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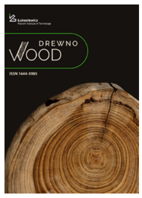

Elastic and Shear Moduli of Poplar Heartwood

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The elastic and shear moduli of Populus canadensis heartwood were measured, and the influence of annual ring width (ARW) on these moduli was determined. Differences between the heartwood and sapwood moduli were identified by comparing the results with reported data. The moduli were dynamically determined by ultrasonic testing and evaluation. Pressure (2.25 MHz) and shear (1 MHz) waves were propagated to obtain the transmission time, which was used to calculate the ultrasonic wave velocities and then the moduli. The average ARW and density were 2.48 cm and 381 kg/m³, respectively. The average elastic moduli in the longitudinal (EL), radial (ER), and tangential (ET) directions, and shear moduli in the LR (GLR), LT (GLT), and RT (GRT) planes were 4728 MPa, 1119 MPa, 407 MPa, 1102 MPa, 579 MPa, and 117 MPa, respectively. Neither good nor moderate relationships between ARW and the moduli were observed in linear regression analysis. According to literature reports, the modulus of elasticity decreases with increasing ARW. However, based on the comparison of reported values for sapwood with the results for heartwood obtained in this study, ER, GLR, and GRT increased with the increase in ARW. It should be noted that no relationship with ARW was found in the case of EL, ET, and GLT.

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Introduction

Reversible deformation under the application of stress, followed by return to the original shape and size when the stress is removed, is a property of elastic behavior. Elastic behavior is a fundamental property for the structural application of natural or engineering materials. Young's modulus, shear modulus, and Poisson's ratios are characteristic elements of elasticity that express how a material responds to different types of stress. The higher the elasticity, the higher the permanent deformation resistance, which is important particularly for structural applications such as load-bearing constructions, as Kamperidou and Vasileiou (2012) described for joints of upholstered furniture frames.

The structure of a material defines its physical properties and mechanical behavior. For example, a crystalline structure presents a regular atomic arrangement and repeating patterns, while an amorphous structure presents an irregular arrangement. The macrostructure (growth rings, early and latewood, and grain orientation), microstructure (cell properties), and chemical structure (cellulose, hemicelluloses, and lignin) of wood make it a natural composite with a polar orthotropic structure. Due to the structure, elastic behavior differs by direction or plane. In general, there are considerable differences between moduli of elasticity in the longitudinal (E_L), radial (E_R), and tangential (E_T) directions, between shear moduli in the LR, LT, and RT planes, and between Poisson's ratios. The orderings

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of the moduli are generally reported as E_L>E_R>E_T and G_{LR}>G_{LT}>G_{RT} (Afoutou et al., 2024; Aydin & Ciritcioğlu, 2021, 2022; Aydın & Yılmaz Aydın, 2020; Güntekin, 2023; Katz et al., 2008; Longo et al., 2018).

The twelve elastic constants of *Populus deltoides* wood were determined by Zahedi et al. (2022) to follow the above-mentioned order. Aydın and Aydın (2023) performed the only study to evaluate the influence of growth ring number and width on the elastic and shear moduli of *Populus x canadensis* wood in the radial direction. The authors determined these features using sapwood samples. However, one of the prominent characteristics of poplar wood is the significant difference in ring widths between the sapwood and the heartwood. Furthermore, even when heartwood, sapwood, mature wood, and juvenile wood all come from the same tree, their mechanical, chemical, and physical characteristics are typically distinct (Bal, 2013) due to the cell structural properties such as wall thickness. In the literature, the mechanical properties of heartwood are reported to be inferior to those of sapwood in the case of *E. grandis* (Bal & Bektaş, 2013), a clone of *Populus deltoides* (Jia et al., 2021), Douglas fir (Duriot et al., 2021), and *Populus usbekistanica* "Afganica" (Bektaş et al., 2020). On the other hand, Xia et al. (2018) reported better physical-mechanical properties for heartwood than for sapwood in the case of *Toona ciliata* M. Roem. Moreover, according to Harte (2009) there is no difference in the mechanical performance of sapwood and heartwood. Therefore, there is no consensus on this issue. Furthermore, when considering the differences between SW and HW, there is no general agreement as to their statistical significance. For example, Merela and Katarina (2013) reported insignificant differences for oak, and Kozakiewicz et al. (2019) found no significant differences for the physical properties of heat-treated black poplar, while Jia et al. (2021) reported significant differences for clones of *Populus deltoides* and *Populus euromaricana* cv. Guariento. Besides these conflicting findings, there are no data presented on the moduli of heartwood in the case of *Populus x canadensis*. It may be that in industrial practice, timber or laths are not separated as sapwood and heartwood due to production methods and certain other factors, such as profitability. However, from a scientific standpoint, the two parts present different physical, mechanical, aesthetic and other properties. Therefore, this study was carried out to determine the moduli of heartwood and to compare reported sapwood values to evaluate the differences.

Materials and methods

The study used Canadian poplar (*Populus x canadensis* M.) wood from a plantation tree in Atabey, Isparta, Türkiye. The heartwood section of the radially cut laths was used to cut fifteen samples containing two proper annual rings. Due to variations in the ARW, the sizes of the samples in the radial direction differed from each other (Fig. 1). The longitudinal and tangential sizes of the samples were approximately 20 mm. Samples were acclimatized (20±1 °C and 65% relative humidity) using a drying chamber (Memmert Gmbh+Co. KG, Schwabach, Germany) until their weight stabilized. They were then placed in a desiccator, and density measurements were performed according to TS ISO 13061-2 (2021).

Two elastic constants, modulus of elasticity and shear modulus, were determined non-destructively by ultrasound propagation. Two different wave types (pressure or longitudinal and transverse or shear) were propagated to measure the propagation duration (μs) of the waves in the appropriate axes and planes for elastic and shear modulus determination, respectively. The central frequencies of the pressure and shear waves were 2.25 MHz and 1 MHz, respectively. Contact type transducers, A133S-RM for pressure and V153-RM for shear (Panametrics-NDT, USA), were used with Epoch 650 (Olympus NDT, USA). Wave propagation took place in direct mode. In this procedure, two transducers (a transmitter and a receiver) are placed opposite each other on the specimen surfaces. Official gels were used to optimize decibel (dB) parameters and provide clear peaks.

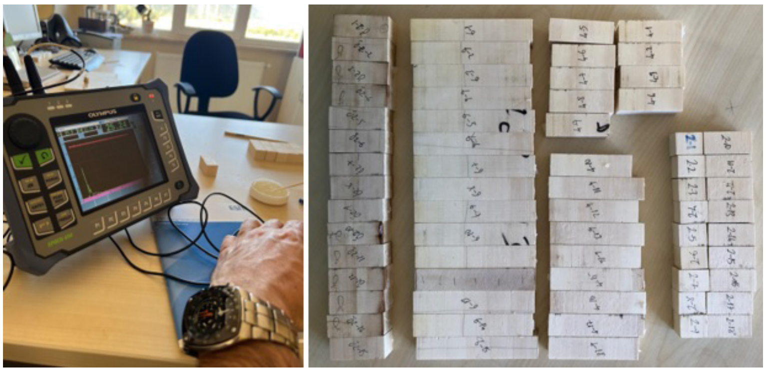

Fig. 1. Ultrasonic measurements (left) and samples (right)

Ultrasonic wave velocities (UWVs) were calculated from the propagation times and path. The elastic and shear moduli were determined by equations (1) and (2), respectively.

$$E_i = \rho V_i^2 10^{-6} \quad (1)$$

where E_i is the elastic modulus (MPa) in direction *i* (L, R, and T), ρ is the density (kg/m^3), and V_i is the pressure wave velocity (m/s) in direction *i* (L, R, and T).

$$G_{ij} = \rho\big((V_{ij} + V_{ji})/2\big)^2 10^{-6} \quad (2)$$

where G_{ij} is the shear modulus (MPa) in the *ij* plane, ρ is the density (kg/m^3), and V_{ij} is the shear wave velocity (m/s) in direction *i* with polarization *j* (LR, LT, RT, RL, TR, and TL).

A fundamental feature of the structure of poplar wood is the varying ARW. Therefore, the relationships between ARW and the elastic and shear moduli were evaluated by linear regression to determine how well the models estimate the relationship between the variables.

Results and discussion

The ARW and density of the samples ranged from 2.42 to 2.52 mm and from 356 to 401 kg/m³, respectively. Descriptives for the ARW and density are presented in Table 1. Reported average values of ARW for the sapwood of *Populus x canadensis* include 5.37 mm (Ziemiańska & Kalbarczyk, 2018) and 17.7 mm (Aydın & Aydın, 2023). Ziemiańska et al. (2020) reported an ARW of 6.63 mm for *Populus x canadensis*. Considering the notable difference between SW and HW, a 24.8 mm ring width is not unusual. Furthermore, much higher values of ARW have been reported, including 27.8 mm (LeBlanc et al., 2020), 28.6 and 28.8 mm (Šēnhofa et al., 2016), and 45 to 55 mm (DeBell et al., 2002). Such differences depend on many factors that directly affect the tree properties, such as climate, soil conditions, elevation, etc. Moreover, there is a strong relationship between ring width and climatic factors (Šēnhofa et al., 2016); it is found that precipitation and temperature influence the width (Bozkurt & Erdin, 1989). However, it should be taken into consideration that the place of sampling on the tree significantly affects the values, and hence the means, as Zhang et al. (2022) reported for poplar hybrids. This inference is also valid for density determination. For example, Aydın and Aydın (2023) reported a density range of 335 to 373 kg/m³ for *Populus x canadensis*, with a mean of 348 kg/m³. In another study, the same authors reported an average density of 339 kg/m³ (Aydın & Yılmaz Aydın, 2024). As seen in Table 1, the HW mean density is 9.57% higher than the SW mean (Aydın & Aydın, 2023). A wider density range (310 to 450 kg/m³) was reported by Flórez et al. (2014). Density means reported in the literature include 365 kg/m³ (YingJie et al., 2017a), 405.6 kg/m³ (Hodoušek et al., 2017), 464 kg/m³ (Villasante et al., 2021), and 529 kg/m³ (Niklas & Spatz, 2010). Considering the growth conditions, such a wide range for the same species is normal, and the average density determined in this study is in line with the reported values.

The regression model (Fig. 2) revealed that there is no relationship between density and ARW. A similar regression plot for density vs. RW (R^2 from 0.01 to 0.11) was presented by Mankowski et al. (2020) for Scots pine. However, a higher R^2 value (0.31) for density vs. ARW was reported for SW (Aydın & Aydın, 2023). Koga and Zhang (2002) reported that wood density demonstrated no significant correlation with annual growth rate (ring width) in either juvenile or mature wood. Nevertheless, a weakly negative correlation was observed in mature wood. However, it has been hypothesized that wood density is contingent not solely on ARW and latewood proportion, but also on the "quality" of latewood (Vavrčík & Gryc, 2012). Furthermore, it has been reported that the relationship between density and climate is stronger and more constant than the relationship between RW and climate (Allen et al., 2012), and the relationship with temperature data was found to be stronger for wood density and RW than for the wood's anatomical features (Pritzkow et al., 2014). Romagnoli et al. (2014) noted that RW affects the density, although it is sometimes related more strongly to mechanical properties. On the other hand, Zobel and Van Bujten (1989) and Dobrowolska et al. (2011) reported a positive relationship between RW and density. Lars et al. (2005) found that the density of larch heartwood

Table 1. Descriptives for Physical properties

	ARW (cm)	Density (kg/m³)
Average	2.48	381.31
Std. Dev.	0.03	11.59
CoV (%)	1.14	3.04

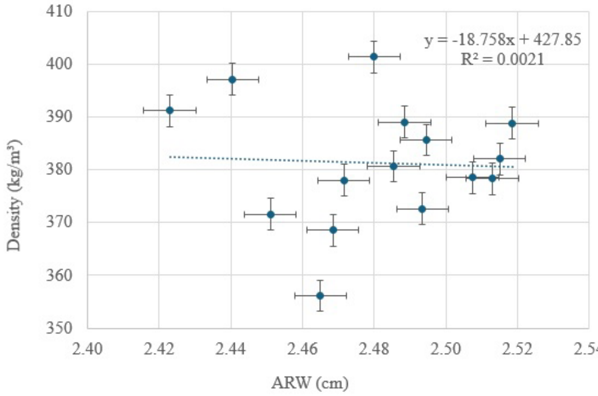

Fig. 2. Regression model for density vs ARW

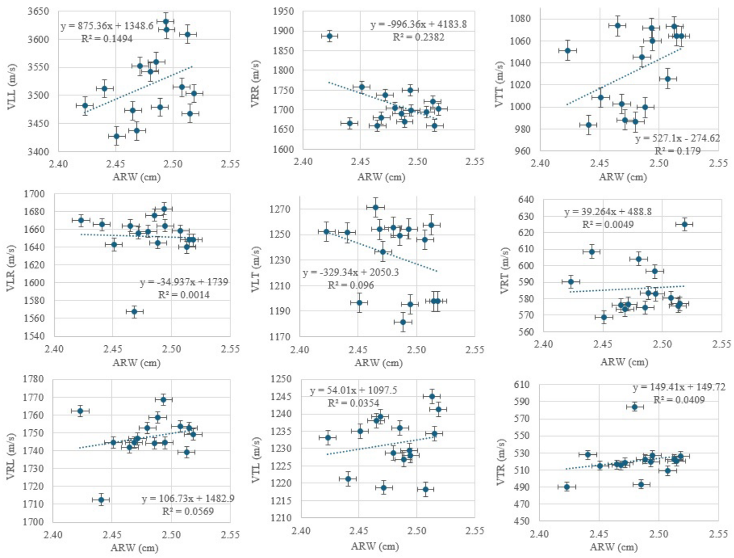

Fig. 3. Regression model for UWV vs ARW

increased with annual ring width up to 2.5 mm and decreased when the ARW was wider than 3 mm.

Averages and descriptives for the velocities are presented in Table 2. In the literature, only Aydın and Yılmaz Aydın (2024) have reported all longitudinal and transverse UWVs for SW, and no data are available for HW. Generally, the UWVs for SW and HW are comparable (with differences of –4.8% to 1.8%). However, the values of V_{RR}, V_{TT} and V_{TR} are 20.3%, 14.6% and 7.6% lower than those given in the literature, while V_{LR} and V_{RL} are 9.1% and 13.3% higher, respectively. Yılmaz Aydın and Özkan (2024) reported V_{LL} as 3620 m/s for SW. Aydın and Aydın (2023) reported V_{RR} as 1607 to 1850 m/s, V_{LR} as 1463 to 1501 m/s, V_{RL} as 1491 to 1588 m/s, V_{RT} as 532 to 565 m/s, and V_{TR} as 504 to 522 m/s for SW. These values are consistent with the data presented in Table 2. When considering the structural differences between the SW and HW, this variation can be assumed to be normal for wood material. Further differences in reported UWV values may be mentioned; for example, Zahedi et al. (2022) determined UWVs of *Populus deltoides*, finding differences of –28.5% (V_{RL}) to 33.6% (V_{TT}).

As Figure 3 shows, there is no relationship between the UWVs and ARW; the R^2 values are extremely low. Similarly low values were also reported by Aydın and Aydın (2023) for SW. However, those authors have also reported much higher R^2 values: 0.57 (V_{LR} vs. ARW) and 0.64 (V_{RL} vs. ARW).

Averages and descriptives for the moduli are presented in Table 3. Yılmaz Aydın and Özkan (2024) reported 4549 to 4735 MPa for E_L (dynamically determined by US) and 5461 to 5910 MPa for MOE in bending. In this study, the range was 4294 to 5046 MPa, and the average E_L is in line with the results of Aydın & Yılmaz Aydın (2024), who determined the E_L of *Populus canadensis* dynamically by ultrasound as 4361 MPa. However, considerably higher values (10113 MPa for MOE bending and 10366 MPa for MOE MTG) have been reported for *Populus canadensis* (Hodoušek

Table 2. Descriptives of UWV

	Longitudinal UWV (m/s)			Shear UWV (m/s)					
	V_{LL}	V_{RR}	V_{TT}	V_{LR}	V_{RL}	V_{LT}	V_{TL}	V_{RT}	V_{TR}
Average	3520.4	1711.9	1033.1	1652.3	1747.7	1233.2	1231.6	586.2	520.4
Std. Dev.	63.81	57.51	35.10	26.52	12.60	29.94	8.09	15.80	20.81
CoV (%)	1.81	3.36	3.40	1.60	0.72	2.43	0.66	2.70	4.00
Aydın and Yılmaz Aydın (Aydın & Yılmaz Aydın, 2024)	3585	2060	1184	1502	1515	1210	1172	563	560

Table 3. Descriptives of elasticity and shear moduli

	Elasticity Modulus (MPa)			Shear Modulus (MPa)		
	E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}
Average	4727.89	1118.88	407.15	1102.13	579.07	116.94
Std. Dev.	238.05	89.53	25.73	41.53	19.39	9.46
CoV (%)	5.04	8.00	6.32	3.77	3.35	8.09

et al., 2017). Also, YingJie et al. (2017b) determined a higher value of MOE in bending (9303 MPa) for *Populus canadensis*. Such variation may be attributed to the test procedures and the uniqueness of the wood specimens. The E_R range and mean for SW of *Populus canadensis*, measured by US, were reported as 705 to 1696 MPa (Aydın & Aydın, 2023) and 1438 MPa (Aydın & Yılmaz Aydın, 2024), respectively. In this study, E_R ranged from 981 to 1393 MPa, and the average given in Table 3 is in agreement with the literature. Values of E_T varied from 369 to 440 MPa, and the average is comparable to the 476 MPa reported for SW (Aydın & Yılmaz Aydın, 2024).

The shear moduli G_{LR}, G_{LT}, and G_{RT} ranged from 1011 to 1167 MPa, 549 to 619 MPa, and 106 to 142 MPa, respectively. Aydın and Aydın (2023) reported ranges of 694 to 912 MPa for G_{LR} and 83 to 125 MPa for G_{RT} for SW of *Populus canadensis*, determined by US. Further reported shear moduli for SW of *Populus canadensis* are 771 MPa, 480 MPa, and 107 MPa, respectively (Aydın & Yılmaz Aydın, 2024), different from those obtained in this study by–30.1%, –17.1%, and –8.5%. It was therefore observed that there are reasonable differences between the moduli of SW and HW. Besides *Populus canadensis*, ranges of 872 to 5000 MPa for E_R, 600 to 2320 MPa for G_{LR}, and 100 to 470 MPa for G_{RT} have been reported for different poplar species (Longo et al., 2018; Sliker & Yu, 1993; Zahedi et al., 2022; Zhou et al., 2021).

Values of R^2 between elastic constant and ring width are presented in Figure 4. The coefficients are extremely low and, except in the case of G_{LR}, are comparable to the R^2 values for *Populus canadensis* reported by Aydın & Aydın (2023): 0.01 (E_R vs. ARW), 0.55 to 0.58 (G_{LR} vs. ARW), and 0.11 to 0.25 (G_{RT} vs. ARW). There is no reported coefficient for the moduli vs. ARW for *Populus canadensis* to compare; however, 0.88 R^2 for MOE vs. ARW for Japanese larch (Wang et al., 2022), 0.21 R^2 for E_R vs. ARW for Norway spruce (Dinulică et al., 2021), and 0.14 to 0.43 and 0.16 to 0.88 R^2 for MOE vs. ARW for Scots pine (Mankowski et al., 2020) have been reported. Therefore, the existence of inconsistent values (a wide range of coefficients) makes it difficult to make a meaningful comparison.

Wang et al. (2022) found that RW was negatively correlated with MOE and that RW is more suitable for evaluating MOE than latewood percentage. Moore et al. (2012) determined that MOE decreased with an increase in mean RW for Sitka spruce. Demirkır et al. (2013) found higher MOE in bending for narrow annual rings (5 mm) than for wide annual rings (10 mm) in stone pine. In a study that compared the influence of RW on the moduli for both SW and HW (Aydın & Aydın, 2023), it was observed that the inverse relationship between the RW and moduli was replaced by a positive relationship. However, this relationship is limited to E_R, G_{LR}, and G_{RT}. Moreover, Dinulică et al. (2021) reported that for Norway spruce, E_R increases with an increase in mean RW for SW, while Tumenjargal et al. (2019) reported that in larch, the MOE of HW was significantly lower than that of SW. However, it should be noted that there are other factors that influence the moduli, such as sampling location. For

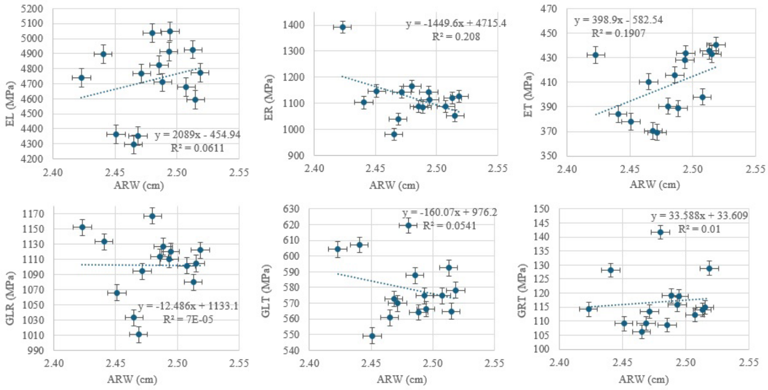

Fig. 4. Regression model for moduli vs ARW

example, MOE increases with an increase in distance from the pith in sentang wood (Ahmad et al., 2023) and in larch (Wang et al., 2022).

Ultrasound propagation in solids such as wood requires attention due to their polar orthotropic nature and natural inhomogeneities in the structure. The propagation properties of P and S waves in a nonhomogeneous porous solid may create some reading difficulties due to phenomena such as dispersion (Saadat-Nia et al., 2011), attenuation, scattering (Bucur, 2006), density, and length interaction (Yılmaz Aydın & Aydın, 2018). In wider growth rings, the share of thick-walled fibers is higher, which positively affects wood density (Arnič et al., 2022). Therefore, when considering structural dissimilarity, even if the samples were prepared from the same log, due to sampling conditions such as location, direction, etc., such variation in the mechanical properties as determined by ultrasound propagation is reasonable.

Conclusions

Elastic and shear moduli in three essential axes and planes for the HW of *Populus canadensis* have been dynamically determined, and the influence of ring width on these values has been evaluated. The values of the moduli were in line with those previously reported. Comparing HW and SW, some moduli values tend to slightly increase with an increase in RW, which is in contradiction to the literature. However, due to the lack of reported data for comparison, it could not be determined whether or not the same tendency applies to E_L, E_T, and G_{LT}. A correlation between ring width and density or modulus values could not be established.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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