

Characterization of the Combustion Parameters of Impregnated and Varnished Cedar Wood (*Cedrus libani*)

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Abstract

The present study investigated the effect of various types of impregnating and surface treatment materials on the fire resistance of wood material indoors and outdoors. Wood samples (*Cedrus libani* A. Rich.) were impregnated with Wolmanit-CB or Tanalith-E according to ASTM D1413-76 (American Society for Testing and Materials 1976). The impregnated surface was treated with either synthetic or water-based outdoor varnish materials. The impregnated and varnished samples were left in outdoor conditions for 1 year. The combustion characteristics of the samples were investigated at the end of 1 year according to the combustion parameters detailed in the ASTM E160-50 (1975) combustion test. The results of this study indicated that the combustion parameters were lower in the 1-year-old samples (89.12% of control values), in the samples impregnated using Wolmanit-CB (89.18% of control values), and in samples treated using water-based varnish (88.43% of control values). The analysis of flue gas indicated that the O₂ content of the 1-year-old samples impregnated with Wolmanit-CB and treated with synthetic varnish was higher, whereas the CO content was lower. In conclusion, impregnated Wolmanit-CB specimens provide higher fire resistance.

It is advantageous for wooden construction materials to burn slowly during a fire, thus slowing the pace of collapse and minimizing casualties. A layer of humidity, foam, or gas can be formed on the surface of wood material through methods such as smearing, spraying, immersion, or diffusion (Akıncıtürk and Perker 2003).

Boron compounds reduce weight losses and are effective as a fire retardant when applied to wood (Baysal 1994, Yalınkılıç et al. 1998, Colak et al. 2002, Temiz and Yıldız 2002, Yıldız et al. 2002).

The physical and economic service life of a poorly selected, nontreated, and nonimpregnated wood material is very limited. Therefore, it is of utmost importance to treat wood material using protective chemical materials in order to extend its lifetime and improve its properties. Therefore, impregnation is a necessary process to protect wood for the long term.

Impregnation is currently used mainly for protection against biotic elements such as fungi, insects, aquatic pests, and bacteria. It finds substantial use outdoors. The main factors affecting impregnation are the characteristics of the wood material, the method of impregnation, the flow line of the liquids, the pit aspiration, and the structure of the pit, among others (Berkel 1972, Bozkurt et al. 1993). Impregnated materials in current use have a major effect on the combustion properties of wood materials.

Salt-based chemicals currently used as fire retardants (ammonium and boron compounds) facilitate the carbonization of the wood, forming an insulating layer that prevents the formation of flammable gases (Browne 1963, Baysal 1994).

Recently, some metal nanoparticles (nanosilver, nano-copper) as well as mineral nanofibers (nano-wollastonite) have been used to enhance fire properties in wood and wood composites (Taghiyari 2014). Borax and boric acid are the most commonly used boron compounds for fire retardancy (Le Van and Tran 1990, Baysal 2002).

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Cedrus libani A. Rich. was employed in this study because it is in regular use both indoors and outdoors (in both furniture and joinery work) in Turkey and because it constitutes a substantial fraction of the forests in Turkey. Water-based varnish was selected owing to its chemical formulation lacking toxic volatiles, and synthetic varnish was selected because of its regular use outdoors in Turkey. The impregnating materials were selected from among the chemicals that are currently the most frequently used in the impregnation of wood materials used outdoors.

Materials and Methods

Materials

The wood material used as heartwood in the study was *C. libani*, which was procured from the Eastern Black Sea Region in Turkey. The experimental samples were cut into 13 by 13 by 76-mm blocks (radial by tangent by length). The wood samples were prepared as directed in the ASTM E160 standard (American Society for Testing and Materials 1975; Table 1). Samples were air dried until they reached 12 percent moisture content. Two impregnating chemicals, Wolmanit-CB and Tanalith-E, were used, and the surfaces were treated using either water-based or synthetic varnishes.

Tanalith from boron-impregnated materials was obtained using arsenic instead of boron found in the salt types copper chrome boron and chromated copper arsenate (Yalınkılıç et al. 1998). Tanalith-E is a water-based solution of copper triazol. It does not contain chromium and arsenic. The composition of Wolmanit-CB is 35 percent copper sulfate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$), 45 percent potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$), and 20 percent boric acid (H_3BO_3 ; Berkel 1972). The water-based varnishes were obtained from acrylic urethane resin. These varnishes are composed of a binder, polyurethane and acrylic resins, water, and glycol ether as the solvent. They are colorless, odorless, nonyellowing materials, and they do not change the natural color of wood. They are resistant to cleaning agents, oil, mustard, wine, and vinegar (Atar et al. 2010). The solutions of synthetic resins prepared by organic solvents are called synthetic varnish. Synthetic resins that have completed the formation are similar to nitrocellulose (Budakçı 1997).

Methods

The vacuum-pressure method was used as stated in ASTM D1413-76 (ASTM 1976). Samples were initially treated with a prevacuum equivalent to 60 cm Hg^{-1} for 60 minutes and were then left under atmospheric pressure in the solution for another 60 minutes. The impregnated materials were left in an air-circulated room for 15 to 20 days to allow for evaporation of the solvent material at a temperature of $20^\circ\text{C} \pm 2^\circ\text{C}$ and relative humidity of 65 ± 3 percent until they achieved a constant humidity of 12 percent.

The extent of retention of the impregnating material of the test samples was determined as provided in the TS 5724 (Turkish Standards Institution 1988) standard and was calculated making use of the values prior to and after impregnation using the following equation. The retention of the samples used in the experiments is provided.

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

where G is $t_2 - t_1$, t_1 is the sample weight prior to impregnation (g), t_2 is the sample weight after impregnation

Table 1.—Test samples from cedar wood prepared for the present study.

Seasonal groups	Impregnating material	Varnish	No.
Age of year	Wolmanit-CB	Water-based varnish	$24 \times 3 = 72$
Control	Tanalith-E	Synthetic varnish	$24 \times 3 = 72$

(g), V is the sample volume (cm^3), and C is the concentration of the solution (%).

The retention of cedar wood was determined as 0.74 and 3.18 kg/m^3 using Tanalith-E and Wolmanit-CB, respectively.

The samples were varnished following impregnation and acclimatization in compliance with the principles provided in ASTM D3023 (ASTM 1988). Manufacturer's recommendations regarding the amount of varnish to be applied were followed. The varnish was weighed on a scale with a precision of 0.01 g. Hardeners, thinners, or diluting media needed to condition the varnish were used in compliance with the recommendations of the manufacturer. The varnished samples were dried at room temperature.

Varnished test specimens were then exposed to external factors on previously prepared stands. Specimens were positioned facing south with a 45° angle. In this study, effects on the combustion resistance of the wooden material exposed to outer environmental conditions were investigated. For this reason, specimens were periodically left in an outer environment together with control groups for a year. After the suggested waiting period for test parts, combustion tests were conducted.

The impregnated samples were removed from the outdoor environment, and their combustion characteristics were determined in the combustor shown in Figure 1 as detailed in the ASTM E160-50 standard (ASTM 1975). The temperature of combustion, the illuminance, the duration of combustion, and the weight loss were determined. The weight loss was determined using the following equation:

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

where WL is weight loss (%), W_0 is the initial dry weight of the samples (g), and W_d is the final dry weight of the sample (g; Temiz et al. 2008).

Measurement of the released gases due to combustion with flame source, without flame source, and glowing was performed with a sigma flue gas analyzer placed on the upper side of the combustion device chimney. The amount of oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), and nitrogen monoxide (NO) released during combustion with or without a heat source as well as during afterglow was determined.

The temperature of combustion, the illuminance, the weight loss, and the results of the gas analysis of the samples (measured in triplicate) were used to conduct an analysis of variance employing a randomized block factorial experimental design using SAS software. The mean values were compared using the least significant difference (LSD) test. Finally, multiple correlation analyses were carried out in order to investigate the relationship between groups (SAS Institute Inc. 1989). Values in the range of 0.75 to 1.00 were

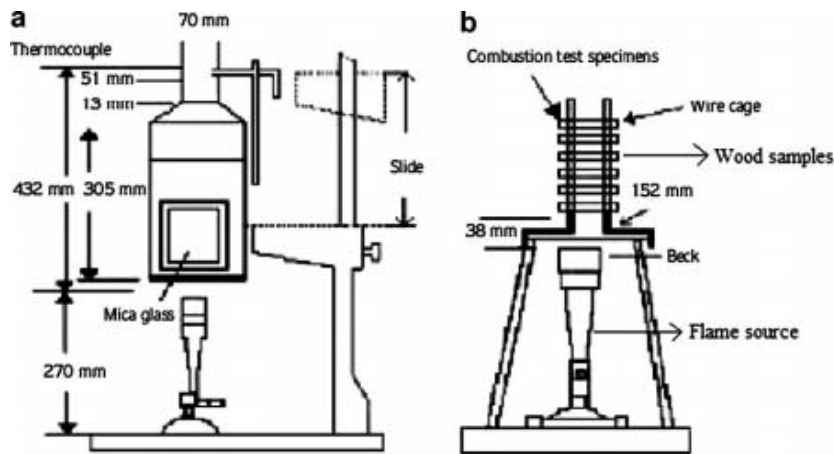


Figure 1.—Fire test apparatus: (a) the entire apparatus; (b) the combustion portion.

considered as high correlation in the multiple correlation analysis.

Results

The results of the analysis of variance of the effect of aging, 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 2, weight loss of the samples is presented in Table 3, and the mean values and the results of the LSD test are given in Table 4.

The differences in the temperature of combustion of cedar wood during combustion with or without flame and during afterglow were determined to be significant at a threshold of 1 percent for the aging parameter and 5 percent for the type of impregnating material. Similarly, the difference in illuminance was significant at a threshold of 1 percent for the aging and varnish type interaction effect of the two parameters and at a threshold of 5 percent for the type of impregnating material, whereas the differences in collapse and total duration of combustion were determined to be significant at thresholds of 1 and 5 percent, respectively, for the aging, the type of impregnating material, and varnish type parameters in the analysis of variance (Table 2).

The differences in the weight loss of cedar wood during combustion with or without flame and during afterglow were determined to be significant at a threshold of 1 percent for the aging and the type of varnish parameters and at a threshold of 5 percent for the type of impregnating material by analysis of variance (Table 3).

The maximum mean temperatures of combustion were determined as 513°C, 619°C, and 348°C for the aging effect; 499°C, 627°C, and 366°C or 498°C, 624°C, and 334°C for the use of Wolmanit-CB or Tanalith-E as the impregnating material, respectively; and 498°C, 624°C, and 335°C or 488°C, 617°C, and 321°C for the water-based or synthetic varnish application during combustion with flame, without flame, and during afterglow, respectively (Table 4).

The maximum illuminances of the impregnated samples were 315, 312, and 315 lux for the aging effect; 301, 298, and 301 lux or 300, 289, and 300 lux for the use of Tanalith-E or Wolmanit-CB as the impregnating material; and 300, 298, and 301 lux or 302, 299, and 303 lux for the water-

based or synthetic varnish application (water-based varnish application resulting in slightly lower but very similar luminosity values) during combustion with flame, without flame, and during afterglow, respectively (Table 4).

The shortest time to collapse and the total time of combustion were determined as 477 and 724 seconds for the 1-year mean effect; 487 and 770 seconds or 452 and 748 seconds for the effect of the use of Tanalith-E or Wolmanit-CB as the impregnating material, with the application of Tanalith-E extending both the time to collapse and to complete combustion; 513 and 789 seconds or 467 and 833 seconds for the water-based or synthetic varnish application, indicating longer time to collapse for water-based varnish application and longer time for complete combustion for synthetic varnish application during combustion with flame, without flame, and during afterglow, respectively (Table 4).

The mean 1-year weight loss ratios (89.21%) were lower than that for the control group (89.32%), lower for the Wolmanit-CB impregnated material (89.18%) than with Tanalith-E (89.20%), and lower for the use of water-based varnish (88.43%) than for the use of synthetic varnish (88.76%; Table 4).

Figure 2 displays the weight loss owing to the combustion of the impregnated wood samples as a function of aging, the type of impregnating material, and the type of varnish. The lowest weight loss ratio was determined for the aged samples impregnated with Wolmanit-CB rather than Tanalith-E and treated using water-based varnish rather than the synthetic type.

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 5, the mean values and the results of the LSD test are given in Table 6, and the graphical representations are provided in Figures 3 to 5.

The differences in the O₂, CO₂, CO, and NO contents of the flue gas released during the combustion of the impregnated cedar wood samples with flame were determined to be significant at a threshold of 1 percent for the aging parameter. The difference in NO content was determined as significant at a threshold of 5 percent for the varnish type. Similarly, the difference in NO content was determined as significant at a threshold of 1 percent for the aging parameter during combustion without flame, and the differences in NO and CO contents were determined as

Table 2.—Results of the analysis of variance of the combustion parameters.^a

Source of variance	Temperature (°C)				Illuminance (lux)			
	df	SS	MSS	F	df	SS	MSS	F
Combustion with flame								
a	1	18,629.80	18,629.80	59.57*	1	12,000.46	12,000.46	1,648.92*
im	2	815.59	407.80	1.30	2	28.78	14.39	1.98**
vt	2	1,111.37	555.69	1.78	2	125.44	62.72	8.62*
a × im	2	2,408.48	1,204.24	3.85**	2	20.04	10.02	1.38
a × vt	2	2,806.93	1,403.46	4.49**	2	96.93	48.46	6.66*
im × vt	4	5,487.19	1,371.80	4.39*	4	41.11	10.28	1.41
a × im × vt	4	4,240.96	1,060.24	3.39**	4	82.74	20.69	2.84**
Error	36	11,259.33	312.76		36	262.00	7.28	
Total	53	46,759.65			53	12,657.50		
Combustion without flame								
a	1	0.07	0.07	0.00	1	11,324.52	11,324.52	1,169.26*
im	2	625.82	312.91	1.39	2	100.48	50.24	5.19**
vt	2	651.59	325.80	1.45	2	113.37	56.69	5.85*
a × im	2	2,361.82	1,180.91	5.25*	2	43.37	21.69	2.24
a × vt	2	1,941.59	970.80	4.32**	2	123.37	61.69	6.37*
im × vt	4	3,059.74	764.94	3.40**	4	50.41	12.60	1.30
a × im × vt	4	3,516.19	879.05	3.91*	4	89.07	22.27	2.30
Error	36	8,095.33	224.87		36	348.67	9.69	
Total	53	20,252.15			53	12,193.26		
Combustion during afterglow								
a	1	64.46	64.46	0.03	1	11,266.67	11,266.67	1,469.57*
im	2	23,205.33	11,602.67	4.66**	2	60.33	30.17	3.93**
vt	2	16,047.00	8,023.50	3.22	2	108.33	54.17	7.07*
a × im	2	30,066.82	15,033.41	6.04*	2	38.11	19.06	2.49
a × vt	2	11,946.04	5,973.02	2.40	2	130.11	65.06	8.49*
im × vt	4	38,652.33	9,663.08	3.88**	4	31.33	7.83	1.02
a × im × vt	4	14,457.52	3,614.38	1.45	4	53.11	13.28	1.73
Error	36	89,608.00	2,489.11		36	276.00	7.67	
Total	53	224,047.50			53	11,964.00		
Time of combustion (s)								
Source of variance	Value of time to collapse				Total time of combustion			
	df	SS	MSS	F	df	SS	MSS	F
a	1	3,052.52	3,052.52	6.59**	1	217,741.50	217,741.50	21.77*
im	2	5,258.33	2,629.17	5.68*	2	90,691.70	45,345.85	4.53**
vt	2	1,333.00	666.50	1.44*	2	77,376.59	38,688.30	3.87**
a × im	2	2,786.70	1,393.35	3.01	2	101,472.44	50,736.22	5.07**
a × vt	2	1,736.26	868.13	1.88	2	8,645.78	4,322.89	0.43
im × vt	4	9,391.67	2,347.92	5.07*	4	222,319.63	55,579.91	5.56*
a × im × vt	4	4,503.52	1,125.88	2.43	4	39,731.78	9,932.94	0.99
Error	36	16,666.00	462.94		36	360,089.33	10,002.48	
Total	53	44,728.00			53	1,118,068.76		

^a df = degrees of freedom; SS = sum of squares; MSS = mean sum of squares; a = aged 1 year; im = materials impregnated; vt = type of varnish. * = 1 percent significance level; ** = 5 percent significance level.

significant at a threshold of 5 percent for the varnish type during afterglow (Table 5).

The results of the flue gas analysis indicated that the mean O₂ content was 15.07, 2.97, and 11.41 percent for the aging effect, all higher than those of the control samples (12.91%, 2.29%, and 10.67%) during combustion with flame, without flame, and during afterglow, respectively. Similarly, the CO content was 13,708, 29,712, and 21,933 ppm for the aging effect, all lower than those of the control samples (16,254, 30,292, and 26,616 ppm) during combustion with flame, without flame, and during afterglow, respectively. The results of the flue gas analysis with respect to the type of impregnating material indicated that the mean O₂ content

was determined as 13.80, 2.26, and 9.82 percent for samples impregnated using Wolmanit-CB, all higher than those treated with Tanalith-E (13.75%, 2.05%, and 9.69%) during combustion with flame, without flame, and during afterglow, respectively, whereas the CO content was lower when samples were impregnated with Wolmanit-CB than when impregnated with Tanalith-E. The results of the flue gas analysis with respect to the type of varnish indicated that the mean O₂ content was higher (14.55%, 2.30%, and 9.49%) for samples treated using synthetic varnish than those treated with water-based varnish (13.65%, 2.28%, and 8.84%) during combustion with flame, without flame, and during afterglow, respectively. However, the CO contents of

Table 3.—Results of the analysis of variance of the weight loss during combustion with or without heat source and that of afterglow.^a

Source of variance	Weight loss (%)			
	df	SS	MSS	F
a	1	2.03	2.03	1.35*
im	2	11.80	5.90	3.92**
vt	2	23.40	11.70	7.77*
a × im	2	13.36	6.68	4.43**
a × vt	2	0.54	0.27	0.18
im × vt	4	18.24	4.56	3.03**
a × im × vt	4	14.02	3.50	2.33
Error	36	54.21	1.51	
Total	53	137.57		

^a df = degrees of freedom; SS = sum of squares; MSS = mean sum of squares; a = aged 1 year; im = materials impregnated; vt = type of varnish.

* = 1 percent significance level; ** = 5 percent significance level.

the same samples (14,528, 29,947, and 18,507 ppm) were lower than those treated with water-based varnish (16,140, 30,408, and 19,471 ppm; Table 6).

The interaction effects among aging, the type of impregnating material, and the varnish type are reported in Table 7.

The following correlations (significant at the 1% level) were determined: between afterglow temperature and the total duration of combustion was negative and significant ($r = -0.77$), between illuminance during combustion with flame and during combustion without flame or during afterglow were both positive and significant ($r = 0.99$ or $r = 0.99$, respectively), between illuminance during combustion without flame and during afterglow was positive and

significant ($r = 0.99$), between O₂ content and CO₂ content during combustion with flame was negative and significant ($r = -0.99$), between O₂ content and CO₂ or CO content during combustion without flame was negative and significant ($r = -0.99$ or $r = -0.82$, respectively), between O₂ content and CO₂ or CO content during afterglow was negative and significant ($r = -0.99$ or $r = -0.94$, respectively), between CO₂ content and CO content during combustion without flame was positive and significant ($r = 0.80$), and between CO₂ content and CO content during afterglow was positive and significant ($r = 0.93$).

Discussion

Results indicated that the highest temperature of combustion occurred in the aged cedar wood samples impregnated with Wolmanit-CB and treated with water-based varnish during combustion with flame, without flame, and during afterglow. The temperatures of combustion for all of the treated samples were higher than that of the control sample. This result is in accordance with the findings of previous studies, which also reported that the temperatures of combustion for treated samples were higher than those of the controls (Keskin et al. 2009).

The lowest ratio of weight loss was determined for the aged samples and those impregnated with Wolmanit-CB and treated using synthetic varnish.

The weight loss ratio was reported as 94 percent for Scots pine and as 92 percent for beech control samples (Atilgan and Peker 2012). The weight loss ratios of the cedar wood samples in the present study were slightly lower, 89.32 percent. Generally, the weight loss is owing to the existence of extractable materials in cedar, redwood, and Scots pine wood.

Table 4.—Mean values and least significant difference (LSD) analysis of combustion.^a

Factor	CT		FWC		FWTC		ADC		
	WL (%)	Time to collapse (s)	Total time of combustion (s)	Temp. (°C)	Illuminance (lux)	Temp. (°C)	Illuminance (lux)	Temp. (°C)	Illuminance (lux)
Annual									
Control	89.32 A	478 A	851 A	476 B	285 B	618 A	283 B	340 A	286 B
Aged 1 yr	89.21 A	477 A	724 B	513 A	315 A	619 A	312 A	348 A	315 A
Means	89.27	478	788	495	300	619	298	344	301
S _x	0.08	0.71	89.80	26.16	21.21	0.71	20.51	5.66	20.51
LSD	0.68	40.27	55.20	9.76	1.49	8.28	1.72	27.53	1.53
Materials impregnated									
Control	89.16 B	495 A	844 A	495 A	299 A	616 A	295 B	316 B	299 B
Wolmanit-CB	89.18 A	452 A	748 B	499 A	300 A	627 A	289 A	366 A	300 A
Tanalith-E	89.20 A	487 A	770 B	498 A	301 A	624 A	298 A	334 AB	301 AB
Means	89.18	478	787	497	300	622	294	339	300
S _x	0.02	22.87	50.29	2.08	1.00	5.69	4.58	25.32	1.00
LSD	0.83	49.32	67.61	11.96	1.82	10.14	2.10	33.73	1.87
Types of varnish									
Control	90.36 A	454 B	740 B	496 A	298 B	616 A	295 B	362 A	299 B
Synthetic	88.76 B	467 AB	833 A	488 A	302 A	617 A	299 A	321 B	303 A
Water based	88.43 A	513 A	789 AB	498 A	300 A	624 A	298 A	335 AB	301 A
Means	89.18	478	787	494	300	619	297	339	301
S _x	1.03	31.00	46.52	5.29	2.00	4.36	2.08	20.84	2.00
LSD	0.83	49.32	67.61	11.96	1.82	10.14	2.10	33.73	1.87

^a WL = weight loss; CT = time of combustion; FWC = combustion with flame; FWTC = combustion without flame; ADC = combustion during afterglow. Within each row, different letters indicate significant differences between average values of the same group.

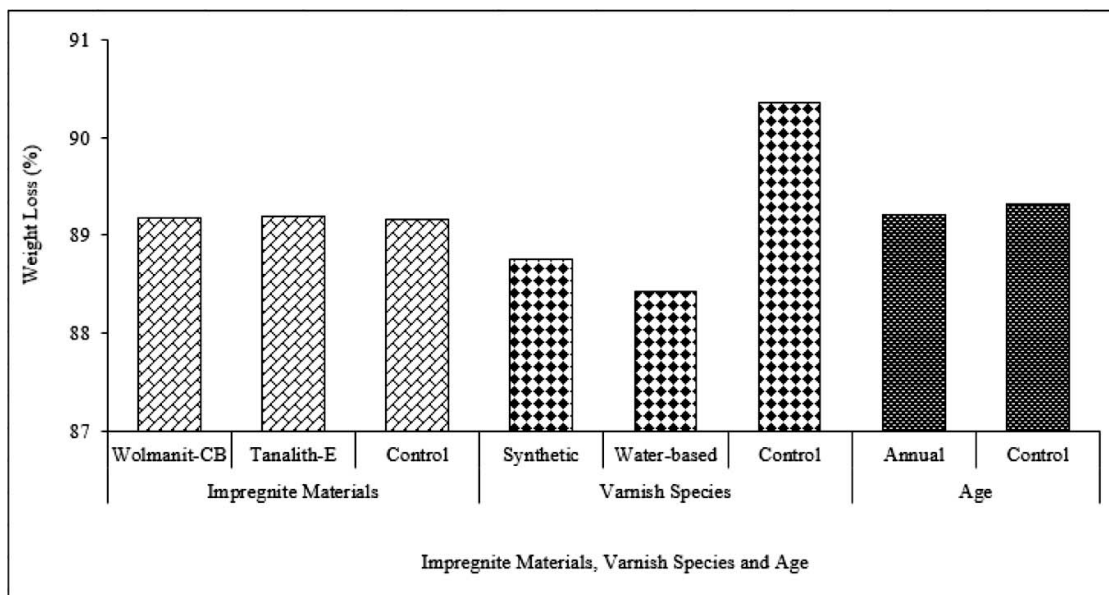


Figure 2.—Weight loss during the annual combustion of cedar wood as it relates to type of impregnating material, type of varnish, and age.

Table 5.—Results of the analysis of variance of the flue gas from combustion.^a

Source of variance	df	O ₂ (%)			df	CO (ppm)			df	NO (ppm)			df	CO ₂ (%)		
		SS	MSS	F		SS	MSS	F		SS	MSS	F		SS	MSS	F
Combustion with flame																
a	1	63.27	63.27	28.94*	1	87,508,566.0	87,508,566.0	10.38*	1	11,276.49	11,276.49	42.58*	1	55.27	55.27	27.52*
im	2	4.92	2.46	1.13	2	29,605,200.3	14,802,600.2	1.76	2	40.94	20.47	0.08	2	5.35	2.67	1.33
vt	2	8.60	4.30	1.97	2	36,808,081.0	18,404,040.5	2.18	2	2,825.45	1,412.72	5.33*	2	7.65	3.82	1.90
a × im	2	2.30	1.15	0.53	2	7,069,351.0	3,534,675.5	0.42	2	285.10	142.55	0.54	2	2.53	1.27	0.63
a × vt	2	23.88	11.94	5.46*	2	144,788,071.4	72,394,035.7	8.59*	2	3,296.77	1,648.39	6.22*	2	20.40	10.20	5.08**
im × vt	4	67.84	16.96	7.76*	4	47,248,285.3	11,812,071.3	1.40	4	4,729.11	1,182.28	4.46*	4	62.66	15.67	7.80*
a × im × vt	4	10.51	2.63	1.20	4	189,536,946.9	47,384,236.7	5.62*	4	3,122.29	780.57	2.95**	4	9.92	2.48	1.23
Error	36	78.70	2.19		36	303,362,873.3	8,426,746.5		36	9,533.10	264.81		36	72.31	2.09	
Total	53	260.02			53	845,927,375.3			53	35,109.24			53	236.07		
Combustion without flame																
a	1	1.34	1.34	0.92	1	4,537,340.9	4,537,340.9	1.51	1	938.58	938.58	46.96*	1	2.49	2.49	1.92
im	2	0.49	0.24	0.17	2	3,276,213.4	1,638,106.7	0.54	2	12.99	6.49	0.32	2	0.34	0.17	0.13
vt	2	0.67	0.33	0.23	2	5,239,407.4	2,619,703.7	0.87	2	51.34	25.67	1.28	2	1.14	0.57	0.44
a × im	2	5.42	2.71	1.86	2	19,599,028.9	9,799,514.5	3.26	2	182.48	91.24	4.56**	2	4.57	2.28	1.76
a × vt	2	20.66	10.33	7.08*	2	18,704,776.0	9,352,388.0	3.11	2	26.10	13.05	0.65	2	18.37	9.19	7.07*
im × vt	4	40.62	10.16	6.96*	4	86,524,607.7	21,631,151.9	7.20*	4	489.80	122.45	6.13*	4	37.97	9.49	7.31*
a × im × vt	4	10.94	2.74	1.88	4	29,000,115.3	7,250,028.8	2.41	4	316.55	79.14	3.96*	4	7.74	1.93	1.49
Error	36	52.50	1.46		36	108,227,865.3	3,006,329.6		36	719.57	19.99		36	46.76	1.30	
Total	53	132.63			53	275,109,355.0			53	2,737.41			53	119.38		
Combustion during afterglow																
a	1	143.41	143.41	40.41*	1	381,593,116.7	381,593,116.7	36.37*	1	3.56	3.56	0.04*	1	126.35	126.35	22.14*
im	2	39.94	19.97	1.20	2	100,181,988.9	50,090,994.5	4.77**	2	742.99	371.50	4.06**	2	34.09	17.04	2.99
vt	2	5.62	2.81	1.97	2	17,164,880.3	8,582,440.1	0.82	2	116.32	58.16	0.64	2	4.84	2.42	0.42
a × im	2	10.34	5.17	1.30	2	15,816,562.9	7,908,281.5	0.75	2	13.25	6.63	0.07	2	12.72	6.36	1.12
a × vt	2	16.38	8.19	1.47	2	8,152,071.1	4,076,035.6	0.3	2	1,097.25	548.62	5.99*	2	17.73	8.87	1.55
im × vt	4	157.90	39.48	5.89*	4	153,508,413.6	38,377,103.4	3.6**	4	1,403.80	350.95	3.83**	4	142.44	35.61	6.24*
a × im × vt	4	102.38	25.60	4.58*	4	271,678,149.2	67,919,537.3	6.4*	4	1,570.08	392.52	4.29*	4	96.26	24.06	4.22*
Error	36	221.68	6.16		36	377,669,527.0	10,490,820.0		36	3,296.04	91.56		36	205.41	5.71	
Total	53	697.64			53	1,325,764,709.0			53	8,243.29			53	639.84		

^a df = degrees of freedom; SS = sum of squares; MSS = mean sum of squares; a = aged 1 year; im = material impregnated; vt = type of varnish. * = 1 percent significance level; ** = 5 percent significance level.

Table 6.—Mean values and least significant difference (LSD) analysis of gas analysis.^a

Factor	FWC				FWTC				ADC			
	O ₂ (%)	CO (ppm)	NO (ppm)	CO ₂ (%)	O ₂ (%)	CO (ppm)	NO (ppm)	CO ₂ (%)	O ₂ (%)	CO (ppm)	NO (ppm)	CO ₂ (%)
Annual												
Control	12.91 B	16,254 A	46.40 A	7.65 A	2.29 A	30,292 A	17.67 C	17.87 A	10.67 A	26,616 B	32.80 C	9.79 B
Aged 1 yr	15.07 A	13,708 B	17.50 C	5.63 B	2.97 A	29,712 A	9.33 D	18.30 A	11.41 B	21,933 A	33.31 C	12.85 A
Means	13.26	15,809	27.13	7.50	2.63	24,865	29.15	14.46	11.04	24,275	39.00	8.66
S _x	1.83	2,323	13.73	1.64	0.48	5,823	26.00	5.13	0.52	3,311	20.26	2.34
LSD	0.81	1,602	8.98	0.78	0.66	957	2.47	0.63	1.37	1,788	5.28	1.32
Materials impregnated												
Control	14.42 A	14,010 B	33.02 A	6.20 A	2.07 A	29,765 A	13.42 A	18.13 A	9.61 A	18,210 B	32.01 AB	10.78 A
Wolmanit-CB	13.80 A	15,106 A	31.95 A	6.84 A	2.26 A	29,342 A	12.95 A	17.97 A	9.82 B	21,197 A	29.12 B	12.44 A
Tanalith-E	13.75 A	15,127 A	30.89 A	6.88 A	2.05 A	29,899 A	14.14 A	18.15 A	9.69 A	21,416 B	38.03 A	10.73 A
Means	13.99	14,748	31.95	6.64	2.13	29,669	13.50	18.08	9.71	20,274	33.05	11.32
S _x	0.37	639	1.07	0.38	0.12	291	0.60	0.10	0.11	1,791	4.55	0.97
LSD	1.00	1,962	11.00	0.96	0.82	1,172	3.02	0.77	1.68	2,190	6.47	1.62
Types of varnish												
Control	13.77 A	14,276 A	42.18 A	6.90 A	2.01 A	29,651 A	13.86 A	18.25 A	8.78 A	19,845 A	33.53 A	11.58 A
Synthetic	14.55 A	14,528 A	27.13 B	6.11 A	2.30 A	29,947 A	12.17 A	18.11 A	9.49 A	18,507 A	31.07 A	10.90 A
Water based	13.65 B	16,140 A	26.55 B	6.91 A	2.28 A	30,408 A	14.48 A	17.89 A	8.84 A	19,471 A	34.57 A	11.47 A
Means	13.99	14,981	31.95	6.64	2.20	30,002	13.50	18.08	9.04	19,274	33.06	11.32
S _x	0.49	1,011	8.86	0.46	0.16	381	1.20	0.18	0.39	690	1.80	0.37
LSD	1.00	1,962	11.00	0.96	0.82	1,172	3.02	0.77	1.68	2,190	6.47	1.61

^a FWC = combustion with flame; FWTC = combustion without flame; ADC = combustion during afterglow. Within each row, different letters indicate significant differences between average values of the same group.

Boron compounds have been reported to have fire retardant properties (Keskin et al. 2009, Atılgan and Peker 2012). Impregnation with Wolmanit-CB is a frequently used technique for fire retardation in wooden construction.

Homes made with wood material must take necessary precautions against fire. Fire protection can be achieved by slowing the combustion rate of wood construction materials. Therefore, the wood should be treated with fire retardant to improve fire safety (Aslan and Çolak 1996). Preservatives

used in this study are known to have a combustion retarding effect because of their boron content.

Flue gas analysis of cedar wood combustion indicated that the highest O₂ and the lowest CO content were determined for the aging parameter in control samples. Similarly, the highest O₂ and the lowest CO contents were determined for the samples impregnated with Tanalith-E and treated using synthetic varnish.

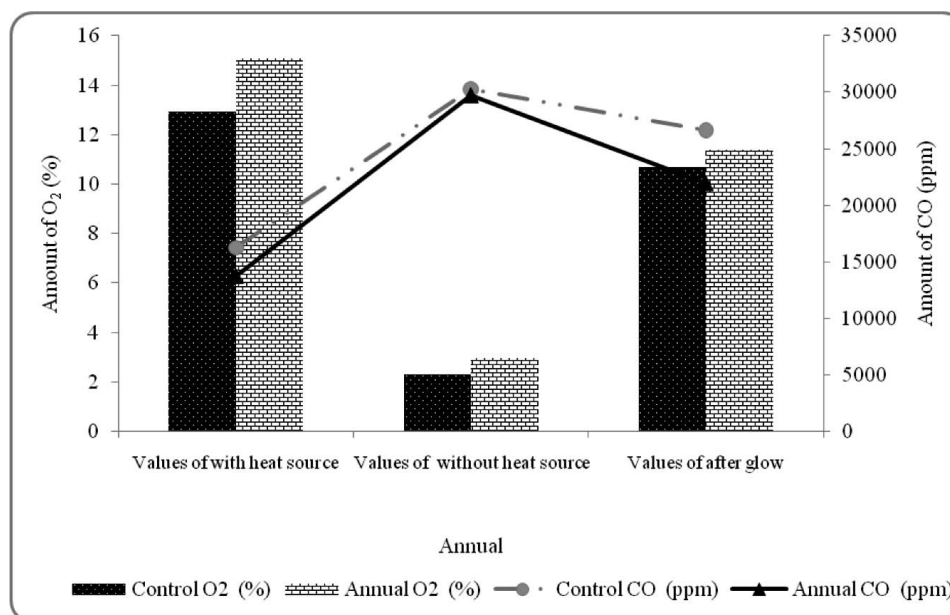


Figure 3.—Relationships between the O₂ and CO content of the gases released during the combustion of the aged samples and of the control sample.

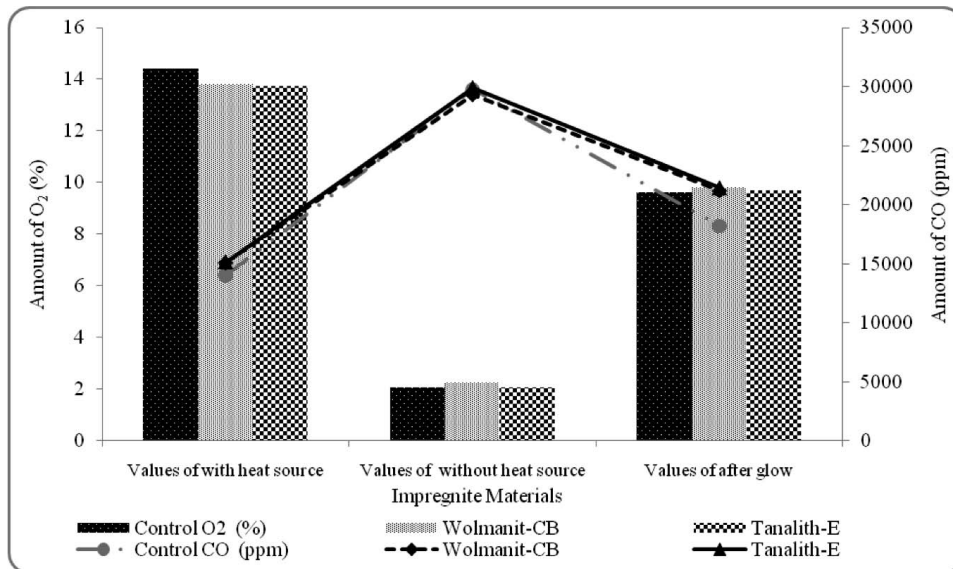


Figure 4.—Relationships between the O₂ and CO content of the gases released during the combustion of the samples impregnated using different materials.

A previously reported gas analysis of laminated veneer lumber samples of white oak (*Quercus alba*) and chestnut (*Castanea* spp.) wood indicated that the O₂ content of the samples was higher than that of the control but that the CO content was lower than that of the control (Ozciftci and Okcu 2008). The results of the present study are in accordance with this finding.

Conclusions

The temperature of combustion and the illuminance of the impregnated aged cedar wood samples were higher than those of the controls. The temperature of combustion, the time to collapse, and the total duration of combustion of the

cedar wood samples impregnated with Wolmanit-CB and water-based varnish were higher than those impregnated with Tanalith-E and synthetic varnish.

The relative weight losses in the impregnated and surface-treated aged cedar wood samples were lower in samples that were impregnated with Wolmanit-CB and treated with water-based varnish. The lower weight loss in the samples that were impregnated using Wolmanit-CB can be attributed to the boron content of the impregnating material.

The flue gas analysis during combustion the O₂ content of the samples was higher and the CO content of the samples was lower than those determined for the control samples. A

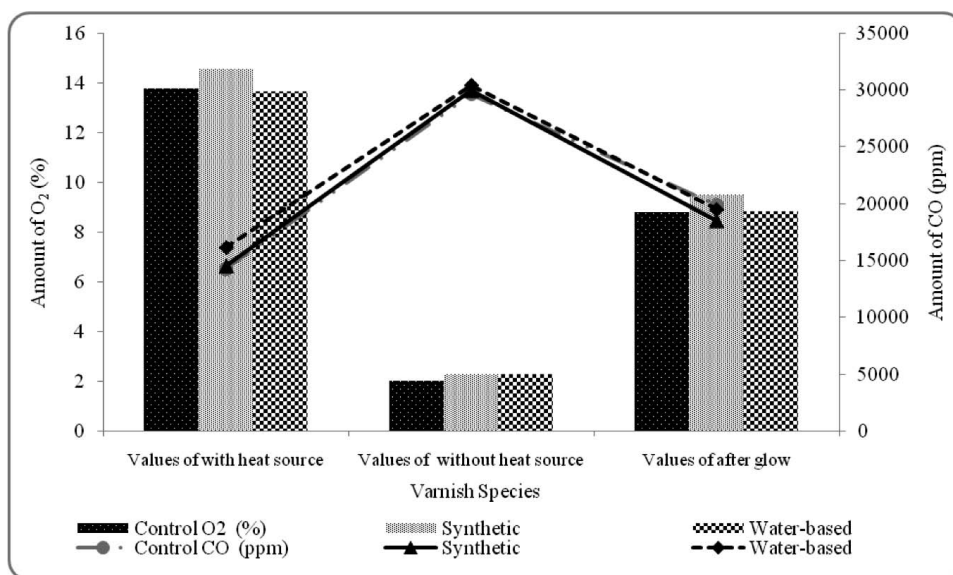


Figure 5.—Relationships between the O₂ and CO content of the gases released during the combustion of the samples treated using different varnishes.

Table 7.—Results of multiple correlation in combustion parameters.^a

	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u
a	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
b	0.63*	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
c	0.14	0.38*	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
d	0.59*	0.03	-0.07	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
e	0.60*	0.08	-0.02	0.99*	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
f	0.58*	0.03	-0.03	0.99*	0.99*	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
g	0.07	-0.38*	-0.11	0.21	0.22	0.21	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
h	-0.27**	-0.10	-0.77*	-0.36*	-0.38*	-0.40*	-0.05	—	—	—	—	—	—	—	—	—	—	—	—	—	—
i	0.26	0.17	0.23	0.13	0.18	0.16	0.02	-0.10	—	—	—	—	—	—	—	—	—	—	—	—	—
j	0.36*	0.15	-0.14	0.53*	0.54*	0.55*	0.23	0.03	0.20	—	—	—	—	—	—	—	—	—	—	—	—
k	0.18	0.13	-0.14	-0.01	0.02	-0.02	0.36*	0.28**	0.29**	0.23	—	—	—	—	—	—	—	—	—	—	—
l	-0.37*	-0.23	-0.54*	-0.34**	-0.36*	-0.39*	0.11	0.64*	-0.04	-0.11	0.65*	—	—	—	—	—	—	—	—	—	—
m	-0.36*	-0.17	0.15	-0.53*	-0.54*	-0.55*	-0.23	-0.05	-0.20	-0.99*	-0.25	0.09	—	—	—	—	—	—	—	—	—
n	-0.16	-0.13	0.17	0.05	0.02	0.06	-0.34**	-0.33**	-0.29**	-0.21	-0.99*	-0.65*	0.23	—	—	—	—	—	—	—	—
o	0.36*	0.23	0.55*	0.33**	0.35**	0.38*	-0.12	-0.64*	0.02	0.11	-0.65*	-0.99*	-0.10	0.66*	—	—	—	—	—	—	—
p	-0.26	-0.38*	-0.13	-0.33**	-0.33**	-0.34	0.28	0.10	-0.13	-0.67*	0.24	0.33**	0.68*	-0.25	-0.33	—	—	—	—	—	—
q	-0.31**	-0.17	0.10	-0.19	-0.20	-0.17	-0.32**	-0.13	-0.32**	-0.34**	-0.82*	-0.54*	0.35*	0.80*	0.55*	0.07	—	—	—	—	—
r	0.39*	0.20	0.46*	0.43*	0.46*	0.48*	-0.07	-0.62*	0.11	0.25	-0.53*	-0.94*	-0.24	0.54*	0.93*	-0.44*	0.42*	—	—	—	—
s	-0.23	0.09	-0.05	-0.56*	-0.54*	-0.55*	-0.14	0.46*	0.28**	0.17	0.36*	0.38*	-0.17	-0.36*	-0.36*	-0.12	-0.20	-0.35*	—	—	—
t	-0.24	0.18	0.01	-0.56*	-0.55*	-0.57*	-0.15	0.15	-0.12	-0.30**	0.14	0.40*	0.31**	-0.12	-0.38*	0.21	0.01	-0.40*	0.27**	—	—
u	0.05	-0.16	0.09	-0.09	-0.10	-0.09	0.11	-0.24	-0.17	-0.26	-0.36*	-0.26	0.28**	0.35*	0.28**	0.38*	0.37*	0.12	-0.18	-0.24	—

^a a = time-temperature with flame; b = time-temperature without flame; c = time-temperature afterglow; d = illuminance with flame; e = illuminance without flame; f = illuminance afterglow; g = time to collapse; h = total time of combustion; i = weight loss; j = amount of O₂ of combustion with flame; k = amount of O₂ of combustion during afterglow; l = amount of O₂ of combustion without flame; m = amount of CO₂ of combustion with flame; n = amount of CO₂ of combustion during afterglow; o = amount of CO₂ of combustion without flame; p = amount of CO of combustion with flame; q = amount of CO of combustion without flame; r = amount of CO combustion without flame; s = amount of NO combustion with flame; t = amount of NO combustion without flame; u = amount of NO combustion without flame. * = 1 percent significance level; ** = 5 percent significance level.

higher O₂ content has not been reported to be associated with more extensive combustion. This is an indicator of the fire retardant properties of the impregnating material (Ozciftci and Okcu 2008).

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