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Comparison of temperature dependent Young's modulus of oriental beech (*Fagus orientalis* L.) that determined by ultrasonic wave propagation and compression test

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Abstract: Mechanic properties of wood material change depending on lots of natural and environmental factors. Temperature is one of these factors and in this study, effect of temperature on Young's modulus of Oriental beech wood was investigated. Longitudinal direction (L) compression test samples exposed to 120, 150, 180 and 210°C temperature for 2, 5 and 8 hours. A drying oven that operates in an atmospheric environment was used for temperature treatment. Static and dynamic Young's modulus values were determined or predicted by compression test and ultrasonic wave propagation method, respectively. Results compared with each other by regression analysis to determine how successful the ultrasonic measurement is. All test samples, 20x20x60 mm, acclimatized at 20 ±2°C and 65% RH conditions. Deformation values of the tested samples were obtained by using bi-axial extensometer and then stress-strain curves were created. Static Young's modulus was calculated by using stress-strain values from the linear elastic region of these curves. E_{dyn} was predicted by using ultrasonic wave velocity and sample density values. Velocities were calculated by using time of flight values obtained by ultrasonic measurements. Reasonable and good relations between dynamic and static modulus of elasticity were determined by the coefficient of determination results that ranged from 0.78 to 0.94 in terms of temperature and exposure duration. Consequently, L direction Young's modulus of Oriental beech wood that exposed to temperature can be well predicted by using ultrasonic measurement.
Keywords: Oriental beech, Young's modulus, Non-destructive test, Ultrasonic

Ultrasonik dalga yayılımı ve basma testi ile elde edilen doğu kayını odununun (*Fagus orientalis* L.) sıcaklığa bağlı Young's modüllerinin karşılaştırılması

Özet: Ahşap malzemenin mekanik özellikleri birçok doğal ve çevresel faktörlere bağlı olarak değişmektedir. Sıcaklık bu faktörlerden biridir ve bu çalışmada sıcaklığın kayın odunu Young's modülü'ne etkisi incelenmiştir. Lif yönlü (L) basma testi örnekleri 2, 5 ve 8 saat süre boyunca 120, 150, 180 ve 210°C sıcaklığa maruz bırakılmıştır. Sıcaklığa maruz bırakma işleminde atmosferik ortamda çalışan etüv kullanılmıştır. Statik ve dinamik Young's modülü değerleri basma testi ve ultrasonik dalga yayılımı yöntemleri ile belirlenmiştir. Ultrasonik ölçümlerin başarısını belirlemek için elde edilen sonuçlar birbirleri ile regresyon analizi ile karşılaştırılmıştır. 20x20x60 mm ölçülerindeki tüm test örnekleri 20±2°C sıcaklık ve %65 bağıl nem koşullarında iklimlendirilmiştir. Test edilen örneklerin deformasyon verileri bi-aksiyal ekstensometre kullanılarak elde edilmiştir ve sonrasında gerilme-şekil değiştirme eğrileri oluşturulmuştur. Statik Young's modülü değerleri gerilme-şekil değiştirme eğrilerinin doğrusal elastik bölgesindeki gerilme-şekil değiştirme verilerinden hesaplanmıştır. E_{dyn} ultrasonik dalga hızı ve örnek yoğunluğundan tahmin edilmiştir. Hızlar, ultrasonik ölçümler ile elde edilen dalga uçuş süreleri kullanılarak hesaplanmıştır. Sıcaklık ve süre bağlamında dinamik ve statik elastikiyet modülleri arasındaki kabul edilebilir ve iyi dereceli ilişkiler 0.78 ile 0.94 arasında değişen belirtme katsayıları ile belirlenmiştir. Sonuç olarak sıcaklığa maruz bırakılmış doğu kayını odununun L yönündeki Young's modülü ultrasonik ölçümler ile iyi bir şekilde tahmin edilebilir.
Anahtar kelimeler: Doğu kayını, Young's modülü, Tahribatsız muayene, Ultrasonik

1. Introduction

Wood is one of the most common used material from past to today. It's a multifunctional material which can be used as building material, energy source or decoration. Also it's a renewable material but if the ratio between consumption and production allows the renewability or redress the balance. Unfortunately there are lots of factors that affect this balance. Increasing population and therefore increase in the demand of wood are not only the unbalancing factors but also decrease in available tree or wood sources and increase in wood processing costs. Therefore, proper and wise use of wood material is important to ensure balance between consumption and production. So, environmental and material properties must be known to provide safe, stable and long-life wooden part or products. And, mechanical testing is the beginning and the crucial step to determine the real-like behavior of parts, products or systems as a whole during daily use. Static or as alias destructive testing (DT), being costly, causes

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deformations which means that tested samples will be unusable anymore, and time-consuming, is one of these tests and the other one is dynamic or as alias non-destructive tests (NDT). Non-destructive evaluation of the materials becomes even more important due to some reasons. Oliveira and Sales (2006) expressed this importance as decrease in sources and increase in costs caused to spread of interest on cost-effective NDT methods to classification or evaluation of wood. And, ultrasonic method, one of the common used NDT techniques, is remarkable in wood evaluation when its' relatively low-cost, safety, and versatility taken into consideration.

Dundar and Divos (2014) published a review study to lay emphasis on NDT and evaluation of wood. Dundar et al. (2016) investigated the usability of ultrasonic wave velocity on the determination of dimensional stability of some hardwoods. Ultrasonic method was used to determine different aspects such as mass density by Metwally et al. (2016), effects of MC by Karlinasari et al. (2016), Yang et al. (2015), Dundar et al. (2016), Van Dyk and Rice (2005), specific gravity by Calegari et al. (2011), hole size and amounts by Wang and Wang (2011), some mechanic properties by Dzbenski and Wiktorski (2007), Gonçalves et al. (2014), Vázquez et al. (2015), Gonçalves et al. (2011), Vázquez et al. (2013), Guntekin et al. (2016a;b) and, etc. Effects of decays on ultrasonic measurements studied by Reinprecht and Hibky (2011), Schubert et al. (2005; 2006) and Titta (2006). Besides, temperature, another important factor that affects the material properties, studied by Becker and Noak (1968) and Bucur (2006) using beech wood, and Ridley-Ellis et al. (2014) using heat treated scots pine wood by ultrasonic evaluation. Effects of temperature on stress wave speed, ultrasonic wave speed and acoustic vibration performance investigated by DeVallance (2009) and Llana et al. (2013, 2014) and Gao et al. (2011) and Zhu et al. (2016), respectively.

Elastic properties of wood, define the elastic behavior, consist of twelve parameters. And, these properties can be determined by different static test methods such as bending, compression, tension etc. Gaff and Gasparik (2015) determined the modulus of elasticity of aspen wood by three-point bending test. Xavier et al. (2012a;b) performed compression test to determine longitudinal modulus of elasticity of maritime pine. Kin and Shim (2010) compared the compressive and tensile Young's modulus of some structural size Korean and Japanese lumber.

As well-known from the literature, environmental factors such as Moisture Content (MC) and temperature (T) are some of the important factors that affect the mechanic properties or material parameters. So, it's important to determine the material properties by taking into consideration of environmental impacts. These parameters, affected or not, can be determined or estimated by DT and NDT methods. Lots of studies reported that results of NDT were comparable and compatible with the DT results. Temperature dependent elastic properties of Beech wood, grown in Turkey, still not figured out and the main aim of this study was to determine some of these properties by DT and NDT methods and present whether results of these two methods are comparable or not. Therefore, in this study, temperature dependent Young's modulus of L direction was determined by compression test (CT) and ultrasonic wave propagation method.

2. Material and method

2.1. Material

Logs were obtained from selected standing Oriental beech (*Fagus orientalis* Lipsky.) trees in Devrek forestry department's zone located at northwest of Black Sea region of Turkey. Diameter of the standing trees were about 50cm and trunk of them were straight. Used logs cut from breast height to 3 meters of tree. And then, logs were sawn into lumbers. Laths, 22x65mm cross-cut, prepared from sapwood of those lumbers by taking fiber direction into consideration. These laths separately exposed to 120, 150, 180 and 210℃ temperature for 2, 5 and 8 hours in a drying oven (NUVE FN500, Ankara, Turkey) which operated in an atmospheric environment. Also each temperature and duration groups had their own control groups to ensure the matching of each tested samples or groups. By this means differentiations between groups and control samples minimized. L direction CT and ultrasonic test (UT) samples, 20x20x60mm, prepared using temperature treated laths as seen in Figure 1. All samples acclimatized around 6-8 weeks at a constant temperature 20±1°C and 65% relative humidity (RH) using HCP108 humidity chamber (Memmert Gmbh+Co. KG, Schwabach, Germany).

2.2. Method

Before performing the tests, density of the samples were determined according to TS 2472 (2005) standard which uses stereo-metric method.

Ultrasonic measurements were performed by using Epoch 650 flaw detector (Olympus, USA). And, contact type transducer that propagates L direction waves at 2.25 MHz frequency were used to measure time of flight (ToF) values. Direct method was used in ultrasonic measurements. Olympus ultrasonic coupling medium was used to minimize to noise and ensure the surface contact between the transducer and samples. Ultrasonic wave velocities (UWV) were calculated by velocity and time relation using obtained ToF values. Then, E_{dyn} calculated using Equation 1.

$$E_{dyn} = \rho V^2 10^{-6} \qquad (1)$$

where; E_{dyn} is dynamic elasticity modulus (N/mm^2), ρ is density (kg/m^3) and V is ultrasonic wave velocity (m/s).

Static (compression) tests were conducted in a room that acclimatized at 20°C and 65%RH conditions. Universal Test Machine (UTM) with 5 metric tons load cell was used for static tests. Loading speed of the tests was 6mm/min. Strain values which is required for calculation of Young's modulus was obtained by using Epsilon 3560 bi-axial extensometer, as seen in Figure 2, (Epsilon, WY, USA) and then stress-strain curves were created. Static Young's modulus values were calculated with stress (σ) and strain (ε) values of linear elastic region of these curves using Equation 2.

$$E_i = \frac{\Delta\sigma_i}{\Delta\varepsilon_i} = \frac{\sigma_{i,2}-\sigma_{i,1}}{\varepsilon_{i,2}-\varepsilon_{i,1}} \; i \in R \qquad (2)$$

Relation between static and dynamic Young's modulus values were statistically evaluated by coefficient of determination (R^2) analysis.

3. Results and discussion

Average density, UWV, E_{dyn}, and Young's modulus values of Beech wood were presented in Table 1. In general, it's seen that density decreased when temperature increased as seen in Figure 3. Average density of the untreated beech wood was calculated as 0.68 g/cm^3. Decrease rates varied according to temperature and duration of the exposure. But, maximum decrease (0.60 g/cm^3) occurred on the samples that exposed to 210ºC for 8 hours. Decrease on density may be related to decrease in Moisture Content (MC), mass loss, and chemical reactions due to increased temperature and exposure duration.

UWV depends on lots of factors such as density, MC, temperature, medium, and etc. As expected, density of the samples decreased when temperature and exposure duration increased. Also, MC of the samples also decreased. As seen in Table 1, UWV increased with the increase of exposure durations for 120ºC group, slightly increased (except 5 hours) for 150 ºC group, nearly became constant for 180ºC group, and decreased through the exposure durations for 210ºC group. These results may be occurring due to combined effects of MC and density loss. But, a significant relation between UWV and density could not be found. So, there is not a consensus among there is a positive relation between UWV and density (Oliveira and Sales, 2006; Baradit and Niemz, 2012) and there is no relation between UWV and density (Oliveira et al. 2002; Ilic, 2003; Teles et al. 2011).

Figure 1. Figurative steps of the sample preparation

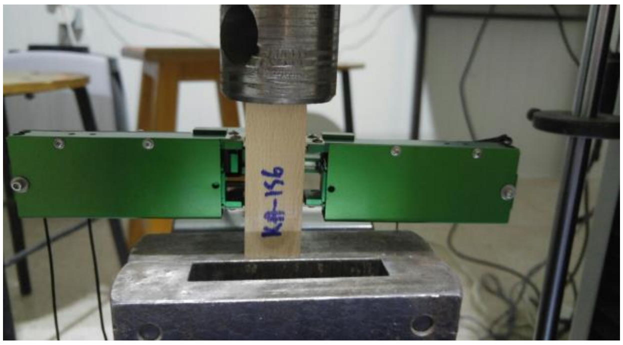

Figure 2. Bi-axial extensometer and compression test configuration

Table 1. Density, UWV, E_{dyn} and Young's modulus values of Beech wood

Temp. ºC	Exposure Duration (Hours)	Density (g/cm^3)	Velocity (m/s)		E_{dyn} (N/mm^2)		Young's Modulus (N/mm^2)	
			Mean	Cov*	Mean	Cov*	Mean	Cov*
120	0	0.68	4584.14	3.09	14230.38	5.70	12984.73	9.20
	2	0.67	4656.90	4.12	14495.00	7.67	13444.53	10.06
	5	0.67	4697.51	2.75	14722.79	5.32	13919.59	7.46
	8	0.66	4793.06	3.40	15172.28	6.45	14359.91	7.65
150	0	0.68	4462.79	4.17	13554.68	8.46	12561.45	8.80
	2	0.67	4667.72	2.50	14535.18	4.68	13868.95	5.79
	5	0.66	4574.03	4.07	14045.30	10.21	14199.94	8.75
	8	0.66	4674.23	4.51	14490.89	9.02	14635.61	8.28
180	0	0.68	4490.86	4.45	13794.61	7.43	12624.24	8.88
	2	0.67	4490.83	3.30	13439.73	6.86	12846.82	7.92
	5	0.65	4468.86	2.90	12921.76	5.57	11905.29	6.98
	8	0.64	4442.52	2.80	12539.22	4.99	11306.79	7.70
210	0	0.68	4510.98	4.43	13847.77	8.10	12491.32	9.57
	2	0.66	4494.00	3.11	13228.53	5.79	11774.00	7.39
	5	0.65	4360.85	4.43	13228.98	7.25	11141.30	11.76
	8	0.60	4383.48	3.32	11439.40	6.81	10010.80	9.19

*Coefficient of Variation (%)

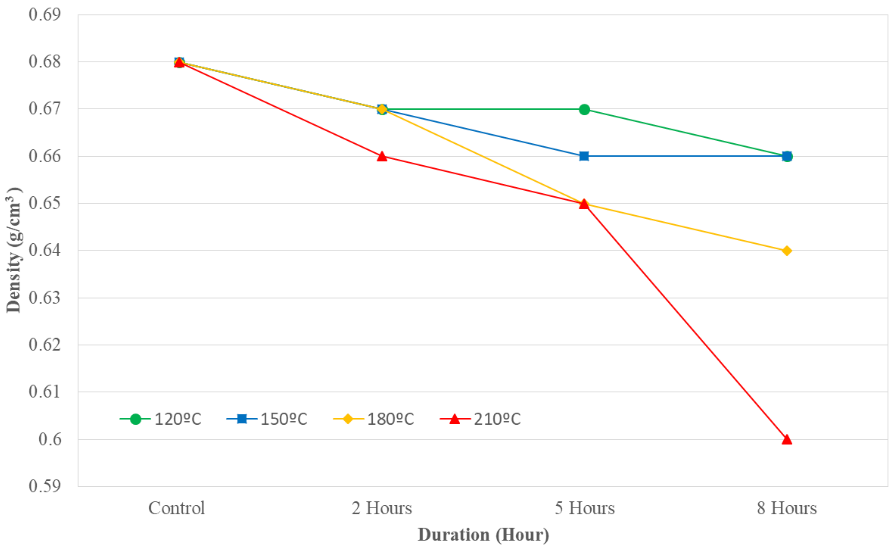

Figure 3. Density change graphs based on temperature and exposure duration

E_{dyn} values, seen in Table 1, presented nearly same behavior with the UWV in terms of temperature and exposure duration. A little amount of increase in E_{dyn} took place just for 120ºC and 150ºC but 19.61% decrease observed when temperature and exposure duration increased from 150 to 210ºC. This decrease may be occurred due to decrease in density and chemical degradation. It's seen that effect of temperature and exposure duration on Young's modulus that predicted by using ultrasound was lesser. Micro-cracks and other invisible inner faults might occurred due to exposure to temperature and these discontinuities can affect the E_{dyn} prediction. Therefore, a few parameters may have effects on non-destructive testing (NDT) and this should be taken into consideration while performing NDT as Llana et al. (2014) reported.

As seen in Table 1, Young's modulus values of Oriental beech wood obtained by compression tests increased 10.59% and 16.51% at 120 ºC and 150ºC temperature treatments while exposure duration increased 0 to 8 hours, respectively. But, values decreased 10.24% and 16.66% when temperature and exposure duration increased up to 180ºC and 210ºC and 0 to 8 hours, respectively. Coefficient of variation (CoV) of static Young's modulus values varied between 5.79% and 11.76%. It's known that temperature has influences on physical and mechanic properties of wood. But influences differ from the temperature level and exposure duration. And it's seen that relatively low temperature levels and higher exposure durations (except for dynamic results of 5 hours at 150ºC) have positive effect on Young's modulus while higher levels have negative. These increases may be related to low moisture content and same results reported by the following literature. Windeisen et al. (2008) and Taghiyari et al. (2012) reported a slight increase in L direction compression stress of thermally treated poplar, beech and ash wood. This increase can be attributed to increase in crystallite index of cellulose. According to Esteves and Pereira (2009) modulus of elasticity in bending increases if the treatment period is short and temperature is low. And, values decrease if treatment period and temperature increase. Same results reported by Holeček et al. (2017) for heat treated Spruce wood. Kubojima et al. (1998) figured out temperature related L and R direction Young's modulus of heat treated (120, 160 and 200°C) Sitka spruce wood. They reported that values increased in the first two hours of treatment and then became constant except 200°C. Young's modulus values increased in the beginning of the treatment at 200°C and then decreased. Kubojima et al. (2000) reported that Young's modulus values increased in the beginning of heat treatment and then decreased. According to Schaffer (1970) modulus of elasticity was much more affected by the temperature above 225°C.

Boonstra et al. (2007) widely discussed the reasons for the changes in mechanic properties. It's mentioned that poly-condensation reaction of lignin which results the cross-linkage has positive effect essentially on longitudinal direction. Lower equilibrium moisture content (EMC) may have positive effect on strength properties of heat treated wood but this effect can be surpassed or made meaningless by the degradation of chemical compounds. It's thought that transformation of hemicellulose into third party by the degradation and vaporization of extractives are the main reasons of decrease in density. It's evaluated that degradation of hemicellulose by increase in temperature and exposure duration is the essential reason of the decrease in mechanic properties (Boonstra et al. 2007). Also, formed micro-cracks by temperature can affect mechanical properties (Esteves and Pereira, 2009).

Ultrasonic testing and evaluation is relatively easy and cost-effective method. And, it can be applicable instead of the static tests if the results of the investigated properties are close to each other. Regression equation between ultrasonic and static tests were created to determine whether it's applicable for prediction of temperature dependent Young's modulus of beech wood as seen in Figure 4, 5, 6 and 7. Relation between static and dynamic (E_{dyn}) Young's modulus values were presented in these figures. And, it's seen that there are reasonable and strong relations between static and dynamic results. Best correlation (R^2: 0.94) was obtained on 2 hours treatment at 120°C and control group of 210°C. Minimum correlation (R^2: 0.78) was obtained on 5 hours treatment at 150°C.

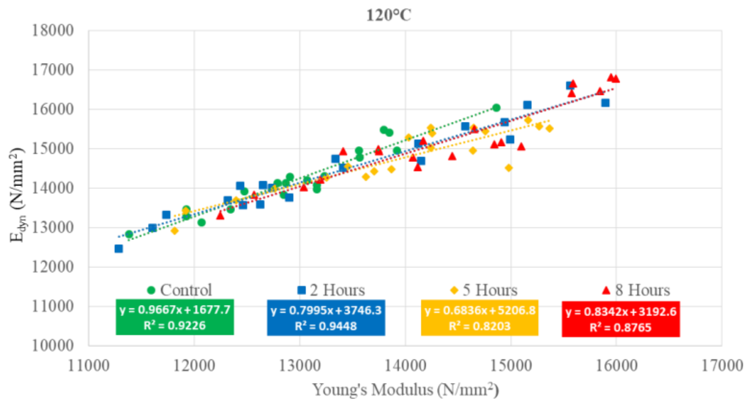

Figure 4. Coefficient of determination between Young's modulus and E_{dyn} at 120°C

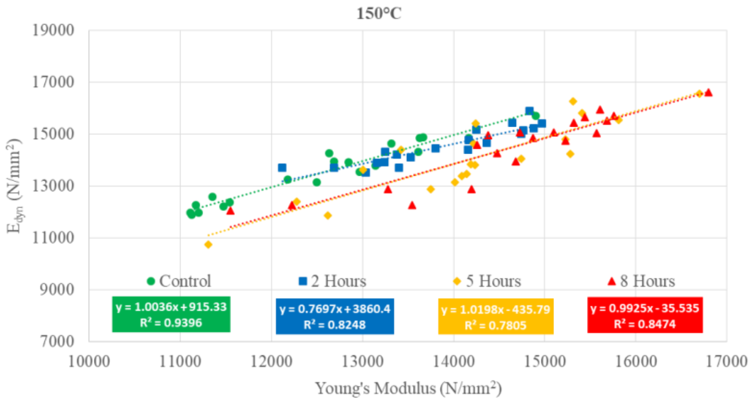

Figure 5. Coefficient of determination between Young's modulus and E_{dyn} at 150°C

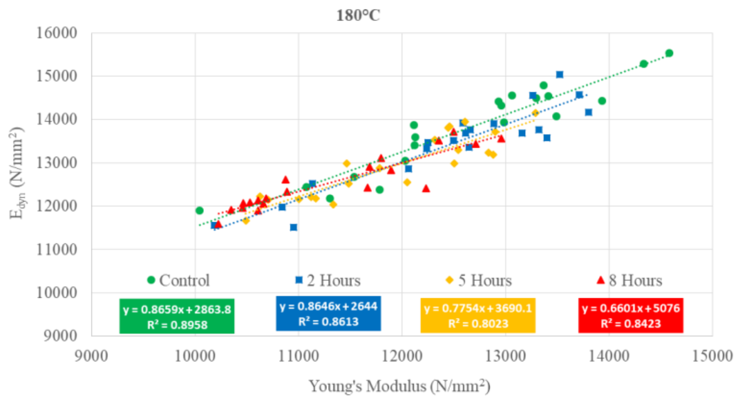

Figure 6. Coefficient of determination between Young's modulus and E_{dyn} at 180°C

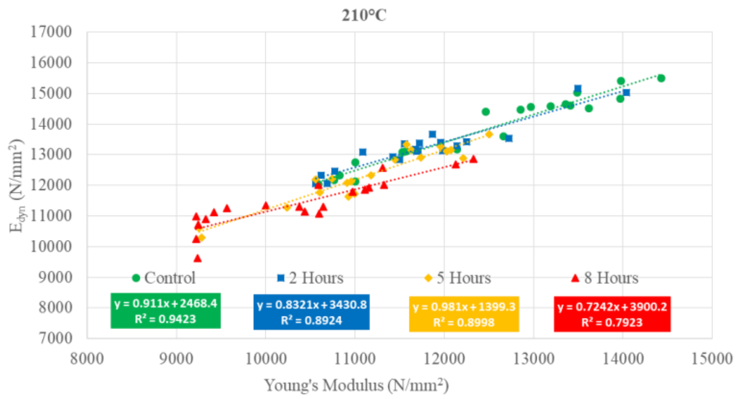

Figure 7. Coefficient of determination between Young' modulus and E_{dyn} at 210°C

4. Conclusion

In this study, Young's modulus of temperature treated Oriental beech wood was determined by using both destructive and non-destructive test methods. Elastic properties of species, grown in Turkey, are represented or interpreted using modulus of elasticity (MOE) values which calculated by bending tests. But elasticity values, obtained by bending tests, include shear deformation and that's why these values are lower than the actual values. Therefore, in this study modulus of elasticity values were calculated by compression test.

According to results, it's seen that temperature and exposure duration have effects on Young's modulus and E_{dyn} values. Increase in exposure duration has positive effect on Young's modulus at 120°C and 150°C temperature levels. But, from this point on, exposure duration and temperature have adverse effects. In this study, values slightly increased in the beginning of the treatment and then decreased with the increase in temperature and exposure duration as literature says. Decrease in MC might have positive effect at the beginning of the treatment but further treatment may cause much more chemical degradation and therefore decreases in values.

As know from the literature, ultrasonic measurements may overestimate the results. And, in this study, E_{dyn} values were little more than static ones. In this sense, results agree with the literature. E_{dyn} values decreased up-to 19.61% when temperature and exposure duration increased.

It's seen that there is a reasonable and good correlation between E_{dyn} and static Young's modulus values. And, coefficient of determination (R^2) values ranged from 0.78 to 0.94. Consequently, results approved that L direction Young's modulus values can be predicted by using Ultrasonic measurements. These results can be used as an input parameter for temperature dependent structural analysis.

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