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COMBUSTION CHARACTERISTICS OF ORIENTAL BEECH WOOD IMPREGNATED WITH COMMONLY USED BORATES

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ABSTRACT

This study was conducted to determine combustion characteristics of Oriental beech impregnated with commonly used borates. Average mass loss and temperature values of Oriental beech wood were determined according to ASTM-E 160-50 (1975) after combustion test. Boric acid (BA) and borax (BX), and sodium perborate (SP) were used as borates. The combustion test method was performed in three stages: Flame stage, without flame stage, and glowing stage. Results indicated that mass loss and temperature values of borate-treated wood specimens were lower compared to untreated wood specimens at three combustion stages. Higher concentration levels of borates resulted in lower mass loss and temperature values of the Oriental beech wood.

KEYWORDS: Borates, oriental beech, combustion properties, mass loss, temperature, values.

INTRODUCTION

Wood and wood-based materials are mainly composed of carbon and hydrogen. For this reason, they are combustible (Ching-Mu and Wang 1991). When heated, wood burns by producing flammable volatiles that may ignite. For wood to spontaneously combust, the temperature must be raised to 275°C. However, if there is a flame source, it can become flammable at lower temperatures (LeVan and Winandy 1990, Yalinkilic et al. 1996, 1997). For wood ignition; oxygen, O_2 flame source, and flammable material are necessary. However, wood has excellent natural fire resistance as a result of its remarkably low thermal conductivity and the fact that wood char is formed when wood is burned. In order to reduce flammability and provide safety, wood is treated with fire-retardant chemicals. In other words, the combustibility of wood may be reduced with flame-retardants or fire-retardants (Nussbaum 1988, Ellis and Rowell 1989, Mitchell 1993). The most common fire retardant chemicals used for wood are the inorganic salts, such as diammonium phosphate, mono ammonium phosphate, zinc chloride, ammonium sulphate, borax, and boric acid (LeVan and Winandy 1990). However, many of the effective poisonous chemicals are also questionable. Increased public concern on the environmental effect of many wood preservatives has rendered a special importance to borates as an environmentally friendly agent. Borates have several advantages as wood preservative in addition to imparting flame retardancy, providing sufficient protection against wood destroying organisms, having a low mammalian toxicity and low volatility. Moreover, they are colorless and odorless (Hafizoglu et al. 1994, Murphy 1990, Yalinkilic et al. 1999, Drysdale 1994, Chen et al. 1997). It is well known that boron compounds work efficiently as fire retardant chemicals for cellulosic materials. Boron containing chemicals such as boric acid and borax are the most common boron compounds which have found many application areas in the wood preservation industry in order to obtain the benefit of their fire retardancy (Hafizoglu et al. 1994, Baysal 1994). The fire resistance properties of boron containing compounds have been surveyed by many scientists and proven to be effective since late 19th century. Boric acid and borax mixtures have some efficacy in retarding flame spread on wood surfaces. In addition to the usual char-forming catalytic effect, they have a rather low melting point and form glassy films when exposed to high temperatures in fires. Borax tends to reduce flame-spread but can promote smoldering or glowing. On the other hand, boric acid suppresses smoldering but has little effect on flame spread (LeVan and Winandy 1990, Baysal 2002). Fire retardant chemicals drastically reduce the rate at which flames travel across the wood surface, thereby reducing the capacity of the wood to contribute to fire (LeVan and Winandy 1990). Several theories have been reviewed about fire retardant's mechanisms by Browne (1958) and LeVan (1984). The most widely accepted mechanism is referred to as the chemical theory. This theory suggests that the fire retardants directly alter the pyrolysis of wood, increasing the amount of char and reducing the amount of volatile combustible vapors (LeVan and Winandy 1990). Browne and Tang (1963) studied fire resistance of sodium borax, sodium chloride, and ammonium phosphate. All compounds increased the residual char weight of material. Brenden (1967) noted that an increased amount of char is correlated with reduced amounts of tar. Shafizadeh (1984) tested 21 different fire retardants; phosphoric acid was the most effective in reducing the amount of volatiles and increasing the amount of residual char, followed by mono and diammonium phosphate, and zinc chloride. Gottlieb (1956) reported that phosphorus compounds act as acid precursors, during combustion or pyrolysis; they form acids that cause selective decomposition of cellulosic material to form increased amounts of combustible volatiles. Ozcifci et al. (2007) studied the fire properties of laminated veneer lumber (LVL) prepared from beech (*Fagus orientalis* Lipsky) veneers treated with some fire retardants. They found that the lowest temperature and mass loss were obtained for specimens treated with diammonium phosphate and boric acid–borax mixture. Lee and Kim (1982) investigated fire resistance of meranti plywoods impregnated with some fire retardant chemicals. They found that diammonium phosphate ranked the greatest in fire-retardant effectiveness.

In this study, it was aimed to improve combustion characteristics such as mass loss and temperature values of Oriental beech wood impregnated with some commonly used borates.

MATERIAL AND METHODS

Preparation of test specimens and chemicals

Wood specimens measuring 13 (tangential) x 13 (radial) x 76 (longitudinal) mm were prepared from air-dried sapwood of Oriental beech (*Fagus orientalis* Lipsky) for combustion test. Aqueous solutions of borates were dissolved in distilled water to concentrations of 2, 4, and 6 %. Borates were supplied by a commercial firm. Wood specimens were oven dried at 103±2°C before and after treatment.

Impregnation method

Wood specimens were impregnated with aqueous solutions of boric acid, borax, and sodium perborate according to ASTM-D 1413 (1976). Treatment solutions were prepared on the day before the impregnation for homogenizing. A vacuum desiccator used for the impregnation process was connected to a vacuum pump through a vacuum trap. Vacuum was applied for 60 min at 760 $mmHg^{-1}$ before supplying the solution into the chamber and this followed by another 60 min at 760 $mmHg^{-1}$ diffusion period under vacuum. Retention was calculated from the following equation:

$$\text{Retention} = \frac{G \times C}{V} \times 10 \quad (kg.m^{-3}) \tag{1}$$

where: G - the amount of solution absorbed by wood that is calculated by T_2-T_1,
T_2 - the weight of wood after impregnation (g),
T_1- the weight of wood before impregnation (g),
C - the solution concentration as percentage,
V - the volume of the specimen as (cm^3).

Combustion test method

Combustion test of Oriental beech wood specimens was determined according to ASTM-E 160-50 (1975). Specimens were conditioned at 27±2°C and 30–35 % relative humidity to the targeted equilibrium moisture content of 7 % prior to combustion test. Twenty four specimens were stored to make 12 layers which formed a square prism (Fig. 1).

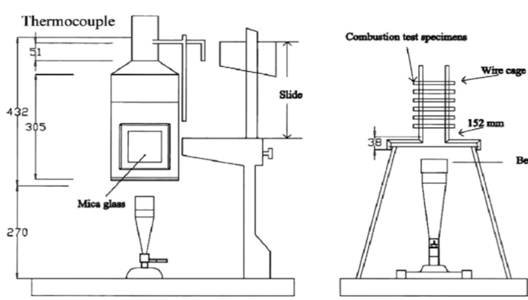

Fig. 1: Combustion test apparatus.

The heating flame was derived from a LPG tank controlled by a sensitive bar gauged valve. The flame was balanced to the standard height before combustion test samples' frame. Combustion test method was performed subsequently (flame stage (FS), without flame stage

(WFS), and glowing stage (GS) according to ASTM-E 160-50 (1975). Temperatures were recorded at the combustion column by thermocouples at 15, 30, and 30 s intervals for combustion with a flame stage, without flame stage, and glowing stage, respectively. The mass loss of test specimens after combustion test was calculated from the following equation:

$$\text{Mass loss} = (W_{bf} - W_{af} / W_{bf}) \times 100 \qquad (2)$$

where: W_{bf} - the weight (g) of a wood specimen before combustion test,
W_{af} - the weight (g) of a wood specimen after combustion test.

Evaluations of combustion test results

Combustion test results were evaluated by a computerized statistical program composed of analysis of variance and following Duncan tests at the 95 % confidence level. Statistical evaluations were made on homogeneity groups (HG), different letters of which reflected statistical significance.

RESULTS AND DISCUSSION

Mass loss

The mass loss of Oriental beech is given in Tab. 1. The mass loss of untreated Oriental beech was higher compared to treated Oriental beech.

Tab. 1: Mass loss of Oriental beech wood impregnated with borates.

Wood species	Chemicals	Concentration (%)	Total retention	Mass loss (%)	
				Mean[a]	± SD
Oriental beech	Control (Untreated)	-	-	88.9	± 0.5
	BA	2	10.8	79.7	± 2.6
		4	22.7	74.1	± 3.0
		6	30.3	73.3	± 2.9
	BX	2	11.6	85.8	± 2.1
		4	22.8	82.1	± 3.6
		6	33	80.6	± 1.3
	SP	2	11.4	88.1	± 2.8
		4	23.7	85.3	± 1.5
		6	30.9	76.9	± 2.7

a : Four replication were made for each group
BA: Boric acid; BX: Borax; SP: Sodium perborate
SD: Standard deviation

The highest mass loss of wood specimens was obtained as 88.9 % for untreated Oriental beech. The lowest mass loss of Oriental beech wood was recorded as 73.3 % for specimens impregnated with 6 percent boric acid. Borate treatments caused lower mass loss when compared to untreated wood. In other words, wood became more difficult to ignite, and more oxygen was needed to burn the impregnated materials as consistent to the effect of boron reported earlier (Wen-Yu 1997, LeVan and Tran 1990). In order to determine the effects of borates and their concentrations on mass loss, ANOVA tests were conducted and homogeneity groups were determined by using SPSS statistical software package (Tab. 2 and 3). The effect of borates on mass loss is given in Tab. 2. The mass loss of wood treated with boric acid was the lowest followed by borax and sodium perborate treatments, respectively.

Tab. 2: Duncan's test results of borates on average mass loss of Oriental beech after combustion test.

Chemicals	Mean (%)	Homogeneity groups*
Control (Untreated)	88.90	A
BA	75.69	C
BX	82.83	B
SP	83.43	B

* Similar letters reflecting statistical insignificance at the 95 % confidence level.

Tab. 3: Duncan's test results of concentrations of borates on average mass loss of Oriental beech after combustion test.

Concentration (%)	Mean (%)	Homogeneity groups*
Control (Untreated)	88.90	A
2	84.53	B
4	80.50	C
6	76.92	D

* Similar letters reflecting statistical insignificance at the 95 % confidence level.

There was a statistical difference in the mass loss value between the untreated wood and the borate-treated wood. However, no statistical difference was found between BX and SP. The effect of borate concentration on mass loss is given in Tab. 3. All borate concentrations significantly lowered the mass loss of Oriental beech. According to Baysal et al. (2003), the mass losses of Calabrian pine (*Pinus brutia* Ten.) specimens impregnated with a mixture of BA and BX (7 % conc.) were approximately 63.4 %. Similarly, Baysal (2003) reported that *Fagus orientalis* wood specimens treated with a mixture of BA and BX (7:3; w/w) lost around 68 % of mass during combustion.

Our results were consistent with the findings of the aforementioned studies. Concentration levels of borates concerning the mass loss of Oriental beech after the combustion test are shown in Fig. 2.

As the concentration levels increased, the retention levels in the wood also increased. Our findings showed that higher concentration levels of borates resulted in lower mass loss of wood. Toker et al. (2009) studied mass loss of borate-treated Oriental beech and Calabrian pine wood specimens. They found that higher concentration levels of borates resulted in lower mass loss of Oriental beech and Calabrian pine wood specimens. Baysal (2011) investigated combustion properties of Calabrian pine impregnated with some aqueous solutions of commercial fertilizers. He found that higher concentration levels of fertilizers improved combustion properties of Calabrian pine. Lee (1984) reported that the rate of weight loss of *Populus alba grandulosa*

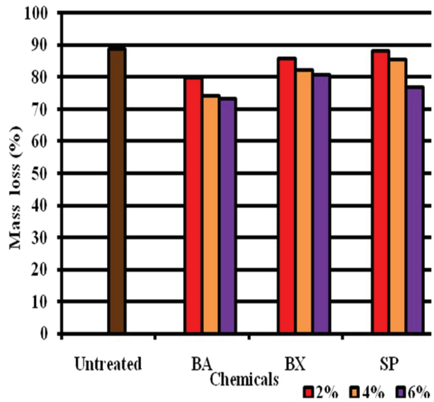

Fig. 2: The mass loss of Oriental beech impregnated with borates.

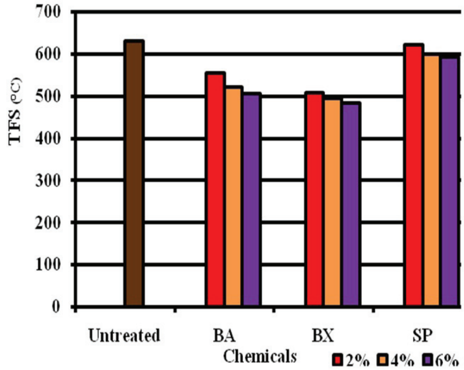

Fig. 3: TFS values of Oriental beech impregnated with borates.

decreased as the chemical retention increased. The results of the present study are consistent with these findings. Therefore, it can be concluded at this stage that aqueous solutions of borates reduced the mass loss of Oriental beech to a greater extent when compared to the untreated control specimens after combustion test. Moreover, higher concentration levels of borates resulted in lower mass loss of wood.

Temperature records at the combustion column during with and without flame stage and glowing stage

Temperatures were steadily recorded at the combustion column by thermocouple at a 15, 30, and 30 s intervals for the combustion with and without flame stage and glowing stage respectively. The recorded temperature degrees in Celsius of with and without flame stage, and glowing stage are listed in Tab. 4. Borate treatments had lower heat release rate at almost all combustion stages indicating inhibitory effects of borates on combustion. Therefore, borate treatments for these trials of combustion had a diminishing effect on heat release rate. These results were consistent with previous studies (Baysal et al. 2003, Yalinkilic et al. 1998, Hafizoglu et al. 1994). Our results showed that generally the higher concentration levels of borates resulted in lower temperature values of wood at all combustion stages.

In order to determine the effects of borates and their concentrations on TFS, TWFS, and TGS values, ANOVA tests were conducted and homogeneity groups were determined by using SPSS statistical software package. The effect of borates on TFS is given in Tab. 5. The TFS of wood treated with borax was the lowest followed by boric acid and sodium perborate treatments, respectively (Fig. 3). All borate treatments significantly lowered the TFS values of Oriental beech. The effect of borate concentrations on TFS value is given in Tab. 6. There was a statistical difference between the TFS values of untreated wood and wood treated with all of the borate concentrations. The effects of borates on TWFS values of Oriental beech are given in Tab. 7. There was a statistical difference between untreated wood and borate-treated wood. TWFS values of of wood were the lowest for borax followed by boric acid, and sodium perborate treatments, respectively, respectively (Fig. 4).

Tab. 4: Temperature records at during flame stage, without flame stage (TFS and TWFS), and glowing stage (TGS).

Wood species	Chemicals	Concentration (%)	TFS (°C)			TWFS (°C)			TGS (°C)		
			Mean[a]	±	SD	Mean[a]	±	SD	Mean[a]	±	SD
Oriental beech	Control (Untreated)	-	630	±	110	783	±	125	233	±	47
	BA	2	554	±	144	607	±	63	206	±	64
		4	522	±	91	601	±	82	157	±	59
		6	507	±	92	581	±	91	155	±	63
	BX	2	509	±	90	533	±	39	220	±	44
		4	495	±	85	405	±	90	167	±	36
		6	484	±	79	365	±	64	181	±	62
	SP	2	623	±	65	598	±	48	208	±	83
		4	600	±	128	728	±	58	189	±	53
		6	592	±	142	520	±	56	202	±	97

a : Four replication were made for each group

BA: Boric acid; BX: Borax; SP: Sodium perborate

SD: Standard deviation

Tab. 5: Duncan's test results of borates on average TFS of Oriental beech after combustion test.

Chemicals	TFS (°C)	Homogeneity groups*
Control (Untreated)	630	A
BA	528	C
BX	496	D
SP	605	B

* Similar letters reflecting statistical insignificance at the 95 % confidence level.

Tab. 6: Duncan's test results of concentrations of borates on TFS of Oriental beech after combustion test.

Concentration (%)	TFS (°C)	Homogeneity groups*
Control (Untreated)	630	A
2	562	B
4	539	C
6	528	D

* Similar letters reflecting statistical insignificance at the 95 % confidence level.

Tab. 7: Duncan's test results of borates on average TWFS of Oriental beech after combustion test.

Chemicals	TWFS (°C)	Homogeneity groups*
Control (Untreated)	783	A
BA	596	C
BX	434	D
SP	615	B

* Similar letters reflecting statistical insignificance at the 95 % confidence level.

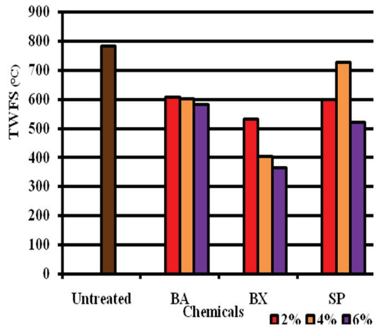

Fig. 4: TWFS values of Oriental beech impregnated with borates.

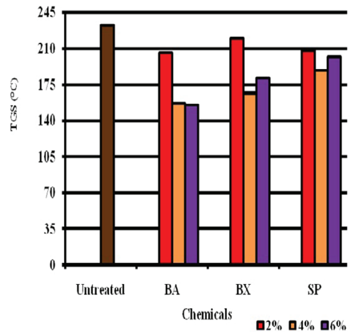

Fig. 5: TGS values of Oriental beech impregnated with borates.

Tab. 8 shows the effect of concentrations of borates on TWFS values of Oriental beech. There were statistical differences in the TWFS values of the untreated wood and wood treated with all of the concentrations of borates. The effects of borates on TGS values of Oriental beech are given in Tab. 9. There was a statistical difference between untreated wood and all borate-treated wood. TGS values of wood were the lowest for boric acid, followed by borax, and sodium perborate treatments, respectively (Fig. 5). Tab. 10 shows the effect of concentrations of borates on TGS values of Oriental beech. There were statistical differences in the TGS values of the untreated wood and wood treated with all of the concentrations of borates. Toker et al. (2009) studied temperature values of Oriental beech and Calabrian pine wood specimens impregnated with boron compounds. They found that higher concentration levels of boron compounds resulted in lower values of Oriental beech and Calabrian pine wood specimens.

Tab. 8: Duncan's test results of concentrations of borates on TWFS of Oriental beech after combustion test.

Concentration (%)	TWFS (°C)	Homogeneity groups*
Control (Untreated)	783	A
2	579	B
4	578	C
6	488	D

* Similar letters reflecting statistical insignificance at the 95 % confidence level.

Tab. 9: Duncan's test results of borates on average TGS of Oriental beech after combustion test.

Chemicals	TGS (°C)	Homogeneity groups*
Control (Untreated)	233	A
BA	173	D
BX	189	C
SP	200	B

* Similar letters reflecting statistical insignificance at the 95 % confidence level.

Tab. 10: Duncan's test results of concentrations of borates on TGS of Oriental beech after combustion test.

Concentration (%)	TGS (°C)	Homogeneity groups*
Control (Untreated)	233	A
2	211	B
4	171	D
6	179	C

* Similar letters reflecting statistical insignificance at the 95 % confidence level.

Grexa and Lübke (2001) investigated the effect of different loads of magnesium hydroxide as a flame retardant on the flammability parameters of particleboard. They found that increasing the amount of magnesium hydroxide significantly improved the overall fire behaviour of particleboard. Also, White (1979) noted that the oxygen index levels increased with an increase in the treatment level of chemicals. The results of this study are consistent with these findings.

CONCLUSIONS

Mass loss and temperature values of Oriental beech treated with water borne solutions of (2, 4, and 6 %) boric acid, borax, and sodium perborate were studied. Borates evidently reduced mass losses to some considerable extent and also reduced the temperature profiles of released heat during combustion after flame stage was removed and at the glowing stage. While in terms of TFS and TWFS values, BX-treated wood specimens gave the best results, in terms of mass loss and TGS values, BA-treated wood specimens gave the best results. The higher concentration levels of borates resulted in lower mass loss and temperature values of Oriental beech wood.

In conclusion, the results of this study indicated that Oriental beech wood specimens treated with borates enhanced mass loss and temperature values. They caused lower mass loss and temperature values of treated wood than untreated wood.

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