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Leachability of Zinc Borate-Modified Oriented Strandboard (OSB)*1

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ABSTRACT

The leachability of boron in zinc borate (ZB)-modified oriented strandboard (OSB) from southern wood species was investigated in this study. The leaching experiments were conducted by exposing edge-sealed OSB samples under running water at 31°C for 8, 24, 72, and 216 h. The results from leached samples were compared with those from the unleached controls. Boron leaching of the modified OSB occurred upon the initial water exposure, and the leaching rate decreased as the leaching time increased. Initial boric acid equivalent (BAE) level, wood species, and sample thickness swelling significantly influenced the leachability. There was no consistent effect of polyethylene glycol (PEG) on zinc borate leaching. The glue-line washing within OSB due to thickness swelling of the test samples under water and decomposition of the borate to form water-soluble boric acid were thought to be two possible causes for the observed leaching. The relationship between assayed BAE and leaching time followed a decaying exponential function for zinc borate treated OSB. From the boron/zinc ratio after each leaching period, boron element in ZB was more or less leachable. The material constant of the regression models allowed comparing the leachability of the modified OSB for various wood species. An unified leaching method for treated wood composite materials is needed.

Keywords : zinc borate, oriented strandboard, leachability, boric acid equivalent, thickness swelling. polyethylene glycol

1. INTRODUCTION

Wood panel industry has little experience in producing wood preservative-treated oriented strandboard (OSB). There has been an increasing concern about possible environmental contamination from leaching losses of wood preservatives from treated-wood in service and from wood products removed from service (Lebow, 1996). Some work has been done to combine powdered borate with wood flakes during the manufacturing of OSB to provide termite and decay resistance of the finished products (Laks *et al.*, 1991; Laks *et al.*, 1995; Sean *et al.*,

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1999). Besides mechanical and physical properties, one of the major concerns for treated products is the leaching of the chemicals under the service conditions.

Leaching is the term used to describe the gradual loss of preservative chemicals from wood through solution and removal in water. Leaching tests of wood preservatives provide a relative measure of the leaching loss from treated-wood products in service. Conditions under which leaching can take place are as follows: 1) the preservatives must be soluble in water, and 2) liquid water must penetrate the wood; it is not sufficient to wet only the surface (Harrow, 1959).

Although boron-based preservatives show many advantages including low toxicity and efficacy against biological attack, boron does not adequately protect wood that has ground contact because of the chemical's susceptibility to leaching (Williams and Amburgey, 1987; Laks *et al.*, 1991). Various studies to fix water-soluble borates were required (Pizzi and Baecker, 1996; Cui and Kamdem, 1999; Gerzer *et al.*, 1999; Freitag *et al.*, 2000).

The zinc borate (ZB) [$2ZnO \cdot 3B_2O_3 \cdot 3.5H_2O$] is now being considered to use during oriented strandboard (OSB) manufacture because those chemicals can be evenly distributed on the surfaces of flakes and are water-insoluble at room temperature. However, when combined into a wood composite material, leaching under direct water exposure may still occur (Barnes *et al.*, 1989; Laks *et al.*, 1991; Sean *et al.*, 1999; Lee *et al.*, 2001; Lee, 2003; Lee *et al.*, 2004).

Sean *et al.* (1999), in evaluating the effect of borate treatment on the physical and mechanical properties of OSB, used polyethylene glycol (PEG) as a flow agent to improve resin flow and curing during hot-pressing. It was reported that the adverse effect of borate on adhesive flow could be minimized by the addition of organic flow agent containing hydroxyl (-OH) groups such as PEG. The influence of PEG on the leachability of PF added OSB is not unknown.

However, systematic information on the effect of wood species, borate type, particle size, and initial BAE level on the leachability of borate-treated OSB is still unknown. The determination of boron leaching coefficients, defined as the rate of leaching loss of treated chemicals can provide a better understanding of boron leaching kinetics. Very few trials have statistically quantified the leachability of ZB at the different boric acid equivalent (BAE) levels over a given leaching time. When the leaching data are fitted by a statistical function, an average leaching coefficient may be predicted by an empirical model.

The specific objective of this work was to investigate the leachability of the borate-modified OSB as influenced by wood species, PEG, and initial BAE level. Understanding these rates will be important in developing models to predict leaching rates of wood-based composites from various wood species and borate types.

2. MATERIALS and METHODS

2.1. OSB Manufacturing

Six-inch long flakes (0.635-mm thick) from eight southern hardwood species were kiln-dried to moisture content of approximately 4.0 percent before blending. These species included ash (*Fraxinus spp.*), cottonwood (*Populus spp.*), cypress (*Taxodium distichum L.*), elm (*Ulmus Americana L.*), locust (*R. pseudoacacia L.*), pecan (*Carya spp.*), red oak (*Quercus spp.*), and southern yellow pine (*Pinus taeda L.*). Borate-modified OSBs were produced with seven mixed hardwood (14.3 percent for each species) and southern pine.

Unbuffered liquid phenol formaldehyde (PF) with 55% non-volatile content was obtained from Neste Resins in Winnfied, LA. ZB ($2ZnO \cdot 3B_2O_3 \cdot 3.5H_2O$) had the density of 2.79 g/m^3 and the particle size of 6.61 μm. ZB presents low acute oral toxicity (LD_{50} (rat) > 10 g/kg of body weight) and dermal toxicity (LD_{50} (rabbit) > 1 g/kg of body weight). Zinc borate is considered as water insoluble at room temperature.

The PF resin (4% based on OD flake weight), wax (1% based on OD flake weight), and deforming agent (0.5 g) were weighed, and then applied with an air-nozzle. The loads of ZB are 0 (control), 1.5, 3.0, and 4.5% based on OD flake weight. Two replications were used for each borate-treated panel.

The PF resin-glued flakes were removed from the drum-type blender and spread evenly by hand over a stainless-steel caul. A removable forming box was used to form the composite mat according to the size specification. Formed mat was loaded to a 60.96-x 60.96-cm single opening hot press with the regulated platen temperature (200°C) for 8 min. Target thickness and panel density were 1.27 cm and 0.75 g/cm^3, respectively.

2.2. Leaching Procedure

2.2.1. Sample Preparation

Leaching experiments were conducted according to a modified AWPA leaching standard. OSB specimens (50.4-x 50.4-x 12.7-mm) were prepared according to borate type, wood species, target borate content level (%), target leaching time (h), and replication within each group. The four sides of each specimen were coated using several layers of a waterproof paint. The paint was allowed to dry at room temperature for several days. Six samples were stacked together with thin wood stickers between individual samples and each stack was secured using rubber bands. The prepared samples were vacuum-soaked for 30 minutes at 10 ~30 mmHg.

2.2.2. Leaching Test under Running Tap Water

After vacuum was released, the specimens were kept in running tap water (pH = 6.7) under water sink for 8, 24, 72, and 216 h. Two replications were performed for an average retention value of different ZB levels for each leach period. After leaching test, the specimens were removed from water sink and oven dried, then dried at room temperature and 75% relative humidity. Then, they were finally Wiley-milled to pass through a coarse screen (20 mesh per 25.4 mm). The same procedure for grinding was applied to the unleached control samples from each group.

2.2.3. Procedure of Analytical Method

For boric acid equivalent (BAE) determination, the wood meal of approximately 3 gram was filled into a bottom-flat flask with 100 mg 2 N HNO_3 solution. It was then digested on a heating mantle by using 2 N HNO_3 at 100°C for 2 h. Thereafter the flask was cooled for 30 minutes while maintaining the seal between a flask and a condenser. The quantitative BAE analysis for ZB-modified OSB after test was performed by ICP-OES (Inductively Coupled Plasma-Optical Emission Spectrometry). Two replications for each sample were conducted for the analysis.

2.2.4. Calculation of Zinc (%) and Boron (%)

From the analysis, the percent of boron and zinc was determined based on the oven-dry wood weight. B/Zn ratio was also calculated from the percent of each element. The percent of boron was finally converted to boric acid equivalent (BAE). The percent of boron, zinc, and BAE in ZB were also determined. The reason that boron analysis expressed in terms of BAE was used is because boric acid was the borate used for the wood preservation in the early days.

2.3. Data Analysis

Statistical comparisons based on analysis of variance (ANOVA) were done to test the effects of wood species, borate level, leaching time, addition of PEG, and their interaction on leachability of boron from the modified OSB (Wozniak and Geaghan, 1994). Exponential analysis was performed to establish the correlations between the assayed BAE and leaching time, and between boron/zinc and leaching time.

3. RESULTS and DISCUSSION

3.1. Leachability of ZB-Modified OSB

Experimental results on density, leachability of boron, and the ratio of B/Zn for ZB-modified OSB at three different ZB levels are summarized in Table 1. The relationships between fixed BAE and leaching time for ZB-modified OSB are fitted with the decaying exponential function in Table 2. The results of ANOVA for the effects of species, leaching time, polyethylene glycol (PEG), and their interactions on leachability of boron at different ZB levels are shown in Tables 3 and 4.

3.2. Assayed Boric Acid Equivalent (BAE)

The leaching results as shown in Table 1 were obtained by averaging from two replications at three target ZB levels for different leaching time. The majority of leaching from ZB-modified OSB panels occurred upon initial exposure to the running water. Assayed BAE (boric acid equivalents) as a function of leaching time is shown in Fig. 1 for the selected four species (i.e., southern pine, red oak, ash, and cottonwood). There was a larger initial leaching rate (up to 24 hour leaching time) and the rate decreased as the leaching time increased. In the southern pine, the assayed BAE level of 0.76 and 1.67% decreased 13.0 and 9.0% after 8-hour leach, respectively. After 24-hour leach, the decrease of BAE content was 4.0 and 5.0%, respectively. In red oak, the assayed BAE level of 0.45 and 1.08% decreased 18.0 and 7.0% after 8-hour leach. This is because unfixed or poorly fixed boron components move out of OSB panel, followed by a rapid decline to more stable leaching rate.

Wood species and initial BAE level significantly affected the leaching rate of boron. Samples with a higher initial BAE level had a larger leaching rate. Considering the severity of the test, OSB from several wood species (e.g., ash and pecan) held the borate fairly well. The order from high leachability to low leachability of eight southern wood species is red oak > southern pine > pecan > ash > elm > cottonwood > locust > cypress. This higher leachability has been attributed to the higher thickness swelling.

It is undoubtedly believed that during the initial exposure to water, a significant thickness swelling occurred within each sample as a result of water absorption. The swelling opened up the glue lines between the flakes and a portion of the chemicals simply got washed out under running water. After the 24-h water exposure, thickness swelling and the washing effect were stabilized, leading to a reduced leaching rate. Thus, the thickness swelling properties of the OSB affected the leaching rate significantly.

Table 1. Summary of the leachability and the ratio of boron/zinc according to leaching time from ZB treated OSB panels

Species	0 h[d]					8 h					24 h					72 h					216 h				
	SG[a]	BAE[b] (%)	B (%)	Zn (%)	B/Zn (%)	SG	BAE (%)	B (%)	Zn (%)	B/Zn (%)	SG	BAE (%)	B (%)	Zn (%)	B/Zn (%)	SG	BAE (%)	B (%)	Zn (%)	B/Zn (%)	SG	BAE (%)	B (%)	Zn (%)	B/Zn (%)
Southern	0.86	0.50	0.58	0.60	0.97	0.88	0.44	0.51	0.65	0.79	0.77	0.37	0.43	0.61	0.72	0.71	0.33	0.38	0.65	0.60	0.77	0.16	0.19	0.59	0.32
pine	0.85	0.76	0.89	0.94	0.95	0.79	0.67	0.78	0.95	0.82	0.86	0.64	0.75	0.96	0.78	0.80	0.56	0.65	0.99	0.66	0.80	0.34	0.39	0.93	0.43
	0.90	1.67	1.95	2.08	0.94	0.90	1.53	1.78	2.02	0.88	0.80	1.46	1.71	1.99	0.86	0.76	1.43	1.67	2.13	0.79	0.88	1.04	1.21	1.94	0.63
(PEG[c])	0.89	0.78	0.91	0.94	0.96	0.74	0.77	0.90	1.11	0.81	0.72	0.52	0.61	0.86	0.71	0.74	0.49	0.57	0.92	0.62	0.75	0.28	0.33	0.86	0.38
(PEG)	0.90	1.69	1.97	2.08	0.95	0.82	1.50	1.75	2.03	0.86	0.75	1.44	1.69	2.13	0.79	0.79	1.36	1.59	1.99	0.80	0.78	1.10	1.29	2.08	0.60
Ash	0.79	0.42	0.38	0.40	0.94	0.88	0.36	0.43	0.45	0.94	0.77	0.29	0.34	0.40	0.85	0.71	0.22	0.25	0.39	0.66	0.77	0.18	0.21	0.41	0.51
	0.85	0.50	0.50	0.53	0.93	0.80	0.39	0.45	0.54	0.84	0.86	0.36	0.42	0.56	0.76	0.80	0.31	0.37	0.53	0.69	0.80	0.21	0.25	0.56	0.45
	0.84	1.07	1.75	1.90	0.92	0.90	1.28	1.50	1.69	0.89	0.80	1.09	1.28	1.55	0.83	0.76	1.03	1.21	1.54	0.78	0.88	0.87	1.02	1.60	0.64
(PEG)	0.87	0.81	0.85	1.07	0.89	0.74	0.66	0.77	0.86	0.90	0.72	0.63	0.74	0.89	0.83	0.74	0.45	0.52	0.83	0.63	0.75	0.38	0.45	0.86	0.52
(PEG)	0.90	1.33	1.56	1.67	0.93	0.82	1.25	1.46	1.59	0.92	0.75	1.18	1.38	1.53	0.90	0.79	1.09	1.27	1.52	0.84	0.78	0.86	1.01	1.54	0.66
Locust	0.81	0.34	0.40	0.43	0.92	0.76	0.35	0.41	0.44	0.93	0.80	0.35	0.41	0.40	1.01	0.70	0.25	0.29	0.40	0.71	0.82	0.29	0.34	0.44	0.76
	0.82	0.60	0.70	0.76	0.92	0.75	0.64	0.75	0.81	0.92	0.83	0.63	0.74	0.75	0.99	0.83	0.54	0.63	0.73	0.87	0.80	0.47	0.56	0.81	0.69
	0.83	1.34	1.57	1.63	0.96	0.77	1.34	1.56	1.66	0.94	0.76	1.27	1.49	1.59	0.94	0.63	1.07	1.26	1.56	0.80	0.83	1.15	1.35	1.71	0.79
(PEG)	0.84	2.51	1.24	1.29	0.96	0.70	0.72	0.85	1.03	0.82	0.72	0.74	0.87	0.93	0.93	0.76	0.68	0.80	0.91	0.88	0.79	0.65	0.76	1.06	0.71
(PEG)	0.85	1.06	1.84	1.94	0.95	0.76	1.18	1.38	1.52	0.91	0.78	1.17	1.37	1.49	0.92	0.85	1.17	1.36	1.55	0.88	0.71	0.80	0.94	1.50	0.62
Elm	0.84	0.30	0.35	0.37	0.97	0.69	0.19	0.22	0.29	0.77	0.72	0.21	0.25	0.34	0.74	0.73	0.16	0.19	0.31	0.60	0.74	0.08	0.09	0.32	0.28
	0.83	0.41	0.48	0.50	0.97	0.75	0.46	0.54	0.59	0.92	0.74	0.50	0.58	0.66	0.88	0.85	0.43	0.50	0.60	0.84	0.80	0.34	0.40	0.67	0.59
	0.84	1.27	1.48	1.63	0.91	0.81	1.29	1.51	1.60	0.94	0.86	1.42	1.66	1.73	0.96	0.77	1.10	1.28	1.55	0.83	0.79	0.95	1.12	1.56	0.71
Pecan	0.86	0.44	0.51	0.52	0.98	0.75	0.42	0.49	0.53	0.93	0.77	0.31	0.46	0.49	0.94	0.71	0.31	0.36	0.43	0.82	0.82	0.26	0.31	0.47	0.66
	0.88	0.65	0.76	0.79	0.96	0.79	0.64	0.75	0.80	0.94	0.73	1.09	1.65	1.73	0.95	0.74	0.50	0.58	0.69	0.84	0.71	0.33	0.39	0.58	0.57
	0.86	1.38	1.61	1.93	0.83	0.82	1.38	1.62	1.67	0.97	0.78	1.09	1.65	1.73	0.95	0.70	1.09	1.28	1.53	0.84	0.74	0.95	1.11	1.59	0.70
Red oak	0.86	0.33	0.39	0.39	1.00	0.69	0.23	0.27	0.36	0.77	0.69	0.16	0.18	0.33	0.56	0.72	0.13	0.15	0.34	0.45	0.74	0.04	0.05	0.19	0.26
	0.84	0.45	0.53	0.56	0.95	0.77	0.38	0.44	0.53	0.84	0.69	0.23	0.27	0.49	0.56	0.85	0.26	0.31	0.52	0.60	0.78	0.11	0.13	0.49	0.26
	0.86	1.08	1.26	1.37	0.92	0.73	1.01	1.18	1.33	0.89	0.82	0.93	1.09	1.33	0.82	0.68	0.62	0.73	1.23	0.59	0.73	0.41	0.48	1.28	0.38
Cypress	0.87	0.16	0.19	0.19	1.00	0.79	0.28	0.33	0.35	0.94	0.81	0.27	0.32	0.35	0.91	0.78	0.52	0.61	0.70	0.87	0.78	0.20	0.23	0.38	0.61
	0.81	0.47	0.50	0.57	0.88	0.76	0.40	0.47	0.54	0.88	0.74	0.43	0.51	0.57	0.89	0.76	0.37	0.43	0.55	0.78	0.77	0.34	0.40	0.61	0.65
	0.86	1.91	2.24	2.38	0.94	0.75	1.97	2.30	2.49	0.92	0.83	2.08	2.44	2.51	0.97	0.82	1.72	2.01	2.39	0.84	0.75	1.73	2.03	2.50	0.81
Cottonwood	0.84	0.42	0.49	0.52	0.95	0.73	0.28	0.32	0.37	0.88	0.79	0.26	0.31	0.37	0.85	0.87	0.21	0.25	0.33	0.74	0.73	0.15	0.18	0.38	0.47
	0.83	0.56	0.49	0.52	0.95	0.73	0.28	0.32	0.37	0.88	0.79	0.26	0.31	0.37	0.85	0.75	0.50	0.59	0.70	0.84	0.79	0.42	0.49	0.73	0.68
	0.86	1.67	1.95	1.79	1.08	0.87	1.43	1.67	1.77	0.94	0.71	1.50	1.76	1.82	0.97	0.82	1.31	1.53	1.72	0.89	0.77	1.18	1.38	1.85	0.74

[a] SG represents the initial specific gravity of borate treated specimens prior to leaching. [b] BAE means the Boric acid equivalents (i.e. BAE = %ZB / 1.17). [c] Polyethylene glycol (PEG) was loaded at the 40% application level based on zinc borate weight. [d] indicates the leaching time under running water.

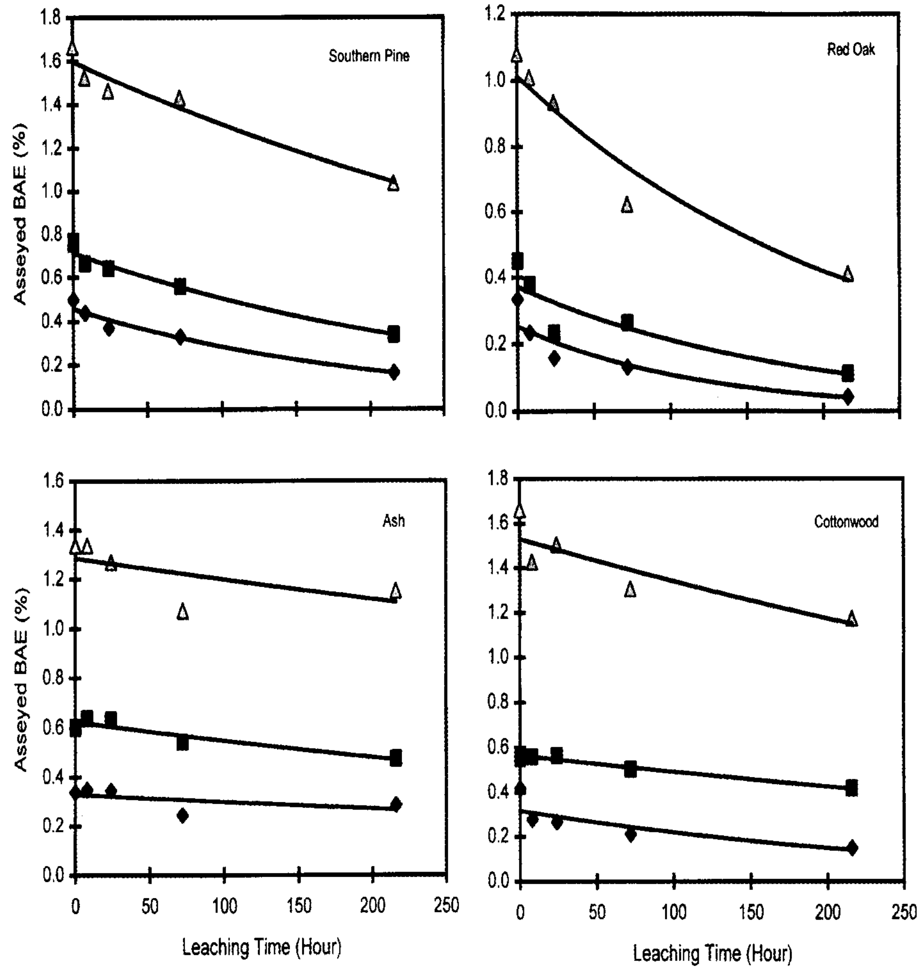

Fig. 1. The relationship between assayed BAE and leaching time for zinc borate-modified OSB from southern pine, red oak, ash, and cottonwood. Lines showing the regression fit.

3.3. Boron/Zinc Ratio

The corresponding boron/zinc ratios of the modified OSB are shown for the selected species in Table 1 and Fig. 2. The initial boron and zinc ratios from the unleached control groups were close to unity for all species. As the leaching time increased, however, the ratio decreased significantly, indicating that boron element leached out at a higher rate compared to zinc. This result shows a possible ZB decomposition during manufacturing under heat and pressure and/or under water exposure, leading to the subsequent formation of zinc hydroxide, $Zn(OH)_2$, and boric acid, H_3BO_3. Zinc hydroxide is less water- soluble than boric acid. As a result, boron element leached out faster than zinc, resulting in decreased B/Zn ratios. The boron/zinc ratios from OSB with a larger thickness swelling (e.g., southern pine and red oak) were generally lower than these species with a small thickness swelling (e.g., locust and cypress). Thus, the reduction of the B/Zn ratio depends on the extent of the water exposure.

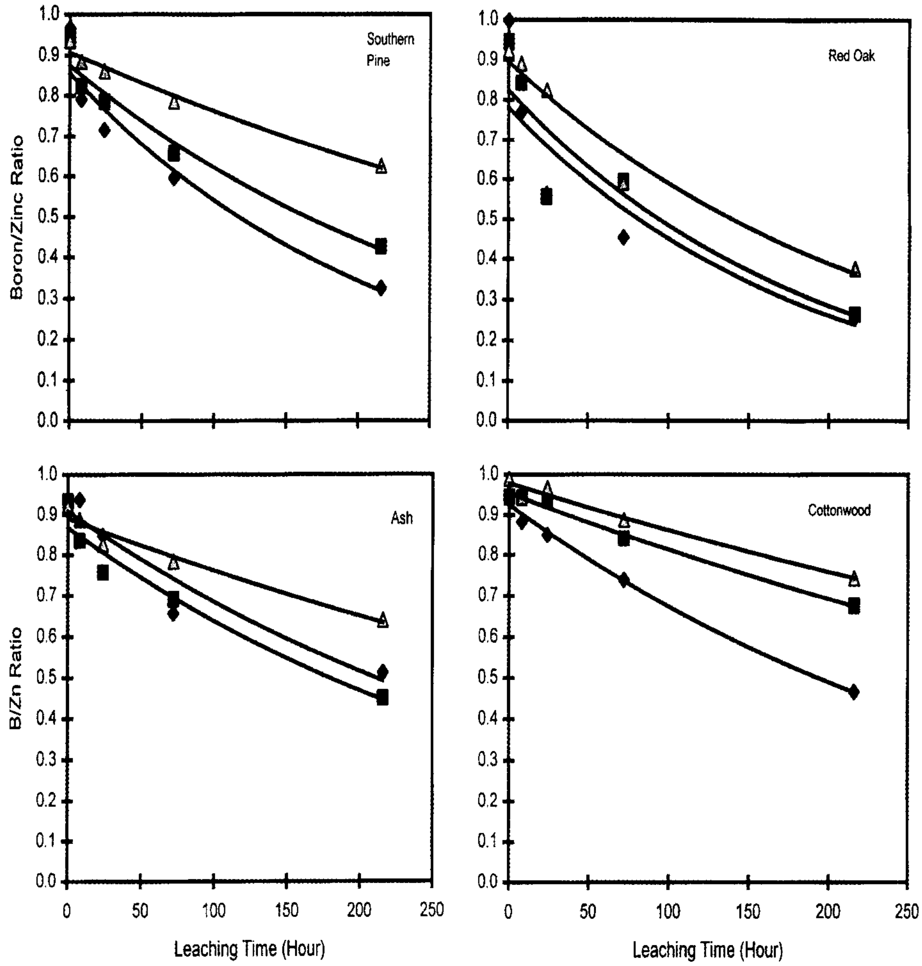

Fig. 2. The relationship between assayed boron/zinc ratio and leaching time for ZB-modified OSB from southern pine, red oak, ash, and cottonwood. Lines showing the regression fit.

3.4. Regression Fit

The leaching kinetics between leachability and leaching time at the initial BAE levels was shown in Table 2. The data of assayed BAE and boron/zinc ratio as a function of time were well fitted with a decaying exponential function:

$$Y = a e^{-bX} \qquad (1)$$

Where, Y = boric acid equivalent (BAE) or boron/zinc ratio, a = regression constant representing the initial BAE level, b = regression constant representing boron leaching rate, and x = leaching time.

A comparison of the normalized BAE (Y/a) predicted by the exponential equation for various species is shown in Fig. 3 at the 3% target BAE level (actual BAE level varying from 1.07 and 2.51% for various species). It is clearly shown the leachability differences among various species. At a given leaching time, red oak showed the smallest BAE value, whereas locust and cypress had the highest BAE values.

Table 2. The relationship between initial BAE and 216-h leaching time of ZB modified OSB

Species	Target ZB (%)	Initial BAE (%)	a	b	R^2
Ash	0.5	0.42	0.319	0.003	0.822
	1.0	0.50	0.399	0.003	0.979
	3.0	1.07	1.290	0.002	0.745
(PEG[a])	1.0	0.81	0.687	0.003	0.797
(PEG)	3.0	1.33	1.271	0.002	0.964
Locust	0.5	0.34	0.331	0.001	0.311
	1.0	0.60	0.625	0.001	0.893
	3.0	1.34	1.285	0.001	0.405
(PEG)	1.0	1.06	0.826	0.001	0.382
(PEG)	3.0	1.57	1.343	0.002	0.805
S. Pine	0.5	0.50	0.458	0.005	0.977
	1.0	0.76	0.715	0.004	0.985
	3.0	1.67	0.598	0.002	0.858
(PEG)	1.0	0.99	0.910	0.004	0.905
(PEG)	3.0	1.69	0.926	0.002	0.909
Cypress	0.5	0.16	0.327	0.002	0.155
	1.0	0.47	0.412	0.001	0.795
	3.0	1.91	1.974	0.001	0.550
Cottonwood	0.5	0.42	0.318	0.004	0.792
	1.0	0.56	0.565	0.001	0.974
	3.0	1.67	0.529	0.001	0.789
Elm	0.5	0.30	0.244	0.005	0.913
	1.0	0.41	0.462	0.001	0.700
	3.0	1.27	1.319	0.002	0.802
Pecan	0.5	0.44	0.414	0.002	0.879
	1.0	0.65	0.637	0.003	0.987
	3.0	1.38	1.381	0.002	0.878
Red oak	0.5	0.33	0.253	0.009	0.938
	1.0	0.45	0.372	0.006	0.869
	3.0	1.08	1.015	0.004	0.944

The BAE and leaching time were fitted accurately with the exponential function, $BAE = a \times EXP^{[-b*(Leaching\ time)]}$. Coefficients a and b represent initial BAE level and leaching rate, respectively. [a] indicates polyethylene glycol (PEG) which was loaded at the 40% application level based on zinc borate weight.

A comparison of the leaching coefficient, b, is shown in Fig. 3. Red oak and southern pine OSB showed a significant larger leaching coefficient compared to OSB from locust and cypress. The high coefficient values indicate high leaching rate of boron under the same leaching condition. Higher leaching coefficients were observed at the low ZB level. It is not

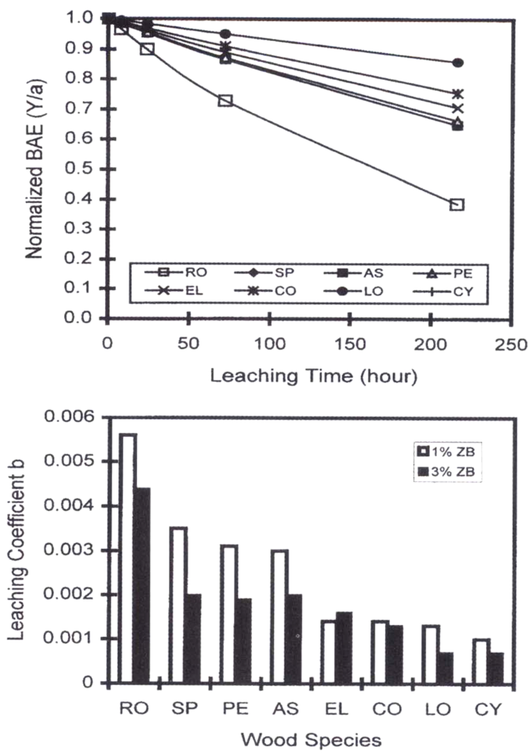

Fig. 3. A comparison of leachability of zinc borate-modified OSB from the eight single wood species. Top: normalized BAE as a function of time (3% target BAE level). Bottom: leaching coefficients from various species at the two target BAE levels. RO-Red oak, SP-southern pine, PE-pecan, AS-Ash, EL-Elm, CO-cottonwood, LO-locust, CY-Cypress.

possible to compare the coefficient values at the different ZB level, because coefficient, a, representing initial ZB level was different. However, leaching coefficient from each species was consistently higher in red oak and southern pine. At three target ZB levels (0.5, 1.0, and 3.0%), red oak showed a significantly higher leaching rate than other wood species, whereas cypress and locust gave excellent fixation rate. This variability of species effect is presumably related to the surface smoothness, porosity, the chemical composition of wood substitutes, and wetability of wood flakes.

3.5. Effect of PEG

The addition of PEG (40% based on target ZB level) helped increase the boron retention for southern pine, ash, and locust. Similar results have been reported for boric acid, sodium borate (Gerzer *et al.*, 1999), and zinc borate (Sean *et al.*, 1999). There was a significant effect of PEG on the leachability of boron at the 1.0% target ZB level. At the 3.0% target ZB level, however, little effect of PEG on the leachability was observed (Table 3). The effect of PEG on boron leachability may reflect the covalent bonding between the OH functional group of PEG and boron during hot-pressing, which substitutes the linkage between boron and the oxygen ion of CH_2OH in PF resin. This allows formation of more durable bonds between wood and the resin. Therefore, adding PEG would help decrease the leachability of boron. However, its effect decreased at the high ZB loading levels.

3.6. Data Analysis

According to the two-way ANOVA (Table 4), the main effects of wood species and leaching time in the three different levels of ZB were highly significant on the leachability of the ZB-modified OSB from eight wood species at the 5% significant level, the interaction effects between wood species and leaching time were not significant. From the three-way ANOVA, the main effect of wood species and leaching time in two different level of ZB were significant on leachability of ZB-modified OSB from PEG-added species at the 5% significant level. The effects of PEG and other interaction at the ZB level of 1.0% were significant. however, those effects at the ZB level of 3.0% are not significant.

Table 3. Three-way ANOVA for leachability of ZB and PEG modified OSB[a]

	Source	DF	Sum of squares	Mean square	F value	Pr > F
1.0% ZB	Model	29	1.563	0.054	10.49	0.0001
	Species	2	0.119	0.060	11.55	0.0002
	Time	4	0.743	0.186	36.16	0.0001
	Species × Time	8	0.113	0.014	2.74	0.0213
	PEG	1	0.213	0.213	41.54	0.0001
	Species × PEG	2	0.159	0.079	15.47	0.0001
	Time × PEG	4	0.147	0.037	7.14	0.0004
	Species × Time × PEG	8	0.069	0.009	1.69	0.1430
	Error	30	0.154	0.005		
3.0% ZB	Model	29	2.884	0.099	6.08	0.0001
	Species	2	0.621	0.310	18.98	0.0001
	Time	4	1.746	0.436	26.69	0.0001
	Species × Time	8	0.054	0.007	0.41	0.9052
	PEG	1	0.025	0.025	1.52	0.2272
	Species × PEG	2	0.008	0.004	0.25	0.7815
	Time × PEG	4	0.253	0.063	3.87	0.0118
	Species × Time × PEG	8	0.177	0.022	1.35	0.2571
	Error	30	0.491	0.016		

[a] Leachability of 3 wood species (ash, locust, and southern pine) was performed under running water (31°C) for 0 (control), 8, 24, 72, and 216 h. PEG (polyethylene glycol) was loaded at the 40% application level based on zinc borate weight. *P* value indicates the statistical probability of observing a difference greater or equal to that observed between the total amount leached from the normal wood samples and that leached from the different wood species and leaching time with/without PEG.

Table 4. Two-way ANOVA for leachability of ZB modified OSB[a]

	Source	DF	Sum of squares	Mean square	F value	Pr > F
0.5% ZB	Model	39	0.910	0.023	1.82	0.0031
	Species	7	0.347	0.050	11.55	0.0002
	Time	4	0.305	0.076	5.95	0.0007
	Species × Time	28	0.258	0.009	0.72	0.8175
	Error	40	0.154			
1.0% ZB	Model	39	1.469	0.038	5.46	0.0001
	Species	7	0.841	0.120	17.42	0.0001
	Time	4	0.454	0.114	16.47	0.0001
	Species × Time	28	0.174	0.006	0.90	0.6065
	Error	40	0.154			
3.0% ZB	Model	39	5.659	0.145	7.55	0.0001
	Species	7	3.431	0.490	25.11	0.0001
	Time	4	1.694	0.424	22.04	0.0001
	Species × Time	28	0.534	0.019	0.99	0.4999
	Error	40	0.154			

[a] Leachability of eight wood species was performed under running water (31°C) for 0 (control), 8, 24, 72, and 216 h (southern pine, locust, ash, pecan, red oak, pecan, cottonwood, and cypress). *P* value indicates the statistical probability of observing a difference greater or equal to that observed between the total amount leached from the different wood species and leaching time.

4. CONCLUSIONS

Leaching tests under running water were conducted to study the leachability of borate-modified OSB in this study. Boron leaching from both ZB-modified OSB occurred upon the initial water exposure, and the rate decreased as the leaching time increased. Initial BAE level, and wood species significantly influenced the boron leachability. There was no consistent effect of PEG on leaching of ZB-treated OSB. The glue-line opening due to thickness swelling of the test samples under water and decomposition of the borate to form more water-soluble boric acid are two possible causes for the observed leaching. The relationship between assayed BAE and leaching time followed a decaying exponential function for ZB. The material constants of the regression models allow comparing leachability of the modified OSB for various wood species. An unified leaching method for treated composite materials is needed.

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