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Influence of Temperature and Exposure Duration on the Bending Properties of Oak Wood

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Abstract

Temperature is one of the environmental factors that has influences on the material properties, and its behavior in service life. In this study, effects of temperature and exposure duration on the ultrasound wave velocity (V_{LL}), dynamic Modulus of Elasticity (E_{dyn}), Modulus of Elasticity in bending (MOE), and Modulus of Rupture (MOR) of oak wood were investigated by the transmission of ultrasound longitudinal wave and three points bending tests. According to results, all determined properties were decreased at intensive treatment conditions. For example, V_{LL}, E_{dyn}, MOE, and MOR values were decreased from $4x10^3$ m/s to $3.8x10^3$ m/s, 11174 N/mm^2 to 9174 N/mm^2, 9811 N/mm^2 to 7480 N/mm^2, and 99 N/mm^2 to 62 N/mm^2, respectively. Maximum decreases were 4.7, 16.6, 20.7, 34.1, and 8.7 % at 210 °C 8 h treatments for V_{LL}, E_{dyn}, MOE, MOR, and density, respectively. However, at moderate temperatures up-to 150 °C, properties (except density) were increased (V_{LL}: 12.7%, E_{dyn}: 20.2%, MOE: 18.1%, MOR: 11.7% at 80°C for 8h) with the increase in exposure time within the groups but decreased between the groups. Pearson correlation coefficients between the variables were ranged from 0.71 to 0.93 for E_{dyn}-MOE, 0.47 to 0.85 for E_{dyn}-MOR, 0.02 to 0.75 for E_{dyn}-V_{LL}, 0.71 to 0.88 for MOE-MOR, 0.02 to 0.78 for MOE-V_{LL}, and 0.01 to 0.81 for MOR-V_{LL}. Furthermore, R^2 values of the linear regression models for E_{dyn}-MOR, MOE-MOR, and E_{dyn}-MOE were 0.71, 0.76, and 0.9, respectively.

Keywords: Oak, ultrasound, bending properties, modulus of elasticity.

Sıcaklık ve Maruz Kalma Süresinin Meşe Odunu Eğilme Özelliklerine Etkisi

Öz

Sıcaklık, malzeme özelliklerine ve malzemenin kullanım esnasındaki davranışına etkisi olan çevresel etkenlerden biridir. Bu çalışmada, sıcaklığın ve maruz kalma süresinin ultrasonik dalga hızı (V_{LL}), meşe odununun dinamik elastikiyet modülü (E_{dyn}), eğilmede elastikiyet modülü (MOE) ve eğilme direncine (MOR) etkisi boyuna ultrasonik dalga yayımı ve üç nokta eğilme testi ile ortaya konulmuştur. Sonuçlara göre, tüm özellikler yoğun muamele koşullarında düşmüştür. V_{LL}, E_{dyn}, MOE ve MOR sırası ile $4x10^3$ m/s'den $3.8x10^3$ m/s'ye, 11174 N/mm^2'den 9174 N/mm^2'ye, 9811 N/mm^2'den 7480 N/mm^2'ye ve 99 N/mm^2'den 62 N/mm^2'ye düşmüştür. En yüksek düşüş, % 4.7, 16.6, 20.7, 34.1 ve 8.7 ile 210 °C 8 saat muamele sonucu V_{LL}, E_{dyn}, MOE, MOR ve yoğunluk değerlerinde olmuştur. Fakat yoğunluk harici özellikler, 150 °C'ye kadar olan ılımlı sıcaklıklarda maruz kalma süresinin artışı ile birlikte grup içinde artarken (80 °C ve 8 saat için V_{LL}: %12.7, E_{dyn}: %20.2, MOE: %18.1, MOR: %11.7) gruplar arasında düşmüştür. Değişkenler arasındaki Pearson korelasyon katsayıları E_{dyn}-MOE için 0.71'den 0.93'e, E_{dyn}-MOR için 0.47'den 0.85'e, E_{dyn}-V_{LL} için 0.02'den 0.75'e, MOE-MOR için 0.71'den 0.88'e, MOE-V_{LL} için 0.02'den 0.78'e ve MOR-V_{LL} için 0.01'den 0.81'e kadar yayılmıştır. Ayrıca, E_{dyn}-MOR, MOE-MOR, ve E_{dyn}-MOE doğrusal regresyon modellerinin R^2 değerleri sırası ile 0.71, 0.76 ve 0.9 olmuştur.

Anahtar Kelimeler: Meşe, ultrases, eğilme özellikleri, elastikiyet modülü.

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1. Introduction

Ultrasound propagation is a relatively easy and effective way to predict mass properties of materials. Propagation of longitudinal and transverse ultrasonic waves in solids does not cause any changes in material properties. Furthermore, in comparison with destructive tests, samples prepared for ultrasonic testing can be used several times by conditioning with different environmental set-ups if the invisible or inner flaws are not occurred.

Material properties, especially bio-degradable materials such as wood, significantly depend on and alter with environmental conditions due to interaction with moisture, temperature, ultraviolet irradiation, wind, etc. Indeed, combined effects of these factors are devastating for the structure of materials. For example, effect of temperature at higher moisture contents is apparent and more significant (Gerhards 1982). Furthermore, determination of the effects of these factors on the mechanical properties of a porous material with polar orthotropic nature is not as easy as homogeneous materials.

Physical, mechanical and biological properties of wood significantly are affected by the thermal modification of wood due to occurred chemical changes during the process. And, it is required to evaluate these alterations for better utilization of products (Kubovský et al. 2020). Sinha et al. (2010) investigated the effect of temperature and exposure time (100 and 200°C, 1 and 2h) on the bending strength (MOR) and stiffness (MOE) of solid sawn lumber (SSL), laminated veneer lumber (LVL), oriented strand board (OSB) and plywood. They stated that elevated temperature caused significant decreases in bending strength and stiffness. Kubovský et al. (2020) evaluated the effect of temperature (160, 180, and 210 °C for 2-3h) on the chemical composition of European oak (*Quercus robur*, L.). Barcik et al. (2015) figured out the effect of temperature on the color changes of Pedunculate oak (*Quercus robur* L.) and sub-fossil oak woods. Bahar et al. (2019) investigated the effects of drying temperature on the modulus of rupture (MOR) and modulus of elasticity (MOE) of Oak (*Quersus canariensis*) and stated that mechanic properties were decreased with increasing drying temperature. Büyüksari et al. (2017) compared the bending strength, modulus of elasticity in bending, compression strength and tensile strength of standard- and micor-sized Oak (*Quercus petraea*) samples. Korkut and Hiziroğlu (2014) investigated the effect of temperature (110 and 200°C for 8h) on the roughness and swelling properties of red oak (*Quercus falcate* Michx.). Effect of temperature on the compression strength and modulus of elasticity parallel to the oak (*Quercus mongolica* Fisch et Turcz.) grain in compression mode studies by Jiang et al. (Jiang et al. 2014). Aydin (2020) predicted temperature dependent orthotropic compression properties of oak wood by ultrasound and compression tests. Studies concerned with temperature dependent orthotropic elastic properties of oak wood are limited. Therefore, in this study, temperature dependent bending properties of oak wood were determined using ultrasound and three point bending tests.

2. Material and Method

2.1. Material

In this study, defect free, clear samples of Oak (*Quercus petraea* L.) wood (origin from Devrek Forest Stand, Zonguldak, Turkey) was used for destructive and non-destructive tests.

2.2. Method

22x70x500 mm samples prepared from air-dried laths were exposed to the temperature. Temperature treatment was performed in five different temperature levels (80, 120, 150, 180, and 210 °C), and four different exposure durations (0, 2, 5, and 8 hours) using laboratory type oven (NUVE FN 500, Ankara, Turkey). Then, 20×20×350 mm and 20x20x20 mm samples were sequentially cut from the temperature treated 22×70×500 mm samples for bending test and ultrasonic measurements, respectively. Following the temperature treatment, samples were conditioned at 65 % relative humidity (RH) and 20 ± 1 °C temperatures. Densities of the acclimatized samples were determined in accordance with TS 2472 (2005) standard.

Three points bending tests (using universal test machine (Marestek, Istanbul, Turkey) with 5 metric tons load cell seen in Figure 1-right) were performed to determine bending properties in compliance with TS 2478 (2005) standard. Modulus of Elasticity in Bending (MOE) and MOR were calculated by Eq. 1 and 2, respectively.

$$MOE = \frac{\Delta F * L^3}{\Delta d * 4 * b * h^3} \ (\mathrm{N/mm^2}) \quad (1)$$

where; ΔF is the difference between the two loads (F2-F1) 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.

$$MOR = \frac{3*F*L}{2*b*h^2} \text{ (N/mm}^2\text{)} \quad (2)$$

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

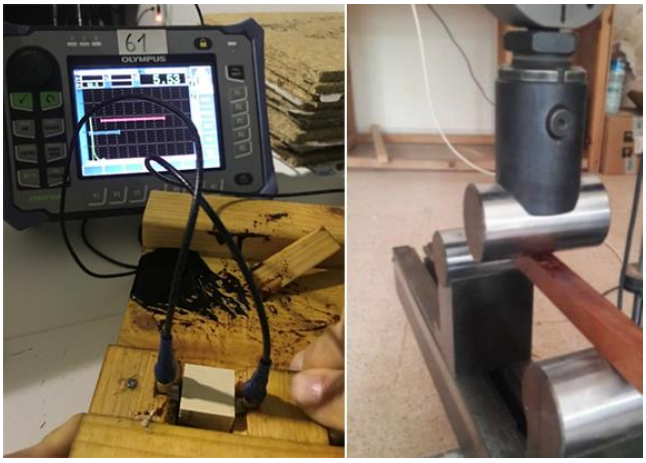

Figure 1. Ultrasonic measurements (left) and three points bending test (right).

Dynamic elasticity modulus (E_{dyn}) was calculated by ultrasonic testing and evaluation. As seen in seen in Figure 1-left, a conventional ultrasonic flaw detector (EPOCH 650, Olympus, USA) was used to obtain time of flight values of 2.25 MHz longitudinal ultrasonic wave propagation in direct transmission mode through the L direction of wood. These values were used to calculate the velocities in longitudinal direction (V_{LL}) of longitudinal ultrasonic wave. Then, E_{dyn} was calculated using the density and V_{LL} properties as seen in Eq. 3.

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

where; ρ is the density of the sample (kg/m3) and *V* is the velocity of ultrasound (m/s).

Pearson correlation coefficients (Person's r) were calculated to figure out between the variables. Also, linear regression models (R^2) were created to reveal the relationships between E_{dyn} vs MOE, E_{dyn} vs MOR, and MOE vs MOR.

3. Results and Discussion

The average density, V_{LL}, E_{dyn}, MOE in bending, and MOR values are presented in Table 1. According to results, average density of the unexposed samples was around 0.69 g/cm^3 and agrees with the literature. As seen in table, prolonged exposure duration caused remarkable decreases in density at 150 °C temperature. As well-known from the literature, density decreases with the increase in temperature due to loss of mass loss and other components. Likewise, maximum and significant decrease in density (8.7%) was observed when temperature and exposure duration increased to 210 °C and 8 hours, respectively. On the other hand, treatments at moderate temperatures up to 150 °C provided some apparent improvements in V_{LL}, E_{dyn}, MOE in bending and MOR within the groups. For example, at 80 °C and 8 hours treatment, these properties were 12.7, 20.2, 18.1, and 11.7 % increased, respectively. However, further temperature treatments, particularly for the extended exposure durations, caused considerable decreases.

It is reported that treatments up to 120 °C and 8 hours have some numerical advances in longitudinal ultrasonic velocity, E_{dyn}, and MOE in bending of Oriental beech wood (Yilmaz Aydin and Aydin 2018). But, further treatments (particularly over 150 °C and 5 hours) significantly decreased density, velocity, and dynamic and static MOE. Similar tendencies were observed in this study for the tested properties. MOE determined by static tests is generally lower than the dynamically determined one by using density and velocity values (Divos et al. 2007). This expression is valid in this study because E_{dyn} is higher (1.13 to 1.25, and 1.17 averages) than MOE in bending for all treatment conditions as seen in Table 1.

Table 1. Average values of the density, V_{LL}, E_{dyn}, MOE in bending, and MOR.

Temp. [°C]	**Exposure [Hours]**	**Density [g/cm³]**	**V_{LL} [m/s] Mean (CoV)**	**E_{dyn} [N/mm²] Mean (CoV)**	**MOE [N/mm²] Mean (CoV)**	**MOR [N/mm²] Mean (CoV)**
80	**0**	0.70	3993.38 (3.21)	11174.18 (10.50)	9810.64 (11.03)	98.71 (7.70)
80	**2**	0.69	4147.11 (3.17)	12356.41 (7.58)	10697.97 (6.54)	103.18 (5.41)
80	**5**	0.69	4486.67 (5.46)	13393.54 (7.85)	10706.56 (9.62)	106.14 (4.93)
80	**8**	0.69	4501.42 (4.88)	13428.03 (7.80)	11585.95 (8.80)	110.21 (4.31)
120	**0**	0.69	3981.32 (5.48)	11084.05 (11.17)	9505.65 (13.67)	96.66 (7.85)
120	**2**	0.69	4090.76 (2.74)	11556.41 (8.10)	10082.97 (7.32)	99.12 (6.35)
120	**5**	0.69	4136.14 (3.57)	11843.54 (8.88)	10466.65 (10.66)	101.03 (5.07)
120	**8**	0.68	4328.37 (3.31)	12824.68 (8.00)	11080.95 (9.37)	101.21 (4.70)
150	**0**	0.68	3960.99 (5.85)	10636.18 (8.54)	9087.25 (10.23)	91.89 (8.29)
150	**2**	0.67	4039.56 (3.21)	11043.76 (8.95)	9415.91 (11.50)	93.81 (8.92)
150	**5**	0.66	4032.04 (4.22)	10831.60 (7.31)	9368.58 (8.23)	90.97 (3.58)
150	**8**	0.66	4048.26 (2.31)	10895.69 (5.65)	9317.13 (6.20)	86.49 (4.78)
180	**0**	0.69	3983.00 (5.07)	10969.37 (10.55)	9466.38 (9.43)	93.65 (2.30)
180	**2**	0.68	3916.98 (5.32)	10387.15 (9.20)	8966.15 (9.17)	86.95 (5.44)
180	**5**	0.65	3917.09 (4.36)	10087.65 (7.72)	8518.98 (9.29)	76.91 (7.39)
180	**8**	0.64	3906.66 (4.38)	9831.06 (10.28)	8303.35 (12.9)	72.29 (7.51)
210	**0**	0.69	3980.27 (3.98)	11000.07 (6.68)	9426.74 (7.72)	94.51 (3.98)
210	**2**	0.65	4063.18 (5.97)	10681.42 (10.61)	9120.49 (11.84)	86.20 (3.50)
210	**5**	0.64	3904.06 (2.41)	9782.06 (7.74)	8278.30 (8.20)	73.72 (5.57)
210	**8**	0.63	3792.31 (7.41)	9174.37 (12.36)	7479.52 (11.37)	62.32 (9.09)

CoV: coefficient of variations.

Person's r values for the relation between temperature influenced E_{dyn}, MOE, MOR, and V_{LL} are presented in Table 2. According to results, Pearson correlation coefficients were ranged from 0.71 (180 °C 8 hours) to 0.93 (210 °C 2 hours) for E_{dyn} and MOE, 0.47 (180 °C 8 hours) to 0.85 (80 °C Control) for E_{dyn} and MOR, 0.02 (80 °C 2 hours) to 0.75 (80 °C Control) for E_{dyn} and V_{LL}, 0.71 (80 °C 8 hours) to 0.88 (210 °C 5 hours) for MOE and MOR, 0.02 (150 °C 8 hours) to 0.78 (150 °C 5 hours) for MOE and V_{LL}, and 0.01 (210 °C 5 hours) to 0.81 (80 °C Control) for MOR and V_{LL}. Therefore, coefficient values were not regularly increased or decreased when temperature and exposure duration increased. Consequently, no stable linear behavior of r values was observed in terms of temperature and exposure duration. As seen in Table 2, there are no exact zero or negative values which mean no linear or negative linear correlations between the variables. However, great majority of the (r) values between the E_{dyn} and V_{LL}, MOE and V_{LL}, and MOR and V_{LL} are closer to 0 than 1. Furthermore, 12 of 20 of MOR-V_{LL} r values are lower than 0.1.

Table 2. Pearson correlation coefficients (r) between variables.

Temp. [°C]	**Exposure [Hours]**	**E_{dyn}-MOE**	**E_{dyn}-MOR**	**E_{dyn}-V_{LL}**	**MOE-MOR**	**MOE- V_{LL}**	**MOR- V_{LL}**
80	**0**	0.92	0.85	0.75	0.84	0.69	0.81
80	**2**	0.87	0.72	0.02	0.81	0.07	0.02
80	**5**	0.82	0.79	0.21	0.84	0.06	0.06
80	**8**	0.91	0.58	0.17	0.71	0.12	0.05
120	**0**	0.87	0.79	0.63	0.79	0.68	0.80
120	**2**	0.83	0.70	0.03	0.81	0.05	0.03
120	**5**	0.79	0.77	0.21	0.78	0.04	0.07
120	**8**	0.88	0.76	0.16	0.79	0.09	0.06
150	**0**	0.90	0.81	0.60	0.74	0.63	0.44
150	**2**	0.77	0.47	0.26	0.71	0.15	0.04
150	**5**	0.91	0.79	0.13	0.78	0.78	0.02
150	**8**	0.77	0.55	0.04	0.75	0.02	0.02
180	**0**	0.82	0.61	0.55	0.81	0.46	0.32
180	**2**	0.75	0.53	0.11	0.74	0.08	0.02
180	**5**	0.87	0.78	0.14	0.84	0.14	0.12
180	**8**	0.71	0.47	0.34	0.73	0.33	0.22
210	**0**	0.91	0.72	0.43	0.85	0.52	0.41
210	**2**	0.93	0.79	0.04	0.86	0.05	0.07
210	**5**	0.85	0.79	0.09	0.88	0.07	0.01
210	**8**	0.80	0.63	0.60	0.80	0.56	0.42

Equations of linear regression models explaining the relation of MOE vs MOR, E_{dyn} vs MOE, and E_{dyn} vs MOR parameters of whole samples are presented in Table 3. According to results, there are strong relations between the variables.

Table 3. Linear regression models and R^2 values.

Parameters	Linear Regression Model	R^2
E_{dyn} vs MOE	y = 0.8646x - 105.12	0.897
MOE vs MOR	y = 0.0085x + 10.588	0.759
E_{dyn} vs MOR	y = 0.0075x + 7.6998	0.714

The relation between E_{dyn} vs MOE, E_{dyn} vs MOR, and MOE vs MOR of whole samples are presented in Figures 2 to 4, respectively. It is obvious that there are strong relations between the variables. Therefore, each property can be estimated at reasonable levels by the related variables in equations seen in Table 3, or Figures 2 to 4.

Temperature influenced R^2 values for E_{dyn} vs MOE of Oriental beech were reported by (Yilmaz Aydin and Aydin 2018). These values were decreased with the increase in temperature treatments, and ranged from 0.75 (210 °C) to 0.82 (120 °C). As seen in Figure 2, such a strong relation was observed for E_{dyn} vs MOE. Therefore, it can be said that same behavior is valid for the relation between statically and dynamically determined temperature dependent elasticity modulus of two different species.

When compared to the relation between the variables, relatively low but statistically high correlation was calculated for E_{dyn} and MOR of all samples. Accordingly, prediction of MOR of oak wood using ultrasound propagation is quite fair by 0.71 R^2 value.

Korkut and Hiziroglu (2009) stated that there is statistically significant differences between the MOR and MOE of control and 180 °C 10 h treated samples of hazelnut. In this study, as expected, significant decreased in MOR and MOE were seen in 210 °C 8 h treatment, but remarkable decreases were also occurred at 180 °C 8 h treatments. Therefore, results of the study indicated the same behavior for different hardwood species.

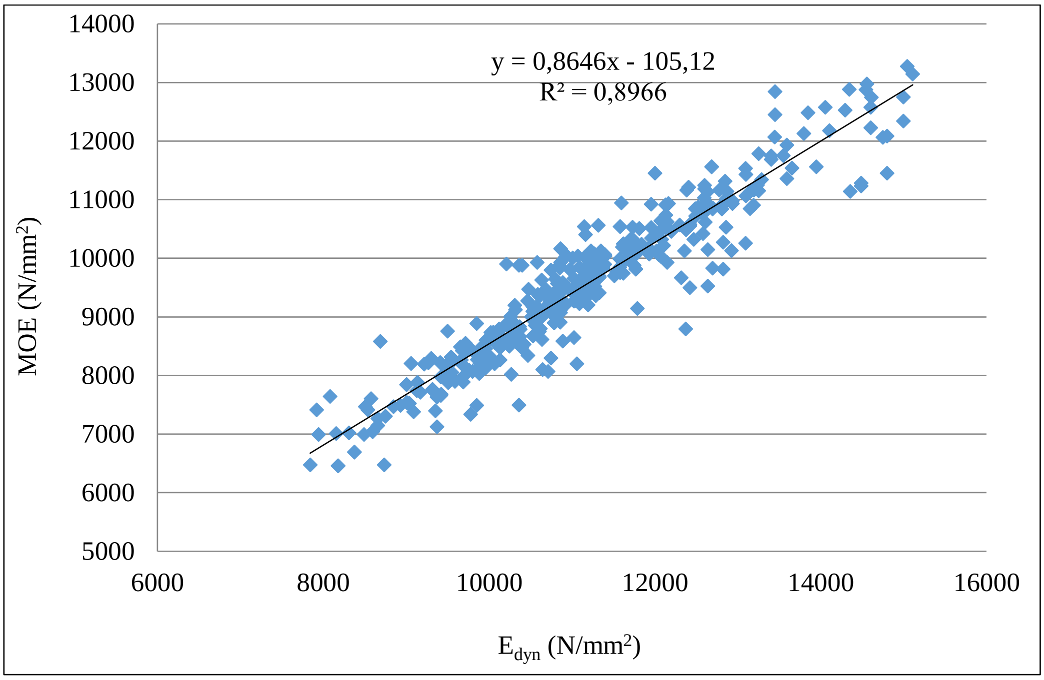

Figure 2. The relationship between E_{dyn} and MOE of all species tested.

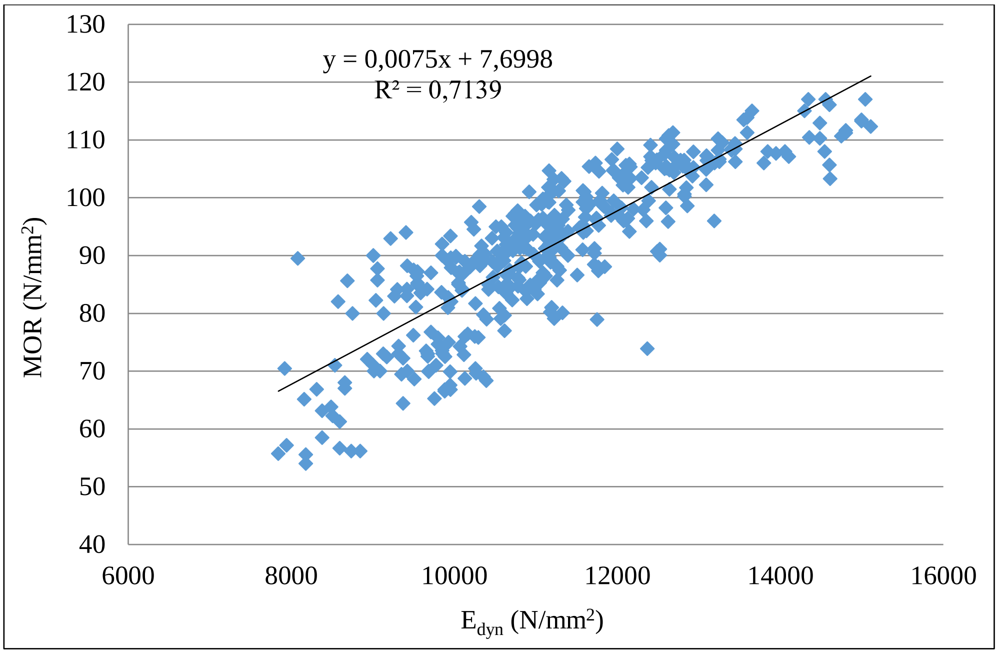

Figure 3. The relationship between E_{dyn} and MOR of all species tested.

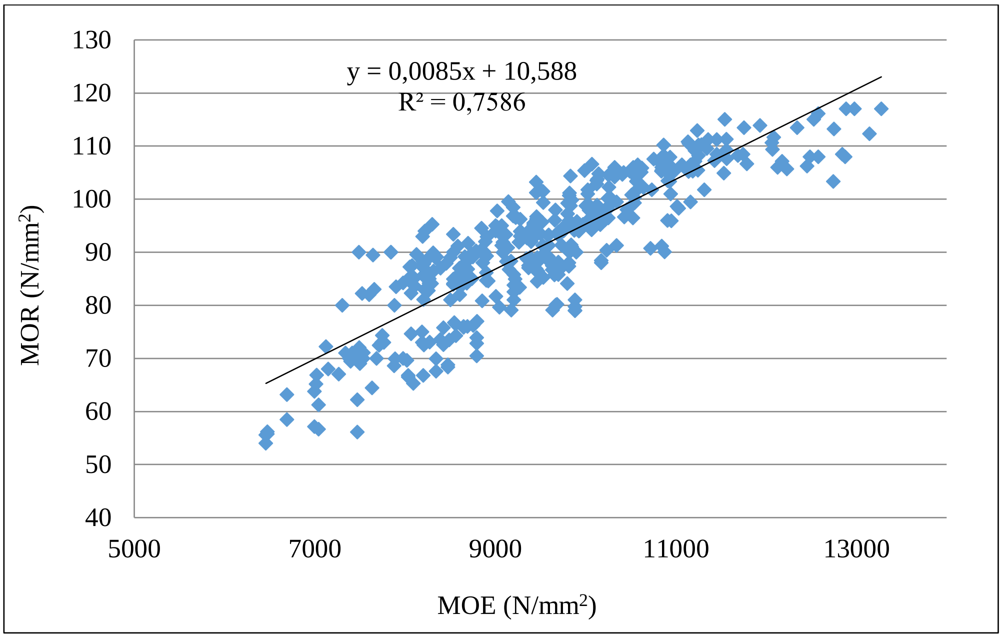

Figure 4. The relationship between MOE and MOR of all species tested.

External factors such as temperature, heating time, type and composition of the surrounding atmosphere have influences on the chemical changes during the heat treatment process of wood. Furthermore, heat treatment conditions significantly affect the lots of competitive reactions that take place simultaneously during the process. Therefore, it is assumed that one of the reasons for the reported values of heat treated wood that significantly differ from one another (Kubovský et al. 2020). However, comparatives in this study were not significantly differed due to almost the same acclimatization and testing tools were used in the stable air-conditioned testing room even if the species were different.

Degradation of the chemical compounds and volatilization of extractives play critical role on the structure unity, and, further temperatures and prolonged exposure durations bring forward the degradative process. For example, effect of temperature is more intensive beyond the 225 °C (Schaffer 1970). But, in this study, such a conditioning was not performed to investigate the effect on MOE of oak wood. Also, low equilibrium MC may be assumed as one of the essential factors for the increases in properties.

4. Conclusion

Short period (up to 8 hours) of exposures to the relatively low temperatures (particularly for 120 °C) makes remarkable improvements on longitudinal ultrasonic wave velocity, modulus of elasticity calculated by velocity and three points bending test, and modulus of rupture. But, further treatments have different negative effects on these properties especially for prolonged exposure duration. According to Pearson correlation coefficients, positive linear correlations between the dynamic vs static results of modulus of elasticity and modulus of rupture, and modulus of elasticity vs modulus of rupture were figure out. However, such fair positive correlations were not observed between the velocity and E_{dyn}, MOE, or MOR.

Coefficients of determination helping to be figured out those dynamically predicted values can fairly estimate the statically determined temperature influenced MOE and MOR values.

Influences of the long term exposure durations and higher temperatures on the relation between static and dynamic results should be evaluated to figure out the applicability of ultrasonic testing and evaluation on the prediction of wide range modification conditions.

Ultrasonic wave velocities are required to calculate the properties of materials. However, they should not directly used for interpretation of the relation between the variables as seen in results.

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