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Some mechanical properties and decay resistance of wood impregnated with environmentally-friendly borates

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ABSTRACT

This study was made to determine some mechanical properties such as compression strength parallel to grain, modulus of rupture, and decay resistance of wood treated with some environmentally-friendly borates. Sodium tetrafluoroborate (SFB), ammonium tetrafluoroborate, (AFB), and ammonium pentaborate octahydrate (APB) were used as borates. Wood specimens were prepared from Oriental beech (*Fagus orientalis* L.) and Scots pine (*Pinus sylvestris* L.). Before tests, wood specimens were impregnated with aqueous solutions (0.25%, 0.50%, 1.50%, and 3.00%) of borates according to ASTM D 1413-76.

Results showed that compression strength parallel to grain (CSPG) and modulus of rupture (MOR) of wood specimens treated with borates were lower compared to untreated control specimen. In general, our results showed that the higher concentration levels of borates, the lower mechanical properties of wood resulted. Borate treated wood showed considerable resistance to the decay fungus compared to that of untreated control specimen.

1. Introduction

Among the construction materials which are used by people wood holds a special place because of its impressive range of attractive properties, including low thermal extension, low density and high enough mechanical strength [1]. 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 [2]. In recent years, there has been a rapid increase in the application of chemicals to wooden materials in order to improve their physical, mechanical, biological, and fire properties [3,4]. However, many of the effective poisonous chemicals were 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 [5]. 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 [6,7]. However, they are generally leachable from treated wood in ground contact under rainfall [8,9]. Many attempts have already been made to reduce leaching of borates from treated wood through chemical fixation of boron. To achieve a longlasting boron effect in wood, one practical approach is the chemical complexion of boron with a fixing agent capable of forming water-insoluble complexes upon dehydration in wood [10]. Lloyd et al. [11] reported that addition of polyols to borate solutions greatly increased the boron stability through borate/polyol chelate complexion. Another practical approach is to physically restrict water access in wood by impregnating by hydrophobic agents to limit boron mobility without interfering with its bioactive structure [5].

Hygroscopic nature of some boron salts may have adverse effect on dimensional stability of wood under humid service conditions and can cause strength losses at elevated temperatures at high retention levels [12,13]. Yildiz et al. [14] determined the effects of wood preservatives on MOR. There were no significant differences in MOR values between untreated (control) and Wolmanit CX-8, Tanalith-3491 impregnated wood. However, there was significant difference in MOR levels between untreated wood and ACQ-2200 and CCA impregnated wood.

Biodegradability of wood material is another criterion of wood treatment for longer serviceability. Borates provide protection against all forms of wood destroying organisms, including decay fungi (such as wet and dry rot), wood boring beetles (such as the common furniture beetle, the house longhorn beetle and powder post beetles) and termites (including dry wood and subterranean termites [15]. Temiz et al. [16] investigated decay resistance of

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Scots pine treated with 4-methoxytrityl tetrafluoborate (MTFB). Decay resistance tests of unleached samples showed that 2%, 1.5%, and 1% concentrations of MTFB gave less than 2% decay of *Coniophora puteana*. Kose et al. [17] investigated that the relative ability of various combinations of copper sulfate with either boric acid or calcium-precipitating agent, N′-N-(1,8-naphthalyl) hydroxylamine (NHA-Na), to inhibit fungal degradation. They found that increased efficacy of copper sulfate against the brown-rot fungus *Tyromyces palustris* was observed when either boric acid or NHA-Na was added.

This study was performed to determine CSPG, MOR, and decay resistance of wood impregnated with aqueous solutions (0.25%, 0.50%, 1.50%, and 3.00%) of sodium tetrafluoroborate (SFB) ammonium tetrafluoroborate, (AFB), and ammonium pentaborate octahydrate (APB).

2. Materials and methods

2.1. Preparation of test specimens and chemicals

Wood specimens measuring 20 (radial) × 20 (tangential) × 360 (longitudinal) mm, and 20 (radial) × 20 (tangential) × 30 (longitudinal) mm were prepared from air-dried sapwood of Oriental beech (*Fagus orientalis* L.) and Scots pine (*Pinus sylvestris* L.) for modulus of rupture and compression parallel to grain tests, respectively. For decay test, wood specimens measuring 15 (radial) × 25 (tangential) × 50 (longitudinal) mm were prepared from air-dried sapwood of Oriental beech (*F. orientalis* L.) and Scots pine (*P. sylvestris* L.). Fungal decay test was made using a white rot fungus, *Coriolus versicolor* (COV) (L. ex Fr.) Quel [FFPRI 1030]. Aqueous solutions of sodium tetrafluoroborate (SFB) ammonium tetrafluoroborate, (AFB), and ammonium pentaborate octahydrate (APB) dissolved in distilled water to concentrations of 0.25%, 0.50%, 1.50%, and 3.00%. Wood specimens were oven dried at 103 ± 2 °C before and after treatment.

2.2. Impregnation method

Wood specimens were impregnated with aqueous solutions of borates according to ASTM D 1413-76 [18]. 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 m Hg^{-1} before supplying the solution into the chamber followed by another 60 min at 760 mm Hg^{-1} diffusion period under vacuum. Retention of boron was calculated from the following equation:

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

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.

2.3. Compression strength parallel to grain

The compression strength parallel to grain test was determined according to the TS 2595 [19] standard by using a 4000-kp capacity universal test machine, and applying 6 mm/min loading time. Before tests, wood specimens had been conditioned at 20 °C and 60% RH for 6 weeks.

2.4. Modulus of rupture

The modulus of rupture (MOR) of wood specimens was determined according to TS 2474 [20]. Wood specimens had been conditioned at 20 °C and 60% RH for 6 weeks prior to testing. The MOR of wood specimens was calculated using the following formula;

$$\text{MOR} = \frac{3 \times P \times I}{2 \times b \times h^2}\ \text{Nt/mm}^2 \qquad (2)$$

where P is the maximum load (Nt), I is span (mm), b is width of specimen (mm), h is thickness of specimen (mm).

2.5. Decay test

Wood specimens measuring 15 (radial) × 25 (tangential) × 50 (longitudinal) mm were prepared for decay test, from air-dried sapwood of Oriental beech (*F. orientalis* L.) and Scots pine (*P. sylvestris* L.). Fungal decay test was made according to JIS A-9201 [21] using a white rot fungus, *C. versicolor* (COV) (L. ex Fr.) Quel [FFPRI 1030]. Wood specimens were sterilized with gaseous ethylene oxide after measuring the initial dry weights. The wood specimens of the same treatment were placed in a glass jar which contained medium of 250 g quartz sand + 80 ml nutrient solution was composed of 3 g $MgSO_4 \cdot 7H_2O$, 2 g KH_2PO_4, 10 g malt extract, and 5 g peptone per 1000 ml distilled water with fungal mycelia grew on it. Then, they were incubated at 26 °C for 12 weeks. Test results were expressed as percentage of mass losses of wood specimens due to fungal attacks after decay test. Ten replicates were used for each treatment groups.

2.6. Evaluations of test results

Mechanical and decay 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), of which different letters reflected statistical significance.

3. Results and discussion

3.1. Compression strength parallel to grain (CSPG)

The CSPG values of wood specimens are given in Table 1 and Fig. 1. The CSPG of untreated Oriental beech was higher compared to untreated Scots pine. The highest CSPG values of wood specimens were obtained as 72.70 and 61.46 Nt/mm^2 for untreated Oriental beech and Scots pine, respectively. The lowest CSPG values

Table 1
The CSPG of Oriental beech and Scots pine impregnated with borates.

Chemicals	Concentrations (%)	Oriental beech				Scots pine			
		Retention (kg/m³)	CSPG[A] (N/mm²)		Change (%)	Retention (kg/m³)	CSPG[A] (N/mm²)		Change (%)
			Mean	SD			Mean	SD	
Control	–	–	72.70[a]	4.72	–	–	61.46[a]	7.54	–
SFB	0.25	1.23	56.74[b]	9.70	−21.96	1.06	57.16[b]	8.30	−7.00
	0.50	2.69	57.81[b]	8.63	−20.49	2.63	56.49[b]	5.39	−8.09
	1.50	7.64	52.39[bc]	6.72	−27.94	8.43	53.09[c]	6.24	−13.62
	3.00	17.42	46.73[cd]	8.23	−35.72	15.98	48.74[d]	7.26	−20.69
AFB	0.25	1.42	65.65[a]	3.44	−9.70	1.09	57.27[b]	9.66	−6.82
	0.50	2.57	65.52[a]	2.59	−9.88	2.58	52.26[c]	9.71	−14.97
	1.50	8.22	54.37[b]	9.76	−25.21	8.17	49.91[d]	3.97	−18.80
	3.00	14.79	42.55[d]	9.55	−41.47	11.48	47.77[d]	6.69	−22.28
APB	0.25	1.40	70.48[a]	1.60	−3.05	0.98	55.35[b]	2.06	−9.94
	0.50	2.44	68.97[a]	1.79	−5.13	2.44	55.49[b]	5.23	−9.72
	1.50	7.00	55.25[b]	9.03	−24.01	7.14	48.45[d]	8.51	−21.17
	3.00	16.04	56.82[b]	10.74	−21.85	9.89	52.87c	4.13	−13.98

Note: Small letters given as superscript over CSPG values represent HG obtained by statistical analysis with similar letters reflecting statistical insignificance at the 95% confidence level.
[A] Results reflect observations of 10 wood specimens, SD: Standard deviation.

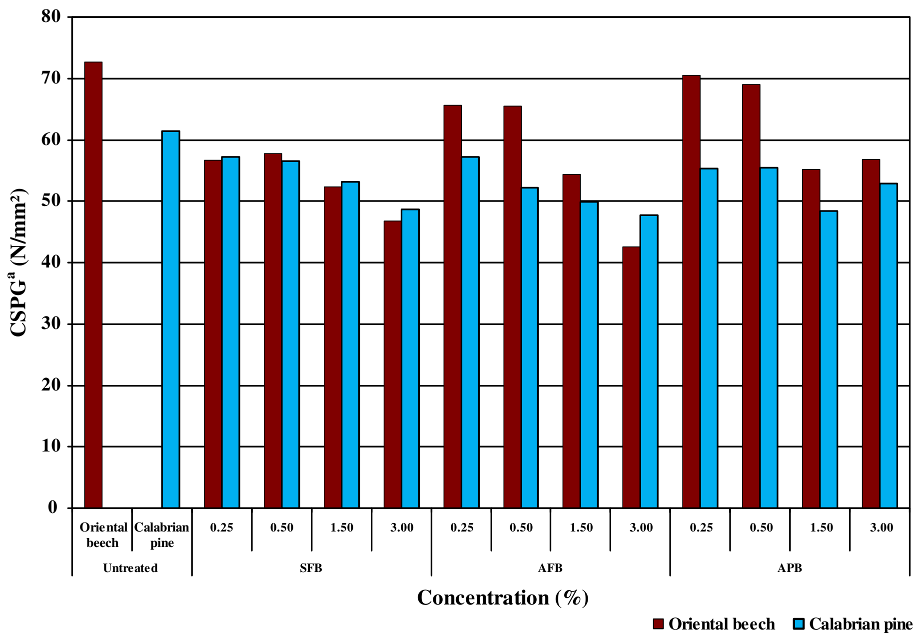

Fig. 1. The CSPG of Oriental beech and Scots pine impregnated with borates.

of wood specimens were obtained as 42.55 and 47.77 Nt/mm^2 treated with 3.00% AFB for Oriental beech and Scots pine, respectively. Results showed that all treated wood species have less CSPG values compared to untreated control. It can be said that borate treatment increased the rate of hydrolysis in the wood, thereby causing loss in strength [22]. Toker et al. [23] reported that for Calabrian pine, treatments with 3%, 4%, 5%, 6% of sodium perborate and, 6% of boric acid; for beech, treatments with 3%, 4%, 5%, and 6% of sodium perborate caused higher 20% CSPG loss. Also, they determined that higher the concentration levels of borates lower the compression strength parallel to grain of Calabrian pine. Laks and Palardy [24] determined that addition of zinc borate to flakeboards caused some decrease in mechanical properties as borate content increased. Our results showed that higher the concentration levels of borates lower the compression strength parallel to grain values of wood specimens. These results are in good agreement with data from Toker et al. [23].

3.2. Modulus of rupture

The MOR values of wood specimens are given in Table 2 and Fig. 2. Modulus of rupture value of untreated Oriental beech was higher compared to untreated Scots pine. The highest MOR values were obtained as 104.18 and 79.99 Nt/mm^2 for untreated Oriental beech and Scots pine, respectively. The lowest MOR values were obtained as 86.64 and 58.09 Nt/mm^2 treated with 3% AFB and 1.5% APB for Oriental beech and Scots pine, respectively. Results showed that borate treatments decreased the MOR values of wood specimens compared to untreated control. Colakoglu et al. [25] found that MOR levels of laminated veneer lumber treated with 1% boric acid were reduced 3.8% compared to untreated control. Another study, Gerhards [26] determined that fire-retardant chemical treatment and kiln-drying reduce the MOR of wood by an average of 13%. LeVan et al. [27] reported that the MOR of Southern pine wood treated some fire-retardant chemicals were reduced

Table 2
The MOR of Oriental beech and Scots pine impregnated with borates.

Chemicals	Concentrations (%)	Oriental beech				Scots pine			
		Retention (kg/m^3)	MOR[A] (N/mm^2)		Change (%)	Retention (kg/m^3)	MOR[A] (N/mm^2)		Change (%)
			Mean	SD			Mean	SD	
Control	–	–	104.18^{a}	18.81	–	–	79.99^{a}	8.53	–
SFB	0.25	1.06	97.97^{abc}	17.65	−5.97	0.73	79.75^{a}	9.31	−0.31
	0.50	2.27	92.66^{abc}	13.35	−11.06	1.72	75.57^{ab}	9.75	−5.54
	1.50	6.54	89.36^{bc}	11.85	−14.22	5.97	64.10^{de}	6.60	−19.87
	3.00	15.79	89.99^{abc}	10.70	−13.63	14.32	65.01^{de}	11.03	−18.73
AFB	0.25	1.04	100.39^{abc}	13.22	−3.64	0.46	74.68^{abc}	8.70	−6.64
	0.50	2.34	91.52^{abc}	7.63	−12.16	1.54	72.25^{bc}	9.14	−9.68
	1.50	8.10	91.64^{abc}	20.12	−12.04	4.65	69.99^{bcd}	6.81	−12.51
	3.00	10.79	86.64^{c}	9.32	−16.84	8.44	68.51^{cd}	2.16	−14.35
APB	0.25	1.27	102.67^{ab}	13.01	−1.45	0.76	58.85^{e}	3.73	−26.43
	0.50	2.20	100.26^{abc}	7.68	−3.77	1.23	61.06^{e}	1.84	−23.67
	1.50	7.26	96.20^{abc}	16.45	−7.67	3.29	58.09^{e}	2.67	−27.39
	3.00	14.13	93.98^{abc}	5.84	−9.79	9.58	61.41^{e}	1.39	−23.23

Note: Small letters given as superscript over MOR values represent HG obtained by statistical analysis with similar letters reflecting statistical insignificance at the 95% confidence level.
[A] Results reflect observations of 10 wood specimens, SD: Standard deviation.

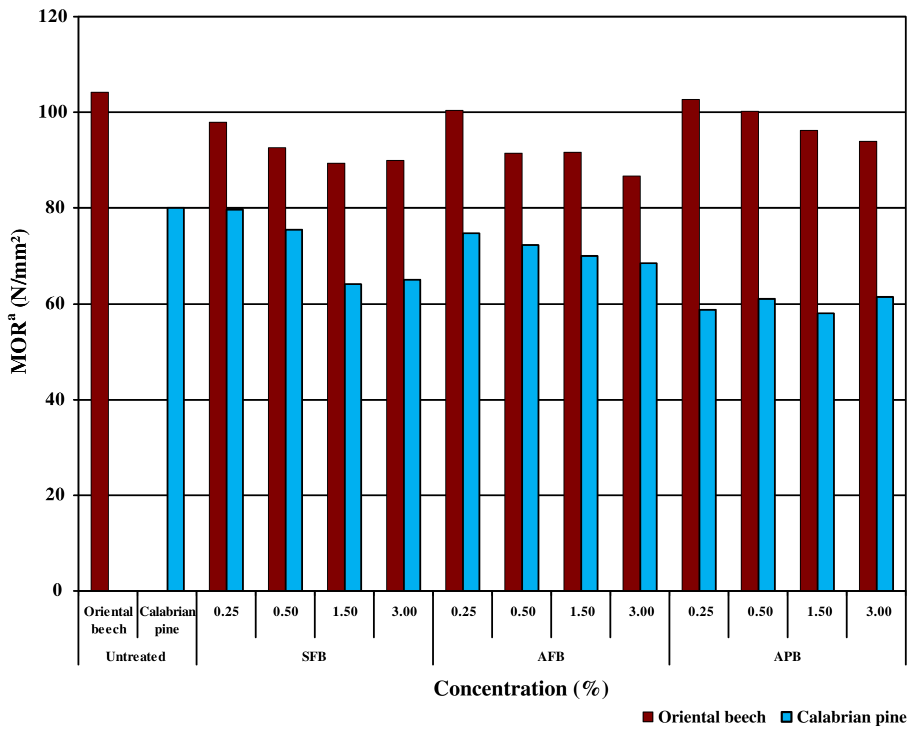

Fig. 2. The MOR of Oriental beech and Scots pine impregnated with borates.

between 10% and 20%. Ayrilmis et al. [28] reported that MOR levels of OSB panels treated with 2%, 4%, and 6% of boric acid treatments were significantly decreased when compared to control values. Wu et al. [29] investigated 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. Hesp and Watson [30] 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. Yildiz et al. [14] reported that 12% decrease in MOR of yellow pine wood samples treated with CCA. Toker et al. [31] reported that the higher concentration levels of boron compounds the lower modulus of rupture of Calabrian pine (*Pinus brutia* Ten.) and Oriental beech (*F. orientalis* L.) resulted. Our results showed that generally the higher concentration levels of borates, the lower MOR of wood resulted. These results are consistent with the previous studies [28,31].

3.3. Decay test

Results of decay test of Oriental beech and Scots pine impregnated with borates after decay test for 12 weeks are given in Table 3 and Fig. 3. Untreated Oriental beech (*F. orientalis* L.) and Scots pine (*P. sylvestris* L.) wood were severely attacked by decay fungi with the large weight losses. Mass loss of untreated Oriental beech was higher than untreated Scots pine. It may be due to lesser susceptibility of angiosperm sapwood to the white-rot fungi. Mass

Table 3
The mass loss values of Oriental beech and Scots pine impregnated with borates after decay test.

Chemicals	Concentrations (%)	Oriental beech			Scots pine		
		Retention (kg/m³)	Mass loss[A] (%)		Retention (kg/m³)	Mass loss[A] (%)	
			Mean	SD		Mean	SD
Control	–	–	30.13[a]	4.67	–	24.37[a]	3.32
SFB	0.25	1.20	2.74[b]	0.49	0.94	3.27[cde]	0.90
	0.50	2.41	2.87[b]	0.31	2.35	3.09[cde]	0.63
	1.50	7.21	3.03[b]	0.77	6.75	3.11[cde]	0.65
	3.00	15.85	2.75[b]	0.47	13.12	2.61[e]	0.47
AFB	0.25	1.24	3.19[b]	0.51	0.86	3.41[bcde]	0.97
	0.50	2.46	2.81[b]	0.53	1.91	3.23[cde]	0.54
	1.50	7.94	2.98[b]	0.71	7.23	3.01[de]	0.55
	3.00	16.86	3.03[b]	0.55	13.89	2.63[e]	0.64
APB	0.25	1.26	3.97[b]	0.37	1.10	4.48[b]	0.54
	0.50	2.41	3.73[b]	0.20	1.93	4.19[bc]	0.49
	1.50	7.11	3.82[b]	0.31	5.95	3.83[bcd]	0.37
	3.00	15.65	3.15[b]	0.50	14.16	3.63[bcde]	1.02

Note: Small letters given as superscript over mass loss values represent HG obtained by statistical analysis with similar letters reflecting statistical insignificance at the 95% confidence level.
[A] Results reflect observations of 10 wood specimens, SD: Standard deviation.

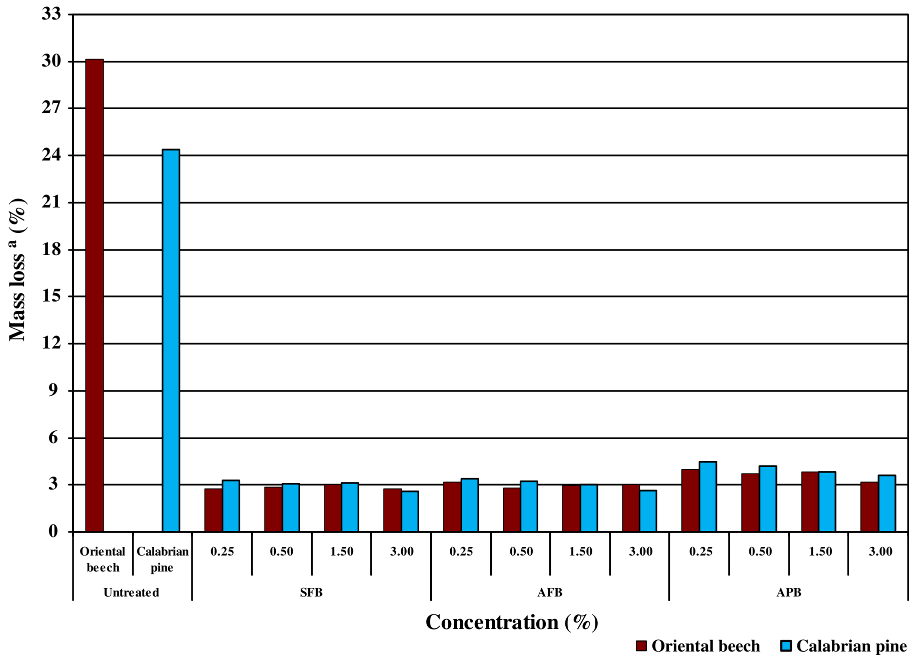

Fig. 3. The mass loss values of Oriental beech and Scots pine impregnated with borates decay test.

loss borate treated wood showed considerable resistance to the decay fungus compared to that of untreated control specimen. It is remarkable that borate in the wood provided good protection against fungal attack even at such a low concentrations. Wood specimens impregnated with borates revealed very small mass loss of 2.61–4.48% during exposure to *C. versicolor* compared with 30.13% and 24.37% for untreated Oriental beech and Scots pine, respectively. The highest mass losses were obtained as 30.13% and 24.37% for untreated Oriental beech and Scots pine, respectively. The lowest mass losses were obtained as 2.74% and 2.61% treated with 0.25% SFB and 3.00% SFB for Oriental beech and Scots pine, respectively. Yalinkilic et al. [32] reported that different levels of boron retention are necessary for biological activity against decay fungi. Around 1% w/w (2.5 kg/m^3) boric acid (BA) loading was found sufficient for decay resistance against *T. palustris* and *C. versicolor*, representing brown- and white-rot fungi, respectively. Another study, Tsunoda [33] determined that the toxic threshold values for sugi sapwood specimens treated with boric acid were 0.8 kg/m^3 against boric acid equivalent against *T. versicolor*. Also, Kartal et al. [34,35] determined that European standards usually require disodium octaborat tetrahydrate retention levels of 0.76 kg/m^3 for protection against *T. versicolor*. Our results showed that even the low loading levels of borate treated wood could resist wood-decaying fungi. There were no remarkable changes in mass loss values of woods among those that are treated with all concentrations of borates.

4. Conclusion

The CSPG, MOR, and decay resistance of Oriental beech and Scots pine treated with aqueous solutions of (0.25%, 0.50%, 1.50%, 3.00%) SFB, AFB, and APB were studied.

Borate treated wood showed considerable resistance to the decay fungus compared to that of untreated control specimen. Lin et al. [36] reported that weight losses due to fungal attack indicating the reasonable level of less than 3%. Also, Yalinkilic [37] determined that mass loss of sugi wood due to *C. versicolor* fungal attack indicating the reasonable level of less than 3%. Our results showed that wood specimens impregnated with aqueous solutions of (0.25, 0.50, 1.50, and 3.00) borates revealed mass loss of 2.61–4.48% during exposure to *C. versicolor*. Therefore, it was suggested that even the low loading levels of borate treated wood could resist wood-decaying fungi.

The CSPG and MOR values of both untreated wood specimens were higher than that of both treated wood specimens. In our study, in general, higher the concentration levels of borates lower the CSPG and MOR of wood. Waterborne preservative treatments generally reduce the mechanical properties of wood more than do oil-type preservative treatments because waterborne preservative chemicals physically react with the wood cell wall material [38]. Many of the metallic oxides commonly used in waterborne 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 [39]. The relative impact of various waterborne preservative systems is directly related to the system's chemistry and the severity of its fixation/precipitation reaction [38]. The National Forest Products Association (NFPA) [40] recommends that the allowable stresses for fire-retardant treated wood for design purposes be reduced by 10% as compared to untreated wood; the allowable loads for fasteners are also reduced 10%. Also, it requires a 10–20% reduction in allowable design stress, depending on mechanical property under consideration [41]. Winandy [42] determined that there appears to be a little relative difference in their effect on strength when retention levels of chemicals were between 4.0 and 9.6 kg/m^3. Mourant et al. [43] reported that wood samples with salts retention values ranging from 24 to 40 kg/m^3 had a significantly lower than the untreated control samples. According to our results, retention values of CSPG and MOR wood specimens were between nearly 1–17 kg/m^3 and borate treatments decreased 3.05–41.47% and 7.00–22.28% of CSPG for Oriental beech and Scots pine, respectively. Also, it decreased 1.45–16.84% and 0.31–27.39% of MOR for Oriental beech and Scots pine, respectively.

In conclusion, borate treatments caused decrease on CSPG and MOR of wood. In general, the higher concentration levels of borates, the lower CSPG and MOR of wood resulted. Borate treated wood showed considerable resistance to the decay fungus compared to that of untreated control specimen.

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