Construction and Building Materials 106 (2016) 711–720

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Original Research Article

Effect of seasonal changes on the combustion characteristics of impregnated cedar (*Cedrus libani* A. Rich.) wood

M. Said Fidan [a,*], Ş. Şadiye Yaşar [b], Mehmet Yaşar [b], Musa Atar [c], Elif Alkan [a]

[a] Gumushane University, Institute of Natural Applied Science, Department of Forestry and Environment Sciences, 29100 Gumushane, Turkey
[b] Gumushane University, Gumushane Vocational High School, Department of Design, 29100 Gumushane, Turkey
[c] Gazi University, Faculty of Technical Education, Department of Furniture and Decoration Education, 06500 Ankara, Turkey

HIGHLIGHTS

- The weight loss was lower during winter.
- The O_2 and CO_2 contents were determined to be the highest in fall during combustion without flame, respectively.
- The winter samples were determined to be safer to employ in areas with high fire risk.

ARTICLE INFO

Article history:
Received 27 August 2015
Received in revised form 23 November 2015
Accepted 17 December 2015

Keywords:
Cedar
Impregnated
Seasonal variations
Varnish
Combustion
Wood

ABSTRACT

Wood is an irreplaceable material used as decorative and structural element both indoors and outdoors. When used as a structural material, wood has several superior characteristics in comparison to other structural constituents, although it is adversely affected by fires as well as biotic pests and abiotic effects. In this study, cedar (*Cedrus libani* A. Rich.) wood samples were impregnated using either Tanalith-E or Wolmanit-CB as detailed in ASTM-D 1413-76 and surface-treated using water-based or synthetic varnish. The impregnated and varnished samples were left outdoors with the aim of investigating the effect of seasonal changes. The samples were later subjected to combustion analysis as detailed in the combustion test standard ASTM-E 160-50. The results of the study indicated that the weight loss was lower during winter (87.82%), for samples that were impregnated using Wolmanit-CB (88.90%) and those that were treated with synthetic varnish (88.45%). On the other hand the O_2 and CO_2 contents were determined to be the highest in fall during combustion without flame (18.16% and 17.96%, respectively); the CO content was the highest during combustion without flame for the winter samples (28,907 ppm) and the NO content was the highest during combustion without flame for the spring samples (76.15 ppm). In conclusion, the winter samples that were impregnated using Wolmanit-CB and treated with synthetic varnish were determined to be safer to employ in areas with high fire risk.

1. Introduction

Wood material has been reported to have approximately 10,000 different areas of application. The main reasons behind this phenomenon are its anatomical structure, physical and mechanical characteristics as well as its chemical structure [1].

The greatest advantage that wood provides in the event of fire is the fact that it burns slowly and forewarns about collapse, thus minimizing the loss of lives. A layer of humidity, foam or gas may be formed at the surface of the wood through methods such as spraying, smearing, immersion or diffusion [2].

The retention and release of water from the wood throughout seasonal changes (due to external factors including rain, snow, hail and sun exposure) wears the material out, causing mechanical and physical aging.

Environmental issues still play a significant role on Earth in the first quarter of the 21st century. The accumulation of asbestos as a consequence of concrete construction has become prevalent, causing numerous health issues including asthma and lung cancers as well as increasing exposure to radon gas associated radiation [3].

Approximately 24% of air pollution and 50% of greenhouse gases produced on Earth as well as 50% of the total energy consumed has

* Corresponding author.
E-mail address: saidfidan@gumushane.edu.tr (M.S. Fidan).

http://dx.doi.org/10.1016/j.conbuildmat.2015.12.133
0950-0618/

been reported to be associated with construction-related activities [3].

Despite its flammability, wood material is renowned for its minimal contribution to fires and its exceptional resistance during the initial stages of a fire incident. In addition to its high resistance against the spreading of a fire, significant reductions in its destruction or resistance have not been observed [4].

Structural elements in buildings should be materials that are resilient against burning and the employment of such materials should be facilitated and popularized. Improvement of the fire resistant characteristics of structural elements and materials will result in achieving structures that are stronger against collapse as well as possibly reducing the complex and poisonous nature of the fumes released during fire [5].

It is common practice recently to employ inorganic chemicals to retard and prevent the burning of wood material. Ammonium sulfate, ammonium chloride, borax, boric acid, phosphoric acid and zinc chloride are among the most frequently employed chemicals. Salt-based chemicals currently used as fire retardants (ammonium and boron compounds) facilitate the carbonization of the wood material, forming an insulating layer preventing the formation of flammable gases [6,7]. Despite all these advantages, boron salt-based impregnating compounds increase the hygrosopicity of wood material. For this reason, salt-impregnated wood materials are not recommended for utilization in humid and water-susceptible environments due to their sensitivity to washing. A combination of other chemicals is employed to prevent the washing of wood, to reduce its hygroscopicity and to improve its dimensional stability and its mechanical characteristics. Wolmanit-CB and Tanalith-E were created by increasing the chromium content of salt-based impregnating materials in order to prevent washing-associated problems [8].

The main aim of present study investigates the seasonal effects on combustion of impregnation and surface treatment materials applied to wood material, which requires protection indoors or outdoors, on its combustion characteristics. The difference between present study and similar previous studies are seasonal effects.

2. Material and method

2.1. Material

Cedar wood was employed as the material in the present study. Cedar wood was employed in the study due to its regular employment both indoors and outdoors in Turkey (in both furniture and joinery work) and due to the fact that constitutes a substantial fraction of the forests in Turkey. The randomly selected timbers were conditioned at a temperature of 20 ± 2 °C and relative humidity of 65 ± 3% until they achieved constant weight in climate room prior to coarse cutting. Care was taken to sample from normally and regularly grown pieces of wood material that were resin-free, regular-fibred, and knot-free.

Two impregnating chemicals, Wolmanit-CB and Tanalith-E, which are frequently employed in outdoor applications, were used. The surfaces were treated using water-based or synthetic varnishes. Two different types of varnish were employed; synthetic varnish, which is frequently used outdoors and indoors, and water-based varnish, which unlike synthetic and polyurethane varnishes, does not release volatile gases harmful for human health. These chemicals were procured from the manufacturers.

2.2. Method

2.2.1. Preparation of the test samples

The experimental samples were regularly cut to a size of 13 × 13 × 76 mm (radial × tangent × length). A total of 1140 test samples were prepared from cedar wood to investigate the effect of 2 different impregnating materials, 2 different types of varnish, 4 seasons and for the control samples with 3 groups with 24 samples in each group (5 × 2 × 2 × 24 × 3). The test sample counts and the treatment chemicals are categorized in Table 1. The test samples were waited at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5% until they reached constant weight prior to impregnate and they were weighed up to a precision of 0.01 g.

2.2.2. Impregnation

The vacuum-pressure method was employed in impregnation as stated in ASTM-D 1413-76 [9]. Samples were initially treated with a pre-vacuum equivalent to 60 cm hg^{-1} for 60 min and were then left under atmospheric pressure in solution for another 60 min. The impregnated materials were left in an air-circulated room for 15–20 days to allow for the evaporation of the solvent material and were kept at a temperature of 20 ± 2 °C and relative humidity of 65 ± 3% until they achieved constant humidity of 12%.

2.2.3. Determination of the extent of retention

The extent of retention of the impregnating material of the test samples was determined as provided in the TS 5724, 1988 standard and was calculated making use of the values prior to and post-impregnation using the following equation [10]. The retention of the samples used in the experiments is provided in Table 2.

$$R = \left[\frac{G.C}{V}\right] \times 10^3 \text{ kg/m}^3 \quad (1)$$

where $G = t_2 - t_1$, t_1 = sample weight prior to impregnation (g), t_2 = sample weight prost impregnation (g), V = sample volume (cm^3), and C = concentration of the solution (%).

2.2.4. Varnish application

The samples were varnished following impregnation and acclimatization in compliance with the principles provided in ASTM-D 3023, 1988 [11]. Sample surfaces were lightly sanded using no. 220 sandpaper and cleaned of dust to make them ready for varnish application. Manufacturer's recommendations on the amount of varnish to be applied were followed. The varnish was weighed on a scale with a precision of 0.01 g. The amount of hardeners, thinners or diluting media needed to condition the varnish were employed in compliance with the recommendations of the manufacturer. The varnished samples were dried at room temperature.

Varnished test samples were left to remain outdoors, as their seasonal groups dictated, to be exposed to weather elements. The sample pieces were placed on the test stand at an angle of 45° facing south. The study investigated the effect of outdoor elements on the combustion characteristics of variably-treated wood material. Therefore, the test samples were periodically left to remain outdoors along with their control samples; summer was analyzed group in mo. 6, the fall group in mo. 9, the winter group in mo. 12 and the spring group in mo 3. Combustion tests were conducted on the samples at the end of each of their test periods.

2.2.5. Combustion tests

The impregnated samples were removed from the outdoor environment and the combustion characteristics of the samples were determined in the combustor as detailed in the ASTM-E 160-50-1975 standard [12]. Each sample group was weighed prior to combustion and were stacked on a gauze tripod. The 24 samples were stacked in 12 levels so as to form a tetragonal prism and were burned in the test. The source of flame was centered directly below the stack and was burned for 3 min. to maintain combustion with flame (CWF), then the source was extinguished to maintain combustion without flame (CWTF) and the afterglow (CAG) stages. The % weight loss was determined using the following formula:

$$WL(\%) = \left[\frac{(W_0 - W_d)}{W_0}\right] \times 100 \quad (2)$$

Table 1
Test samples prepared for the present study.

Wood type	Seasonal groups	Impregnating material	Varnish	Number
Cedar	Spring			24 × 3 = 72
	Summer			24 × 3 = 72
	Fall	Wolmanit-CB	Water-based varnish	24 × 3 = 72
	Winter	Tanalith-E	Synthetic varnish	24 × 3 = 72
	Control			24 × 3 = 72

Table 2
Extent of retention of the test samples used in the experiments.

Wood type	Retention (kg/m^3)	
	Tanalith-E	Wolmanit-CB
Cedar	0.74	3.18

where WL denotes weight loss (%), W_0 denotes the initial dry weight of the samples (g), and W_d denotes the final dry weight of the sample (g) [13].

The temperature of combustion, the illuminance, the weight loss ratios of the samples and the duration of combustion for each sample were determined during combustion.

2.2.6. Combustion flue gas analysis

The relative amount (%) of oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO) and nitrogen monoxide (NO) gases released during combustion with or without heat source as well as during afterglow were determined.

2.2.7. Statistical evaluation of the data

The temperature of combustion, the illuminance, the duration of combustion, the weight loss and the results of the gas analyses of the samples during combustion with or without flame as well as during afterglow measured in triplicate were used to conduct an analysis of variance employing randomized block factorial experimental design using SAS software. The mean values were compared using the least significant difference (LSD) test. Finally, multiple correlation analysis was carried out in order to investigate the relationship between groups [14]. Values in the range of 0.50–0.75 were identified as moderately correlated and those in the range of 0.75–1.00 were identified as high correlation in the multiple correlation analysis.

3. Results and discussion

The extent of impregnation material retention of the samples employed in the present study were determined as detailed in Table 2.

The results of the analysis of variance of the season, type of impregnating material and the type of varnish on the temperature of combustion, illuminance and the duration of combustion of cedar wood during combustion with or without flames and during afterglow are presented in Table 3.

The differences in the temperature of combustion of cedar wood during combustion with or without flame and during afterglow were significant at a threshold of 1% for the effect of seasons and the type of varnish employed. The difference in illuminance was significant at a threshold of 1% for the seasonal effects and the type of impregnating material, whereas the differences in time to collapse and total duration of combustion were significant at a threshold of 1% for the seasonal changes, the type of impregnating material and varnish type parameters (Table 3).

Table 3
Results of the analysis of variance for the temperature of combustion, illuminance, and duration of combustion during combustion with or without heat source and during afterglow.

Source of Variance	Values of temperature (°C)				Values of illuminance (lüx)			
	F.D.	S.S.	S.M.	F.V.	F.D.	S.S.	S.M.	F.V.
Combustion with flame								
Change of seasonal (sc)	4	11007.67	2751.92	6.22*	4	512779.30	128194.83	2022.47*
Materials of impregnate (im)	2	2296.31	1148.16	2.60	2	522.53	261.27	4.12*
Types of varnish (vt)	2	6526.53	3263.27	7.38*	2	181.51	90.76	1.43
sc * im	8	7256.95	907.12	2.05**	8	2800.65	350.08	5.52*
sc * vt	8	9182.95	1147.87	2.60**	8	677.90	84.74	1.34
im * vt	4	4586.36	1146.59	2.59**	4	1285.56	321.39	5.07*
sc * im * vt	16	22315.50	1394.72	3.15*	16	3033.48	189.59	2.99*
Error	90	39790.67	442.12		90	5704.67	63.39	
Total	134	102962.93			134	526985.60		
Combustion without flame								
Change of seasonal (sc)	4	43250.10	10812.53	40.22*	4	499997.01	124999.25	1905.26*
Materials of impregnate (im)	2	1178.33	589.16	2.19	2	709.62	354.81	5.41*
Types of varnish (vt)	2	3322.24	1661.12	6.18*	2	93.17	46.59	0.71
sc * im	8	9963.67	1245.46	4.63*	8	4270.24	533.78	8.14*
sc * vt	8	7274.87	909.36	3.38*	8	471.13	58.89	0.90
im * vt	4	8311.23	2077.81	7.73*	4	789.81	197.45	3.01**
sc * im * vt	16	15501.88	968.87	3.60*	16	3317.23	207.33	3.16*
Error	90	24194.00	268.82		90	5904.67	65.61	
Total	134	112996.33			134	515552.86		
Combustion during afterglow								
Change of seasonal (sc)	4	122997.67	30749.42	25.05*	4	504278.42	126069.60	2276.23*
Materials of impregnate (im)	2	18484.64	9242.32	7.53	2	317.17	158.59	2.86*
Types of Varnish (vt)	2	13446.10	6723.05	5.48*	2	171.79	85.90	1.55
sc * im	8	58425.88	7303.24	5.95*	8	3309.94	413.74	7.47*
sc * vt	8	32798.64	4099.83	3.34*	8	456.87	57.11	1.03
im * vt	4	2905.14	726.29	0.59	4	1015.85	253.96	4.59*
sc * im * vt	16	58069.01	3629.31	2.96*	16	2999.70	187.48	3.39*
Error	90	110466.67	1227.41		90	4984.67	55.39	
Total	134	417593.75			134	517534.41		
Time of combustion (sn)								
	Value of time to collapse				Total time of combustion			
Change of seasonal (sc)	4	111371.93	27842.98	56.44*	4	750004.7852	187501.20	19.32*
Materials of impregnate (im)	2	9380.37	4690.19	9.51*	2	374234.8444	187117.42	19.29*
Types of varnish (vt)	2	1942.33	971.16	1.97*	2	326886.9333	163443.47	16.85*
sc * im	8	27758.74	3469.84	7.03*	8	300157.5259	37519.69	3.87*
sc * vt	8	18000.34	2250.04	4.56*	8	248990.5481	31123.82	3.21*
im * vt	4	11778.56	2944.64	5.97*	4	160332.7556	40083.19	4.13*
sc * im * vt	16	10655.66	665.98	1.35	16	469396.2074	29337.26	3.02*
Error	90	44395.33	493.28		90	873241.333	9702.68	
Total	134	235283.26			134	3503244.933		

F.D.: Degrees of Freedom, S.S.: Sum of Squares, S.M.: Mean of Squares, F.V.: *F* Value.
*, **: 1% and 5% significance level, respectively.

Table 4
Results of the analysis of variance of the weight loss during combustion with or without heat source and that of afterglow.

Source of variance	Weight loss (%)			
	Degrees of freedom	Sum of squares	Mean of squares	*F* value
Change of seasonal (sc)	4	111.87	27.97	22.18*
Materials of impregnate (im)	2	2.59	1.30	1.03
Types of varnish (vt)	2	9.55	4.78	3.79**
sc * im	8	42.65	5.33	4.23*
sc * vt	8	20.76	2.59	2.06**
im * vt	4	0.67	0.17	0.13
sc * im * vt	16	39.65	2.48	1.97**
Error	90	113.50	1.26	
Total	134	341.24		

*, **: 1% and 5% significance level, respectively.

The results of the analysis of variance of the seasonal effect, type of impregnating material and the type of varnish on the weight loss of impregnated cedar wood samples are presented in Table 4.

The differences in the weight loss of impregnated cedar wood were determined to be significant at a threshold of 1% for the seasonal effects and at a threshold of 5% for the type of varnish in the conducted analysis of variance (Table 4).

The mean values and the results of the LSD test are given in Table 5. The maximum mean temperatures of combustion were 489 °C, 619 °C and 347 °C for the seasonal effect, with spring values the highest; 482 °C, 602 °C, and 317 °C for the effect of the impregnating material with the employment of Tanalith-E yielding higher values (in comparison to that of Wolmanit-CB, 478 °C, 601 °C, and 316 °C); and 485 °C, 600 °C, and 313 °C for the effect of the type of varnish with the employment of water-based varnish yielding higher values (in comparison to that of synthetic varnish application, 468 °C, 593 °C, and 295 °C) during combustion with flame, without flame and during afterglow, respectively, as given in Table 5.

The highest temperature of combustion of cedar wood was determined for the spring samples impregnated with Tanalith-E and treated with water-based varnish during combustion with flame, without flame and during afterglow. At the same time, the temperature of combustion for the treated samples was determined to be higher than that of the control sample.

The maximum value of temperature (371.08 °C) was obtained from the immersol aqua impregnated beech material, water-based varnished [8]. The highest temperature according to the mean values of temperature, was obtained from the materials, impregnated with Tanalith-E and water-based varnished (362.88 °C). It has been concluded that chemicals used in impregnation processes affected the temperature values, also, water-based varnishes had an accelerating effect on combustion [15].

The temperature of combustion for treated samples has been reported to be higher than that of control samples in previous studies as well [13,16].

The maximum illuminance of the impregnated samples was 460 lux, 455 lux and 458 lux for the seasonal effect with the summer samples having the highest values; 354 lux, 352 lux, and 356 lux or 353 lux, 351 lux, and 355 lux for the employment of Tanalith-E or Wolmanit-CB as the impregnating material (the values when Tanalith-E was applied were similar but slightly higher); and 354 lux, 351 lux, and 356 lux or as 351 lux, 349 lux, and 354 lux for the water-based or synthetic varnish application (water-based varnish application resulted in slightly higher but very similar luminosity values) during combustion with flame, without flame and during afterglow, respectively (Table 5).

The shortest time to collapse and the total time of combustion were 485 s and 848 s, respectively, for the seasonal effect, with the highest obtained for the summer samples; 437 s and 746 s for the effect of the employment of Tanalith-E, which was higher than those for Wolmanit-CB application (435 s and 742 s); and 442 s and 761 s or 447 s and 856 s for the water-based or synthetic varnish application, indicating shorter time to collapse and shorter time for complete combustion upon water-based varnish application (Table 5).

Table 5
Mean values of the temperature of combustion, illuminance, duration of combustion, and weight loss and the groups resulting from the least significant difference (LSD) analysis during combustion with or without heat source and that of afterglow.

Factor		Combustion with flame		Combustion without flame		Combustion during afterglow		Time of combustion		Weight loss (%)
		Temp. (°C)	Illuminance (lüx)	Temp. (°C)	Illuminance (lüx)	Temp. (°C)	Illuminance (lüx)	Time to collapse (sn)	Total Time of combustion (sn)	
Change of seasonal	Summer	487 a	460 a	586 c	455 a	265 c	458 a	485 a	852 a	88.34 c
	Fall	468 b	300 b	574 d	296 c	282 c	299 c	455 b	823 a	90.36 a
	Winter	468 b	354 c	598 b	357 b	338 a	363 b	420 c	653 c	87.82 c
	Spring	489 a	363 d	619 a	358 b	347 b	365 b	402 d	758 b	88.29 c
	Control	476 b	285 e	618 a	283 d	340 a	286 d	449 b	851 a	89.32 b
	Means	478	352	599	350	314	354	442	787	88.83
	S_x	10.06	68.89	19.72	68.09	37.96	68.31	32.21	84.28	1.02
	LSD	11.37	4.31	8.87	4.38	18.95	4.02	12.00	53.26	0.61
Materials of impregnate	Wolmanit-CB	478 ab	353 a	601 ab	351 a	316 a	355 ab	435 b	742 b	88.90 a
	Tanalith-E	482 a	354 a	602 a	352 a	317 a	356 a	437 b	746 b	89.91 a
	Control	472 b	350 b	600 b	347 b	292 b	346 b	454 a	861 a	88.93 a
	Means	477	352	601	350	308	352	442	783	89.25
	S_x	5.03	2.08	1.00	2.65	14.15	5.51	10.44	67.58	0.57
	LSD	8.81	3.33	6.87	3.39	14.67	3.12	9.30	41.26	0.47
Types of varnish	Synthetic	468 b	351 a	593 b	349 a	295 b	354 a	447 a	856 a	88.45 b
	Water-Based	485 a	354 a	600 a	351 a	313 a	356 a	442 a	761 b	89.00 a
	Control	480 a	352 a	605 a	349 a	318 a	353 a	438 a	744 b	89.03 a
	Means	478	352	599	350	309	354	442	787	88.83
	S_x	8.74	1.53	6.03	1.15	12.10	1.53	4.51	60.36	0.33
	LSD	8.81	3.33	6.87	3.39	14.67	3.12	9.30	41.26	0.47

a, b: the difference between the average value of the same group with different letters in the same row.

The mean seasonal effect on weight loss ratios was the lowest for the winter group (87.82%); lower when Wolmanit-CB was used as the impregnating material (88.90%) than Tanalith-E (89.91%), and lower for the use of synthetic varnish (88.45%) than for the use of water-based varnish (89.12%) (Table 5).

The results of the analysis indicated that despite seasonal variations, the lowest ratio of weight loss occurred in the winter samples impregnated with Wolmanit-CB and treated using synthetic varnish.

The maximum weight loss after combustion (93.17%) was found in the group of impregnated beech with boric acid, applied synthetic varnish [8]. Some researchers have found results of weight loss, among control and observation groups were similar [17]. However, Tanalith-E impregnated mahogany wood control samples gave the highest weight loss values in combustion tests (69.71%), according to their average weight losses [15].

The weight loss ratio was reported as 92.06% for Scots pine and as 89.13% for alder control samples [13]. The weight loss ratio of the cedar wood samples was determined as 89.32% in the present study. This value was lower than that reported for the alder and higher than those reported for Scots pine samples. This is thought to be a result of the existence of extractive materials in cedar, redwood and Scots pine wood samples.

Uysal and his colleagues (2008), have found that varnishes had trigger and promoting effects during the combustion of scots pine materials. Therefore, varnishes used in varnish process must be considered with their characteristics of facilitating combustion, increasing the temperature and the gases produced by the reaction, in case of fire. It is stated that in the environments with the risk of fire, it is more beneficial to use the materials, on which the varnishing process was not applied.

Figs. 1 and 2 display the weight loss due to the combustion of the impregnated wood samples as a function of seasonal changes,

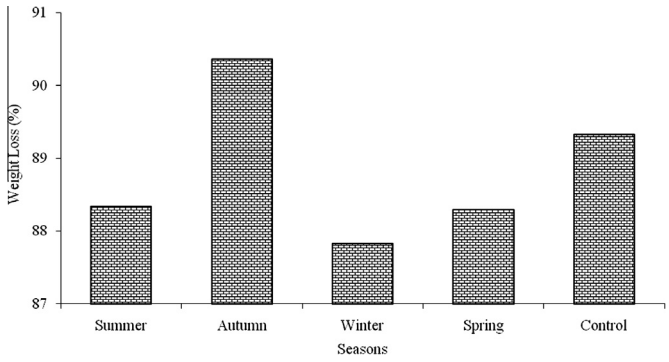

Fig. 1. Seasonal variations in weight loss during combustion of cedar wood impregnated with different materials.

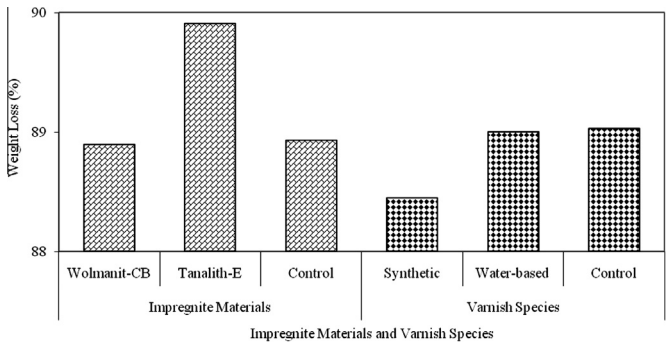

Fig. 2. Weight loss during combustion of cedar wood impregnated and varnished with different materials.

the type of impregnating material used and the type of varnish employed.

The lowest weight loss ratio was determined for the winter samples and the highest for the fall samples. Weight loss was lower for the samples impregnated with Wolmanit-CB rather than Tanalith-E and for those treated using synthetic varnish rather than water-based varnish (Figs. 1 and 2) with different materials.

The results of the analysis of variance of the flue gas content during combustion with or without flames and during afterglow are presented in Table 6. The mean values and the results of the least significant difference (LSD) test are given in Table 7.

The differences in the O_2, CO_2, CO and NO contents of the flue gas released during the combustion of the impregnated cedar wood samples with flame significant at a threshold of 1% for the seasonal effects and significant at a threshold of 5% for the varnish type. Similarly, the differences in the O_2 and CO contents were determined as significant at a threshold of 1% for the seasonal effects and at a threshold of 5% for the effect of the type of impregnating material during combustion without flame. The differences in CO_2 and NO contents were significant at a threshold of 1% for the seasonal effects and for the varnish type parameter both during combustion without flame and during afterglow (Table 6).

The results of the flue gas analysis indicated that the lowest mean contents were 10.16% O_2 (spring), 6.11% CO_2 (winter), 12,469 ppm CO (winter), and 11.09 ppm NO (winter). The highest were 15.11% O_2 (winter), 10.33% CO_2 (spring), 18,533 ppm CO (spring), and 40.61 ppm NO (fall) during combustion with flame. The lowest values were 2.23% O_2 (fall), 4.84% CO_2 (winter), 16,002 ppm CO (winter) and 8.00 ppm NO (winter) and the highest were 13.61% O_2 (winter), 17.96% CO_2 (fall), 28,907 ppm CO (fall), and 76.15 ppm NO (spring) during combustion without flame. The lowest were 12.55% O_2 (winter), 6.39% CO_2 (spring), 8101 ppm CO (spring), and 13.40 ppm NO (winter) while the highest values were 18.16% O_2 (fall), 7.94% CO_2 (summer), 21,474 ppm CO (winter), and 75.25 ppm NO (spring) during afterglow (Table 7).

The results of the flue gas analysis with respect to the type of impregnating material as displayed in Table 7 indicated that the O_2 and NO content of the samples impregnated using Tanalith-E were high, whereas the CO_2 and CO contents were lower than those impregnated using Wolmanit-CB during combustion with or without flame.

The results of the flue gas analysis with respect to the type of varnish indicated that the mean O_2 content was higher for samples treated using water-based varnish whereas the CO_2, CO and NO contents were lower than those treated using synthetic varnish during combustion with flame, without flame and during afterglow (Table 7).

The results of the flue gas analysis of the impregnated cedar wood combustion indicated that the O_2 content of samples that were treated using water-based varnish was higher during combustion with flame, without flame and during afterglow and that the CO_2, CO and NO contents were lower than those of samples to which synthetic varnish was applied (Table 7).

As a result of the gas analysis, the maximum amount of O_2 evolved (18.64%) was found in the mahogany group impregnated with boric acid and polyurethane varnished; the highest amount of CO (5125.32 ppm) was found in the beech group impregnated with immersol aqua and water based varnished; and also, the highest NO value (152.41 ppm) was found in the Tanalith-E impregnated mahogany tree material group which were treated by water-based varnish [8].

For the gas quantities evolved, amounts of CO were found at higher values, whilst results of other gases has shown close or equivalent values to the control samples [17].

As a result of combustion test, the highest value according to measured average oxygen (O_2) value was measured in the samples

Table 6
Results of the analysis of variance of the flue gas during combustion with or without heat source and during afterglow.

Source of variance	Amount of O_2 (%)				Amount of CO_2 (%)				Amount of CO (ppm)				Amount of NO (ppm)			
	F.D.	S.S.	S.M.	F.V.	F.D.	S.S.	S.M.	F.V.	F.D.	S.S.	S.M.	F.V.	F.D.	S.S.	S.M.	F.V.
Combustion with flame																
sc	4	340.27	85.07	15.94*	4	252.51	63.13	11.55*	4	585,310,577	146,327,644	13.12*	4	22462.43	5615.61	38.91*
im	2	11.99	5.99	1.12	2	9.65	4.83	0.88	2	42,532,201	21,266,101	1.91	2	6.82	3.41	0.02
vt	2	46.98	23.49	4.40**	2	38.79	19.39	3.55**	2	124,443,323	62,221,662	5.58*	2	926.39	463.20	3.21**
sc * im	8	109.36	13.67	2.56**	8	134.26	16.78	3.07**	8	270,474,598	33,809,325	3.03*	8	662.92	82.86	0.57
sc * vt	8	301.77	37.72	7.07*	8	307.47	38.43	7.03*	8	547,047,122	68,380,890	6.13*	8	7157.86	894.73	6.20*
im * vt	4	49.97	12.49	2.34**	4	59.97	14.99	2.74**	4	38,784,296	9,696,074	0.87	4	2647.10	661.78	4.59*
sc * im * vt	16	193.38	12.09	2.26*	16	173.80	10.86	1.99**	16	461,540,752	28,846,297	2.59*	16	7980.86	498.80	3.46*
Error	90	480.40	5.34		90	492.11	5.47		90	1003870431	11,154,116		90	12988.40	144.32	
Total	134	1534.12			134	1468.56			134	3074003299			134	54832.78		
Combustion without flame																
sc	4	3352.37	838.09	26.36*	4	3080.33	770.08	162.84*	4	3816853224	954,213,306	83.12*	4	78521.15	19630.29	74.61*
im	2	258.83	129.42	4.07**	2	13.15	6.57	1.39	2	97,798,949	48,899,475	4.26**	2	646.88	323.44	1.23
vt	2	192.99	96.50	3.04	2	57.84	28.92	6.12*	2	86,041,930	43,020,965	3.75**	2	2930.50	1465.25	5.57*
sc * im	8	821.22	102.65	3.23*	8	107.33	13.42	2.84*	8	361,477,536	45,184,692	3.94*	8	4123.44	515.43	1.96*
sc * vt	8	597.66	74.71	2.35**	8	86.27	10.78	2.28**	8	283,185,913	35,398,239	3.08*	8	6305.15	788.14	3.00*
im * vt	4	450.78	112.69	3.54*	4	88.17	22.04	4.66*	4	197,233,812	49,308,453	4.30*	4	2527.23	631.81	2.40*
sc * im * vt	16	1864.79	116.55	3.67*	16	222.16	13.89	2.94*	16	419,561,632	26,222,602	2.28*	16	18295.79	1143.49	4.35*
Error	90	2861.07	31.79		90	445.00	4.10		90	1033167169	11,479,635		90	23679.47	263.11	
Total	134	10399.71			134	4606.00			134	6295320166			134	137029.62		
Combustion during afterglow																
sc	4	834.53	208.63	11.28*	4	169.40	42.35	14.40*	4	2538076820	634,519,205	90.54*	4	54390.63	13597.66	102.42*
im	2	140.71	70.36	3.80*	2	4.21	2.10	0.71	2	16,174,160	8,087,080	1.15	2	2585.53	1292.77	9.74*
vt	2	67.07	33.53	1.81	2	8.21	4.11	1.40	2	6,919,872	3,459,936	0.49	2	633.56	316.78	2.39
sc * im	8	347.84	43.48	2.35**	8	36.92	4.61	1.57	8	247,630,408	30,953,801	4.42*	8	4822.80	602.85	4.54*
sc * vt	8	409.32	51.17	2.77*	8	42.85	5.36	1.82	8	143,076,142	17,884,518	2.55**	8	732.36	91.54	0.69
im * vt	4	114.08	28.52	1.54	4	26.88	6.72	2.28	4	83,447,576	20,861,894	2.98**	4	1329.35	332.34	2.50**
sc * im * vt	16	1255.55	78.47	4.24*	16	231.55	14.47	4.92*	16	401,422,968	25,088,936	3.58*	16	6766.57	422.91	3.19*
Error	90	1664.15	18.49		90	394.00	3.7		90	630,730,681	7,008,119		90	11948.16	132.76	
Total	134	4833.26			134	1676.00			134	4067478626			134	83208.95		

F.D.: Degrees of Freedom, S.S.: Sum of Squares, S.M.: Mean of Squares, F.V.: *F* Value, sc: Change of Seasonal, im: Materials of Impregnate, vt: Types of Varnish. *, **: 1% and 5% significance level, respectively.

Table 7
Mean values of the flue gas composition and the groups resulting from the least significant difference (LSD) analysis during combustion with or without heat source and during afterglow.

		Combustion with flame				Combustion without flame				Combustion during afterglow			
	Factor	O_2 (%)	CO_2 (%)	CO (ppm)	NO (ppm)	O_2 (%)	CO_2 (%)	CO (ppm)	NO (ppm)	O_2 (%)	CO_2 (%)	CO (ppm)	NO (ppm)
Change of seasonal	Summer	13.21 b	7.73 b	16,165 b	20.88 b	7.48 b	13.90 b	23,992 b	41.46 b	14.49 b	7.94 b	16,606 b	42.06 b
	Fall	13.17 b	7.53 b	17,722 ab	40.61 a	2.23 c	17.96 a	28,907 a	22.27 c	18.16 a	7.24 bc	16,953 b	37.16 bc
	Winter	15.11 a	6.11 c	12,469 c	11.09 c	13.61 a	4.84 c	16,002 d	8.00 d	12.55 bc	7.76 b	21,474 a	13.40 d
	Spring	10.16 c	10.33 a	18,533 a	26.27 b	13.17 a	13.90 b	20,286 c	76.15 a	13.51 b	6.39 c	8101 c	75.25 a
	Control	12.91 b	7.65 b	16,254 b	46.40 a	2.29 c	17.87 a	30,292 a	17.67 c	10.67 c	9.79 a	16,616 b	32.80 c
	Means	12.90	7.87	16,229	29.05	7.76	13.69	23,896	33.11	13.88	7.82	15,950	40.13
	S_x	1.80	1.53	2328	14.42	5.57	5.34	5945	26.97	2.78	1.25	4848	22.44
	LSD	1.25	1.26	1806	6.50	3.05	1.18	1832	8.77	2.33	0.93	1431	6.23
Materials of impregnate	Wolmanit-CB	12.61 a	8.25 a	17,006 a	29.16 a	9.71 a	13.33 a	22,702 b	35.22 a	12.86 b	8.05 a	15,776 a	37.28 b
	Tanalith-E	13.32 a	7.65 a	15,978 a	29.26 a	9.90 b	14.09 a	24,360 a	34.02 a	15.27 a	7.80 a	15,641 a	46.32 a
	Control	12.80 a	7.72 a	15,702 a	28.74 a	6.66 b	13.66 a	24,626 a	30.09 a	13.50 ab	7.62 a	16,433 a	36.80 b
	Means	12.91	7.87	16,229	29.05	8.76	13.69	23,896	33.11	13.88	7.82	15,950	40.13
	S_x	0.37	0.33	687	0.28	1.82	0.38	1043	2.68	1.25	0.22	424	5.36
	LSD	0.96	0.98	1399	5.03	2.36	0.91	1419	6.79	1.80	0.72	1109	4.83
Types of varnish	Synthetic	13.31 a	7.58 b	15,385 b	26.97 b	7.43 ab	12.92 b	22,987 b	28.23 b	13.31 a	7.52 a	15,769 a	39.00 ab
	Water-Based	14.08 b	8.62 a	14,572 a	27.44 b	9.36 a	13.65 ab	22,771 ab	39.39 a	13.44 a	7.82 a	15,712 a	43.16 a
	Control	13.35 a	7.41 b	15,730 b	32.75 a	6.48 b	14.52 a	24,930 a	31.72 b	14.87 a	8.13 a	16,269 a	38.23 b
	Means	13.58	7.87	15,229	29.05	7.76	13.70	23,563	33.11	13.87	7.82	15,917	40.13
	S_x	0.43	0.66	595	3.21	1.47	0.80	1189	5.71	0.87	0.31	306	2.65
	LSD	0.97	0.98	1399	5.03	2.36	0.91	1419	6.79	1.80	0.72	1109	4.83

a, b: the difference between the average value of the same group with different letters in the same row.

Table 8
Multiple correlation analysis of the weight loss ratios, temperature values, illuminance, and the duration of combustion, as well as that of the concentrations of liberated oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO) and nitrogen monoxide (NO) during combustion with or without heat source and during afterglow.

	A	B	C	D	E	F	G	H	I	K	L	M	N	O	P	R	S	T	U	V	Y
A	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
B	0.62*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
C	−0.01	0.35*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
D	0.23*	−0.10	−0.28*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
E	0.22**	−0.11	−0.25*	0.99*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
F	0.21**	−0.10	−0.25*	0.99*	0.99*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
G	−0.22**	−0.49*	−0.31*	0.21**	0.22**	0.19**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
H	−0.04	−0.17**	−0.60*	−0.04	−0.05	−0.06	0.39*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
I	0.04	−0.10	0.02	−0.37*	−0.39*	−0.39*	0.04	0.23*	–	–	–	–	–	–	–	–	–	–	–	–	–
K	−0.12	−0.14	−0.06	0.02	0.02	0.02	0.10	0.13	0.12	–	–	–	–	–	–	–	–	–	–	–	–
L	0.18**	0.29*	0.12	0.32*	0.34*	0.34*	−0.26*	−0.21**	−0.35*	0.13	–	–	–	–	–	–	–	–	–	–	–
M	0.06	−0.27*	−0.30*	0.02	0.01	0.01	0.14	0.09	0.22*	0.08	0.02	–	–	–	–	–	–	–	–	–	–
N	0.12	0.11	0.09	0.01	0.01	0.02	−0.09	−0.16	−0.12	−0.96*	−0.13	−0.10	–	–	–	–	–	–	–	–	–
O	0.11	−0.04	−0.19**	−0.32*	−0.36*	−0.37*	0.19**	0.37*	0.46*	−0.26*	−0.67*	0.04	0.25*	–	–	–	–	–	–	–	–
P	0.06	0.15	0.32*	−0.17**	−0.17**	−0.18**	−0.01	−0.01	0.24*	0.17	−0.33*	−0.50*	−0.09	0.34*	–	–	–	–	–	–	–
R	0.19**	0.03	−0.05	−0.05	−0.06	−0.07	0.09	−0.09	0.02	−0.80*	−0.17**	0.05	0.78*	0.37*	−0.22**	–	–	–	–	–	–
S	−0.01	−0.17	−0.14	−0.40*	−0.43*	−0.43*	0.28*	0.30*	0.40*	−0.24*	−0.75*	0.03	0.24*	0.86*	0.45*	0.32*	–	–	–	–	–
T	−0.22**	−0.21**	0.19**	−0.08	−0.05	−0.06	0.10	−0.22**	0.06	0.37*	−0.19**	−0.26*	−0.29*	−0.24*	0.57*	−0.39*	0.10	–	–	–	–
U	0.11	0.07	−0.01	−0.41*	−0.42*	−0.43*	0.14	0.31*	0.40*	0.07	−0.16	0.23*	−0.10	0.43*	−0.01	0.01	0.38*	−0.22*	–	–	–
V	0.32*	0.28*	−0.09	0.30*	0.28*	0.28*	−0.16	−0.01	−0.08	−0.31*	0.52*	0.02	0.28*	0.07	−0.21**	0.22**	−0.15	−0.56*	0.04	–	–
Y	0.22**	0.10	−0.06	0.17**	0.14	0.15	−0.15	−0.03	0.04	−0.52*	−0.06	0.11	0.49*	0.35*	−0.19**	0.47*	0.12	−0.64*	0.09	0.50*	–

A: Time temperature with flame, B: Time temperature without flame, C: Time temperature aftergrow, D: Illuminance with flame, E: Illuminance without flame, F: Illuminance aftergrow, G: Time to Collapse, H: Total Time of Combustion, I: Weight Loss, K: Amount of O_2 of combustion with flame, L: Amount of O_2 of combustion without flame, M: Amount of O_2 of combustion during afterglow, N: Amount of CO_2 of combustion with flame, O: Amount of CO_2 of combustion without flame, P: Amount of CO_2 of combustion during afterglow, R: Amount of CO of combustion with flame, S: Amount of CO of combustion without flame, T: Amount of CO of combustion without flame, U: Amount of NO of combustion with flame, V: Amount of NO of combustion without flame, Y: Amount of NO of combustion without flame. *, **: 1% and 5% significance level, respectively.

impregnated with boric acid and applied polyurethane varnish (18.63%) Due to the excess amount of the oxygen, a retarding effect against combustion has been observed in the polyurethane varnished samples. Along with this, they observed that water-based varnish had a reducing effect on the amount of oxygen (O_2), for the all combustion samples it was applied on. Depending on these lower oxygen values emerged, water-based varnishes has an accelerating effect on the combustion. The highest amount according to average carbon monoxide values (CO) was obtained from the samples, impregnated with Tanalith-E and varnished with water-based varnish. According to these results, the researchers concluded that the kind of impregnation substance and the type of varnish have increasing effects on the amount of carbon monoxide emerged [15].

A previous gas analysis in LVL samples of white oak and chestnut wood indicated that the O_2 content of the samples was higher than that of controls but the CO content was lower than that of control [18]. The results presented in this study are in accordance with previously conducted studies.

The interaction effects among seasonal changes, the type of impregnating material and the varnish type are reported in Table 8.

The temperatures of combustion with flame and without flame were significantly positively correlated ($r = 0.62^*$); the temperature of afterglow and the total duration of combustion were significantly negatively correlated ($r = -0.60^*$); the correlation between the O_2 content during combustion with flame and the NO content during afterglow was significant and negative ($r = -0.52^*$); that between the O_2 content and the CO_2 or NO contents during combustion without flame was significant and negative ($r = -0.67^*$) and significant and positive ($r = 0.52^*$), respectively.

Between the O_2 content and the CO_2 content was significant and positive ($r = 0.57^*$) during afterglow; that between the NO content and the CO_2 content was significant and negative ($r = -0.50^*$) during afterglow; that between the CO content and the NO content was significant and negative ($r = -0.64^*$) during afterglow; and the correlation of the NO content between the samples tested during combustion without flame and those that were tested during afterglow was determined as significantly positive ($r = -0.50^*$) with all these relationships identified to be moderately correlated as indicated in Table 8.

The correlation between illuminance during combustion with flame and during combustion without flame or during afterglow were both determined to be positive and significant ($r = 0.99^*$ or $r = 0.99^*$, respectively); that between illuminance during combustion without flame and during afterglow was determined to be positive and significant ($r = 0.99^*$); that between the O_2 content and the CO_2 or CO content during combustion with flame was determined as negative and significant ($r = -0.96^*$ and $r = -0.80^*$, respectively).

Between the O_2 content and the CO content during combustion without flame was determined as negative and significant ($r = -0.75^*$); that between the CO_2 content and the CO content during combustion with flame was determined as positive and significant ($r = 0.78^*$); and that between CO_2 content and CO content during afterglow was determined as positive and significant ($r = 0.86^*$) with all these relationships identified to be highly correlated (Table 8).

4. Conclusions

The temperature of combustion was determined to be higher for the spring samples of the impregnated cedar wood than for the rest, whereas the illuminance, time to collapse and total duration of combustion were determined to be higher for the summer samples with respect to the seasonal differences. The samples that were impregnated with Tanalith-E had higher temperature of combustion and illuminance as well as longer time to collapse and longer duration of combustion than those that were impregnated with Wolmanit-CB. The samples that were treated using water-based varnish had higher temperature of combustion and illuminance whereas the total time to collapse and the duration of combustion was longer for the samples that were treated using synthetic varnish.

The relative weight loss in the impregnated and surface-treated cedar wood samples was lower in winter samples that were impregnated with Wolmanit-CB and treated with synthetic varnish.

The lower weight loss in the samples that were impregnated using Wolmanit-CB was attributed to the boron content of the impregnating material. Boron compounds have been previously reported to have fire retardant properties [13,15]. Therefore, impregnation with Wolmanit-CB can be suggested as a technique what will result in further fire retardation in wooden structures.

The results of the flue gas analysis indicated that the highest O_2, CO_2, CO and NO contents occurred in the winter, spring, spring and fall samples, respectively, during combustion with flame; for winter, fall, fall, spring samples, respectively, during combustion without flame; and for fall, summer, winter and spring samples, respectively, during afterglow. The O_2 and CO contents of the samples that were impregnated with Tanalith-E were determined to be lower than of those that were impregnated with Wolmanit-CB during combustion with flame and during afterglow, whereas the CO and NO contents were higher. This observation was completely reversed during combustion without flame. The O_2 content of the samples that were treated using synthetic varnish was higher than for those that were treated using water-based varnish whereas the CO_2, CO and NO contents were lower during combustion with flame.

The O_2 content of the samples was higher and the CO content of the samples was lower than those determined for the control samples. A higher O_2 content has not been reported to be associated with more extensive combustion. This is regarded as an indicator of the fire retardant properties of an impregnating material [18].

Multiple correlation analysis indicated a highly positive correlation for the illuminance during combustion with flame and during combustion without flame or during afterglow, as well as for the illuminance during combustion without flame and during afterglow; and between the CO_2 and CO contents during combustion with or without flame, whereas a highly negative correlation was observed between the O_2 content and the CO_2 or CO contents during combustion with flame and between the O_2 and the CO content during combustion without flame.

In conclusion, the winter samples that were impregnated using Wolmanit-CB and treated with synthetic varnish were determined to be safer to employ in areas with high fire risk.

Acknowledgement

This study was supported as Scientific Research Project (Project Number: 13.B0116.02.1), Gumushane University, Gumushane 2014 (in Turkish).

References

[1] Y., Bozkurt, N., Erdin, Wood Technology, Number of İstanbul University Faculty Publications: 3998, Number of Faculty Publications: 445, 1997, 372, İstanbul.
[2] N., Akıncıtürk, S., Perker, Insulation structure fire in the wood on the 700-year history of Cumalıkızık, TMMOB Chamber of Mechanical Engineers, Insulation and Energy Management Congress, 2003, 151–159.
[3] D. Eryıldız, Sustainability and architecture in the file ecological architecture, Arredamento Archit. 154 (2003) 71–75.
[4] B. Richardson, Wood Preservation, The Construction Pres. Ltd., Lancester, England, 1978. p. 238.

[5] G.R., Gann, D.J., Averill, M.K., Butler, W.W., Jones, W.G., Mulholland, L.J., Neviaser, J.T., Ohlemîller, D.R., Peacock, A.P., Reneke, R.J., Hail Jr, International study of the sublethal effects of fire smoke on survivability and health (SEFS): Phase I Final Report, National Institute of Standart and Technology (USA), Technical Note 1439, 2001.
[6] F., Browne, Theories of the combustion of wood and its control, U.S. Forest Products Laboratory, Report No. 2136, 1963.
[7] E., Baysal, Several of the compounds of boron and WR effect on some physical properties of pine wood, Karadeniz Teknik University Institute of Natural Applied Sciences, MS Thesis, 1994, 114.
[8] R., Esen, Determination of Effects of Impregnated Wood Finishing Processes on Combustion Strength of Wood Materials, Karabük University Institute of Natural Applied Sciences, M.Sc., Thesis, 2009, 111.
[9] ASTM D 1413, Standart test methods of testing wood preservatives by laboratory soilblock cultures, Annual Book of ASTM Standarts, 1976, 452–460.
[10] TS 5724, Preservation of wood – determination of water-soluble wood preservative in the impregnated and boron, copper, chromium and arsenic – volumetric method, TS Standarts, Ankara, 1988.
[11] ASTM D 3023, Practica for determination of resistance of factory applied coatings of wood products of stain and reagents, USA, 1988.
[12] ASTM E 160-50, Standart test method for combustible properties of terated wood by the crib test, ASTM Standards, U.S.A., 1975, 809–813.
[13] A. Temiz, E.D. Gezer, U.C. Yıldız, S. Yıldız, Combustion properties of alder (*Alnus glutinosa* L.) Gaertn. Subsp. Barbata (C.A. Mey) Yalt.) and southern pine (*Pinus sylvestris* L.) wood treated with boron compounds, Constr. Build. Mater. 22 (2008) 2165–2169.
[14] SAS, SAS Institute, Inc.SAS/STAT User's Guide: Version 6.0 Ed., SAS Institute Inc., Cary, NC, 1989.
[15] B., Uysal, Ş., Kurt, R., Esen, C., Özcan, M.N., Yıldırım, İ. Kılınç, Effects of combustion resistance of the top surface to the process on sapele wood impregnated with some chemicals, in: 6th International Advanced Technologies Symposium (IATS'11), 16–18 May 2011, Elazığ, Turkey, p. 269.
[16] H. Keskin, M. Atar, M. İzciler, Impacts of impregnation chemicals on combustion properties of the laminated wood materials produced combination of beech and poplar veneers, Constr. Build. Mater. 23 (2009) 634–643.
[17] M., Atar, A.C., Yalınkılıç, E., Aksoy, Effects of combustion characteristics of material wood on the color process, Tubitak Project No: 1090043, Ankara, Turkey, 2010, pp. 34–51.
[18] A. Ozciftci, O. Okcu, Impacts of some chemicals on combustion properties of impregnated laminated veneer lumber (LVL), J. Mater. Process. Technol. 199 (2008) 1–9.