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MOISTURE-INDUCED ELASTIC CONSTANTS OF POPLAR

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ABSTRACT

Twelve elastic constants of *Populus × canadensis*, previously unavailable in the literature, were determined using ultrasonic testing.Samples were conditioned at a temperature of 20 °C ± 1 °C and 45 %, 65 %, and 85 % relative humidity. An Olympus EPOCH 650 flaw detector was used with V153-RM (1 MHz shear wave), and A133S-RM (2,25 MHz pressure wave) contact transducers. A contact medium was applied. Wave propagation times were measured along the principal directions (L, R, T), the main planes (LR, LT, RT, RL, TL, TR), and the off-axis planes (LR45°, LT45°, RT45°). Ultrasonic wave velocities were calculated across the specified directions and planes. These velocities were then used to estimate moduli (E_L, E_R, E_T, G_{LR}, G_{LT}, G_{RT}) and Poisson's ratios (µLR, µLT, µRT, µRL, µTL, µTR) via stiffness matrix analysis. Moduli were also calculated using a simple formula multiplying the density and velocity for comparison. Elastic moduli derived from the stiffness matrix were substantially lower than those from the simple density–velocity formula, while shear moduli remained nearly identical. Both moduli steadily decreased with the increase in moisture content. Moisture content significantly affected all moduli. In contrast, Poisson's ratios showed no consistent trend with moisture. Specifically, µLR and µRL increased linearly with moisture, while the other ratios decreased irregularly. For µRT, the effect of moisture was insignificant. Relationships between density and velocity, moduli, and Poisson's ratios were assessed using coefficients of determination.The coefficients ranged from 0,23 to 0,56 for velocities, 0,08 to 0,37 for elasticity, 0,23 to 0,31 for shear, and 0 to 0,10 for ratios. When the coefficient was calculated within the humidity groups significant increases were observed. It was assumed that water-related increases in density did not reflect structural solidification, and therefore did not lead to improved elasric properties. This effect is explained by the well-known reduction in wave velocities caused by water, which dominates the calculations.

Keywords: Elasticity modulus, shear modulus, Poisson's ratio, *Populus x canadensis*, ultrasonic testing, nondestructive evaluation, wood anisotropy.

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INTRODUCTION

The elastic behavior of materials is defined by three constants which are elasticity modulus, shear modulus, and Poisson's ratios. The structure of material forms these constants. For example, isotropic materials have one value for each constant while anisotropic or orthotropic materials have three values for each constant. Therefore, due to its polar orthotropic structure, wood has twelve elastic constants; three elasticity moduli, three shear moduli, and six Poisson's ratios. Because of the complex and year-by-year varied formation of structure, wood assumed as one of the most complicated materials. This complexity requires attention while characterizing the mechanical properties of wood.

Because when it is used in construction and building, not only the strength properties must be known but also elastic behavior should be defined to ensure safe conditions in service life. However, another issue that must be known for the wood material is the biological nature which means both physical and mechanical properties are in contact with the external factors. One of the most important external factors that influence the wood's properties is moisture because wood absorbs and desorbs moisture from the surrounding environment. Thus, dimensional stability and mechanical behavior vary which may create safety concerns. Such an important influence of moisture on wood properties has drawn attention from the past to now, and many studies stand in the literature.

When the literature reviewed; the following are the studies dealt with moisture-dependent elastic properties of wood species. Effect of moisture content (MC) on twelve elastic constants of fir by ultrasound (US) (Yılmaz Aydın and Küçükkose 2020) and compression test (CT) (Yılmaz Aydın and Ozveren 2019), naturally aged black pine (Aydın and Yılmaz Aydın 2020), beech (Fu *et al*. 2021, Hering *et al*. 2012), walnut and cherry (Bachtiar *et al*. 2017) and Chinese fir (Jiang *et al.* 2017) are some of the recent studies. Besides, the influence of MC on some elastic constants and strength properties of wood is commonly evaluated. Indeed, moisture affected dynamic modulus of elasticity (MOE_{dyn}) by US (Ettelaei *et al.* 2019) by stress wave (Gray *et al.* 2008), MOE_{static} and yield stress (Huang *et al*. 2020), Young's modulus and stress-strain relationship (Pierre *et al.* 2013) of different poplar species are reported.

Neglecting the moisture effect, in general, the E_L of different poplar species, cottonwood oriental (*Populus deltoides* Bartram ex Marshall) clones (Murthy *et al.* 2017), poplar (Aydın *et al.* 2007), white poplar (*Populus alba* L.) and black poplar (*Populus nigra* L) (Monteiro *et al.* 2019), and hybrid black poplar (*Populus euramericana* (Dode) Guinier) cv. I-69/58 (Guo *et al.* 2011), and E_L, G_{LR}, and G_{LT} of cottonwood oriental (*Populus deltoides* Bartram ex Marshall) (Roohnia *et al.* 2010) were reported. Full elastic constants of poplar were determined for cottonwood oriental (*Populus deltoides* Bartram ex Marshall) using US (Zahedi *et al.* 2022). However, full moisture-induced elastic constants for canadian poplar (*Populus x canadensis* Moench) were not presented before. Indeed, Hodousek *et al.* (2017), Casado *et al*. (2010), and Zhang *et al.* (2017) provided MOE of canadian poplar (*Populus x canadensis* Moench). Elastic engineering constants are critical for designing durable and safe contructions. Therefore, these parameters are required for achieving reliable construction in design phase using numeric modeling such as finite element modelling. Moreover, wood interacts with the surrounding conditions (particularly temperature and moisture) which can cause critical degradations. Therefore, this study aimed to provide full elastic constants and the influence of MC.

MATERIALS AND METHODS

Cultivated canadian poplar (*Populus x canadensis* Moench) species which is grown in Atabey, Isparta, Türkiye was used. Air-dried laths from the breast height of the logs were used to cut samples. Defect-free samples were climatized at 20 °C ± 1 °C temperature and 45 %, 65 %, and 85 % relative humidity (RH) using the HCP108 chamber (Memmert Gmbh+Co. KG, Schwabach, Germany). Density measurements were performed in accordance with the TS ISO 13061-2 (2021) standard using Equation 1 by determining the ratio of mass to volume. Therefore, mass and dimension of the samples were measured using precision balance (Radwag, Radom, Poland) and digital caliper (Mutitoyo, Kawasaki, Japan), respectively.

$$\rho = \frac{m}{V} \quad (1)$$

Where; ρ is density (kg/m³), m is mass (kg), and V is volume (m³).

Elastic constants were nondestructively determined by ultrasonic testing and evaluation (UT&E) via V153-RM and A133S-RM transducers connected to Epoch 650 (Olympus NDT, USA) flaw detector. Official gels were used to minimize noise and ensure proper contact. Propagation times were measured through L, R, and T directions with no polarization for longitudinal, and with X direction and Y polarization (LR, LT, RT, RL, TL, and TR) for transverse waves including 45° off-axis.

The basic difference between the longitudinal (compression) and transverse waves is particle movement. Particles move parallel and perpendicular to the wave direction in longitudinal and transverse waves, respectively. Therefore, the wavelenght and displacement (peaks) are certain in transverse wave while longitudinal wave has rarefactions or expansion (particles are spread out) and compression (particles are getting close) sections. However, both longitudinal and transverse waves are required to determine the elastic constants. As can be seen in Table 1, diagonal and off-diagonal terms of the stiffness matrix (*C*) (Equation 2) were determined using the density and calculated ultrasonic wave velocities (UWV). The compliance matrix (*S*) (Equation 3) which provides the elastic constants was obtained by inversing the (*C*).

Table 1: Equations for determining the matrix elements.

Propagation-Polarization	Type of wave		Equation for the diagonal and off-diagonal terms
Axis (L, R, and T)	V_{LL}	Longitudinal	$C_{11} = C_{LL} = \rho V_{LL}^2$
	V_{RR}		$C_{22} = C_{RR} = \rho V_{RR}^2$
	V_{TT}		$C_{33} = C_{TT} = \rho V_{TT}^2$
	$V_{TR/RT}$	Shear (Transverse)	$C_{44} = C_{RT} = \left(\frac{\rho V_{RT}^2 + \rho V_{TR}^2}{2}\right)$
	$V_{LT/TL}$		$C_{55} = C_{LT} = \left(\frac{\rho V_{LT}^2 + \rho V_{TL}^2}{2}\right)$
	$V_{LR/RL}$		$C_{66} = C_{RL} = \left(\frac{\rho V_{RL}^2 + \rho V_{LR}^2}{2}\right)$
Off-axis (RT45°)	$V_{RT/RT}$	Quasi-shear (Transverse)	$(C_{23} + C_{44})n_2 n_3 = \pm\sqrt{\left[\left(C_{22}n_2^2 + C_{44}n_3^2 - \rho V_{\propto}^2\right)\left(C_{44}n_2^2 + C_{33}n_3^2 - \rho V_{\propto}^2\right)\right]}$
Off-axis (LT45°)	$V_{LT/LT}$		$(C_{13} + C_{55})n_1 n_3 = \pm\sqrt{\left[\left(C_{11}n_1^2 + C_{55}n_3^2 - \rho V_{\propto}^2\right)\left(C_{55}n_1^2 + C_{33}n_3^2 - \rho V_{\propto}^2\right)\right]}$
Off-axis (LR45°)	$V_{LR/LR}$		$(C_{12} + C_{66})n_1 n_2 = \pm\sqrt{\left[\left(C_{11}n_1^2 + C_{66}n_2^2 - \rho V_{\propto}^2\right)\left(C_{66}n_1^2 + C_{22}n_2^2 - \rho V_{\propto}^2\right)\right]}$

Where; ρ (kg/m³) is density, V_{ii} is the longitudinal UWV (m/s), V_{ij} is the transverse UWV (m/s), and Vα is the quasi-transverse UWV(m/s) (Vázquez *et al*. 2015), n_1 = cosα; n_2 = sinα, and n_3 = 0 for C_{23}, n_1 = cosα; n_3 = sinα, and n_2 = 0 for C_{13}, and n^2 = cosα; n_3 = sinα, and n_1 = 0 for C_{12} (Gonçalves *et al.* 2014, Ozyhar *et al.* 2013).

$$(C)=\begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \quad (2)$$

$$(S)=\begin{bmatrix} \frac{1}{E_L} & -\frac{\upsilon_{21}}{E_R} & -\frac{\upsilon_{31}}{E_T} & 0 & 0 & 0 \\ -\frac{\upsilon_{12}}{E_L} & \frac{1}{E_R} & -\frac{\upsilon_{32}}{E_T} & 0 & 0 & 0 \\ -\frac{\upsilon_{13}}{E_L} & -\frac{\upsilon_{23}}{E_R} & \frac{1}{E_T} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{RT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{LT}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{LR}} \end{bmatrix} \quad (3)$$

Where; C_{ii} are the diagonal and C_{ij} and C_{ji} are the off-diagonal terms.

Where; E_i is Young's modulus, G_{ij} is shear modulus, and ν_{ij} and ν_{ji} are Poisson's ratios.

To figure out the influence of calculation way, elasticity, and shear moduli were also determined using the Equation 4 and Equation 5, respectively and compared to matrix results.

$$E_i = \rho V_{ii}^{2} 10^{-6} \quad (4)$$

Where E_i, is the elasticity modulus (MPa) in the I direction, ρ is sample density (kg/m^3), and V_{ii} is longitudinal UWV (m/s).

$$G_{iJ} = \rho \left(\frac{V_{ij} + V_{ji}}{2} \right)^2 10^{-6} \quad (5)$$

Where G_{iJ} is the shear modulus (MPa) in IJ planes, ρ is sample density (kg/m^3), and $V_{Ij} \neq V_{Ji}$ is transverse UWV (m/s) in I or J direction with J or I polarization.

The one-way analysis of variance (P<0,05) and Duncan's multiple range tests were performed to reveal the influence of MC on elastic constants. The interaction between density and UWVs or constants was determined through linear regression analysis.

RESULTS AND DISCUSSION

The density averages are presented in Table 2, and they are in the reported density averages of the non-treated canadian poplar (*Populus x canadensis* Moench) solid wood that ranges from 334 kg/m³ to 468 kg/m³ (Casado *et al.* 2010, Hodousek *et al*. 2017, Papandrea *et al*. 2022, Villasante *et al*. 2022, Zhang *et al*. 2017). Differences between the means are statistically significant and coefficients of variation (CoV) are notably low. Density around 1,7 % and 4,6 % increased with the increase in MC.

Table 2: Statistics for density.

Property	Groups	Mean*	Std. Deviation	Std. Error	95 % CI** for Mean (Bounds)	
					Lower	Upper
Density (kg/m³) s. (F 16,727, P 0)	45 % RH	346a	4,704	1,488	342,83	349,56
	65 % RH	352b	7,693	2,433	346,42	357,43
	85 % RH	362c	5,308	1,679	357,86	365,45

s. Significant, * Duncan's homogeneity groups, and ** Confidence Interval

The UWV averages are presented in Table 3. Both longitudinal and transverse UWVs were decreased with the increase in MC. However, V_{RT} was the most influenced UWV. This adverse effect of MC was found to be statistically significant. However, for $V_{LT45°}$ and $V_{RT45°}$ there was no difference between 45 % and 65 % RH. As expressed in the introduction, the lack of data for the comparison is the fact for canadian poplar (*Populus x canadensis* Moench). However, 1782 m/s to 1850 m/s (V_{RR}), 1463 m/s to 1501 m/s (V_{LR}), 1491 m/s to 1588 m/s (V_{RL}), 532 m/s to 565 m/s (V_{RT}), and 504 m/s to 522 m/s (V_{TR}) UWVs for canadian poplar (*Populus x canadensis* Moench). were reported by Aydın and Yılmaz Aydın (2023) in the study which the authors evaluated the ring number and width on UWVs.

When compared to the 65 % RH results of this study, there are -7,4 % to -10,8 %, 0,5 % to 3,1 %, 2,5 % to 9,2%, -2 % to -7,7 %, and -3,1 % to -6,5 % differences with the reported UWVs, respectively. Ettelaei *et al*. (2019) reported 5433-5887 m/s for V_{LL} of hybrid black poplar (*Populus euramericana* (Dode) Guinier) which is around 50,5 % to 63,1% higher than those of this study. Furthermore, particularly for the lower bound, a closer V_{LL} (3877 m/s to 4761 m/s) was reported for the I-214 clone obtained by stress wave speed (Casado *et al*. 2010, Papandrea *et al*. 2022). Indeed, a complete set of UWVs was available only for cottonwood oriental (*Populus deltoides* Bartram ex Marshall) which Zahedi *et al*. (2022) reported as 3360 m/s (V_{LL}), 1850 m/s (V_{RR}), 1380 m/s (V_{TT}), 1370 m/s (V_{LR}), 1250 m/s (V_{RL}), 1140 m/s (V_{LT}), 1350 m/s (V_{TL}), 670 m/s (V_{RT}), 650 m/s (V_{TR}), 1510 m/s ($V_{LR\ 45°}$), 1210 m/s ($V_{LT\ 45°}$), and 740 m/s ($V_{RT\ 45°}$) for 390 kg/m³ density solid wood. The diffractions between these values and the results of this study are -6,9 %, -7,4 %, 27,9 % -5,9 %, -14,1 %, -3,3 %, 15,8 %, 16,2 %, 20,6 %, -4,6 %, 13,4 %, and 10,4 %, respectively. Such differences are not abnormal for wood material due to the uniqueness of each tree and wood sampling.

Table 3: Statistics for UWVs.

Groups	Property	Mean*	Property	Mean*	Property	Mean*
45 % RH	V_{LL} (m/s) s. (F17,234, P0)	3756a (3,5)**	VRR (m/s) s. (F15,890, P0)	2084a (5,2)	VTT (m/s) s. (F9,265, P0)	1132a (5,1)
65 % RH		3609b (-4)*** (3,1)		1998b (-4) (2,1)		1079b (-5) (4,5)
85 % RH		3450c (-8) (3)		1903c (-9) (2,4)		1027c (-9) (5,5)
45 % RH	V_{LR} avg (m/s) s. (F23,672, P0)	1520a (3,2)	VLT avg (m/s) s. (F28,664, P0)	1220a (2,3)	VRT avg (m/s) s. (F24,176, P0)	587a (4,8)
65 % RH		1455b (-4,3) (3,3)		1172b (-3,9) (2,2)		558b (-5) (3,1)
85 % RH		1395c (-8,3) (1,4)		1133c (-7,1) (2,1)		522c (-11,1) (2,8)
45 % RH	$V_{LR45°}$ (m/s) s. (F26,204, P0)	1636a (3,3)	VLT45° (m/s) s. (F8,646, P0,001)	1083a (2,9)	VRT45° (m/s) s. (F20,881, P0)	683a (2,8)
65 % RH		1583b (-3,3) (1,9)		1067a (-1,5) (3,7)		670a (-1,9) (2)
85 % RH		1516c (-7,3) (1,2)		1015b (-6,2) (4,1)		636b (-6,9) (2,8)

s. Significant, * Duncan's homogeneity groups, ** values in the bracelets are the Coefficient of variation, and *** values in the parentheses are % diffraction from 45 % RH.

The averages of the elasticity and shear modulus are presented in Table 4. An increase in MC caused decreases in all modulus values, but the G_{RT} was the most influenced one among them. The decreasing tendency is linear-like with the increase in MC. Fluctuations were not observed. According to ANOVA results, all moduli were statistically significantly affected by the MC. Furthermore, the CoVs are at reasonable levels.

As for UWVs, particularly for canadian poplar (*Populus x canadensis* Moench), there is limited data for the moduli comparison. Just Aydın and Yılmaz Aydın (2023) noted 899 MPa to 1211 MPa for E_R, 772 MPa to 876 MPa for G_{LR}, and 93 MPa to 111 MPa for G_{RT} for 345 MPa to 354 kg/m³ density canadian poplar (*Populus x canadensis* Moench) solid wood. The diffractions between (Aydın and Yılmaz Aydın 2023) and this study are -13,8 % to -36 % (-13,4 % to 16,6 % for E_R mtrx), 3,5 % to 17,4 % (same for G_{LR} mtrx), and -15,1 % to 1,3 % (-15,2 % to 1,2 % for G_{RT} mtrx), respectively. As can be seen in the table, calculation methods (plain formula (Equation 3 and Equation 4) vs matrix Equation 1 and Equation 2) cause remarkable differences in elasticity moduli (-4,1 % to -5,2 % for E_L, -26,1 % to -29,4 % for E_R, and -26,5 % to -30,4 % for E_T) while shear moduli are almost the same (-0,2 % to 0 %). However, to determine full elastic constants, using a matrix is the way.

Apart canadian poplar (*Populus x canadensis* Moench), E_L, E_R, E_T, G_{LR}, $G_{LT,}$ and G_{RT} were reported by Zahedi *et al*. (2022) as 4,52 GPa, 1,37 GPa, 0,74 GPa, 0,69 GPa, 0,62 GPa, and 0,17 GPa for cottonwood oriental (*Populus deltoides* Bartram ex Marshall) which determined by US, respectively. E_L, $E_{R,}$ and G_{LR} are comparable but E_T, $G_{LT,}$ and G_{RT} are 80,3 %, 28,1 %, and 55,2 % higher than those of this study, respectively. These diffractions are reasonable and can be attributed to method (calculation way, tools, etc.), and sampling (form, dimension, location, etc.). Furthermore, for comparison, reported 10231 MPa (Kaymakci and Bayram 2021) and 5693 MPa (Sözbir *et al.* 2019) MOE values for different poplar species indicate that the range is wide for elasticity.

Table 4: Statistics for Moduli.

Groups	Property	Mean*	Property	Mean*
45 % RH	E_L (MPa) s. (F9,736, P0,001)	4891a (7,4)**	E_L mtrx (MPa) s. (F5,948, P0,007)	4635a (9,9)
65 % RH		4588b (-6,2)*** (6,2)		4399ab (-5,1) (6,3)
85 % RH		4306 (-12)c (5,3)		4117b (-11,2) (5,5)
45 % RH	E_R (MPa) s. (F10,825, P0)	1506a (9,4)	E_R mtrx (MPa) s. (F3,363, P0,050)	1064a (10,5)
65 % RH		1405b (-6,7) (4)		1038ab (-2,4) (8,8)
85 % RH		1310c (-13) (4,4)		960b (-9,8) (7,6)
45 % RH	E_T (MPa) s. (F5,2, P0,012)	445a (10,3)	E_T mrtx (MPa) s. (F8,746, P0,001)	310a (5,8)
65 % RH		411ab (-7,7) (9,5)		302a (-2,6) (6,1)
85 % RH		383b (-13,9) (11,6)		278b (-10,1) (5,8)
45 % RH	G_{LR} (MPa) s. (F15,176, P0)	801a (5,4)	G_{LR} mtrx (MPa) s. (F15,312, P0)	801a (5,4)
65 % RH		746b (-6,8) (6,8)		746b (-6,9) (6,8)
85 % RH		704c (-12,1) (2,2)		704c (-12,1) (2,2)
45 % RH	G_{LT} (MPa) s. (F15,568, P0)	516a (4,1)	G_{LT} mtrx (MPa) s. (F15,539, P0)	516a (4,1)
65 % RH		484b (-6,1) (5,2)		484b (-6,2) (5,2)
85 % RH		464c (-9,9) (3,2)		465c (-10) (3,2)
45 % RH	G_{RT} (MPa) s. (F15,893, P0)	119a (9,4)	G_{RT} mtrx (MPa) s. (F16,163, P0)	120a (9,2)
65 % RH		110b (-8,3) (6,4)		110b (-8,3) (6,3)
85 % RH		99c (-17,5) (5,7)		99c (-17,4) (5,8)

s. Significant, * Duncan's homogeneity groups, ** values in the bracelets are the Coefficient of variation, and *** values in the parentheses are % diffraction from 45 % RH.

The Poisson's ratio averages are presented in Table 5. Reported µLR, µLT, µRT, µTR, µRL, and µTL ranges for hardwood species are 0,297-0,495, 0,374-0,651, 0,560-0,912, 0,213-0,496, 0,018-0,086, and 0,009-0,051, respectively (Kretschmann 2010), and except for 45 % RH and 85 % RH values of µRT, ratios are in the reported ranges. Furthermore, it was noted that µRL and µTL are much smaller than other ratios (Kretschmann 2010) and this is valid for this study. As can be seen in the table, MC created conflict in ratios. The influence of MC on µLR and µRL is positive while others are negative. Except for µRT, the influence of MC on the ratios is insignificant. Insignificant effect was reported by Güntekin *et al*. (2016a). A partially significant influence of MC on ratios was reported by Aydın and Yılmaz Aydın (2020) for naturally aged black pine and Jiang *et al*. (2017) for Chinese fir.

Contrary to the moduli, a linear-like decrease was not observed for µLT, µTL, µRT, and µTR. Indeed, these ratios fluctuated with the increase in MC. Nonlinear behavior for some moisture-related ratios was reported by Aydın and Yılmaz-Aydın (2020) for black pine, and Yılmaz-Aydın and Özveren (2019) for fir wood. Oscillation instead of increase or decrease in all ratios of Chinese fir was noted (Jiang *et al.* 2017). However, a linear-like effect of MC on µLR and µRL was observed in this study. Linear-like behavior was also reported by aforementioned studies but for different ratios.

Mizutani and Ando (2014) reported that µLR and µLT of Japanese cypress and magnolia decrease with the increase in MC below fiber saturation point (FSP) but increase above FSP. Burubai *et al*. (2008) noted that the Poisson's ratio of African nutmeg decreased with the increase in MC from 8 % to 28,7 %. The authors also reported 0,96 R^2 for ratios vs MC. Güntekin *et al*. (2016b) reported that six Poisson's ratios of sessile oak steadily increased with the increase in MC below FSP. Authors also observed oscillations for oriental beech when below FSP. Therefore, a general deduction is not possible for the MC effect. It should be noted that determining the moisture-induced Poisson's ratio requires special care because the effects of shrinkage and swelling have already noticeable impacts on the Poisson´s ratios in a very short time as Winter *et al*. (2023) expressed. For this study, samples were taken into the desiccator from the climate chamber and stored before and after measurements. However, it cannot be neglected that applying medium on a surface while measurements may have changes on this issue. This issue should be addressed in a future study.

Yılmaz Aydın (2022) reported -45 % to 109 % differences between the Poisson's ratios of heat-treated red pine. As seen in Table 5, the diffraction range, -24 % to 14,1 %, is remarkably lower than the reported ones.

However, the CoVs are high, particularly for µLT and µTL but this is not abnormal as Gómez-Royuela *et al.* (2021) state it is a fact for wood material. It should be taken into consideration that Poisson's ratios vary within and between species (Kretschmann 2010) and there is no information in the standards about Poisson's ratios (Obara 2018). Therefore, such numerically huge discrepancies in the literature are meaningful.

Table 5: Statistics for Poisson's ratio.

Groups	Property	Mean*	Property	Mean*
45 % RH	µLR ns. (F0,121, P0,886)	0,184 a (43,4)**	µRL ns. (F0,126, P0,882)	0,043a (49,9)
65 % RH		0,195 a (6)*** (42,9)		0,047 a (8,5) (43,3)
85 % RH		0,209 a (13,3) (73,7)		0,05 a (14,1) (75)
45 % RH	µLT ns. (F1,111, P0,344)	0,486 a (38,3)	µTL ns. (F1,119, P0,341)	0,034 a (46,2)
65 % RH		0,376 a (-22,7) (45,7)		0,026 a (-24) (43,3)
85 % RH		0,381 a (-21,6) (52,9)		0,026 a (-23,1) (54,4)
45 % RH	µRT s. (F3,755, P0,036)	0,954 a (4)	µTR ns. (F0,449, P0,643)	0,28 a (11,9)
65 % RH		0,899b (-5,7) (5)		0,264 a (-5,7) (15,5)
85 % RH		0,915 ab (-4,1) (5,8)		0,268 a (-4,4) (16,4)

s. Significant, ns. Not Significant, * Duncan's homogeneity groups, ** values in the bracelets are the Coefficient of variation, and *** values in the parentheses are % diffraction from 45 % RH.

Density is one of the major determinants of the properties that multiply the UWVs for elastic constant calculation. Linear regression models and R^2 for density vs UWVs, moduli, and Poisson's ratios are presented in Figure 1, Figure 2, Figure 3, respectively. In literature, the coefficient of determination for V_{LL} vs density was commonly figured out. For example, 0,64 (Oriental beech) (Yılmaz-Aydın and Aydın 2018b), 0,77 to 0,91 (sessile oak) (Yılmaz Aydın and Aydın 2018d), 0,84 to 0,89 (cedar) (Yılmaz-Aydın and Aydın 2018c), 0,82-0,87 (Scots pine), 0,79 to 0,88 (red pine), 0,86 to 0,92 (black pine), and 0,88 to 0,95 (oriental beech) (Yılmaz-Aydın and Aydın 2018a), and 0,80 to 0,88 (eucalypts species separately) and 0,31 (whole eucalypts samples) (Oliveira and Sales 2006) are some of the recently reported coefficients. As can be seen in Figure 1, R^2 values are not as high as the reported coefficients. Therefore, a good to a little amount of variance can be explained by models.

As can be seen in Figure 2, except for E_R, considerable low values were calculated for elasticity modulus. However, this is not unusual for wood material because in the literature 0,14 (heartwood) and 0,17 (sapwood) for silk wood (Kiaei and Farsi 2016) 0,37 for softwood (sugi, hinoki, icho, akamatsu, and kaya) and hardwood (yamaguruma, buna, hoonoki, keyaki, and arakashi) species (Miyoshi *et al*. 2018), and 0,43 for spruce (Keunecke *et al*. 2007) and 0,48 for the heartwood of five tropical hardwoods (Baar *et al*. 2015) coefficients were reported for elasticity vs density.

However, the linear relationship between density and modulus of elasticity is the known fact for the wood (Puszyński *et al*. 2015) and much higher values; 0,68 (yew) (Keunecke *et al*. 2007), 0,82 for eucalypts (Hein *et al*. 2013), 0,85 (45° annual ring inclination) (Miyoshi *et al*. 2018), 0,87 for four different species (Puszyński *et al*. 2015), and 0,93 for teak (Izekor *et al*. 2010) were reported. Therefore, such variations in the models are possible which can be attributed to lots of factors such as density increase which is not acoompanied by solidification. However, absorbing the water directly affects the UWVs that are used to dynamically calculate both elasticity and shear moduli. In this respect, coefficients for shear moduli (Figure 3) can be assumed relatively low.

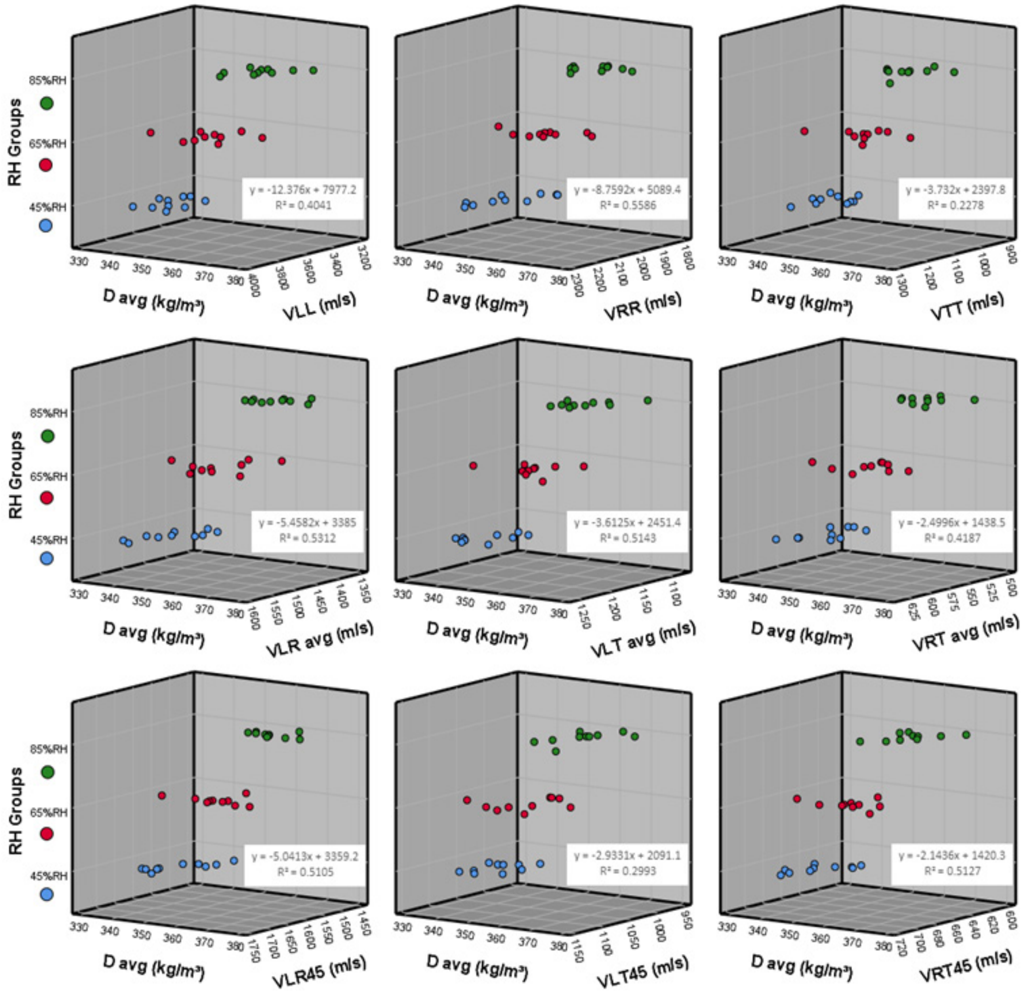

Figure 1: 3D scattering of UWV and linear regression models for density vs UWV.

It is not evident from any of the aforementioned papers that Poisson's ratios and density are highly correlated (Sliker and Yu 1993). The authors also figured out insignificant relationships for µLR or µLT Poisson's ratios as functions of density. However, Lu *et al*. (2022) stated that there is a positive correlation between density and Poisson's ratio for bamboo. Considering this contradiction, the results of linear regression (Figure 4) do not represent a good prediction of variables. Nevertheless, the increase in water content on the samples caused an increase in density instead of augmentation of structural elements. Thus, UWVs were decreased and caused a reduction in elastic properties. Furthermore, coefficients represent the whole RH groups, but when separately correlated within the RH groups coefficients significantly differ such as 0,25 for µLT, 0,23 for µLR, 0,13 for µRL, 0,22 µTL, 0,21 µTR, and 0,15 µRT. Therefore, it should be taken into consideration that dynamic predictions of the moisture-related ratios by US may not reflect the overall interaction.

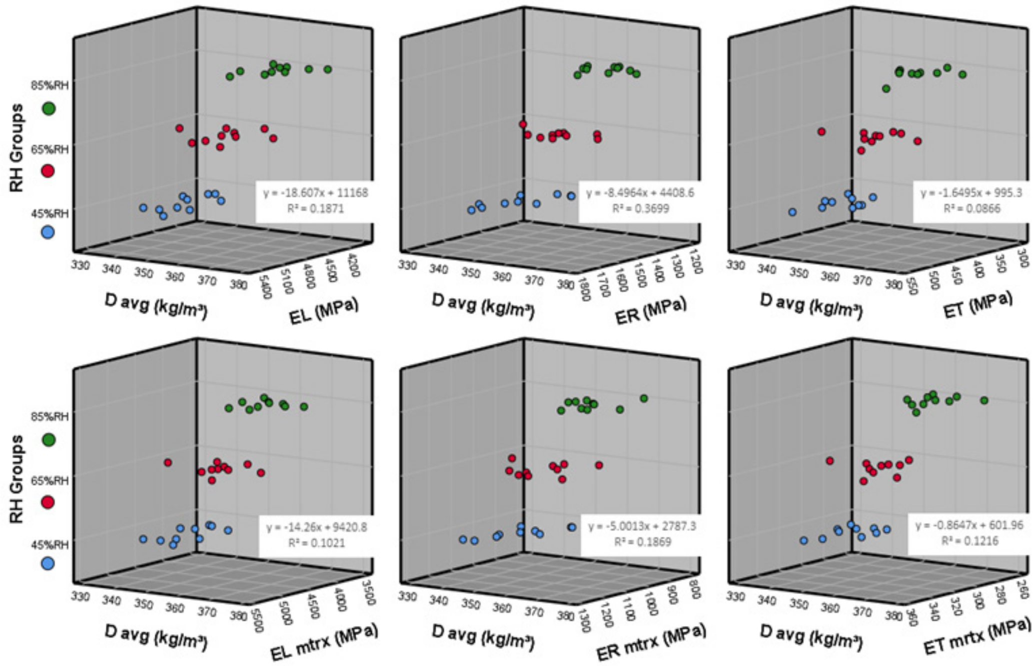

Figure 2: 3D scattering of Young's moduli and linear regression models for density vs elasticity.

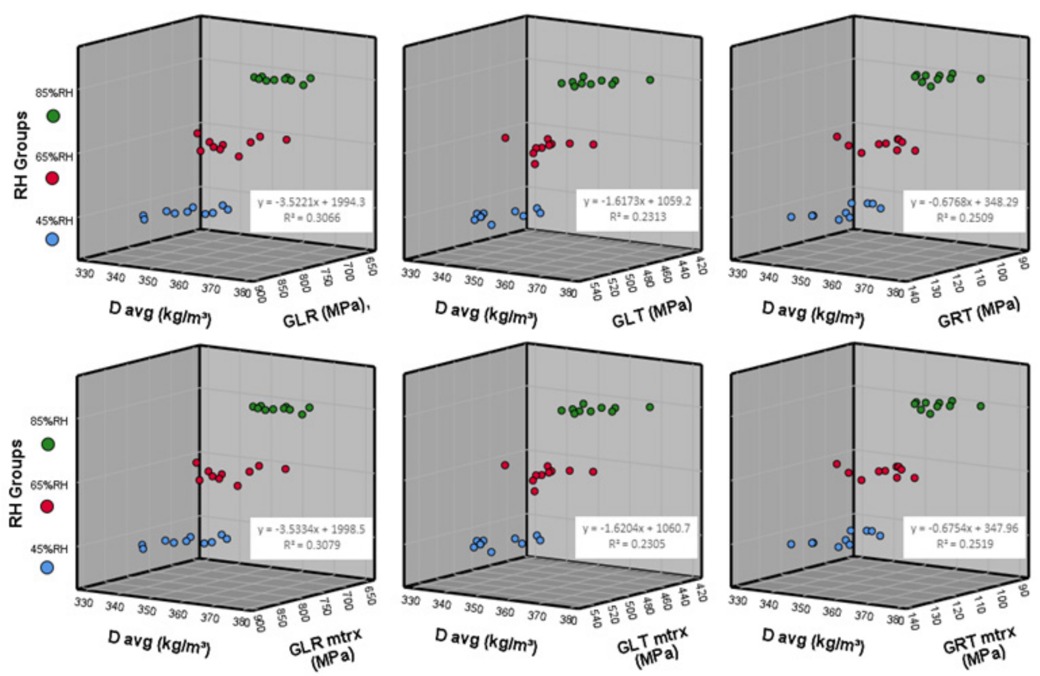

Figure 3: 3D scattering of shear moduli and linear regression models for density vs shear modulus.

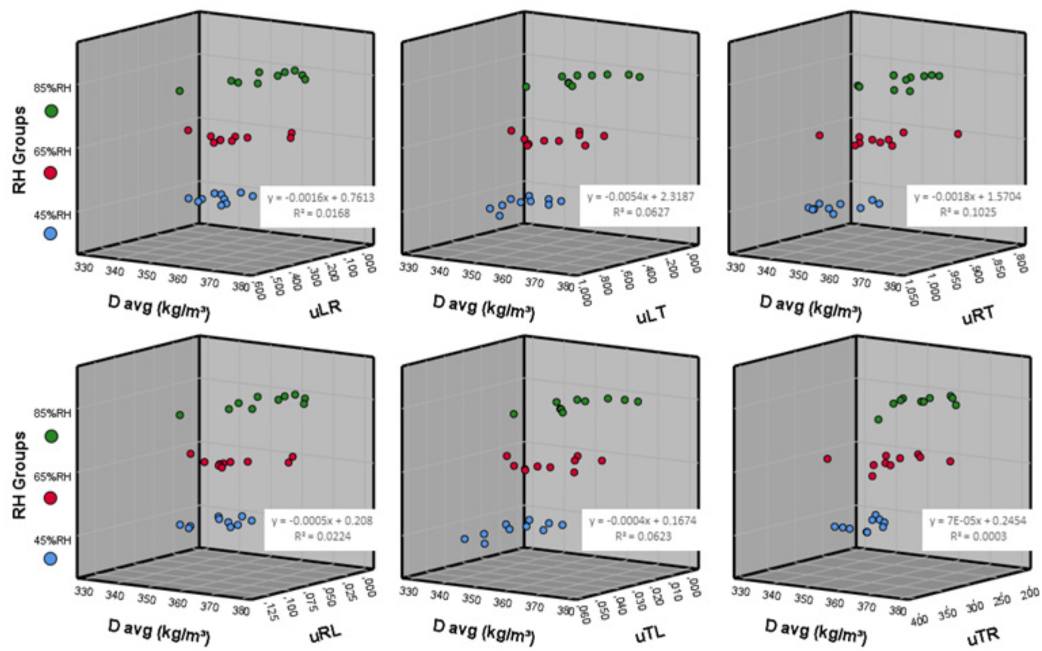

Figure 4: 3D scattering of Poisson's ratios and linear regression models for density vs ratios.

CONCLUSIONS

Full elastic constants of canadian poplar (*Populus x canadensis* Moench), unavailable in the literature yet, were provided. Both elasticity and shear moduli decreased with the increase in MC. The influence of MC on moduli was found to be significant while Poisson's ratios (except for µRT) were insignificant. Furthermore, contrary to moduli, linear increases in µLR and µRL were observed with moisture increase. However, other ratios were decreased but these reactions against moisture increases were not stable, and fluctuation is the fact for moisture-induced ratios.

Coefficients for density vs measured properties were found to be relatively low when compared to the literature but these results were assumed as a function of absorbed water which caused velocity decreases and did not incorporate structural solidification for density increases.

The matrix is the way to calculate the full elastic constants but provides lower values than the simple formula. Considerable numerical differences between the calculation methods were observed in all the elasticity moduli while all shear moduli were almost equal.

This study provided essential parameters to designers who creates numerical modelings to evaluate the structural behavior of wooden elements or contructions. Wooden elements interact with the surrounding factors which can cause considerable changes in physical and mechanical properties. Therefore, providing moisture related elastic engineering parameters ranges also let the engineers create more reliable designs by adapting the on site properties. However, it should be considered that the phsycial and mechanical properties of wood materials signifcanlty vary within the species due to grow-up conditions. Therefore, the diversification of data due to method, sampling, etc. requires a wide spectrum of considerations in interpreting the mechanical behavior of wood materials. Considering this situation, it is recommended to take suitable averaged values into account in numerical modeling and analysis.

AUTHORSHIP CONTRIBUTIONS

T. Y. A.: Conceptualization, investigation, methodology, resources, formal analysis, data curation, validation, visualization, writing- original draft, writing – review and editing. M. A.: Conceptualization, investigation, methodology, resources, formal analysis, data curation validation, visualization, writing- original draft, writing – review and editing.

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