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ARTICLE

# Physical, Anatomical, and Photochemical Analyses of Some Exotic Wood Species Submitted to Heat Treatment

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**ABSTRACT**

The objective of this study was to evaluate the effect of heat treatment on decorative properties including glossiness, color coordinates including lightness (L), blue-yellow (b*) and red-green (a*), hardness (shore-D) morphological characterization and thermal properties of some exotic wood species. Heat treatment of anigre (*Aningeria altissima*), cedrorana (*Cedrelinga catenaeformis*), cemara (*Casuarina sumatrana*) and coronilla (*Scutia buxifolia*) wood materials were performed in an oven with a programmable controller at 210°C for 3 h. The obtained samples were conditioned in a climate cabin and the decorative properties, morphological characterization with scanning electron microscopy (SEM) and thermal properties with thermogravimetric analyzer (TGA) of the obtained samples were determined. The test results showed that color got darker with heat treatment, specifically L and b* decreased, and a* increased for anigre and cedrorana but a* decreased for cemara and coronilla. The glossiness for all samples generally increased from 20° to 85° but heat treatment decreased the glossiness. The density generally decreased with heat treatment and decrease ratio in the density was found to be in range from 5.6% to 10.6%. According to the SEM analysis, some cracks, pit aspiration and layer decomposition in the micro level of the wood structure were detected. TGA showed that heat treatment makes thermally more stable wood. As a result, it can be said that heat treatment improved the decorative properties of the exotic wood.

**KEYWORDS**

Heat treatment; color; gloss; hardness; anigre wood; cedrorana wood; cemara wood; coronilla wood

## 1 Introduction

Considerable research has been done on the improving of wood properties by heat treatment. Heat treatment is an environmentally friendly and effective method to improve wood dimensional stability and durability. Several thermal treatment methods were developed for industrial applications [1]. Thermal treatment is generally applied at the temperatures of 180°C and 220°C with the gradual heating to increase dimensional stability and decay resistance, but leads to the darkening of wood. On the other hand, thermal treatment reduces the mechanical properties and flexibility of wood when compared to untreated wood [2]. However, process parameters strongly effect the properties of during thermal treatment [3].

According to Poncsak et al. [4], increasing in temperature above 200°C reduce the mechanical properties such as modulus of rupture (MOR) and resistance against screw withdrawal, while hardness slightly increases above that temperature. Kocaefe et al. [5] investigated the effect of treatment parameters on weight loss and mechanical properties of heat-treated aspen; found that increasing temperature above 160°C decreased the hardness, whereas increased by increasing holding time and heating rate. Boonstra et al. [6] proposed that in addition to the improvement of compressive strength, and apparent increase in the Brinell hardness parallel to the grain might favor the use of thermally treated wood for certain applications. Increasing of treatment temperatures from 180°C to 220°C during the thermal treatment of *Eucalyptus grandis* wood significantly decreased the Janka hardness perpendicular to grain of 12.1% and 20.7% as compared to untreated wood [7]. Bekhta et al. [8] found strong correlation between total color change and mechanical properties of spruce wood exposed to heat treatment. On the contrary, Johansson et al. [9] reported that color is not suitable parameter for the prediction of strength since they found nonhomogeneous color distribution in thermally treated birch. They also indicated that Lightness is the main contributor to the uneven color distribution. Increase in color change and decrease in lightness due to the heat treatment were attributed to the decreasing in the hemicellulose of wood cell wall components especially pentosane [10]. Tolvaj et al. [11] reported that extractive content of wood is an important factor in the color change during thermal treatment and light irradiation, and red color change was reduced by thermal treatment at 200°C. Dos Santos et al. [12] obtained attractive color and lower hygroscopicity and suggested that heat treatment is a good approach to improve value of the tropical woods in the market.

As seen the physical and mechanical properties of the wood materials after the heat treatment, color parameters such as a*, b* and L* and glossiness values of the wood materials tend to be darker with heat treatment according to the wood species. In studies on glossiness and color parameters of Anigre, Cedrorana, Cemara, Coronilla, they were found to be got darker after the treatment [13–17]. In another studies, Anigre (*Aningeria altissima*) determined density 0.6 g/cm$^3$ [18], compression parallel to grain 28.1 N/mm$^2$, shear parallel to grain 8.5 N/mm$^2$, modulus of rupture 38 N/mm$^2$, modulus of elasticity 6161 N/mm$^2$ [19], and 940, 22.8, 16.2, 3.3 μm respectively for the fibre length, diameter, lumen width, cell wall thickness of the stem [20]. Cedrorana (*Cedrelinga catenaeformis*) obtained lignin 29.4%, extractives 10.5%, holocellulose 60.2% [21]. It has various local uses, such as furniture, door and window frames, artwork, and light construction [22]. Cemara (*Casuarina sumatrana*) is very heavy, hard, tough and durable timber but difficult to work [23]. Coronilla (*Scutia buxifolia*) is still highly exploited due to the excellent quality of its wood as firewood [24]. The wood is fine-textured, straight-grained, heavy, hard to cut and very durable. Almost indestructible, the wood is ideal for external use as bridge supports, posts etc., and is also used for lathe work, carpentry etc. [25]. In literature, wood species commonly used in the industrial products such as Beech, Pine, Oak, etc. were generally investigated by many scientific studies [26–29], but is that there is insufficient information and almost no research on these species are subjected to this study. Therefore, the exotic species including Anigre, Cedrorana, Cemara and Coronilla woods were heat treated at 200°C for 3 h under atmospheric medium, and the decorative properties including color, glossiness, hardness, structural analysis with FTIR, thermal properties with TGA and morphological characterization with SEM of the obtained heat-treated woods was investigated.

## 2 Materials and Methods

### *2.1 Materials*

Wood species anigre (*Aningeria altissima*), cedrorana (*Cedrelinga catenaeformis*), cemara (*Casuarina sumatrana*) and coronilla (*Scutia buxifolia*) were selected from the lumber with the dimensions of 100 × 10 × 2 cm in the longitudinal, radial, and tangential direction, respectively. The air-dried densities

of the Anigre wood, cedrorana wood, cemara wood, coronilla wood were 0.56, 0.57, 0.73 and 0.81 g/cm$^3$. The all samples before testing have a moisture content of 10%.

### *2.2 Methods*

#### *2.2.1 Thermal Treatment*

Heat treatment was applied on the test samples in an oven chamber capable of controlling the temperatures within a range of ±1°C. Treatment was applied at 210°C for 3 h under inert atmosphere. During heat treatment, temperature was increased gradually with heat rate of 20°C and the samples were kept at 210°C for 3 h. After the heat treatment, all samples have a moisture content of approximately 0% and all the samples were conditioned in a climatic chamber at relative humidity of 80% and temperature of 20°C. After the conditioning, all the samples have a moisture content of 10%. Before chemical structure analysis with fourier transfer infrared spectroscopy, heat-treated (HT), and un-treated (UT) (control) samples were ground in a Wiley mill into a homogenous meal according to the TAPPI T257 cm-0221 standard [30].

#### *2.2.2 Determination of Color, Glossiness and Hardness (Shore-D) Measurements*

The color parameters (L*, a* and b*) were recorded with CS-10 colorimeter (CHN Spec, made in China) (Fig. 1A) using an 8°/diffused illumination, CIE 10° standard observer; CIE D65 light source [31]. Color parameters were measured using ten replicates of each sample to determine the average value. The total color change (ΔE*), was calculated from the parameters Δa*, ΔL* and Δb* respectively according to the equations Eqs. (1)–(4),

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{1}$$

$$\Delta L^* = L^*_{heat\sim treated} - L^*_{untreated} \tag{2}$$

$$\Delta a^* = a^*_{heat\sim treated} - a^*_{untreated} \tag{3}$$

$$\Delta b^* = b^*_{heat\sim treated} - b^*_{untreated} \tag{4}$$

where the $L^*$ axis represents lightness, varying from 100 (white) to zero (black), $a^*$ is the red (+) or green (−) tone; and $b^*$ is the yellow (+) or blue (−) tone [32].


(A) (B) (C)

**Figure 1:** Color measuring (A), brightness (B), Shore-D hardness (C)

Glossiness levels parallel to the grain at 20°, 60° and 85° angles in untreated and heat-treated samples were recorded with a glossmeter (Chine) (Fig. 1B) according to ISO 2813 standard [33].

Shore-D hardness (stand: model Ld-J Loyka) (Fig. 1C) was loaded with 5 kg according to ASTM D2240 standard [34]. Ten replicates for each wood types were used.

*2.2.3 Fourier Transfer Infrared Spectroscopy (FTIR)*

FTIR-ATR analysis was conducted with a Shimadzu spectrometer equipped with a single reflection ATR accessory. Each sample were scanned in the wavenumbers from 800 $cm^{-1}$ to 4000 $cm^{-1}$ with a resolution of 4 $cm^{-1}$. Three replicates for each wood types were used in FTIR analysis.

*2.2.4 Morphological Characterization*

The samples for morphological characterization were obtained by cutting along longitudinal direction of the un-treated and heat-treated woods without any fragmentation. For morphological analysis, it was tried to obtain the samples, which are near to each other as possible. The morphological analysis of the un-treated and heat-treated wood materials were conducted with scanning electron microscopy (SEM) with an accelerating voltage of 5 kV. For enhance of electron conductivity, the surface of all samples was sputter-coated with a gold particle using a Denton sputter coater. Morphological characterization was conducted on the one replicate for each wood types.

*2.2.5 Thermogravimetric Analysis (TGA)*

Thermal behavior and mass loss of un-treated and heat-treated exotic wood materials were investigated using a Perkin Elmer TGA analyzer, which was fully supported by computer–controlled software options for control and data handling. TGA tests were run under nitrogen atmosphere flowing at 40 mL/min and at a scanning rate of 20 °C/min. According to the TG curves, the degradation temperatures of the samples at 10% weight loss ($T_{10\%}$), 50% weight loss ($T_{50\%}$), and 75% weight loss ($T_{75\%}$) were calculated. By seeing the derivative thermogravimetric peaks (DTG) curves, the maximum degradation temperature in the DTG ($DTG_{max}$) and the mass loss of the samples were calculated. Three replicates for each wood types were used in TGA analysis.

*2.2.6 Statistical Analysis*

Variance analysis in SPSS 17 (Sun Microsystems, Inc., Santa Clara, CA, USA) statistical program using the data of the brightness, color and shore D hardness tests determined on the heat-treated and untreated samples of the wood types used in the study, standard deviations, arithmetic means, maximum values, minimum values, homogeneity groups and variation coefficients were calculated.

## 3 Results and Discussion

The multi-way analysis of variance (MANOVA) was conducted to determine the changes in the decorative properties such as shore-D, glossiness parallel to the grain at 20°, 60° and 85° angles, color parameters including L*, a*, and b* after the heat treatment of exotic wood materials. The results indicate that there was a significant difference between the colors, gloss and shore-D hardness of the samples and wood type (A), heat treatment (B), and interaction (AB) between these variables were found to be significant at 95% confidence level. Tab. 1 shows statistical results for the decorative properties including color, gloss and shore-D tests. The Duncan analysis was also done to find the differences among the test groups according to the data obtained.

**Table 1:** Analysis of variance results for color, gloss and shore D tests

| Test | Source of variation | Sum of Squares | Degrees of Freedom | Mean square | *F* Value | Significant |
|---|---|---|---|---|---|---|
| L* | Wood type (A) | 3727.448 | 3 | 1242.483 | 9131.910 | 0.000* |
| | Heat treatment (B) | 19620.101 | 1 | 19620.101 | 144202.418 | 0.000* |
| | Interaction (AB) | 683.183 | 3 | 227.728 | 1673.737 | 0.000* |
| | Error | 9.796 | 72 | 0.136 | | |
| | Total | 217809.826 | 80 | | | |

(Continued)

**Table 1 (continued).**

| Test | Source of variation | Sum of Squares | Degrees of Freedom | Mean square | *F* Value | Significant |
|---|---|---|---|---|---|---|
| a* | Wood type (A) | 117.995 | 3 | 39.332 | 608.873 | 0.000* |
| | Heat treatment (B) | 68.062 | 1 | 68.062 | 1053.631 | 0.000* |
| | Interaction (AB) | 908.300 | 3 | 302.767 | 4686.960 | 0.000* |
| | Error | 4.651 | 72 | 0.065 | | |
| | Total | 5549.197 | 80 | | | |
| b* | Wood type (A) | 770.788 | 3 | 256.929 | 2096.944 | 0.000* |
| | Heat treatment (B) | 1526.966 | 1 | 1526.966 | 12462.411 | 0.000* |
| | Interaction (AB) | 707.963 | 3 | 235.988 | 1926.026 | 0.000* |
| | Error | 8.822 | 72 | 0.123 | | |
| | Total | 21332.430 | 80 | | | |
| //20° | Wood type (A) | 3.132 | 3 | 1.044 | 826.121 | 0.000* |
| | Heat treatment (B) | 4.950 | 1 | 4.950 | 3916.582 | 0.000* |
| | Interaction (AB) | 0.240 | 3 | 0.080 | 63.396 | 0.000* |
| | Error | 0.091 | 72 | 0.001 | | |
| | Total | 31.850 | 80 | | | |
| //60° | Wood type (A) | 139.699 | 3 | 46.566 | 341.459 | 0.000* |
| | Heat treatment (B) | 50.403 | 1 | 50.403 | 369.592 | 0.000* |
| | Interaction (AB) | 12.008 | 3 | 4.003 | 29.351 | 0.000* |
| | Error | 9.819 | 72 | 0.136 | | |
| | Total | 1083.790 | 80 | | | |
| //85° | Wood type (A) | 2809.167 | 3 | 936.389 | 445.537 | 0.000* |
| | Heat treatment (B) | 237.016 | 1 | 237.016 | 112.773 | 0.000* |
| | Interaction (AB) | 271.387 | 3 | 90.462 | 43.042 | 0.000* |
| | Error | 151.323 | 72 | 2.102 | | |
| | Total | 11921.110 | 80 | | | |
| Shore D | Wood type (A) | 7371.850 | 3 | 2457.283 | 1058.160 | 0.000* |
| | Heat treatment (B) | 583.200 | 1 | 583.200 | 251.139 | 0.000* |
| | Interaction (AB) | 18.500 | 3 | 6.167 | 2.656 | 0.055** |
| | Error | 167.200 | 72 | 2.322 | | |
| | Total | 321892.000 | 80 | | | |

Note: *Significant at 95% confidence level, **Insignificant.

As can be seen from the Tab. 2, heat treatment lowered L values and b values, i.e., samples tended to be dark in terms of L and blue in terms of b after heat treatment. However, redness (a*) increased for Anigre and Cedrorana while decreased for Cemara and Coronilla towards the green hue. Salca et al. [35] reported that the reduction in lightness values was related to the degradation of hemicelluloses during heat treatment. A summary of test results showing the arithmetic means, homogeneity group, standard deviation, highest value and coefficient of variation of shore-D hardness of all woods obtained is given in Tab. 2. Decorative properties including color changes and hardness values were significantly affected by heat treatment in all specimens. After heat treatment, the decrease in L* were measured as 53.5%, 35.1%, 56% and 49.5% for Anigre, Cedrorana, Cemara, Coronilla wood types, respectively. The a* and b* of all samples generally decreased with the treatment expect for a* value in Anigre. As seen as Tab. 2, the

glossiness at all angles decreased with the treatment and the maximum decrease ratio in all angles (20°, 60°, 85°) were found as 75% for Anigre, 56% for Coronilla and 44.3% for Cemara, respectively. The shore-D hardness values of the all-heat-treated wood types significantly had to be lower than the un-treated wood and after the treatment, the decrease ratio in the shore-D values were measured as 10.61% for Anigre 9.7% for Cedrorana 5.6% for Cemara and 7.9% for Coronilla.

**Table 2:** Statistical data for color parameters, glossiness values and shore D hardness

| Decorative Properties | | Wood type | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | UT | | | | HT | | | |
| | | Anigre | Cedrorana | Cemara | Coronilla | Anigre | Cedrorana | Cemara | Coronilla |
| L* | | 68,6 B (±0,2) | 71.3A (±0,3) | 67,1 C (±0,2) | 52,6 D (± 0,3) | 31,9 F (±0,1) | 46,3 E (±0,7) | 29,5 G (±0,2) | 26,6 H (±0,5) |
| a* | | 5,1 E (±0,3) | 4,5 F (±0,2) | 8,1 C (±0,1) | 15,9 A (±0,2) | 7,9 C (±0,1) | 9,2 B (±0,2) | 5,9 D (±0,2) | 3,2 G (±0,6) |
| b* | | 18,4 C (±0,6) | 20,1 A (±0,2) | 20,2 A (±0,2) | 19,5 B (±0,3) | 11,5 D (±0,2) | 18 A (±0,3) | 8,1 E (±0,3) | 3,5 F (±0,6) |
| Glossiness | // 20° | 0,8 C (±0,00) | 1,1 A (±0,05) | 0,9 B (±0,05) | 0,4 E (±0,05) | 0,2 G (±0,00) | 0,6 D (±0,00) | 0,3 F (±0,05) | 0,1 H (±0,00) |
| | // 60° | 3,3 C (±0,05) | 5,5 A (±0,6) | 5,2 AB (±0,6) | 2,5 D (±0,4) | 1,6 E (±0,05) | 4,9 B (±0,00) | 2,5 D (±0,5) | 1,1 F (±0,1) |
| | // 85° | 3,9 F (±0,2) | 16 B (±0,8) | 21,9 A (±2,2) | 6,1 E (±1,9) | 3,8 F (±0,2) | 14,5 C (±0,4) | 12,2 D (±2,7) | 3,8 F (±0,3) |
| Shore-D | | 51,8 F (±1,6) | 63 D (±1,8) | 67,9 C (±1,5) | 78,6 A (±0,7) | 46,3 G (±2,1) | 56,9 E (±1,9) | 64,1 D (±0,9) | 72,4 B (±1,4) |

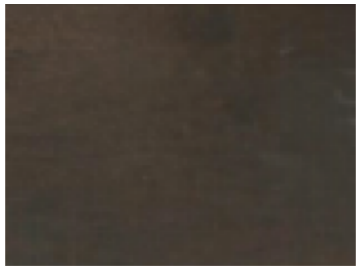
In all test, 30 specimens (n) were used to the statistical analysis. (±) shows the standard deviation of the samples and the letters such as A, B, C show the homogeneity about the samples.

ΔL*, Δa*, Δb* and the total color difference (ΔE*) are given in Tab. 3. Cemara wood showed a significantly higher ΔE* than the other species (39.5%) followed by Anigre (37.5%), Coronilla (33%), Cedrorana (25.4%). The color darkening of the thermally modified wood is caused by the subsequent formation of low molecular weight sugars and the degradation reactions of hemicelluloses [4,36], as well as the formation of oxidation products such as quinones [37,38].

Heat treatment process changes the physical, mechanical and other material properties of wood. Chemical elements of wood including cellulose, hemicellulose and lignin modifies with heat treatment and the chemical changes is generally detected with Fourier transform infrared spectroscopy (FTIR) and in this study, FTIR was used to detect the changes in the chemical structure of wood after the heat treatment. The obtained FTIR graph for the all samples were given in Fig. 2.

The changes between FTIR peaks in the UT and HT-wood materials were hard to interpret. However, there were small differences in the spectra of wood materials since the thermal degradation occurred with the heat treatment process as can be seen in the FTIR graph of woods (Fig. 2). The differences in the FTIR peaks are not significant changes but after heat treatment, some peaks in the x-axis were detected to slightly shift. Previous studies showed that the changes in the chemical structure with heat treatment start by deacetylation followed by depolymerization occurred by the released acetic acid Tjeerdsma et al. [39],

**Table 3:** Values before and after heat treatment

| Un-Treated (UT) | Heat-Treated (HT) | Values |
|---|---|---|
|  |  | ΔL*: −36.69 ↓ |
| | | Δa*: 2.82 ↑ |
| | | Δb*: −6.93 ↓ |
| | | ΔE*: 37.45 ↑ |
| UT-Anigre | HT-Anigre | Shore-D: −%10,6 ↓ |
|  |  | ΔL*: −24.97 ↓ |
| | | Δa*: 4.67 ↑ |
| | | Δb*: −0.05 ↓ |
| | | ΔE*: 25.40 ↑ |
| UT-Cedrorana | HT-Cedrorana | Shore-D: −%9,7 ↓ |
|  |  | ΔL*: −37.60 ↓ |
| | | Δa*: −2.19 ↓ |
| | | Δb*: −12.04 ↓ |
| | | ΔE*: 39.54 ↑ |
| UT-Coronilla | HT-Coronilla | Shore-D: −%5,6 ↓ |
|  |  | ΔL*: −26,02 ↓ |
| | | Δa*: −12,68 ↓ |
| | | Δb*: −15,94 ↓ |
| | | ΔE*: 33,04 ↑ |
| UT-Cemara | HT-Cemara | Shore-D: −%7,9 ↓ |

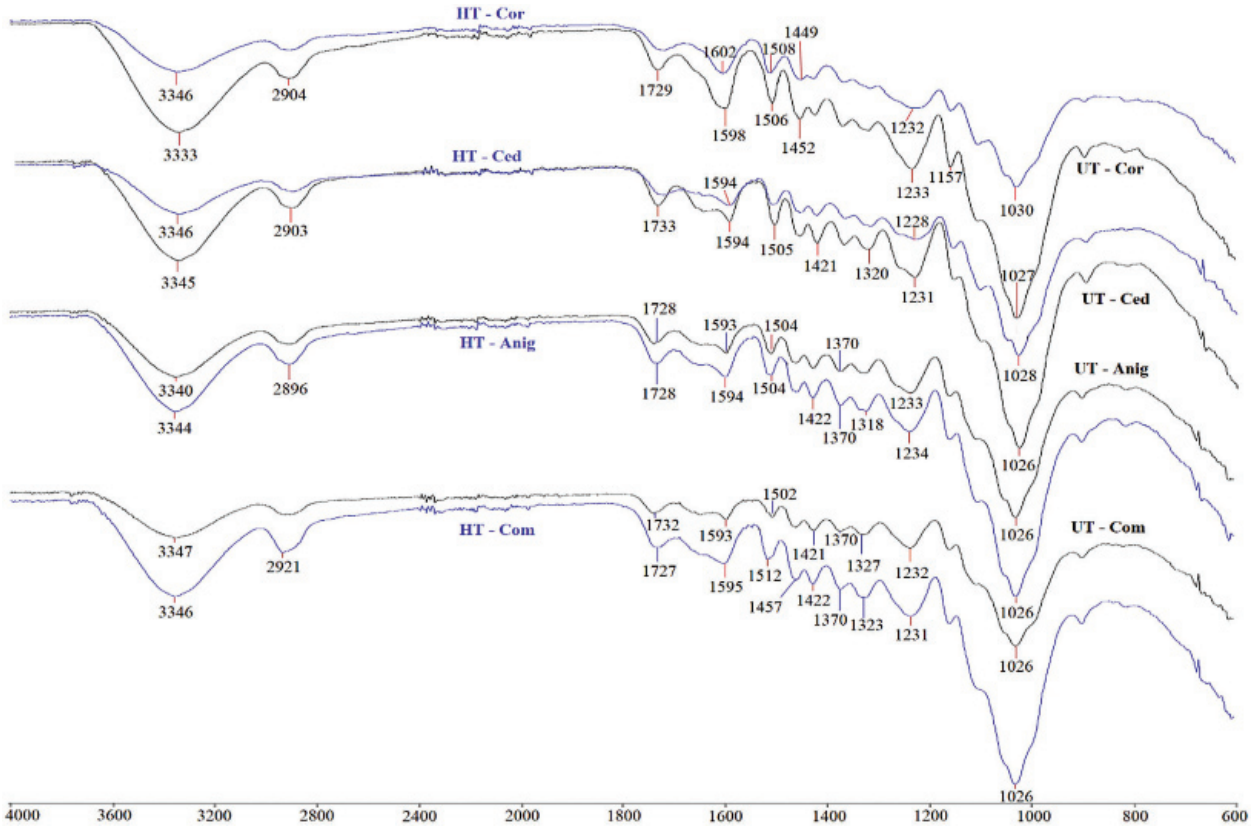



**Figure 2:** The FTIR peaks of the heat-treated and un-treated wood materials

Nuopponen et al. [40], Esteves et al. [41] and later a carbohydrate dehydration occurs due to reducing accessible OH groups Weiland et al. [42] and lignin bonds are cleaved with high concentration of phenolic groups [43]. Esteves et al. [41] found that the peaks of heat-treated wood showed a broadening to lower wavenumbers of the band at 3430 $cm^{-1}$ corresponding to the O-H stretching vibration from alcohols (3600–3300 $cm^{-1}$) and carboxylic acids (3300–2500 $cm^{-1}$), present either in polysaccharides and lignin and the broadening might be due to the increase in carboxylic acids due to primary OH oxidation and/or hydrolysis of acetyl groups from hemicelluloses. Esteves et al. [44] expressed that O-H stretch due to polysaccharides should decrease, at the same time O-H from phenolic groups in lignin increases due to the percentage of the lignin with carbohydrate degradation [44]. Another studies determined to be a benzene ring skeleton of lignin in wavenumbers of 1590–1600 $cm^{-1}$ [45], C-H bending,-$CH_3$ (lignin),-$CH_2$ (carbohydrates), lignin-carbohydrate complexes bonds for 1370 $cm^{-1}$ [39], C-O deformation in cellulose, symmetric C-O-C, stretching of dialkyl ethers, aromatic C-H deformation in lignin in wavenumbers of 1026–1030 $cm^{-1}$ [39,46,47], alkyl-arykther bonds, lactones in wavenumbers of 1225–1235 $cm^{-1}$ [48,49].The important bands and their assignment that are detected with FTIR analysis obtained for the un-treated and heat-treated wood in our study were given in Tab. 4.

Heat treatment changes the all-material behavior such as physical, mechanical, chemical, morphological properties and therefore the determining the properties of heat-treated wood is important for the structural application. In this study, the changes in the morphological structure of heat-treated and un-treated wood were determined by using scanning electron microscopy (SEM). The all samples were cut along longitudinal section after heat treatment process and attention was paid to the fragmentation of the samples during the preparation of the all samples. While cutting the preparation of heat-treated wood, it

was realized that the heat-treated wood get brittle as compression to the un-treated wood and it was detected that heat-treated wood brakes easily. Previous studies Boonstra et al. [55,56], Ling et al. [57] found that heat treatment make wood more brittle according to the untreated wood and the status hard to process the heat-treated wood. Figs. 3 and 4 show that SEM images of the heat-treated and un-treated exotic woods.

**Table 4:** FTIR absorption bands from spectra obtained for control and heat-treated wood samples and their assignment

| | Wavenumber ($cm^{-1}$) | | Band assignment | References |
|---|---|---|---|---|
| | UT | HT | | |
| Anigre | 3345 | 3346 | O-H stretching vibration from alcohols and carboxylic acids | [41] |
| | 1594 | 1594 | A benzene ring skeleton (lignin) | [45] |
| | 1231 | 1228 | alkyl-arykther bonds, lactones | [48,49] |
| | 1026 | 1028 | C-O deformation in cellulose, symmetric C-O-C, stretching of dialkyl ethers, aromatic C-H deformation in lignin | [39,46,47] |
| Cedrorana | 3340 | 3348 | O-H stretching vibration from alcohols and carboxylic acids | [41] |
| | 1728 | 1728 | C=O stretching in unconjugated ketones, carbonyls, aldehydes and ester groups | [50] |
| | 1593 | 1594 | A benzene ring skeleton (lignin) | [45] |
| | 1504 | 1504 | C=C stretching of the aromatic skeletal vibrations (lignin) | [39,49] |
| | 1370 | 1370 | C-H bending,-$CH_3$ (lignin), -$CH_2$ (carbohydrates), lignin-carbohydrate complexes bonds | [39] |
| | 1233 | 1234 | alkyl-arykther bonds, lactones | [48,49] |
| | 1026 | 1026 | C-O deformation in cellulose, symmetric C-O-C, stretching of dialkyl ethers, aromatic C-H deformation in lignin | [39,46,47] |
| Cemara | 3347 | 3346 | O-H stretching vibration from alcohols and carboxylic acids | [41] |
| | 1732 | 1727 | C=O stretching in unconjugated ketones, carbonyls, aldehydes and ester groups | [50] |
| | 1593 | 1595 | A benzene ring skeleton (lignin) | [45] |
| | 1502 | 1512 | C=C stretching of the aromatic skeletal vibrations (lignin) | [39,51] |
| | 1421 | 1422 | $CH_2$ bending vibrations related to the structure of cellulose; aromatic skeletal vibrations | [52–54] |
| | 1370 | 1370 | C-H bending, -$CH_3$ (lignin), -$CH_2$ (carbohydrates), lignin-carbohydrate complexes bonds | [39] |
| | 1232 | 1231 | alkyl-arykther bonds, lactones | [48,49] |
| | 1026 | 1026 | C-O deformation in cellulose, symmetric C-O-C, stretching of dialkyl ethers, aromatic C-H deformation in lignin | [39,46,47] |
| Coronilla | 3333 | 3346 | O-H stretching vibration from alcohols and carboxylic acids | [41] |
| | 1598 | 1602 | A benzene ring skeleton (lignin) | [45] |
| | 1506 | 1508 | C=C stretching of the aromatic skeletal vibrations (lignin) | [39,51] |
| | 1233 | 1232 | alkyl-arykther bonds, lactones | [48,49] |
| | 1027 | 1030 | C-O deformation in cellulose, symmetric C-O-C, stretching of dialkyl ethers, aromatic C-H deformation in lignin | [39,46,47] |

As seen as SEM images in Figs. 3 and 4, heat-treated wood surface was found to be rougher that un-treated wood due to high brittleness. SEM images shows that same individual wood part, micro cracks and some cell collapse occurred during the heat treatment and also some cell delamination due to thermal decomposition between cell layers was detected in the heat-treated Coronilla wood. In previous studies, heat-treated wood caused exhibited some cracks, pit aspirations resulted from decomposition between different wood cell layers [1,57,58]. Heat treatment changes thermal stability of wood materials due to thermal degradation in the wood cells and in this study,

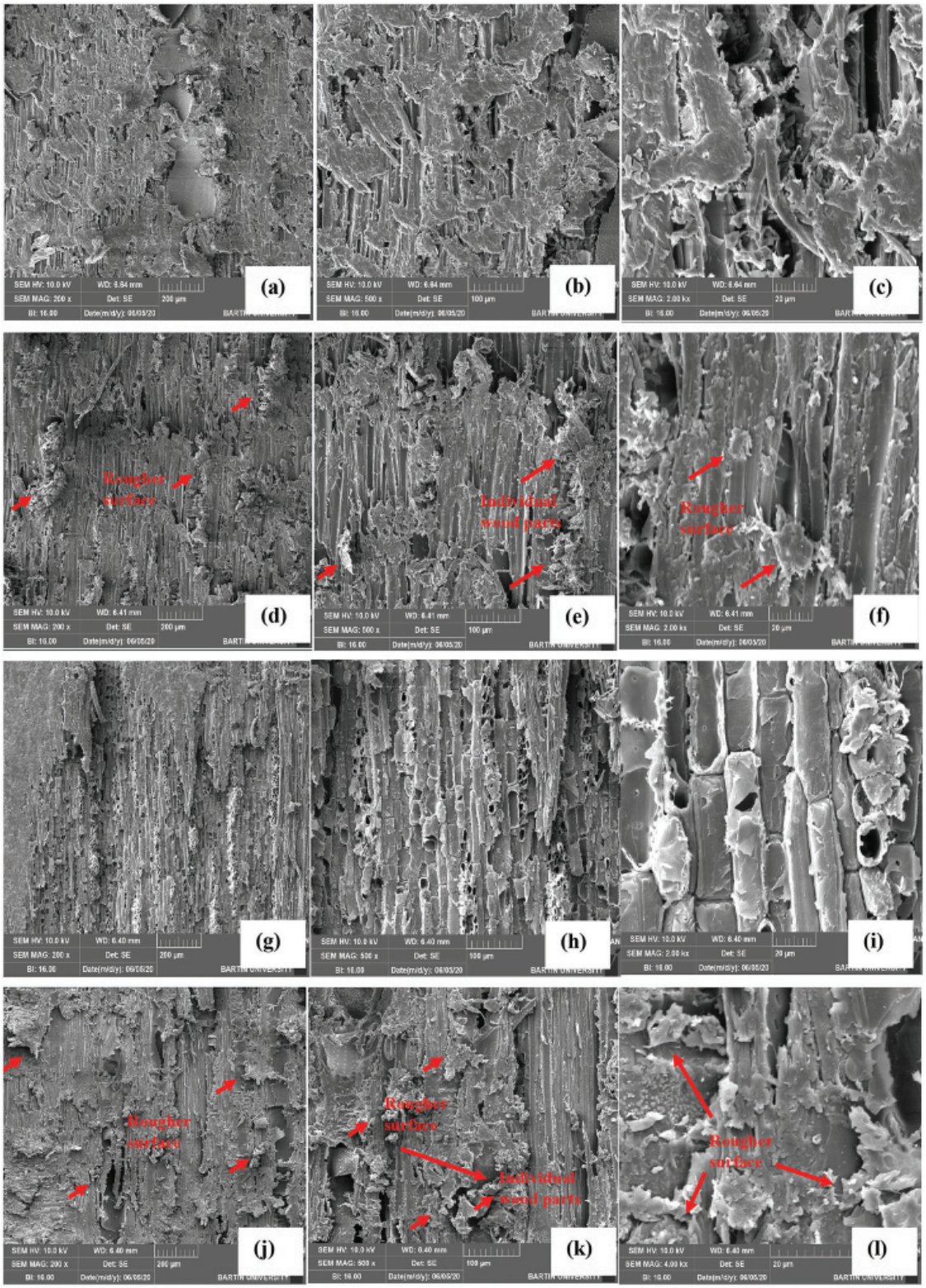



**Figure 3:** SEM images of the exotic wood materials. (a, b, c) un-treated Cedrorana, (d, e, f) heat-treated Cedrorana, (g, h, i) un-treated Cemara, (j, k, l) heat-treated Cemara

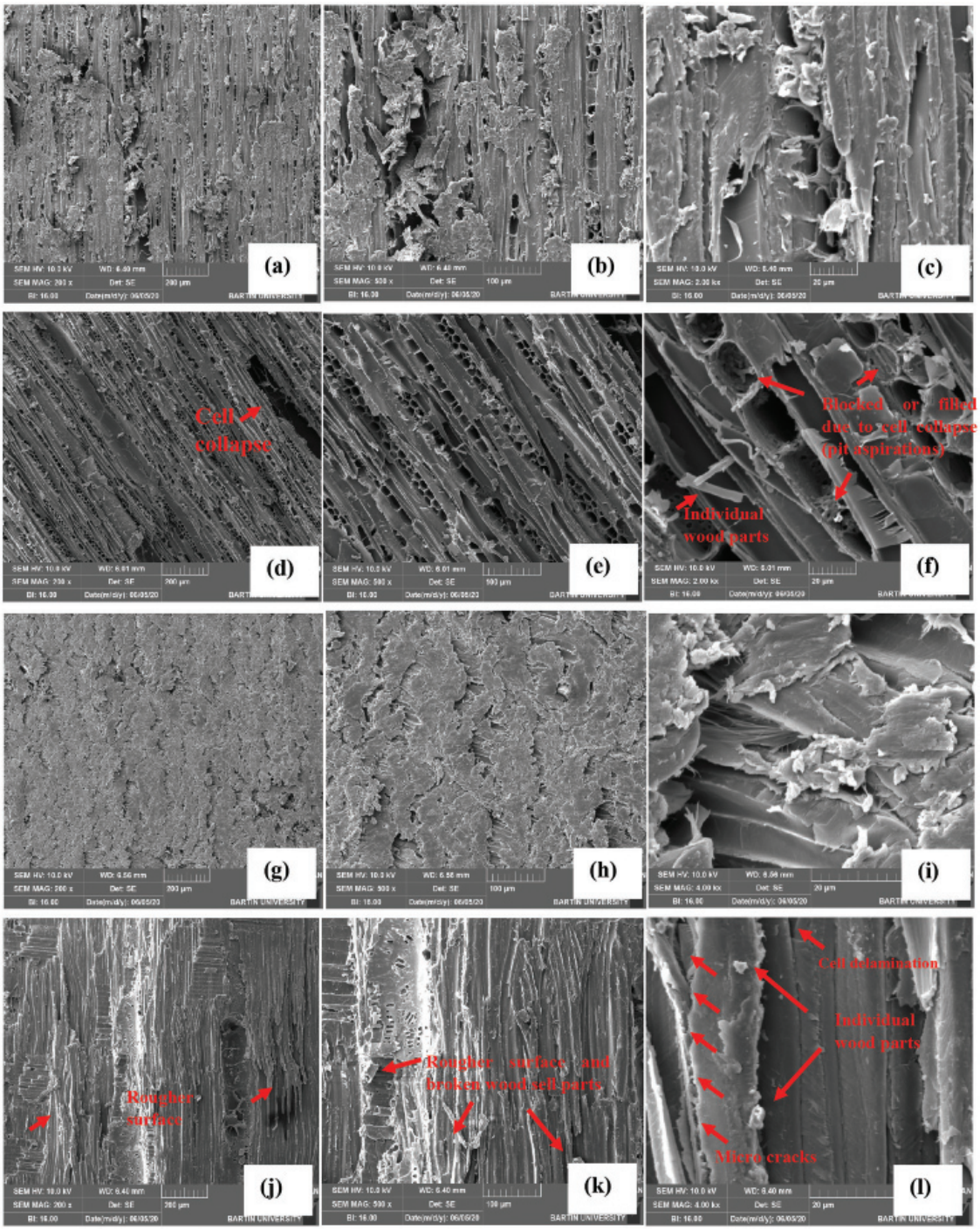



**Figure 4:** SEM images of the exotic wood materials. (a, b, c) un-treated Anigre, (d, e, f) heat-treated Anigre, (g, h, i) un-treated Coronilla, (j, k, l) heat-treated Coronilla

thermogravimetric analysis (TGA) was conducted to determine the thermal behavior of the materials after heat treatment. Figs. 5–7 show the thermogravimetric (TG) curves, derivative thermal gravimetry (DTG) and derivative thermal analysis (DTA).

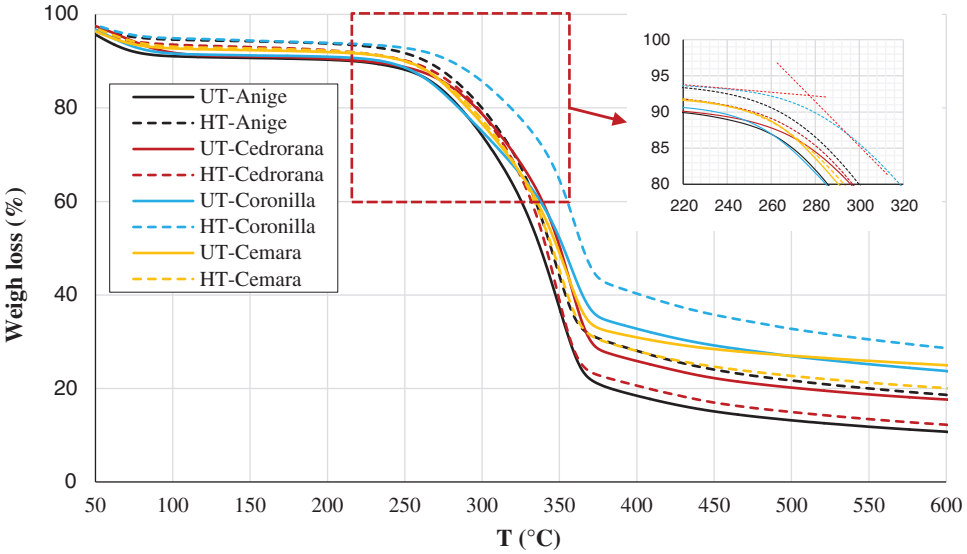



**Figure 5:** TGA curves of the un-treated and heat-treated exotic wood materials

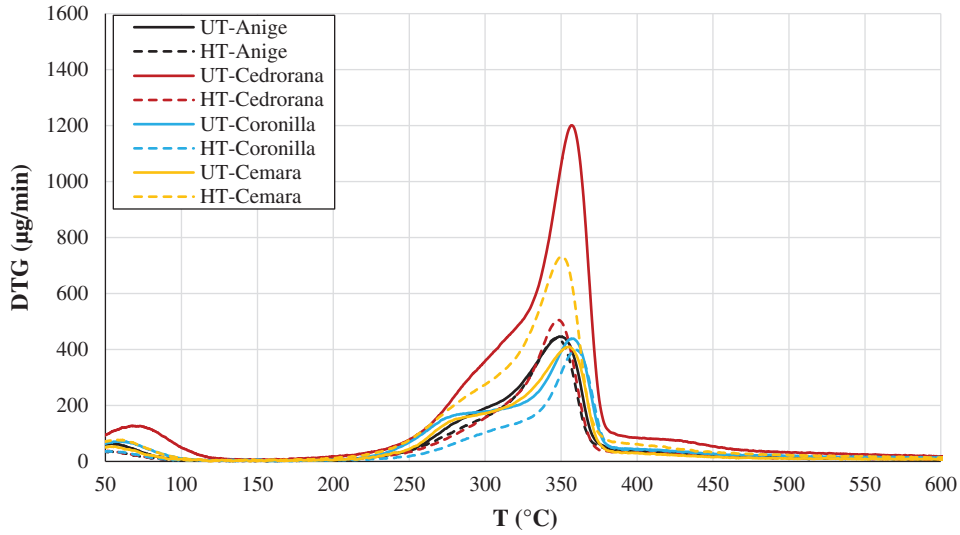



**Figure 6:** DTG curves of the un-treated and heat-treated exotic wood materials

TGA tests were run under a dynamic nitrogen atmosphere and at a heat rate of 10 °C/min. As seen as Fig. 5, three regions were detected on the TG curves. First region on the TG curves between 80–150°C are generally due to evaporation of water and volatile extractives from the wood, second region between 150 and 300°C is due to thermal degradation of phenolic compound degradation. including hemicellulose, cellulose and lignin etc., and finally third region above 300°C is followed by slow carbonization of residual materials. According to the Fig. 6, there are two regions on the DTA graph for thermal decomposition of the wood

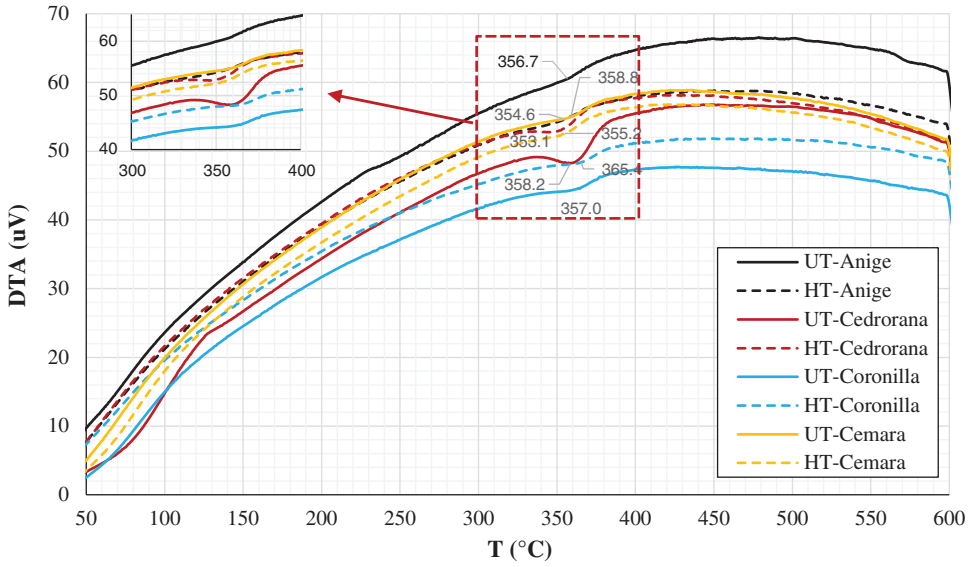



**Figure 7:** DTA curves of the un-treated and heat-treated exotic wood materials

constitutes. First one is due to evaporation of wood and phenolic compounds and other is due to thermal decomposition of wood elements. In the DTA graph, thermal decomposition temperature (TD) was seen. Tab. 5 shows the summary of TG analysis of the un-treated and heat-treated wood materials.

**Table 5:** The summary of TG analysis of the un-treated and heat-treated wood materials

| | TG-DTG | | | | | DTA |
|---|---|---|---|---|---|---|
| Samples | T15% (°C) | T50% (°C) | T75% (°C) | $DTG_{max}$ (°C) | Weight loss (%) | Td (°C) |
| UT-Anigre | 219 | 338 | 363 | 349 | 90 | 357 |
| HT-Anigre | 264 | 345 | 436 | 347 | 82 | 355 |
| UT-Cedrorana | 225 | 351 | 412 | 357 | 83 | 358 |
| HT-Cedrorana | 253 | 342 | 365 | 348 | 88 | 353 |
| UT-Coronilla | 236 | 353 | 557 | 358 | 77 | 357 |
| HT-Coronilla | 279 | 365 | – | 359 | 72 | 365 |
| UT-Cemara | 251 | 349 | 601 | 355 | 75 | 359 |
| HT-Cemara | 250 | 345 | 444 | 351 | 80 | 355 |

As seen Tab. 5, T15% of the exotic wood materials generally increased with heat treatment and the increase ratio was calculated as 11–17%, but T15% for Cemara wood didn't change with heat treatment. T50% of the exotic wood materials increased as 2% and 3.5% for Anigre and Coronilla wood with heat treatment, respectively, however, T50% and T75% for Cedrorana and Cemara wood decreased as 2.5% and 1.2%, respectively. Heat treatment didn't significantly affect the $DTG_{max}$. Weigh loss (%) of Anigre and Coronilla wood decreased as 8.9% and 6.5% with heat treatment, respectively, however, weigh loss for Cedrorana and Cemara wood increased as 6% and 6.3%, respectively. DTA peaks affected negatively with heat treatment and DTA peaks generally decreased.

## 4 Conclusions

In this study, it was investigated the effects of heat treatment on decorative properties including glossiness, color and shore-D, morphological and thermal properties of some exotic wood including Anigre, Coronilla, Cedrorana and Cemara. After the treatment, the glossiness and color of the woods got darker as comparison with untreated wood and the hardness was found to decrease with the treatment. The results of the statistical analysis as depending on the wood type, heat treatment, and their interaction showed that the changes among the samples were significant for shore-D hardness, glossiness and color parameters after heat treatment. Color, glossiness and shore-D hardness was significantly affected by heat treatment in all specimens. According to the SEM images, the heat treatment was found to cause some cracks, pit aspirations resulted from decomposition between different wood cell layers. The all-treatment defects were detected in the all samples. Thermal treatment generally improved the thermal stability of the samples, but thermal treatment slightly affected the thermal stability of Cedrorana and Cemara wood.

As a result, it can be said that heat treatment has been shown to improve the decorative properties and appearance of all exotic wood materials, and the use of these materials in products used for decorative purposes may be recommended.

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