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EFFECTS OF SOME ENVIRONMENTALLY-FRIENDLY FIRE-RETARDANT BORON COMPOUNDS ON MODULUS OF RUPTURE AND MODULUS OF ELASTICITY OF WOOD

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ABSTRACT

This study was designed to determine some mechanical properties such as modulus of rupture (MOR) and modulus of elasticity (MOE) of wood treated with some environmentally-friendly fire-retardant boron compounds. Sodium perborate (SP) boric acid, (BA), and borax (BX) were used as boron compounds. Wood specimens were prepared from Calabrian pine (*Pinus brutia* Ten.) and beech (*Fagus orientalis* Lipski) wood. Before MOR and MOE tests, wood specimens were impregnated with aqueous solutions (1, 2, 3, 4, 5, and 6 %) of borates according to ASTM D 1413-76.

Our results showed that MOR values of wood specimens treated with borates were lower compared to untreated control specimens. The MOR and MOE values of wood specimens were the lowest for treatments with SP followed by BX and BA, respectively. In general, the higher concentration levels of borates, the lower MOR of wood resulted.

KEY WORDS: modulus of rupture, modulus of elasticity, boron compounds, environmentally-friendly, impregnation

INTRODUCTION

Wood is an environmentally desirable material for fiber and structural use. It is efficient in both economic and environmental costs to users. To extend its utility into new markets, wood is sometimes treated with chemicals (Winandy and Richards, 2003). One of the major objections to the use of wood for many purposes is of course the question of its long-term resistance to the natural processes of degradation, particularly at sites and in situations where there is high biological hazard and where no form of chemical or physical protection is afforded to the material. With an increased demand for timber worldwide and moves towards fast-grown plantation species, the need to impart additional protection, usually in the form of chemical treatment, has become necessary to confer long-term performance in these wood products (Eaton and Hale 1993). However, many of the effective poisonous chemicals were questionable. Increased public concern on the environmental effect of many wood preservatives has rendered 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 low mammalian toxicity and low volatility. Moreover, they are colorless and odorless (Hafizoglu et al. 1994, Murphy 1990, Yalinkilic et al. 1999a, Drysdale 1994, Chen et al. 1997). Boron containing chemicals such as boric acid (BA) and borax (BX) 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).

Many of the metallic oxides commonly used in water borne preservative formulations do react with the cell wall components by undergoing hydrolytic reduction upon contact with wood sugars. This process, known as fixation, oxidizes the wood cell wall components and may reduce wood strength (Winandy 1988). The relative impact of various waterborne preservative systems is directly related to the system's chemistry and the severity of its fixation/precipitation reaction (Winandy 1996). Gerhards (1970) reported that modulus of rupture (MOR) is consistently lower and modulus of elasticity (MOE) are generally lower for fire-retardant treated wood than untreated wood if fire-retardant treatment is followed by kiln drying. Winandy (1995) reported that there appears to be a little relative difference in their effect on strength when retention levels of chemicals were between 4.0 to 9.6 kg /m^3. LeVan et al. (1990) reported that the MOR of Southern pine wood treated some fire-retardant chemicals were reduced between 10 and 20 percent. Winandy et al. (1988) investigated the effects of fire retardant treatments on mechanical properties of Douglas- fir and aspen plywood. They found that FR treatment did not affect MOE of both species, whereas it reduced the other mechanical properties. Also, they reported that CZC treatment had a far greater negative effect than did the other FR treatments. It is probable that the high level of chloride in CZC treatment promoted hydrolysis via an intermediate formation of hydrochloric acid. Hesp and Watson (1964) studied the mechanical properties of Scots pine impregnated with CCA. They found some reductions in modulus of rupture (MOR) of Scots pine. But, these reductions were of little practical consequence.

This study was performed to determine MOR and MOE levels of wood treated with aqueous solutions (1%, 2%, 3%, 4%, 5%, and 6%) of some fire-retardant boron compounds such as sodium perborate, boric acid, and borax.

MATERIAL AND METHODS

Preparation of test specimens and chemicals

Wood specimens measuring 20 (tangential) x 20 (radial) x 300 (longitudinal) mm were prepared from air-dried sapwood of Calabrian pine (*Pinus brutia* Ten.) and beech (*Fagus orientalis* Lipski). Aqueous solutions of sodium perborate (SP), boric acid (BA), and borax (BX) dissolved in distilled water to concentrations of 1%, 2%, 3%, 4%, 5%, and 6%. Wood specimens were oven dried at 103 ± 2 °C before and after treatment.

Impregnation methods

Wood specimens were impregnated with aqueous solutions of borates according to ASTM D 1413-76 (1976). Treatment solutions were prepared 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 mHg^{-1} before supplying the solution into the chamber followed by another 60 min. at 760 $mmHg^{-1}$ diffusion period under vacuum. Retention of boron was calculated from the following equation:

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

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

Mechanical tests

The modulus of rupture (MOR) and modulus of elasticity (MOE) of wood specimens were determined according to TS 2474 (1976) and TS EN 310 (1999), respectively. Wood specimens had been conditioned at 20 °C and 60 % RH for 6 weeks prior to testing. The MOE and MOR of wood specimens treated with some fire-retardant were calculated using the following formulas;

$$MOR = \frac{3 \times P \times I}{2 \times b \times h^2} \; N/mm^{-2} \tag{2}$$

$$MOE = \frac{P \times I^3}{4 \times b \times h^3 \times Y} \; N/mm^{-2} \tag{3}$$

Where P is the maximum load (N), I is span (mm), b is width of specimen (mm), h is thickness of specimen (mm), P is load to proportional limit (mm), and Y is deflection (mm).

RESULTS AND DISCUSSION

MOR levels of wood treated with some fire-retardant boron compounds

The MOR values of wood specimens are given in Tab. 1. Modulus of rupture value of untreated beech was higher compared to untreated Calabrian pine. In order to determine the effects of borates and their concentrations on MOR, ANOVA tests were made and homogeneity groups were determined by using SPSS statistical software package (Tab. 2-3). The highest MOR values were obtained as 92.32 and 109.93 N/mm^{-2} for untreated Calabrian pine and beech, respectively. The lowest MOR values were obtained as 72.16 and 77.52 N/mm^{-2} treated with 6% BX for Calabrian pine and 6 % SP for beech wood, respectively. Results showed that boron treatments decreased the MOR values of wood specimens compared to untreated control. The effects of borates on MOR are given in Tab. 2. There was a statistical difference in MOR values between untreated wood and borate treated wood. However, no statistical difference was found between BX and BA whereas there was a statistical difference between SP and BA. It can be said that borate treatment increased the rate of hydrolysis in the wood, thereby causing loss in strength (Kollman and Cote 1968). Yildiz et al. (2004) determined the effects of wood preservatives on modulus of rupture. They reported that there were no significant differences in MOR values between untreated and Wolmanit CX-8 and Tanalith-3491 impregnated wood. However, there was a significant difference in MOR levels between untreated wood and ACQ-1900, ACQ-2200, and CCA impregnated wood. Colakoglu et al. (2003) found that MOR levels of laminated veneer lumber treated with 1 % boric acid were reduced 3.8 % compared to untreated control. Another study, Gerhards (1970) found that fire retardant chemical treatment and kiln-drying reduce the MOR of wood by an average of 13 %. The effects of concentrations of borates on MOR are given in Tab. 3. There was a statistical difference in MOR values between untreated wood and treated with all concentrations of borates. Laks and Palardy (1990) showed that addition of zinc borate to flakeboards caused some decrease in mechanical properties as borate content increased. Wu et al. (2002) studied some mechanical properties of borate-modified oriented strandboard (OSB). They reported that there was some reduction for the specific modulus of rupture of OSB at higher 2.5 % BAE borate loading levels indicating a negative effect of borate on panel strength. Our results showed that generally the higher concentration levels of borates, the lower MOR of wood resulted.

MOE levels of wood treated with some fire-retardant boron compounds

The MOE values of wood specimens are given in Tab. 4. Modulus of elasticity value of untreated beech wood was higher compared to untreated Calabrian pine. In order to determine the effects of borates and their concentrations on MOE, ANOVA tests were made and homogeneity groups were determined using SPSS statistical software package (Tab. 5-6). The MOE values were obtained as 10180.8 and 10836.6 N/mm^{-2} for untreated Calabrian pine and beech, respectively. The lowest MOE values were obtained as 7856.0 and 8452.0 N/mm^{-2} treated with 6 % BX for Calabrian pine and 3 % SP for beech wood, respectively. The effects of borates on MOE are given in Tab. 5. There was a statistical difference in MOE values between untreated wood and borate treated wood. However, no statistical differences were found among SP, BX, and BA. The MOE levels were the lowest for wood specimens treated with SP followed by BX and BA, respectively. Yildiz et al. (2004) studied the effects of wood preservatives on modulus of elasticity. They reported that there were no significant differences in MOE values between untreated and ACQ-1900, ACQ-2000, CCA, and Tanalith E 3491 impregnated wood. The effects of concentrations of borates on MOE are given in Tab. 6. There was a statistical difference in MOE values between untreated wood and treated with all concentrations of borates. However, no statistical differences were found among 1%, 2%, 3%, 4%, and 5% concentrations of borates. Wu et al. (2002) reported that the specific modulus of elasticity of borate-modified oriented strain board was affected little at room condition by borate up to the 3.5 % BAE level. Colakoglu et al. (2003) reported that MOE values of laminated veneer lumber treated with 1 % boric acid were reduced 5.1 % compared to untreated control. Gerhards (1970) found that fire retardant chemical treatment and kiln-drying reduce the MOE of wood by an average of 5 %. Our results showed that generally borate treatments decreased the MOE of wood compared to untreated control.

Tab. 1: MOR values of wood specimens treated with boron compounds

Wood species	Chemicals	Concentration (%)	Retention (Kg/m^{-3})	MOR (Nt/mm^{-2})	
				Mean[a]	SD
Calabrian pine *Pinus brutia* Ten.	SP	Control	-	92.32	9.23
		1	5.26	83.09	6.64
		2	8.24	81.98	3.90
		3	14.75	80.14	5.99
		4	17.12	88.69	2.33
		5	23.89	76.62	6.48
		6	25.73	80.09	6.58
	BA	1	4.93	86.67	3.52
		2	10.59	85.34	12.34
		3	12.82	83.67	12.76
		4	19.68	82.93	6.57
		5	28.26	80.64	9.20
		6	28.91	76.70	4.82
	BX	1	5.36	90.52	6.03
		2	10.38	88.29	6.99
		3	14.58	87.70	10.67
		4	19.09	85.40	13.84
		5	24.78	79.08	4.45
		6	31.34	72.16	8.78
Beech *Fagus orientalis* Lipsky	SP	Control	-	109.93	15.35
		1	3.75	91.44	5.83
		2	7.80	89.33	10.21
		3	13.64	88.22	11.22
		4	14.65	86.14	12.11
		5	16.27	84.74	1.41
		6	18.09	77.52	14.69
	BA	1	4.37	105.89	13.73
		2	8.78	101.26	17.74
		3	11.38	93.88	6.86
		4	17.88	93.68	6.56
		5	23.11	92.13	8.99
		6	25.33	89.35	5.17
	BX	1	4.54	98.42	12.62
		2	9.09	96.27	14.82
		3	12.97	91.16	9.66
		4	18.12	91.03	13.29
		5	21.95	86.09	16.79
		6	26.44	83.98	9.94

[a]Results reflect observations of ten wood specimens
SP: Sodium perborate; BA:Boric acid; BX: Borax
SD:Standard deviation

Tab. 2: Duncan test results of borates on MOR

Chemicals	Mean	Homogeneity groups*
Control (Untreated)	101.12	A
SP	83.99	C
BA	89.34	B
BX	88.00	B C

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

Tab. 3: Duncan test results of concentrations on MOR

Concentration (%)	Mean	Homogeneity groups*
Control (Untreated)	101.12	A
1	93.67	B
2	90.41	B C
3	87.97	C D
4	87.46	C D
5	83.21	D E
6	79.96	E

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

Tab. 4: MOE values of wood specimens treated with boron compounds

Wood species	Chemicals	Concentration (%)	Retention (Kg/m^{-3})	MOE (N/mm^{-2})	
				Mean[a]	SD
Calabrian pine *Pinus brutia* Ten.		Control	-	10180.8	1430.9
	SP	1	5.26	9338.2	1839.6
		2	8.24	9369.1	1860.0
		3	14.75	8277.4	649.7
		4	17.12	10364.1	1365.2
		5	23.89	8144.6	1544.4
		6	25.73	8080.2	1562.8
	BA	1	4.93	9490.8	1642.0
		2	10.59	8707.7	2250.9
		3	12.82	8862.9	1555.6
		4	19.68	8638.6	1573.8
		5	28.26	8651.1	1654.7
		6	28.91	8328.6	748.8
	BX	1	5.36	9020.0	1407.1
		2	10.38	9749.3	1534.8
		3	14.58	9860.7	1519.0
		4	19.09	9215.9	2132.1
		5	24.78	8281.6	1424.2
		6	31.34	7856.0	1405.6
Beech *Fagus orientalis* Lipski		Control	-	10836.6	1039.4
	SP	1	3.75	9190.0	562.5
		2	7.80	9093.9	1131.2
		3	13.64	8452.0	692.0
		4	14.65	8939.2	386.3
		5	16.27	8562.7	357.8
		6	18.09	8636.4	476.4
	BA	1	4.37	10700.7	1142.3
		2	8.78	9884.0	1455.7
		3	11.38	9783.3	731.9
		4	17.88	9826.4	487.7
		5	23.11	9311.9	549.6
		6	25.33	9166.9	826.5
	BX	1	4.54	9454.1	791.0
		2	9.09	9789.2	767.3
		3	12.97	9575.5	711.2
		4	18.12	9361.0	699.7
		5	21.95	9199.9	1071.3
		6	26.44	8973.1	797.6

[a]Results reflect observations of ten wood specimens
SP: Sodium perborate; BA:Boric acid; BX: Borax
SD:Standard deviation

Tab. 5: Duncan test results of borates on MOE

Chemicals	Mean	Homogeneity groups*
Control (Untreated)	10508.7	A
SP	8870.6	B
BA	9279.4	B
BX	9194.7	B

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

Tab. 6: Duncan test results of concentrations on MOE

Concentration (%)	Mean	Homogeneity groups*
Control (Untreated)	10508.7	A
1	9532.3	B
2	9432.2	B
4	9390.9	B
3	9135.3	B C
5	8691.9	B C
6	8506.8	C

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

CONCLUSION

MOR and MOE values of wood treated with water born solutions of (1%, 2%, 3%, 4%, 5%, and 6%) SP, BA, and BX were studied. The MOR values of untreated wood specimens were higher than that of treated wood specimens. The MOR and MOE values of wood specimens were the lowest for treatments with SP followed by BX and BA, respectively. But, there were no significant differences for MOE values among these chemicals. Generally, the higher concentration levels of borates, the lower MOR of wood resulted. Modulus of elasticity is a measure of the stiffness of a material, while MOR has proved to be a more reliable measure of strength than stress at the proportional limit. This is due to the fact that the maximum load can be determined more precisely than the proportional limit (Yalinkilic et al., 1999b).

Preservatives and FR treatments generally reduce the mechanical properties of wood (Winandy 1988). FR chemicals used today are inorganic salts; they diffuse throughout the wood with moisture movement. As the moisture moves, at each new site, the acidic salts can cause further degradation (LeVan and Winandy 1990). According to our results, in general, boron compounds caused decrease in MOR and MOE values of wood.

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