ISPARTA UYGULAMALI BİLİMLER ÜNİVERSİTESİ

Turkish Journal of Forestry | Türkiye Ormancılık Dergisi

2024, 25(4): 514-519 | Research article (Araştırma makalesi)

Moisture dependent bending properties of poplar

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Abstract: The influence of moisture on the physical (density) and mechanical (modulus of rupture-MOR, modulus of elasticity-MOE) properties of *Populus x canadensis* M. were figured out by three three-point bending tests and ultrasonic testing . Samples were conditioned at 20±1 °C and 45, 65, and 85% relative humidity. The calculated ultrasonic longitudinal wave velocity (V_{LL}) was used to determine dynamic MOE (4549 to 4735 MPa) and compared to static MOE (5461 to 5910 MPa). Static MOE values are around 15.3% to 28.1% higher than dynamic values. MOR values, the most influenced properties, decreased from 70.1 MPa to 51.3 MPa with the increase in moisture. Pearson correlation coefficients ranged from 0.52 (MOR vs V_{LL}) to 0.94 MOE_{dyn} vs V_{LL}). The R^2 values ranged from 0.187 (V_{LL} vs MOR at 85% RH) to 0.94% (V_{LL} vs E_{dyn} at 65% RH).
Keywords: *Populus x canadensis*, Modulus of rupture, Modulus of elasticity, Ultrasound

Kavak odununun rutubete bağlı eğilme özellikleri

Öz: Rutubetin, *Populus x canadensis* M.'in fiziksel (yoğunluk) ve mekanik (Eğilme direnci-MOR, Elastikiyet modülü-MOE) özellikleri üzerindeki etkisi üç nokta eğme testi ve ultrasonik test yöntemi ile belirlenmiştir. Örnekler 20±1 °C'de ve %45, 65 ve 85 bağıl nemde şartlandırılmıştır. Hesaplanan ultrasonik boyuna dalga hızı (V_{LL}) dinamik MOE'yi (4549 ila 4735 MPa) belirlemek için kullanılmış ve statik MOE (5461 ila 5910 MPa) ile karşılaştırılmıştır. Statik MOE değerleri dinamik değerlerden yaklaşık %15.3 ila %28.1 daha yüksektir. Rutubetten en çok etkilenen özellik olan MOR değerleri, rutubetteki artışla birlikte 70.1 MPa'dan 51.3 MPa'ya düşmüştür. Pearson korelasyon katsayıları 0.52 (MOR vs V_{LL}) ile 0.94 MOE_{dyn} vs V_{LL}) arasında değişmektedir. R^2 değerleri 0.187 (%85 bağıl nemde V_{LL} vs MOR) ile %0.94 (%65 bağıl nemde V_{LL} vs E_{dyn}) arasında değişmiştir.
Anahtar kelimeler: *Populus x canadensis,* Eğilme direnci, Elastikiyet modülü, Ultrases

1. Introduction

Environmental conditions define the materials' behaviors and lifetime, and moisture is one of the essential factors that influence the materials' physical and mechanical properties. Shrinkage and swelling are the two basic behaviors of wood material when moisture content decreases and increases from the fiber saturation point (FSP). Therefore, there is an interaction between the surrounding factors such as humidity and wood. As an organic and biological material, wood material can be easily and dramatically affected by moisture if it is not preserved. Furthermore, changes in physical and mechanical properties can be irreversible. Therefore, to prevent damage in wood structure, various methods are in use to modify wood structure. The basic and one of the oldest ways is the air-drying (natural) of wood. By technological advancements engineering methods were developed such as kiln drying. However, devastating interaction between the humid conditions and wood somehow proceeds. In this case, further modification processes such as heat-treatment are required to minimize interactions.

The tie between wood and humidity requires in-site utilization knowledge which is directly related to physical and mechanical properties. Because of equilibration, absorption and desorption of moist from the surrounding air cyclically and regularly occur in terms of weather conditions related to the seasons and geological locations. For interior utilization, this cycle is a less-concern issue due to engineering acclimatization of the interiors while the top-of-mind due to the wide range diffraction for humidity at the outside. Therefore, irreversible impacts of moisture on wood properties may not be critical for decorative objects or interior production but may play a vital role when wooden materials are used for structural purposes particularly for outside applications. Therefore, the influence of moisture on wood material properties should be known. When considering the mechanical properties of wood, the critical factor is the FSP. Because, when moisture content of wood decreases below the FSP, mechanical properties increase (Gerhards, 1982).

Poplar trees were once thought of as weed trees that should be taken out of wood stands (Balatinecz and Kretschmann, 2002). Furthermore, wood obtained by poplar species were generally utilized in relatively low value-added applications. For example, upholstered type furniture, one of the covering materials of metal structured sofa bed is the poplar. However, it should also bear in mind that due to low-density, poplar installation in such furniture production provides lightness and cost efficiency. The main characteristics of the poplar species are the relatively low density and diffuse porous structure. Against the relatively low strength properties, bending strength and stiffness of some poplar species can be compared by some softwood species and products made using poplar species can

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✓ **Received** (Geliş tarihi): 10.09.2024, **Accepted** (Kabul tarihi): 22.11.2024

Citation (Atıf)**:** Yılmaz Aydın, T., Özkan, U., 2024. Moisture dependent bending properties of Poplar. Turkish Journal of Forestry, 25(4): 514-519.

DOI: 10.18182/tjf.1547421

successfully compete with products made of softwoods (Balatinecz and Kretschmann, 2002). Contrary to the abovementioned disadvantages, one of the most prevalent fast-growing tree species is the poplar (Varivodina et al., 2018) and recently founds a wide range of application field by advanced value-added modifications.

Populus x canadensis Moench is one of the poplar species which naturally grown by natural hybridization of *Populus nigra* and *Populus deltoides*. *Populus x canadensis* Moench is a tree that is extensively found in Türkiye (Davis, 1982). However, in literature, there are limited studies that figured out *Populus x canadensis* while other species were generally evaluated. For example, Ettelaei et al. (2019) determined moisture-influenced modulus of elasticity (MOE) of *Populus euramericana* by propagation of 22kHz ultrasonic wave. Gray et al. (2008) predicted moisture-influenced MOE of yellow-poplar by stress wave and stated that propagation time increases with the increase in moisture content. Pierre et al. (2013) figured out the effect of moisture on Young's modulus of *Populus euramericana* cv. I214. On the other hand, Hodoušek et al. (2017), is one of the limited studies which determined the MOE of *Populus x canadensis* using an MTG Timber grader, and accelerometer and compared it to static bending test results. Therefore, moisture influenced elastic and strength properties of *Populus x canadensis* are required for wood science and technology field either for comparison or numerical analysis.

From a holistic perspective, the aim of this study is to determine the moisture influenced MOE and modulus of rupture (MOR) by bending test and compare the static MOE values with the values which were determined by ultrasonic measurements for the *Populus x canadensis* Moench which is not evaluated before.

2. Materials and methods

Samples were prepared using Canadian poplar (*Populus x canadensis* Moench) laths which logs were cut in Atabey, Isparta, Türkiye.

As seen in Figure 1, static bending test pieces were prepared according to TS ISO 13061-3 (2021) with 20x20 mm cross-section and 350 mm in length along the grain direction. 20x20x20 mm cubic test pieces for ultrasonic measurements were cut sequentially from each bending test samples for ensuring the matching and minimizing the variations. Recently a national or an international standard which defines the ultrasonic testing and evaluation for the strength or elasticity determination of wood is not available. Therefore, this process was based on previously published studies (Bachtiar et al., 2017), (Longo et al., 2018) or (Yılmaz Aydın and Aydın, 2018). All the samples were acclimatized by humidity chamber (HCP 108, Memmert Gmbh+Co. KG, Schwabach, Germany).

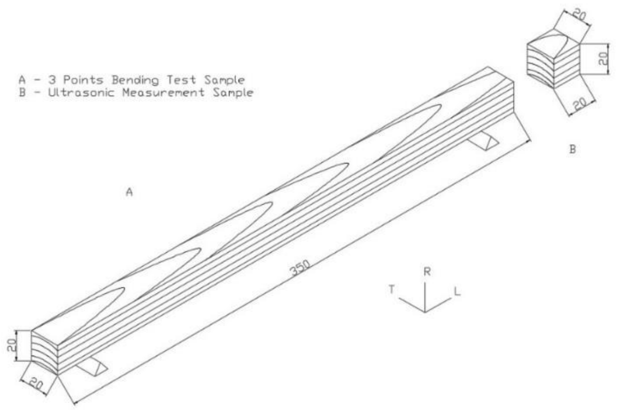

Figure 1. Schematics for samples

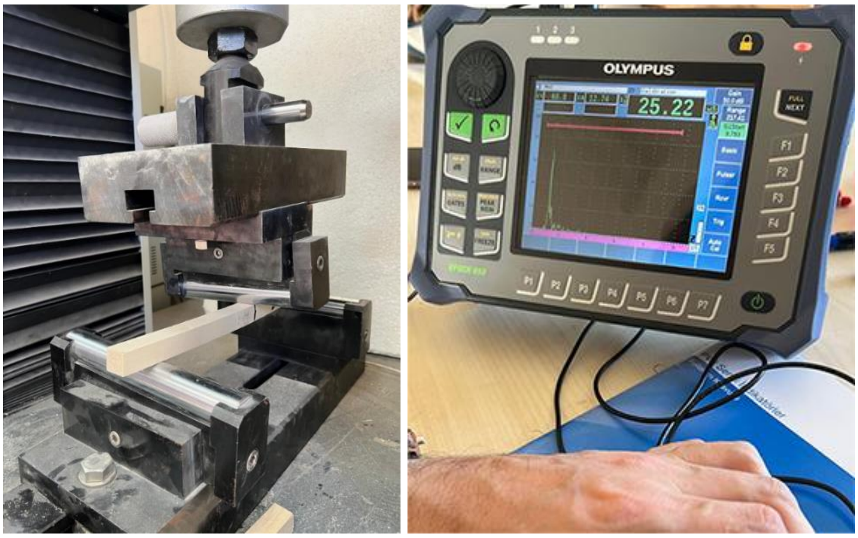

Figure 2. 3 points bending test (left) and ultrasonic measurements (right)

The density and moisture content of the samples were determined according to TS ISO 13061-2 (2021) and TS 2472 (2005) standards, respectively.

The MOE and MOR were determined by performing a three-point bending test using a universal test machine. The Eqs. 1 and 2 were used to calculate MOE and MOR, respectively.

$$MOE = \frac{\Delta F x L^3}{\Delta d x 4 x b x h^3} \text{ (MPa)} \quad (1)$$

where; ΔF is the difference between the two loads (F_2-F_1) in the linear elastic region, L is the span (mm), Δd is the deflection (mm), b and h are the width (mm), and thickness (mm) of the sample, respectively.

$$MOR = \frac{3 x F x L}{2 x b x h^2} \text{ (MPa)} \quad (2)$$

where; F is the load at failure (N), L is the span between supports (mm), and b and h are the depth (mm) and width (mm) of the sample, respectively.

The E_{dyn} was determined using Eq. 3. The velocities were calculated using the propagation time of the longitudinal wave (2.25 MHz) which was transmitted and received by an ultrasonic flaw detector (EPOCH 650, Olympus, USA).

$$E_{dyn} = \rho x V_{LL}^2 x 10^{-6} \text{ (MPa)} \quad (3)$$

where; ρ is the density of the sample (kg/m³) and V_{LL} is longitudinal ultrasound wave velocity (m/s).

Pearson correlation tests and linear regression models were determined to figure out the similarities and relationships between the variables, respectively.

3. Results and discussion

The descriptives for the physical and mechanical properties are presented in Table 1. The density for the *Populus x canadensis* solid wood in the literature ranges from 334-468 kg/m³ (Casado et al., 2010; Hodoušek et al., 2017; YingJie et al., 2017; Villasante et al., 2021; Papandrea et al., 2022; Aydın and Aydın, 2023). The density averages are in the range but close to the lower bound. However, 300 kg/m³ average density for *Populus x canadensis* Moench veneer was reported by Meija et al. (2020). Therefore, such diffraction is not abnormal. Around 6% and 9% increases were observed with the increase in moisture.

The V_{LL} decreased and then surpassed the initial values. The numerical differences for the V_{LL} by the increase in moisture were -0.84% and +0.23%, respectively. The V_{LL} for populous canadensis is not available in the literature. However, 3360 m/s for *Populus deltoides* (Zahedi et al., 2022) were reported. This speed makes sense when considering that the *Populus x canadensis* is the naturally occurring hybrid of *Populus nigra* and *Populus deltoides*. Apart from UWVs, 3877 to 4761 m/s stress wave speed (V_{LL}) for the I-214 clone was mentioned (Casado et al., 2010; Papandrea et al., 2022).

The E_{dyn} 1.4% decreased and then 2.6% increased with the increase in moisture. The MOE_{stat} 3.9% and 7.6% decreased with the increase in moisture. Hodoušek et al. (2017) reported 4268 to 11018 MPa MOE_{stat} and 3650 to 9276 MPa MOE_{dyn} ranges. The averages of the MOE_{stat} and MOE_{dyn} were 7135 MPa, 6180 MPa (timber grader), and 6331 MPa (accelerometer), respectively. As can be seen in Table 1, the MOE_{stat} values of this study were 20.7%, 25.6%, and 30.7% lower than those of Hodoušek et al. (2017). Dynamic values were around 30.5% to 39.2% lower. Furthermore, the MOE_{stat} values are 28.1%, 24.9%, and 15.3% lower than the MOE_{dyn}. Also, YingJie et al. (2017) reported 9014 MPa MOE_{stat} for *Populus canadensis* (0.468 g/cm³ density) which is considerably higher than those of this study.

As can be seen in Table 1, the most influenced feature was the MOR because 12.7% and 26.8% decreases were observed, respectively. Such linear-like decreases were not seen in ultrasonic testing, and it was thought that the increase in density by the water absorption did not accommodate the linear-like increase in velocity. YingJie et al. (2017) reported 55.9 MPa MOR for *Populus canadensis* (0.468 kg/m³ density) which is comparable to the results of this study. However, for the I-214 clone, 37.8 MPa (Koman et al., 2013) and 48.5 MPa (Kurt, 2010) were also reported, which are considerably lower than those of this study. As can be seen in Table 1, contrary to MOE_{stat}, the MOR of this study is higher than those of the reported values.

Hodoušek et al. (2017) reported 0.898 and 0.906 correlation values for MOE_{dyn} vs MOE_{stat}. As can be seen in Figure 3, lower coefficients were calculated between these variables. In the literature, there are similar and much higher or lower coefficients for different wood species. For example, closer coefficients were calculated by Papandrea et al. (2022) for poplar while Baar et al. (2015) reported 0.59 (MOR vs MOE_{stat}) and 0.60 (MOE_{dyn} vs MOE_{stat}) for zebrano wood.

Hodoušek et al. (2017) reported 0.81 and 0.82 R^2 values for MOE_{dyn} vs MOE_{stat}. However, lower values (0.67-0.71 R^2) for the I-214 clone (Gallego et al., 2021) and (0.44-0.61 R^2) for *Populus euramericana* (Ettelaei et al., 2019) were also reported. Contrarily, higher values such as 0.83 (Yilmaz Aydin, 2021) and 0.897 (Yılmaz Aydın and Aydın, 2020) for different species are also mentioned. As presented in Figure 3, comparable coefficients were calculated.

The coefficients for V_{LL} vs E_{dyn} are the highest among them due to calculation elements seen in Eq. 3. Furthermore, as can be seen in Figs. 1-6, the models can predict 18.7% (V_{LL} vs MOR at 85% RH) to 94% (V_{LL} vs E_{dyn} at 65% RH) variables. As can be seen in Figures 4, 5, 6, 7, and 8, the prediction ability of the models dramatically decreases when the moisture increases.

Table 1. Averages for the properties

R.H. (%)	M.C. (%)	Density (g/cm³)	V_{LL} (m/s) [CoV]*	E_{dyn} (MPa) [CoV]	MOE (MPa) [CoV]	MOR (MPa) [CoV]
45	10.20	0.33	3650.06 [4.40]	4613.66 [11.58]	5910.31 [9.50]	70.10 [5.68]
65	12.83	0.35	3619.59 [2.59]	4548.65 [9.73]	5679.91 [6.53]	61.17 [2.22]
85	16.45	0.36	3658.58 [4.40]	4734.64 [11.75]	5460.96 [7.41]	51.32 [2.86]

*Coefficient of variation

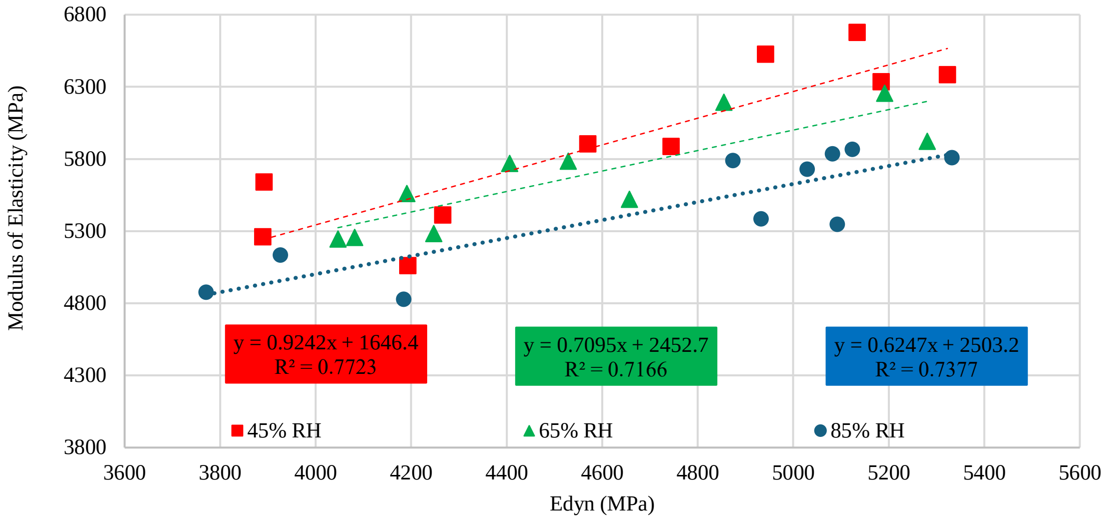

Figure 3. Coefficient of determination between MOE_{stat} and E_{dyn}

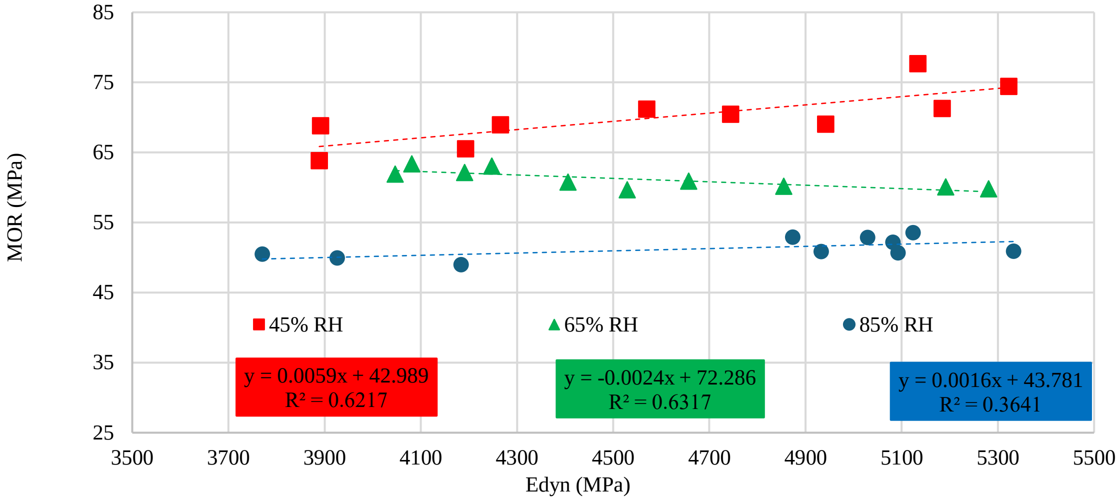

Figure 4. Coefficient of determination between MOR_{stat} and E_{dyn}

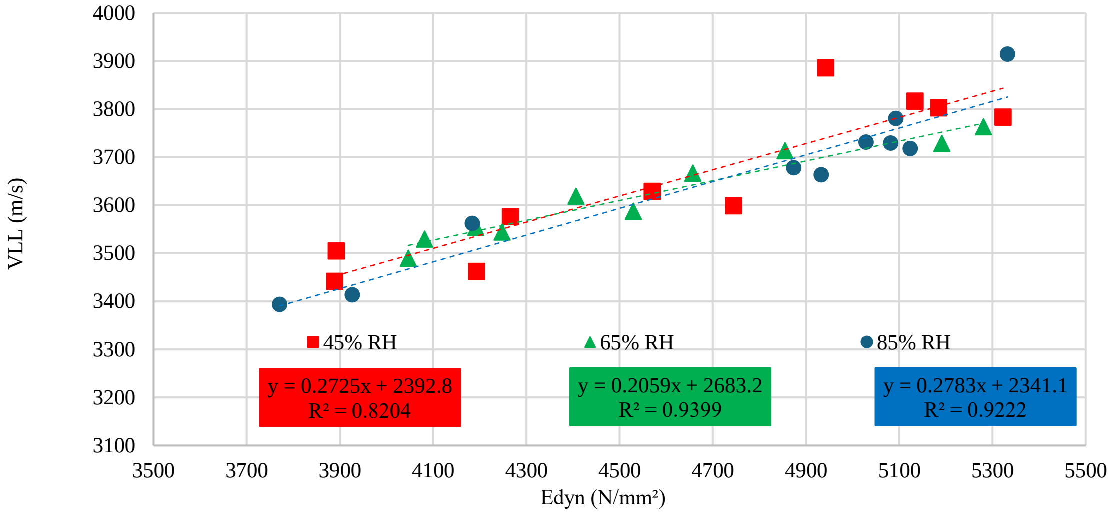

Figure 5. The coefficient of determination between V_{LL} and E_{dyn}

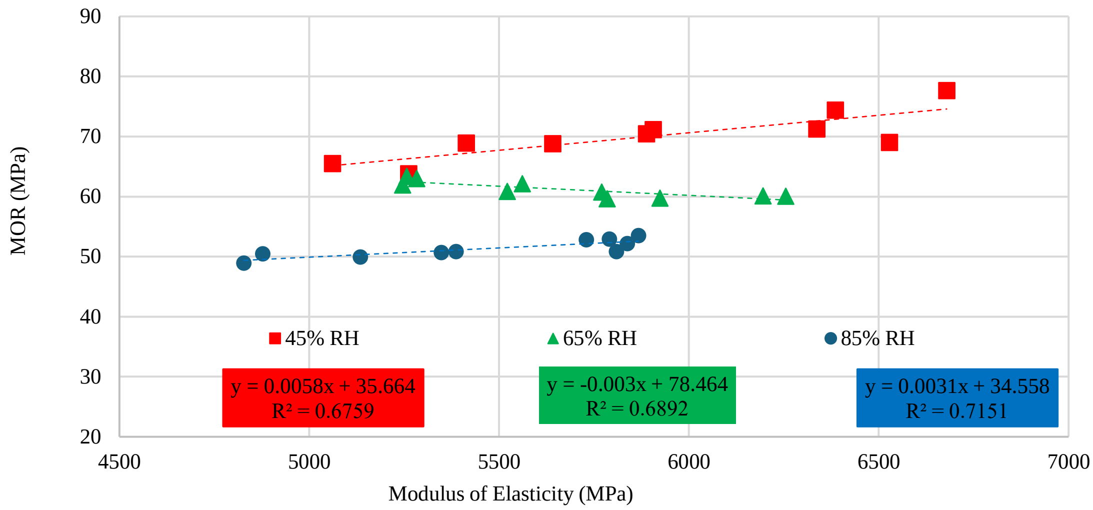

Figure 6. Coefficient of determination between MOE and MOR

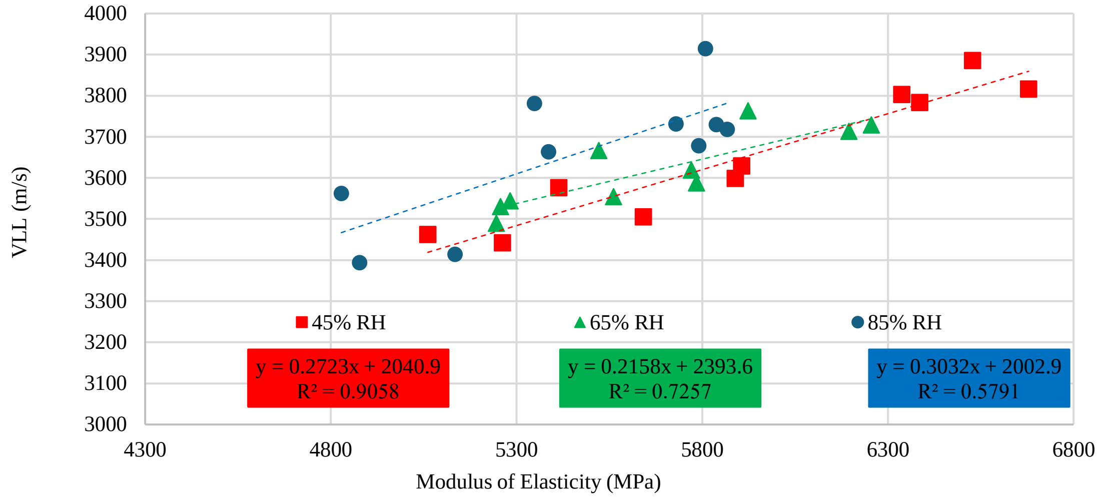

Figure 7. Coefficient of determination between MOE and V_{LL}

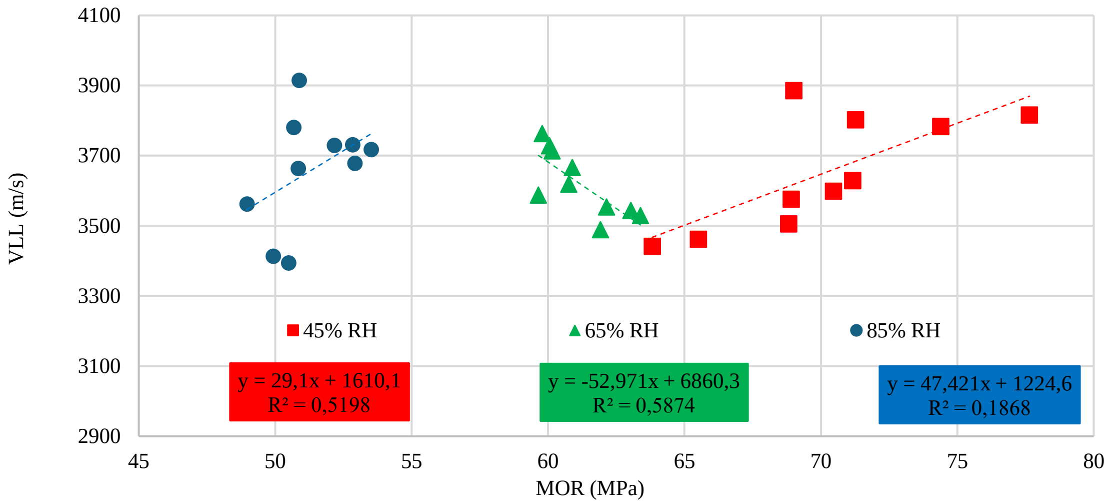

Figure 8. Coefficient of determination between MOR and V_{LL}

4. Conclusion

The bending properties of *populus canadensis* M. were destructively and non-destructively evaluated. Moisture content changes have caused different effects on the physical and mechanical properties.

The densities of the samples were increased with the absorption of the water as it should be. Density is one of the main determinants of E_{dyn} along with velocity. As well-known, the ultrasonic wave velocity is around 4.3 times higher in water than air. In this case, significant increases in V_{LL} might be expected when considering the water absorbing capacity of poplar due to its porous structure. However, such advancement in velocity was not observed. Indeed, velocity fluctuated by the increase in moisture content. This behavior was attributed to structural solidification failure which may cause propagation alterations.

As a result of V_{LL} fluctuations, E_{dyn} was also oscillated (deceased and surpassed the initial values).

Contrary to E_{dyn}, linear-like changes were observed in static test results. Both MOE_{stat} and MOR were linearly and remarkably decreased with the increase in moisture content, but MOR was the most influenced property.

Except in some cases, a fair amount of variables can be predicted by the linear regression models.

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