The Effect of Hygroscopic Wood Structure on Some Properties of Heat Treated Products Formed with the Thermowood Method

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Changes were determined for the values of physical and mechanical properties resulting from hygroscopicity in some wood species after heat treatment (HT), and to reveal statistically the relationships between the properties. For this purpose, aspen (*Populus tremula*) and fir (*Abies nordmanniana* subsp. *bornmuelleriana*) species were evaluated for weight loss (WL) during HT as well as water thickness swelling (WTS) and weight and volume change rates upon water imersion. The amounts and density values of longitudinal, radial, tangential, and volumetric contractions and expansions, static bending resistance (MOR) and static bending modulus of elasticity (MOE) were examined. From the results and correlation analysis, it was determined that while WL increased in all variations with HT, the WTS values from the HT samples in water for 24 h decreased with the increase in temperature and time, while water retention was at similar rates in all variations, including UT. At the same time, HT resulted in significant decreases in all density values and contraction and expansion values, and the dimensional stability improved. On the other hand, it was understood that HT did not negatively affect both MOR and MOE resistance values at the 180 °C and 200 °C conditions. These results showed that heat-treated wood products can be a good alternative to avoid problems caused by hygroscopicity under the influence of intense water contact.

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INTRODUCTION

Wood material, which has natural advantages such as superior strength, lightness in weight, thermal insulation, easy workability, and better seismic performance (Dukarska and Radosław 2023), has been used as a building material since ancient times. Wooden material continues to be widely used today as an environmental-friendly and renewable building material suitable for the sustainable development in many other areas (Zongying *et al.* 2019). In recent years, wood material has been used extensively in the production and use of urban furniture within the scope of landscaping applications (Ulay and Yeler 2020). In addition, as an extreme example, it is even reported that it is possible to use very small-sized wood material, as it provides improvement in the dimensional stability properties of brake pads (Akıncıoğlu *et al.* 2019).

When it comes to the use of wood material both for structural purposes and in urban furniture, its hygroscopicity stands out as a key feature, as in many other areas of use.

Hygroscopicity is seen as a positive feature in most industrial applications based on wood materials. However, there is a strong negative relationship between the lifespan of a structural unit and hygroscopicity, as it weakens the strength and increases the risk of fungal and insect attacks (Zongying *et al.* 2019). This situation is mostly caused by the change in dimensional stability in water exchanges below the fiber saturation point (LDN) of the wood material, in connection with hygroscopicity (Korkut and Budakçı 2010; Güller 2012). On the other hand, wood material actually offers a wide range of options for structural purposes, thanks to a wide range of products with different technological and usage features, not only natural but also derived from it, many of whose features have been improved compared to its natural state. However, mostly wood derivatives contain negative effects caused by hygroscopicity, and the negative effects that occur with natural wood materials also occur in tree species (Vololonirina *et al.* 2014).

It is certain that the hygroscopicity of wood, which has a wide and widespread use as an industrial raw material, will play an important role in its correct evaluation. In this regard, it is necessary to understand the wood material-water relations about hygroscopicity. Wood, which is a hygroscopic material, absorbs moisture from its surroundings or gives moisture to its surroundings in the same way, depending on the amount of moisture present in the material. In addition to the environmental properties of the wood, the chemical composition of the wood, such as the presence of hydroxyl groups, also play an important role in moisture exchange. Moisture exchange continues until the water vapor pressure of the air and the water-attracting power or water-repelling power of the wood are equal and an equilibrium is established between the air and the wood. This balance, which occurs at humidity levels below the fiber saturation point, is called "hygroscopic balance". When the wood material absorbs water from the surrounding air (adsorption), it expands in size, and when it releases water to the surrounding air (desorption), it shrinks; these two situations are expressed as "working of the wood" (Berkel 1970; Kantay 1993; Örs and Keskin 2001). The fact that the size change that occurs with the working of wood does not cause problems in all areas of use of wood materials and derivatives depends on the work remaining within certain limits. However, the relationship of wood materials used for purposes such as decks and benches with water is multifaceted and is not limited to just adsorption and desorption. In practice, wood material exposed to the influence of pool water, rain, snow, frost, and fog in open areas can be in contact not only with water vapor but also with liquid water molecules or directly in water. In this case, there is an additional volumetric expansion and thickness swelling caused by the presence of water in the dimensions of the wood material (Aytin *et al.* 2018). In addition, as the amount of water in the wood material changes, many mechanical properties are affected, and as the water content increases, the resistance values decrease (Kherais *et al.* 2024). It is desired that the wood material maintains its current state, that is, be stable, even if it is in intense contact with water. Therefore, it is necessary to prevent problems arising from hygroscopicity for wood materials, to somehow cut off contact with water or minimize the effect of contact. For this purpose, it is possible to prevent water-borne effects by applying various methods such as impregnation, drying, surface treatments, and modification. Choosing the best method where the wood material will be used, expected product performance, economy, applicability, and environmental priorities may vary depending on many factors. Several modification methods are used to reduce the hycroscopicity in wood material. Among these, heat treatment (HT) stands out as a convenient option and an environmentally friendly modification method to minimize the hygroscopic property of wood material. In HT, dimensional stability changes, increased resistance to fungal degradation, and a homogeneous coloring occurs along with darkening of color (ThermoWood® Handbook 2003; Boonstra and Tjeerdsma 2006; Sundqvist *et al*. 2006; Esteves 2009; Sandberg *et a*l. 2017). One of the most basic recovery of HT is the expectation regarding the minimum consistency of volumetric change despite the highest amount of water absorbed below the fiber saturation point. However, HT also affects the mechanical strength values. While compressive strength increases depending on HT conditions, decreases are observed in other mechanical strength values (ThermoWood® Handbook 2003; Aytin 2013; Kamperidou *et al*. 2014; Aytin *et al*. 2018), which limits the potential use of HT (Wang *et al*. 2020).

It is of great importance to know the values of hygroscopicity and other relevant usage properties in order to evaluate HT materials within the scope of mandatory standards in places of use, where the changes caused by HT in the wood material structure are taken into consideration. At the same time, revealing the relationships between these features with concrete numerical data is very valuable in terms of the guidance it will give to the users. Considering its dimensional stability and water retention properties, a study conducted with ash tree (*Fraxinus angustifolia* Vahl.) growing naturally in Turkey is promising, and it is stated in the study that wood material properties can be improved specific to their usage areas by applying HT without the use of toxic chemicals (Şahin and Guler 2018). Additionally, considering that the product performance in mechanical properties remains at a sufficient level and/or is close to it, it is clear that the contribution of HT to the evaluation of wood material will be quite large.

In this study, an attempt was made to reveal the relationship of HT with the presence of water in some tree species, the change of this relationship in comparison to natural wood material, and the relationship between these changes, important static bending for the usage areas of the same tree species, and the change of elasticity modulus in static bending. Thus, it was aimed to reveal the potential of using HT-applied wood materials for usage areas where the wood material is under the influence of intense moisture and direct contacts with water. For this purpose, after the wood samples were subjected to HT with the ThermoWood® method, water retention, swelling in thickness, and specific gravity change were determined by soaking in water for 24 h; dimensional stability and specific gravity change in samples; weight loss; bending resistance and elasticity modulus changes in static bending were determined. Relationship analysis (correlation) was done to reveal changes in physical and mechanical properties with HT and their interaction with each other.

EXPERIMENTAL

Materials

The tree species used in the study were obtained from Düzce Forest Management Directorate of Düzce province in Türkiye and TS 4176/1984. In this context, five trunks each of poplar (*Populus tremula*), fir (*Abies nordmanniana* subsp. *bornmuelleriana*), rowan (*Sorbus torminalis*), and cherry (*Cerasus avium* (L.) Monench) trees, which have significant potential in trade, were taken from their natural habitats. The selected trees were divided into 2 (m) trunk sections after a height of 1.30 (m) from the bottom, and the trunk sections were sawn into 60 (mm) thick planks using the sharp cutting method according to TS 2470/1976 (Figs. 1a, b, c, d, e, f, g, h, i). Then, the planks were dried to an average of 12% final humidity by the classical drying method and were kept in the air conditioning room that can be adjusted to 20±2°C and 65±5% relative humidity.

a. Rowan log b. Fir log c. Cherry log

d. Fir plank production e. Rowan plank production f. Cherry plank production

g. Rowan- Aspen stacking h. Cherry stacking treatment i. Cherry before heat

Fig. 1. Selected tree samples

Heat Treatment

Heat treatment was carried out using the ThermoWood® method by Nova Orman Ürünleri San.. Tic. A.Ş.'s Gerede/Bolu factory with air-dried wood materials. In the ThermoWood® method, heat treatment is carried out under steam protection and at temperatures of 190 °C and above. In this study, four different variations were created for the working trees in accordance with the production program of the enterprise. After the test samples to be used within the scope of the study from the HT planks were prepared according to TS CEN/TS 15679, they were kept in the air conditioning room with 20%±2 °C temperature and 65±5% relative humidity for 2 months until they reached a constant weight and experimental studies were carried out (Table 1).

Table 1. Trial Pattern Variations of the Wood Materials Used in the Study

Control	Untreated	-	UT
HT variations	190 °C	1 saat	HT_1
		2 saat	HT_2
	212 °C	1 saat	HT_3
		2 saat	HT_4

Weight Loss (WL)

The heat-treated WL samples were weighed after drying completely at 103±2 °C, and the WL (%) change was calculated the formula (Eq. 1):

$$WL = [(M_{TWo\ (1,2,3,4)} - M_{UTo}) / M_{UTo}] \times 100\ (\%) \tag{1}$$

In the formula, WL refers to the weight loss, M_{TWo} refers to the full dry weights of (1,2,3,4) thermal variations, and M_{UTo} refers to the full dry weight of the control sample.

Determination of Density

The principles of TS ISO 13061-2 (2021) and TS ISO 13061-1 (2021) were followed to determine their densities.

Determination of Radial, Tangential, and Volumetric Shrinkage (β) and Swelling (α)

The standards TS ISO 13061-13 (2021), TS ISO 13061-15 (2021), TS ISO 13061-14 (2021), and TS ISO 13061-16 (2021) were used to determine the amounts of the compression and expansion.

Determination of Water Thickness Swelling (WTS), and Water Retention Amount (WR)

The test pieces were immersed in water at 20 ± 1 °C with a pH value of 7.0 ± 1.0. The samples were placed vertically at the bottom of the water tank so the samples did not touch the sides. According to TS EN 317 (1999), the upper parts of the test pieces must be approximately 25 mm ± 5 mm inside the water. After 24 h, the test sample immersion process measurements were taken by pouring off the excess water. The WTS and WR were calculated as a percentage according to Eq. 2,

$$A = [\ I - E\ ] / \mathrm{I} \times 100\ (\%) \tag{2}$$

where A is the change between initial measure and final measure as a percent, I is initial measure, and E is the final measure (Aytin et *al*. 2015).

Determination of Static Bending Strength (MOR), and Static Bending Modulus of Elasticity (MOE)

Among the mechanical properties, MOR according to TS ISO 13061-3 (2021), and MOE according to TS ISO 13061-4 (2021) were obtained. After the MOR test, the humidity values were determined according to TS ISO 13061-1 (2021).

Statistical Calculation

The values obtained from the experiments were evaluated using SPSS 15.0 for the Windows Evaluation Version (IBM, New York, USA). The statistical evaluation of the results was completed through the basic variance analysis (BVA) using SPSS. Significant differences between the average values of the control and treated samples were determined using Duncan’s multiple range test. Additionally, correlation analysis was performed on the test results using SPSS 15.0. In the correlation analysis, “Pearson's Correlation Coefficient (r)” was used. Pearson’s Correlation Coefficient is used to measure the degree of linear relationship between two variables, thus providing an answer to the question of whether there is a significant relationship between two variables. In this study, the analysis was made according to the “r” value between the two variables, as given in Table 2.

Table 2. Classification According to the "r" value between Two Variables

r	Relationship	Group
0.00-0.25	Very weak	1
0.26-0.49	Weak	2
0.50-0.69	Medium	3
0.70-089	High	4
0.90-1.00	Very high	5

RESULTS AND DISCUSSION

Results of Weight Loss (WL)

The WL results caused by HT in fir, cherry, aspen, and rowan trees were determined in terms of wood type (WT), HT, and the interaction of WT and HT (SUB$_{HT}$), and the analysis of variance (VA) and homogeneity test results are given in Table 3.

Table 3. Analysis of Variance and Homogeneity (HG) Test Results Regarding WL

VA	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
	WT	303.833	3	101.278	0.821	0.483
	HT	3583.223	3	1194.408	9.687	0.000
	SUB$_{HT}$	939.292	9	104.366	0.846	0.574
HT			**WT**			
HT	**M**	**Sig.**	**Fir**	**Aspen**	**Cherry**	**Sorbus**
HT_4	**12.02 (c)**	0.084	**16.24 (d)**	**12.50 (cd)**	**8.52 (abcd)**	**10.84**
HT_3	8.97 (bc)	0.131-0.084	9.43 (bcd)	10.68 (bcd)	6.01 (abc)	9.79 (bcd)
HT_2	6.32 (ab)	0.055-0.131	4.85(abc)	7.88 (abc)	7.72 (abc)	4.85(abc)
HT_1	**2.94 (a)**	0.131	**0.63 (a)**	**4.73 (abc)**	**2.69 (ab)**	**3.72 (ab)**
*** It represents the significance value**			0.06 (a)	0.057 (b)	0.068 (c)	0.58(d)

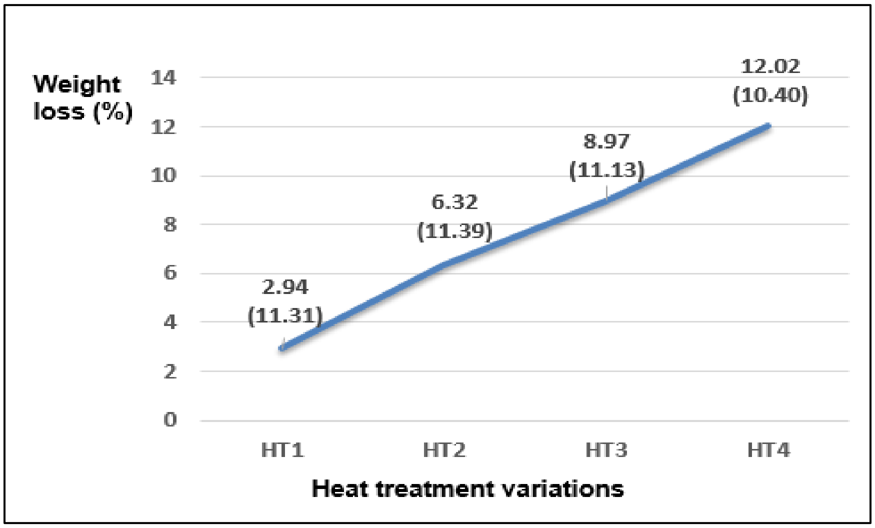

Fig. 2. Change in WL (%) according to heat treatment variations. *The numbers in parentheses indicate standard deviation.

The VA results from WL tests in Table 3 indicates that the differences between HT variations were found to be statistically significant at the $P \leq 0.05$ level. The results of the Duncan test, which was performed to determine which variations differ, showed that the highest and lowest WL percentages were 12.02 and 2.94 in HT4 and HT1 variations, respectively. In Fig. 2, the change in WL according to HT variations is given as a percentage.

Although the rates of change in WL reveal numerical values about the effect of HT, determining the direction of the relationship between HT and WL will also be important in terms of providing the basis for a better understanding of the subject. For this, there is a need for correlation analysis regarding the WL changes occurring with HT applied in four different variations of tree species, and it is given in Table 4.

Table 4. Correlation Analysis of WL Changes Occurring with HT in Fir, Cherry, Aspen, and Rowan Trees

		WT	**HT**	**SUB_{HT}**	**WL**
HT	Pearson correlation (PC)	-0.514**	1	0.243*	0.361**
	Significance 2-tailed (S2T)	0.000 (3***)	(5)	0.015 (1)	0.000 (2)

* Correlation is significant at the 0.05 level (2-tailed), ** Correlation is significant at the 0.01 level (2-tailed, and *** The "r" value is given in parentheses.

According to Table 4, there was a positive but weak relationship between HT and WL occurring in tree species with a value of 0.361 at the $P \leq 0.01$ level. It is understood that there is a statistically positive but very weak relationship between WL and SUB_{HT} at the $P \leq 0.01$ level. Both results show that HT causes WL.

According to the data in Tables 3 and 4 and Fig. 2, it is seen that WL increased as the HT temperature increased and as well as HT duration increased. These results are compatible with the literature, and many studies in the literature report that HT conditions cause WL in wood materials. Zaman *et al.* (2000) in their study with *Pinus sylvestris* and *Betula pendula*, found that WL increased from 5.7% to 15.2% at temperatures from 200 °C to 230 °C and for periods from 4 to 8 h; Kocaefe *et al.* (2007) WL increased from 0.83% in 15 min to 2.12% in 45 min; and Leite *et al.* (2024) reported that the WL in murici (*Byrsonima crispa* A. Juss.) wood, which was heat treated at 220 °C incresed to 14%.

Water Retention, Density Change, and Water Thickness Swelling Results

Analysis of variance results and average values of water retention (WR), water thickness swelling (WTS), and density change (DC) values of fir and aspen wood samples after soaking in water for 24 h and Duncan test results for these values are given in Table 5.

Analysis of variance results in Table 5 show that HT had a signficant effect on WR, WTS, and DC, and there were statistically significant differences at the $P \leq 0.05$ level between UT and HT variations in all three features. Duncan test was performed to determine which variations showed differences. The highest and lowest values in all three WR, DC, and WTS properties were in HT4 and UT variations, respectively. For example, the highest value in WTS is 5.27 in HT4 and the lowest value was 2.36 in UT. The results show that as the HT temperature increases and its duration increases, smaller values occur in HT variations compared to UT in all three properties. Changes in WR, WTS, and DC properties are shown graphically in Fig. 3.

Table 5. Analysis of Variance, Mean Values, and HG Results for WTS, WR, and DC along with HT in Fir and Aspen Trees

		DV	SUM	MS	df	F	Sig.
VA	**S**	**WR**	2733.728	683.432	4	4.930	0.001
		WTS	92.273	23.068	4	13.781	0.000
		ÖAD	1388.589	347.147	4	2.710	0.035
Average values and HG		**WR**		**DC**		**WTS**	
	HT_4	29.18 (b)	0.37	26.17 (b)	0.58	2.36 (c)	1.000
	HT_3	30.90 (b)	0.37	26.83 (b)	0.58	3.17(b)	0.48
	HT_2	30.75 (b)	0.37	26.66 (b)	0.58	3.22(b)	0.48
	HT_1	32.87 (b)	0.37	28.36 (b)	0.58	3.48 (b)	0.48
	UT	43.66 (a)	1.000	36.14 (a)	1.000	5.27 (a)	1.000

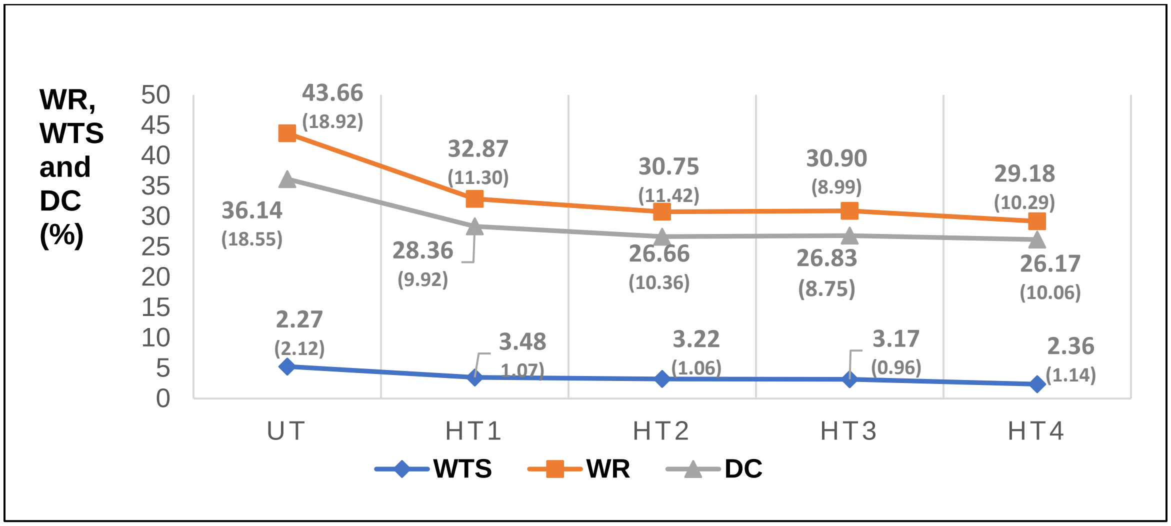

Fig. 3. Changes in WR, WTS, and DC properties with heat treatment

The correlation analysis of WR, WTS, and DC caused by HT in fir and poplar trees is given in Table 6.

Table 6. Correlation Analysis of WR, WTS, and DC caused by HT in Fir and Aspen Trees

		WT	HT	WR	WTS	DC
HT	PC	0.000	1	2	*-0.533***	*-0.246**
	S2T	0.000 (1)	(5)	0.001 (1)	0.000 (3)	0.014 (1)
WR	PC	*-0.297***	*-0.326***	1	0.329**	0.988**
	S2T	0.003 (2)	0.001 (2)	(5)	0.001 (2)	0.000 (5)
WTS	PC	*-0.213**	*-0.533***	0.329**	1	0.194
	S2T	0.033 (1)	0.000 (3)	0.001 (2)	(5)	0.053 (1)
DC	PC	-0.270**	-0.246*	0.988**	0.194	1
	S2T	0.007 (2)	0.014 (1)	0.000 (5)	0.053 (1)	(5)

According to Table 6, there was a statistically moderate negative relationship between HT and tree species at the $P \leq 0.01$ level on WTS with 0.533, a negative and weak relationship with WR at 0.326, and a negative but very weak relationship with 0.246 at $P \leq 0.05$ level. In other words, it is seen that the % changes in all three properties decreased depending on the HT temperature increase and duration. On the other hand, there was a very high and positive relationship between DC and WR, with a statistical value of 0.988 at the $P \leq 0.01$ level.

The results of the study are consistent with the literature. Korkut *et al.* (2008) reported that wood processed at high temperatures has lower hygroscopicity than natural natural wood. Heat treatment reduces WR, and the wood cell wall absorbs less water due to the reduction in the amount of hydroxyl groups in the wood. As a result of the decrease in the number of hydroxyl groups, swelling and shrinkage become less.

In addition to better durability, the advantages of heat-treated wood include reduced hygroscopicity and increased dimensional stability. Zhang *et al.* (2017) reported in their study that the water uptake rate of the wood material treated at 400 °C for 10 min decreased from 0.28 mg/mm^3 to 0.038 mg/mm^3 compared to the control samples. In another study, it was stated that the moisture values of beech sawdust subjected to HT at 160 °C for 8 h decreased and the water retention rate decreased from 65.53% to 47.79% (Ihnát and Lübke 2023).

Within the scope of this subject, Zhou *et al.* (2020) stated that there was a significant decrease in the hygroscopicity of the wood material processed at high temperatures in their studies with mahogany wood, and that the LDN (determined by nuclear magnetic resonance spectroscopy), surface free energy and surface wettability of the wood also decreased with HT, which caused a decrease in the hygroscopicity of the heat-treated wood. Thus, they stated that the mahogany wood became less sensitive to the effects of moisture due to HT, and they also emphasized that this effect was more pronounced in trees processed at high temperatures. Similar results were also reported in a study conducted with Douglas fir (*Pseudotsuga menziesii*); it was reported that dimensional stability increased in samples subjected to HT for 1, 2, 3 and 4 h at 160, 180, 200 and 220 °C; compared to control samples, water absorption (WR) and volume swelling (WTS) properties of treated wood decreased to 42.63%, 34.93% and 67.47%, respectively. In the same study, it was stated that the higher the HT temperature and the longer the duration, the lower the values, and when the HT temperature was above 180 °C, the WR amount of treated samples had a more significant decrease than WTS (Li *et al.* 2011).

The results of this study show that there was a decrease in DC values with increasing HT temperature and extending its duration in all tree species. These results are compatible with the literature (Guller 2012; Zhou *et al.* 2021; Taraborelli *et al.* 2022). Guller (2012) states that the density decreased by 2.57% to 12.6% in tree samples where HT was applied at different temperatures (190, 200, 212 and 225 °C) and durations (60, 120 and 180 min). Taraborelli *et al.* (2022) in their studies, state that the density in samples with HT decreases by 2.50% to 10.00% compared to UT samples.

Shrikage (β) and Swelling (α) values, and Density Changes in β and α Samples

The analysis of variance results of the measurements made to determine the effect of HT on the β and α properties of fir and aspen trees are given in Table 7.

Table 7. Average Values and HG Results Regarding *β* and *α* Values According to the HT Factor

	DV	SUM	df	MS	F	Sig.	PES*
VA	**αl**	3.961	4	0.990	6.158	0.000	0.43
	αt	341.092	4	85.273	38.820	0.000	0.94
	αr	57.176	4	14.294	8.384	0.000	0.82
	αv	766.311	4	191.578	29.799	0.000	0.83
	Drα**	183154.44	4	45788.610	14.439	0.000	0.99
	Doα	51271.953	4	12817.988	6.332	0.000	0.99
	βl	0.937	4	0.234	1.395	0.242	0.16
	βt	187.703	4	46.926	46.451	0.000	0.97
	βr	41.405	4	10.351	20.521	0.000	0.94
	βv	424.412	4	106.103	40.059	0.000	0.96
	Drβ	181147.26	4	45286.815	13.867	0.000	0.99
	Doβ	34764.9	4	8690.22	4.224	0.004	0.99

Average values and HG		αl		αr		αt		αv		Drα		Doα	
		M-HG	Sig.	M-HG	Sig.	M-HG	Sig.	M-HG	Sig.	M-HG	Sig.	M-HG	Sig.
	HT$_4$	0.309 (b)	0.063	1.974 (c)	0.257	3.767 (d)	0.081	6.050 (d)	0.380	636.0 (c)	0.611	399.0 (c)	0.062
	HT$_3$	0.143 (b)	0.063	2.022 (c)	0.257	4.593 (cd)	0.081-0.192	6.758 (cd)	0.380-0.189	645.1 (c)	0.611	399.6 (c)	0.062
	HT$_2$	0.136 (b)	0.063	2.475 (bc)	0.257-0.204	5.208 (bc)	0.192-0.071	7.819 (c)	0.189	694.6 (b)	0.073	427.3 (bc)	0.062-0.658
	HT$_1$	0.397 (b)	0.063	3.004 (b)	0.204	6.066 (b)	0.071	9.467 (b)	1.000	726.9 (ab)	0.073-0.358	459.1 (a)	0.076
	UT	0.677 (a)	1000	4.015 (a)	1.000	9.125 (a)	1.000	13.81 (a)	1.000	743.4 (a)	0.358	433.6 (ab)	0.658-0.076
		βl		Bt		βt		βv		Drβ		Doβ	
	HT$_4$	0.206 (a)	0.81	2.101 (d)	0.197	3.787 (d)	1.000	6.096 (d)	1.000	636.0 (c)	0.616	397.7 (c)	0.449
	HT$_3$	0.100 (a)	0.81	2.393 (cd)	0.197-0.056	4.704 (c)	0.814	7.197 (c)	0.089	645.1 (c)	0.616	408.6 (bc)	0.449-0.055
	HT$_2$	0.122 (a)	0.81	2.829 (c)	0.056	5.129 (c)	0.814	8.081 (c)	0.089	694.6 (b)	0.090	434.8 (ab)	0.055-0.449
	HT$_1$	0.095 (a)	0.81	3.394 (b)	1000	6.164 (b)	1.000	9.653 (b)	1.000	725.6 (ab)	0.090-0.327	446.4 (a)	0.449
	UT	0.351 (a)	0.81	3.865 (a)	1000	7.789 (a)	1.000	12.00 (a)	1.000	743.4 (a)	0.327	437.9 (ab)	0.449-0.055

*(PES) Partial Eta Squared **Moisture and oven dry density values calculated on shrinkage and swelling samples (Doα: oven dry density in swelling samples; Drα: moisture density in swelling samples; Drβ: moisture density in swelling samples; Doβ: oven dry density in shrinkage samples). PES is used to understand the effect level of factors on dependent variables, and it is accepted that the effect increases as the value approaches 1.

According to Table 7, it is understood that the density had a very high effect, from 0.443 to 0.994, on all dependent variables related to βv, αv, and specific gravity, except for the narrowing in the longitudinal direction. According to the results of the changes in radial, tangential, β_v, and α_v amounts, it is apparent that as the HT temperature increased and its duration increased, the dimensional stability improved (*β* and *α* values decreased), and the stability in HT compared to UT increased by 50% in both βv and αv. On the other hand, according to the full wet density (Drβ, Drα) and full dry density (Doβ, Doα) values calculated from the βv and αv test samples, it is seen that as the HT temperature increased and the duration increased, the specific gravity values decreased compared to UT in all HT variations. These results show that there was a strong relationship between dimensional stability and specific gravity change with HT. Density values and β_v and α_v amounts according to control samples and HT variations are given graphically in Fig. 4.

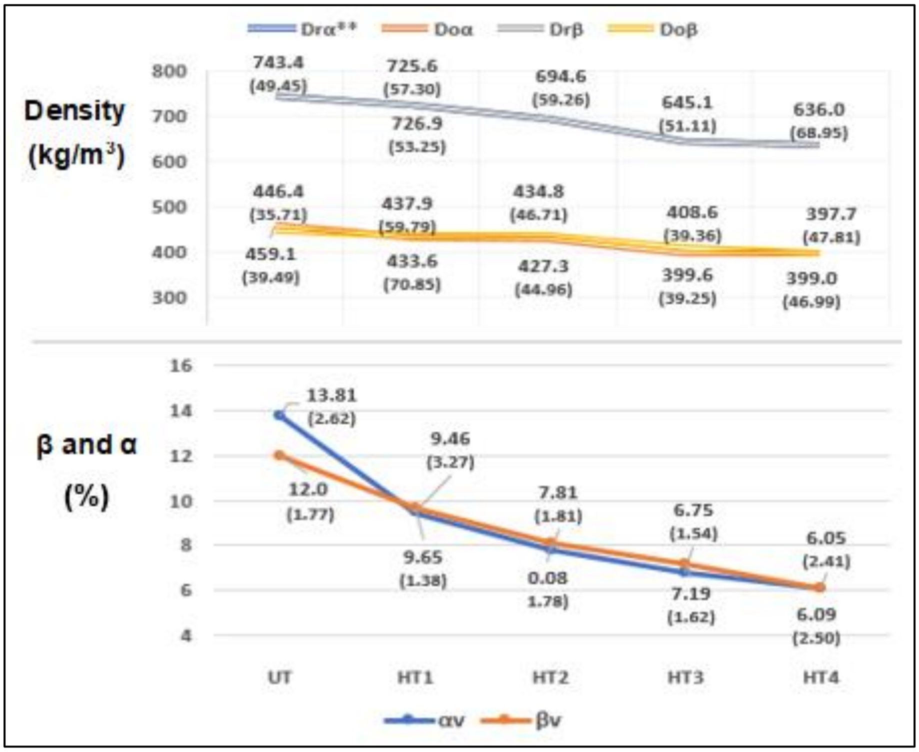

Fig. 4. Density values, β_v and α_v amounts according to UT and HT variations

The correlation analysis regarding the density values, β_v and α_v changes resulting from HT applied in four different variations of tree species is given in Table 8.

According to Table 8, there was a negative relationship between HT and all β and α, and density values. Between HT and all β and α and density values, "r" was determined at $P \leq 0.01$ level. Accordingly, there was a negative and highly statistically significant relationship between HT and β_v with 0.740. Similarly, it was understood that there was a negative and highly significant relationship between HT and βt with 0.700. In addition, it is seen that there was a moderate level of "r" in the properties of HT and α_t, α_v, $D_{r\alpha}$, and $D_{r\beta}$.

It is seen that, with the HT, "r", which is negative among all β and α and density values, has taken positive values, with different sizes of "r" among all β and α and density values. Among the features, "r" is very high with 0.986 for $D_{r\beta}$ and $D_{r\alpha}$, 0.935 for β_t and β_v for 0.914 for α_v and α_t. Its value ranged from 0.824 between β_t and α_t, and 0.808 between β_v and αt. According to these results, it is seen that all β and α and density values with HT decreased due to the increase in HT temperature and prolongation of its duration, and that this decrease was linear among all properties.

Table 8. Correlation Analysis of Density Values, β_v, and α_v Changes Caused by HT in Fir and Aspen

		HT	α_t	α_v	$D_{r\alpha}$	$D_{o\alpha}$	β_l	β_t	β_v	$D_{r\beta}$	$D_{o\beta}$
HT	**PC**	1	-0.68**	-0.68**	-0.60**	-0.34**	-0.098	-0.70**	-0.74**	-0.59**	-0.34**
	S2T	(5)	0.00 (3)	0.00 (3)	0.00 (3)	0.00 (2)	0.33 (1)	0.00 (4)	0.00 (4)	0.00 (3)	0.00 (2)
αt	**PC**	-0.68**	1	0.914**	0.456**	0.163	0.250*	0.824**	0.808**	0.458**	0.162
	S2T	0.00 (3)	(5)	0.00 (5)	0.00 (2)	0.01 (1)	0.01 (1)	0.00 (4)	0.00 (4)	0.00 (2)	0.01 (1)
αv	**PC**	-0.68**	0.914**	1	0.481**	0.193	0.354**	0.718**	0.793**	0.499**	0.231*
	S2T	0.00 (3)	0.00 (5)	(5)	0.00 (2)	0.05 (1)	0.00 (2)	0.00 (4)	0.00 (4)	0.00 (2)	0.02 (1)
Drα	**PC**	-0.60**	0.456**	0.481**	1	0.460**	0.077	0.602**	0.608**	0.986**	0.522**
	S2T	0.00 (3)	0.00 (2)	0.00 (2)	(5)	0.00 (2)	0.48 (2)	0.00 (3)	0.00 (3)	0.00 (5)	0.00 (3)
Doα	**PC**	-0.34**	0.163	0.193	0.460**	1	-0.003	0.089	0.153	0.446**	0.548**
	S2T	0.00 (2)	0.10 (1)	0.05 (1)	0.00 (2)	(5)	0.98 (1)	0.38 (1)	0.13 (1)	0.00 (2)	0.00 (3)
βt	**PC**	-0.70**	0.824**	0.718**	0.602**	0.089	0.209*	1	0.935**	0.588**	0.181
	S2T	0.00 (4)	0.00 (4)	0.00 (4)	0.00 (3)	0.38 (1)	0.03 (1)	(5)	0.00 (5)	0.00 (3)	0.07 (1)
βv	**PC**	-0.74**	0.808**	0.793**	0.608**	0.153	0.433**	0.935**	1	0.598**	0.263**
	S2T	0.00 (4)	0.00 (4)	0.00 (4)	0.00 (3)	0.13 (1)	0.00 (2)	0.00 (5)	(5)	0.00 (3)	0.01 (2)
Drβ	**PC**	-0.59**	0.458**	0.499**	0.986**	0.446**	0.073	0.588**	0.598**	1	0.527**
	S2T	0.00 (6)	0.00 (2)	0.00 (2)	0.00 (5)	0.00 (2)	0.47 (3)	0.00 (3)	0.00 (3)	(5)	0.00 (3)
Doβ	**PC**	-0.34**	0.162	0.231*	0.522**	0.548**	0.084	0.181	0.263**	0.527**	1
	S2T	0.00 (2)	0.11 (1)	0.02 (1)	0.00 (3)	0.00 (3)	0.41 (1)	0.07 (1)	0.01 (2)	0.00 (3)	(5)

These results are compatible with literature studies in terms of both dimensional stability and the change of density values with HT (Guller 2012; Tiryaki *et al.* 2016; Chung *et al.* 2017; Şahin and Güler 2018). Tiryaki *et al.* (2016) reported in their studies in which they subjected wood samples to HT at varying temperatures and varying times that the experimental results showed that the volumetric β and α in the wood material decreased depending on the heat treatment conditions. Şahin and Güler (2018) emphasize in their study that HT improves dimensional stability in wood material, and temperature increase and duration play an important role in this improvement. In a similar study, Guller (2012) states that dimensional stability can be improved up to 66% depending on HT conditions.

Findings on Static Bending Strength (MOR) and Modulus of Elasticity (MOE) Changes in Static Bending

The results of analysis of variance for measurements of static bending strength and elasticity modulus in static bending in fir and aspen trees are given in Table 9.

According to PES values from Table 9, it is understood that MOR and MOE values showed significant differences with HT. According to the results of the Duncan test performed to determine the differences, the highest MOR was obtained in the UT variation and the lowest in the HT_4 variation, and it was determined that MOR decreased as the HT temperature increased and its duration increased. On the other hand, while MOE was low in UT and increased with HT, it decreased again as HT temperature increased and its duration became longer, and it reached almost the same value as UT.

Table 9. VA and HG Results Regarding MOR and MOE Values According to HT Factor

	DV	SUM	df	MS	F	Sig.
VA	**MOR**	70829.614	4	17707.404	3.363	0.013
		500208.32	95	5265.351		
		571037.93	99			
	MOE	3813594984.94	4	953398746	2.842	0.028
		31874126261	95	335517118		
		35687721246.4	99			
Average values and HG	**DV**	**MOR**			**MOE**	
	HT$_4$	352.65 (c)	0.135		99774.5 (bc)	0.409-0.058
	HT$_3$	384.56 (bc)	0.135-0.282		111411.1 (bc)	0.058-0.094
	HT$_2$	381.31 (bc)	0.135-0.282		103732.5	0.409-0.058-0.094
	HT$_1$	433.07 (a)	0.147		114030.6 (b)	0.094
	UT	403.85 (ab)	0.282-0.147		98639.6 (a)	0.049

The correlation analysis regarding the MOR and MOE changes caused by HT applied to four different variations of tree species is given in Table 10.

Table 10. Correlation Analysis of MOR and MOE Changes caused by HT in Fir and Aspen Trees

		WT	HT	MOR	MOE
AT	PC	1	0.000	0.378**	0.223*
	S2T	(5)	0.000 (1)	0.000 (2)	0.026 (1)
HT	PC	0.000	1	-0.282**	-0.003
	S2T	0.000 (1)	(5)	0.004 (2)	0.979 (5)
MOR	PC	0.378**	-0.282**	1	0.459**
	S2T	0.000 (2)	0.004 (2)	(5)	0.000 (2)
MOE	PC	0.223*	-0.003	0.459**	1
	S2T	0.026 (1)	0.979 (1)	0.000 (2)	(5)

According to Table 10, there was a weak relationship between HT and MOR, with a statistical value of 0.282, at the $P \leq 0.01$ level in tree species. It is seen that there was a negative and very weak relationship between heat treatment and MOE at the level of 0.003. These results reveal that the values of both resistance properties are negatively affected by HT.

The results of this study show that HT performed at temperature environment between 180 and 200 °C will have similar values compared to UT in both MOR and MOE resistance values. However, it is understood that as both the temperature and the HT time increases, the resistance values will decrease significantly, especially above 210 °C, and literature studies show similar results. For example, Tang *et al.* (2019) stated in their study that the mechanical performance such as MOE and MOR in Moso bamboo (*Phyllostachys heterocycla*), in which they HT with tung oil, did not decrease below 200 °C, compared to UT bamboo. Herrera-Builes *et al.* (2021) stated that the MOR value in *Pinus oocarpa* wood treated at 170 and 190 °C increased by 47% and 22% compared to UT, revealing statistically significant differences. Cademartori *et al.* (2013) found in their study with *Eucalyptus grandis* wood that HT reduced the MOR resistance values by 21.91% and 49.90% compared to UT at 180 °C for 4 h and 240 °C for 8 h, respectively.

CONCLUSIONS

1. According to the results of the study, it is seen that weight loss (WL) increased with the increase in heat treatment (HT) temperature and prolongation of its duration, and there was a positive correlation between HT and WL values.
2. The results from this study showed that water retention (WR), water thickness swelling (WTS), and specific gravity values decreased as the HT temperature and duration increased. Correlation analysis revealed that there was a negative relationship between HT and WR, WTS, and specific gravity changes at different levels. On the other hand, the correlation within the investigated properties was different and more positive; for example, there was a statistically very high and positive relationship between specific gravity change and water retention.
3. The results show that HT improved dimensional stability, and as the HT temperature and duration increased, dimensional stability increased by 50% compared to the control samples.
4. The distribution values calculated from the shrinkage and swelling test samples decreased compared to the control analyses, contrary to the dimensional stability in all HT voids, as the temperature of the heat treatment increased and the time changed. According to the study, as the HT temperature increased and its duration increased, all torsion, expansion and density values decreased and decreased, and this decrease was linear among all properties.
5. It has been determined that while static bending resistance decreased in heat-treated wood species, the modulus of elasticity (MOE) in static bending increased with temperature, but it decreased again as time increases. Correlation analysis results showed that there was a weak relationship between HT, and modulus of rutpure (MOR) and MOE values in static bending. These results reveal that the resistance values of both properties are negatively affected by heat treatment.

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