to be significantly higher than the values of the other two plantations (see *Table 5*).

Table 5. The dynamic MOE expected according to the average SWV- and the density values of sapwood

Expected average values	Újrónafő 11G (young)	Győr 540B (middle-aged)	Kapuvár 35A (old)
Dynamic MOE $_{\text{sapwood}}$ (N/mm^2)	>8100	>7700	>7500

4 CONCLUSIONS

The DBH test results of trees were not evaluated statistically due to the significantly different ages of the plantations. However, the average DBH values in Újrónafő 11G – the youngest plantation, planted with the closest spacing (3 m × 4 m) on different soil conditions – were significantly lower than the values of the other two plantations. The average DBH values of the 22-year-old trees in Újrónafő 11G plantation were 21.3 cm, while the DBH values of the 24-year-old logs in Győr 540B plantation (being the closest in age) were 39.5 cm (*Table 1*).

According to our one-way ANOVA results, there was no significant difference between the average SWV values of the young (Újrónafő 11G) and the middle-aged (Győr 540B) plantation groups in case of 15–20 °C material temperature, 150–170% moisture content and 0.05 level of significance. Nevertheless, the difference between the average values of the young and old plantations was significantly different. The findings are similar for middle-aged and old plantation trees. While the 22-year-old Újrónafő 11G trees exhibited the highest SWV values of 4276.2 m/s, the 29-year-old Kapuvár 35A logs had the lowest average SWV values of 4139.4 m/s (*Table 2*).

The density results of the samples originating from the test logs indicated that Pannónia poplar sapwood might differ significantly from its heartwood, which could influence its usage as structural timber. Based on the laboratory test results, the highest dynamic MOE can be expected in Újrónafő 11G plantation, which has the highest sapwood and the highest heartwood density values (*Table 3* and *Table 4*). The higher dynamic MOE means better raw material for structural uses (*Table 5*); therefore, we can forecast that Újrónafő 11G may be the most suitable among the tested sites for producing poplar lamellas for load-bearing, glued laminated timber.

Acknowledgements: The authors are grateful to the National Research, Development and Innovation Office Hungary (NKFIH) for the financial support in frame of the project OTKA K116216 “Complex analysis of the physico-mechanical and surface-physical properties of wood with low density”.

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