FORMOSAN SUBTERRANEAN TERMITE RESISTANCE OF BORATE-MODIFIED STRANDBOARD MANUFACTURED FROM SOUTHERN WOOD SPECIES: A LABORATORY TRIAL[1]

Sunyoung Lee†
Graduate Research Assistant

Qinglin Wu†
Associate Professor

and

W. Ramsay Smith†
Professor
School of Renewable Natural Resources
Louisiana State University Agricultural Center
Baton Rouge, LA 70803

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ABSTRACT

The behavior of Formosan subterranean termites (FST) toward zinc borate (ZB) and calcium borate (CB)-treated oriented strandboard (OSB) from southern mixed hardwoods and southern yellow pine was examined in laboratory tests. Loading of ZB and CB in OSB provided protection from severe structural damage, but did not completely eliminate termite activity. The level of borate used showed significant effects on weight loss, percent termite mortality, and termite damage rating. Borate types had a significant effect on the sample weight loss and damage rating, but not on termite mortality. Wood species showed no significant effect on the termite resistance. Correlations between weight loss and damage rating and between weight loss and termite mortality for both wood species were fitted well by a decaying exponential function. A three-way regression analysis showed a significant curvilinear relationship among damage rating, weight loss, and termite mortality. Zinc and calcium borate treatment to retention levels greater than 1.0% BAE provided sufficient protection from FST attack. Additional field tests may be needed to determine whether ZB and CB treatments will protect OSB from large-scale attack by FST and if modified OSB panels will be acceptable commercially.

Keywords: Formosan subterranean termites, oriented strandboard, zinc borate, calcium borate, mortality, weight loss, damage rating.

INTRODUCTION

Formosan subterranean termites (FST) are one of the most destructive termite species in the world. These termites are a major cause of wood deterioration in the southern United States and Hawaii. They attack above-ground wood structures and can remain above ground, if the structures provide moisture through condensation from roofs, siding, floors, plumbing leaks, or drainage overflow (Radcliffe 1999; Su and Scheffrahn 1990).

Soil chemical barriers and termite baits have provided promising techniques to prevent attack by the FST. These methods, however, do not completely protect the structure. One simple solution to the FST destruction is by using wood species that are resistant to termite attack. Redwood (*Sequoia sempervirens*) and western red cedar (*Thuja plicata*) have been shown to be more resistant to the FST attack than Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), Englemann spruce (*Picea spp.*), and western hem-

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† Member of SWST.

lock (*Tsuga Canadensis*) (Su and Tamashiro 1986). Grace and Yamamoto (1994a, b) stated that the FST damaged pine and Douglas-fir equally, but damages were significantly less on Alaska yellow cedar (*Chamaecyparis nootkatensis*) and redwood. The content of extractives in heartwood shows a significant relationship to the toxicity of those species against termites (Behr 1972). Therefore, unless old growth heartwood is available, this may not be a viable solution.

As an ultimate solution against FST deterioration, the potential for employing termite-resistant chemicals in wood-based products in residential construction is warranted. Consequently, a need exists for developing effective preservatives that are environmentally benign for residential construction use. Boron compounds have been proven to be a very effective chemical against insects and decay fungi (Barnes et al. 1989; Laks et al. 1988). Powder from zinc borate (ZB) and calcium borate (CB) are described as being almost insoluble in water, therefore, it would be relatively simple to introduce the borates during the blending process for the manufacturing of wood-based composites such as oriented strandboard (OSB). This approach can provide the impetus for borate chemicals to play an expanding role within the wood composites industry, with minimal impacts on the environment.

Studies regarding the success of inorganic borates in preventing FST attack are not in total agreement. The effect of boron on termite resistance has been shown to vary with chemical types. For example, wood treatment with disodium octaborate tetrahydrate (DOT) has been shown to provide good protection against the FST with only trivial cosmetic damage. In a laboratory study on the FST, Williams et al. (1990) found that a boric acid equivalent (BAE) level of 0.54% led to high termite mortality with only about 1.0% weight loss in banak (*Virola spp.*). Douglas-fir heartwood, treated to retentions over 0.35% BAE for DOT, not only drastically reduced termite feeding, but also resulted in 100% termite mortality within three weeks (Grace et al. 1992). In a field study, a 0.54% BAE level for DOT protected southern pine wood from significant damage by the FST for two years (Preston et al. 1986). OSB panels treated with 1.0% ZB had good termite resistance, having the highest rating of 10 (i.e., sound, surface nibbles permitted) against FST in laboratory tests, compared to the control OSB panels with a rating of below 5 (Sean et al. 1999). ZB-treated aspen waferboard, at loadings above 1.0% BAE, exhibited better termite resistance than sodium borate-treated boards at an equivalent loading level (Laks et al. 1991). Laks and Manning (1997) reported that the damage rating by termite attack on aspen waferboard treated with 3.0% ZB and 3.0% DOT was 10 after one year of exposure in a field site in Florida.

On the other hand, Preston et al. (1996) reported that the DOT treatment on Douglas-fir interior structural lumber was subject to attack at all retention levels. A nonlinear regression analysis of the data predicted the protection threshold in excess of 24 kg/m^3. In another study (Archer et al. 1991), Douglas-fir samples, treated with DOT solutions and kept for an 8-week diffusion period, were found to be subject to severe degradation from termite attack. Wafers from Douglas-fir treated with 0.64% DOT revealed evidence of termite feeding, having ratings of 7 to 9 (Grace and Yamamoto 1994a). Slash pine treated with 0.54% BAE of DOT did not show adequate protection from the FST and higher retention levels were thus suggested to protect the wood in buildings (Mauldin and Kard 1996). Jones (2002) studied the feasibility of adding calcium borate powder in southern pine flakeboard to increase its resistance to FST and decay fungi. The results indicate that the addition of CB negatively affected the panel strength and swelling properties. The presence of CB only slightly deterred termite and fungi damage. The CB used in this study had particle size varying from 45 to 300 μm. The large particle size and large particle size variability significantly affected the results of the panel properties.

Currently, limited data available showing the effects of ZB and CB treatment levels against FST for OSB are inconclusive. The work reported here is part of a large research project on durability analysis of borate-treated OSB from southern wood species. The objectives of this study were to determine the effects of borate types, borate levels, and wood species on termite resistance; and to establish the correlations among weight loss of test samples, termite mortality, and sample damage ratings.

MATERIALS AND METHODS

Panel manufacturing

Green boards from each of the following eight species were obtained from a local saw mill in Louisiana. These species included ash (*Fraxinus spp.*), cottonwood (*Populus spp.*), cypress (*Taxodium distichum L.*), elm (*Ulmus americana L.*), locust (*Robinia pseudoacacia L.*), pecan (*Carya spp.*), red oak (*Quercus spp.*), and southern yellow pine (*Pinus taeda L.*). All boards were cross-cut and flaked to produce 76.2-mm-long flakes (0.635-mm-thick) using a laboratory disc flaker. The flakes were dried to 2–3% moisture content (MC) at 90°C temperature, and were used to manufacture mixed hardwoods and southern pine OSB with zinc and calcium borate.

The panels were fabricated with dry flakes and phenol formaldehyde (PF) resin having a 55% nonvolatile content at a loading level of 4.0% (based on the oven-dry wood weight). Wax was used at the 1.0% level (based on oven-dry wood weight). The zinc borate ($2ZnO \cdot 3B_2O_3 \cdot 3.5H_2O$) used had a density of 2.79 g/m^3 with a mean particle size of 6.61 μm in diameter. ZB presents low acute oral toxicity (LD_{50} (rat) $>$ 10 g/kg of body weight) and dermal toxicity (LD_{50} (rabbit) $>$ 10 g/kg of body weight). The calcium borate ($Ca_2B_6O_{11} \cdot 5H_2O$) had a density of 2.42 g/cm^3 with a mean particle size of 6.43 μm. CB has little or no hazard and low acute oral toxicity (LD_{50} (rat) $>$ 1g/kg) and exhibits dermal toxicity (LD_{50} (rabbit) $>$ 1 g/kg of body weight). Powder ZB and CB were sprayed into the blender during the blending process. The target loading levels for ZB and CB were 0 (control), 0.5, 1.0, 3.0, and 4.5% based on the oven-dry flake weight in the panel.

After blending, wood flakes were removed from the blender, and random mats were formed by hand. Two replicate panels at each borate level were constructed. The pressing time was 6 min at 1.71 MPa pressure and 200°C temperature. The target thickness and panel specific gravity (SG) were 1.27 cm and 0.75, respectively. The resulting boards (55.9 × 50.9 × 1.27 cm) were cooled and conditioned at 22°C and 55% RH prior to testing.

Boron analysis

OSB samples (5.08 × 5.08 × 1.27 cm) were cut from each panel for boron chemical analysis. The samples were Wiley-milled to pass through a 20-mesh screen. Five grams of wood meal were selected and placed in a flat-bottom flask with a solution of 100 mg 2N HNO_3. The flask was connected to a water-cooled condenser. The flask was heated on a heating mantle for 2 h at 100°C for digesting. The flask was then cooled for 30 min while maintaining seals between the flask and the condenser. The digested samples were finally filtered using Whatman #2 filter paper over a filter funnel, and the analyte was analyzed by an Inductively Coupled plasma-Optical Emission Spectrometry (ICP-OES) to determine actual chemical composition in the sample.

The percentages of boron, zinc, and calcium were determined on the basis of the molecular weight of ZB and CB. The boron/zinc (B/Zn) and boron/calcium (B/Ca) ratios were calculated from the percentage of each element. The percentage of boron was finally converted to actual BAE. The term ‘‘assayed BAE’’ refers to the amount of boric acid equivalent in the sample on the assumption that all of the assayed boron comes from boric acid. The percentage of B, Zn, and Ca in ZB and CB was determined with the following formulas, respectively:

TABLE 1. *Summary of results for a four-week laboratory efficacy test on Formosan subterranean termite resistance to zinc borate and calcium borate modified southern yellow pine and mixed hardwoods OSB.*[a]

Borate type	Wood species	Actual BAE (%) [gh]	B:Zn ratio B:Ca ratio [ij]	SG[b]	MC (%)	Rating[c]	WL[d] (%)	TM[e] (%)
ZB	MHW	0/0	N/A	0.74 (0.05)	7.0 (0.23)	2.96 (2.03)[c]	16.48 (1.97)[a]	17.50 (3.32)[b]
		0.97/0.97	1.01/0.97	0.69 (0.03)	6.8 (0.17)	8.54 (0.79([b]	4.58 (0.50)[b]	34.95 (5.38)[a]
		1.72/1.86	0.95/0.94	0.59 (0.03)	6.8 (0.12)	8.52 (0.96)[b]	4.17 (0.52)[b]	40.05 (5.66)[a]
		3.00/2.96	0.96/0.95	0.71 (0.09)	6.6 (0.13)	9.54 (0.52)[a]	3.07 (0.23)[b]	37.95 (2.90)[a]
ZB	SP	0/0	N/A	0.74 (0.07)	7.0 (0.20)	2.36 (1.76)[c]	21.02 (3.59)[a]	19.50 (2.22)[b]
		1.04/1.02	0.94/0.95	0.72 (0.05)	7.3 (0.11)	9.80 (0.31)[a]	2.70 (0.29)[b]	32.45 (5.89)[a]
		1.78/1.76	1.06/1.04	0.70 (0.04)	7.6 (0.15)	8.86 (1.00)[b]	3.84 (0.96)[b]	32.25 (6.26)[a]
		3.02/2.81	0.97/0.95	0.67 (0.06)	7.4 (0.11)	9.18 (0.68)[ab]	3.51 (0.58)[b]	37.00 (7.30)[a]
CB	MHW	0/0	N/A	0.75 (0.05)	6.3 (0.12)	2.98 (1.64)[c]	21.32 (2.32)[a]	27.70 (13.8)[b]
		0.95/0.90	0.97/0.97	0.79 (0.06)	7.0 (0.25)	7.01 (1.10)[b]	7.58 (1.54)[b]	33.70 (8.21)[ab]
		1.87/1.82	0.97/0.96	0.80 (0.05)	6.7 (0.31)	8.00 (0.81)[a]	5.24 (0.66)[bc]	42.60 (9.03)[ab]
		3.02/3.06	0.98/0.97	0.81 (0.05)	6.6 (0.15)	8.68 (0.84)[a]	4.20 (0.44)[c]	46.45 (6.72)[a]
CB	SP	0/0	N/A	0.78 (0.05)	7.1 (0.28)	3.76 (1.74)[c]	18.99 (1.00)[a]	19.00 (2.37)[c]
		0.99/0.94	0.98/0.97	0.73 (0.09)	7.0 (0.26)	6.76 (1.09)[b]	5.88 (1.41)[b]	31.95 (2.94)[b]
		1.86/1.84	0.97/0.96	0.76 (0.07)	7.1 (0.23)	8.46 (0.88)[a]	4.54 (0.72)[b]	37.60 (3.66)[b]
		3.07/3.00	0.98/0.96	0.70 (0.04)	6.9 (0.10)	8.12 (1.14)[a]	3.57 (0.15)[b]	50.95 (1.30)[a]
N/A[f]	SPW	N/A	N/A	N/A	7.1 (0.42)	1.00 (0.57)	31.15 (2.45)	11.70 (4.89)

[a] Each Mean (± SD) represents five replicates of zinc borate- and calcium borate-modified OSB. Means within each column followed by the same letter are not significantly different (ANOVA, Tukey's Studentized-Range Test, $P = 0.05$). MHW: mixed hardwood, SP: southern pine, and SPW: untreated southern pine solid wood. ZB: zinc borate and CB: calcium borate.
[b] SG—Specific gravity based oven-dry weight and volume at about 7% moisture content.
[c] Rating—Based on 0–10 scale with 0 denoting the most damage.
[d] WL—Wood weight loss expressed as percentage of the original oven-dry weight.
[e] TM—Termite mortality expressed as percentage of the initial number of termites.
[f] N/A = not applicable.
[g] Actual BAE before the termite test, and [h]—Actual BAE after the termite test.
[i] Actual boron to Zn (or Ca) ratio before the termite test, and [j]—Actual boron to Zn (or Ca) ratio after the termite test.

$$\%\ \text{Boron, Zinc, and Calcium} = [V_a\, C\, 100]/W_w \qquad (1)$$

$$\%\ B_{ZB} = \%\ \text{Boron}/0.1492 \qquad (2)$$

$$\%\ Zn_{ZB} = \%\ \text{Zinc}/0.30 \qquad (3)$$

$$\%\ B_{CB} = \%\ \text{Boron}/0.168 \qquad (4)$$

$$\%\ Ca_{CB} = \%\ \text{Calcium}/0.30 \qquad (5)$$

$$\%\ \text{BAE (Boric Acid Equivalents)} = [\%\ B_{ZB} \text{ or } B_{Ca}]/1.17 \qquad (6)$$

where, V_a = The volume of analyte (ml); C = The concentration of boron, zinc, and calcium ($\mu g \times 10^{-6}$); W_w = The weight of OD wood meal (g); 0.1492 = The ratio of molecular weight of boron to ZB; 0.168 = The ratio of molecular weight of B to CB; 0.30 = The ratio of molecular weight of zinc to ZB; 0.20 = The ratio of molecular weight of Ca to CB; and 1.17 = The ratio of the molecular weight of $3(B_2O_3)$ to $3(BO_3)$.

Formosan subterranean termite resistance test

Termite tests were conducted in accordance with AWPA E1-97 (AWPA 1999). The FSTs were collected in termite bait crates at a Louisiana state park. The crates, built with small wood square beams, were buried under ground for several months to attract the termites. The crates were then removed and transported to Baton Rouge, Louisiana, in large plastic bins. They were stored in a termite lab until needed. During the test, the FSTs were collected from the wood beams used to attract termites to the crates. Paper towels, dampened with distilled water, were used to transfer termites to a 10-liter pail. Tests were performed with a mixture of worker and soldier termites in an air-conditioned room at 26 ± 0.5°C and 90% RH.

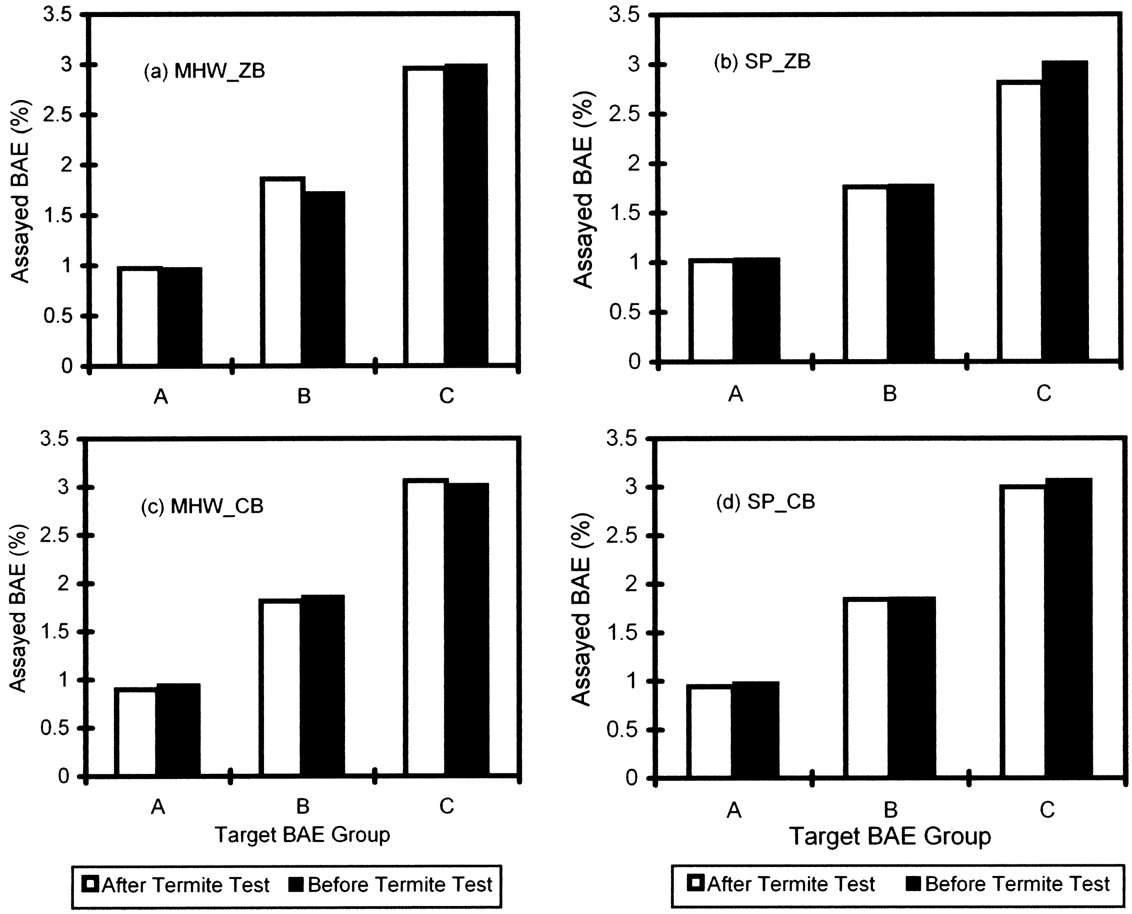

FIG. 1. A comparison of assayed BAE of ZB-MHW (a), ZB-SP (b), CB-MHW (c), and CB-SP (d) OSB before and after a 28-day laboratory termite test for boards at three target BAE levels (A: 1.5%, B: 3.0%, and C: 4.5%).

OSB specimens (1.78 × 1.78 × 1.27 cm) for the termite test were cut from mixed hardwoods and southern pine OSB. Two sets of matched specimens were prepared according to borate types (ZB and CB), target borate levels (0, 1.5, 3.0, and 4.5%), and wood species (southern pine and mixed hardwoods), with five replications in each group (i.e., 2 × 3 × 2 × 5 complete random factorial experiment). One set was used for the termite tests, and the other set for MC determination. Each block was identified with a label on the sample surface. Five samples of untreated southern pine solid wood were used as controls in this study. Prior to the termite test, all blocks were oven-dried at 105°C for 24 h. Sample weight (W_1) and dimensions were measured prior to testing.

Each test bottle (80 mm in diameter × 100 mm in height) was autoclaved for 30 min at 105 KPa and dried. Autoclaved sand (150 grams) and distilled water (30 ml) were added to each bottle. A single-choice procedure was used with one test block placed on a foil base slightly larger than test specimens on the surface of the sand in each bottle, prior to the placement of termites. Average weights of individual termites were determined after weighing five groups of over 100 termites each and calculating an average weight per termite.

Four hundred termites (approximately 380

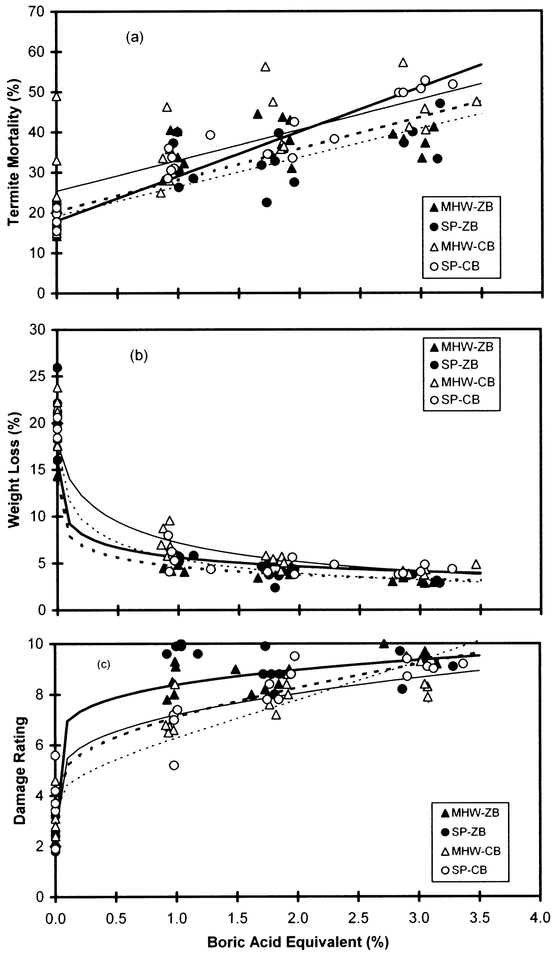

FIG. 2. Termite mortality (a), sample weight loss (b), and sample damage rating (c) as a function of BAE for ZB- and CB-modified southern pine and mixed hardwoods OSB after a 28-day termite laboratory test. Lines indicate the best regression fit.

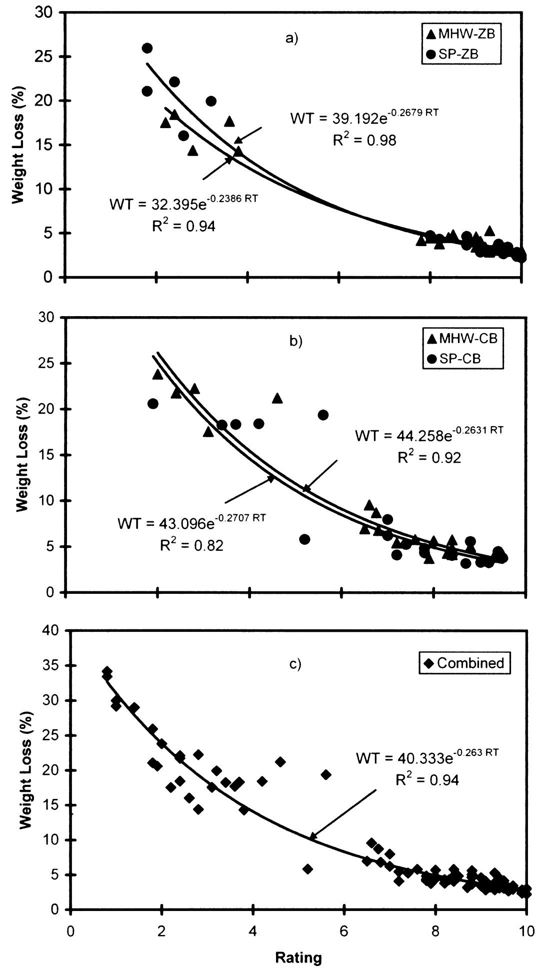

FIG. 3. Correlation between sample weight loss and damage rating for ZB (a), CB (b), and combined data (c) from southern pine and mixed hardwoods OSB after a 28-day laboratory termite test.

workers and 20 soldiers) were added to the opposite side of the test block in the container. All containers were maintained at 26°C and 90% RH for four weeks. The bottle caps were placed loosely. After the 28-day termite test, the bottles were dismantled. Live termites were counted and test blocks were removed and cleaned, using a small brush and rinsing with distilled water. Each block was oven-dried at 105°C for 24 h, and its oven-dry weight measured (W_2). The weight loss in each sample was calculated as follows:

$$\text{Weight loss (\%)} = [(W_1 - W_2)/W_1] \times 100 \quad [7]$$

where, W_1 = sample weight prior to the termite test (gram); and W_2 = sample weight after the termite test (gram).

Termite mortality was determined as a ratio of the number of living termites to the initial termite number (400) and subtracting from 1.00. Test blocks were visually rated by five different people according to AWPA E1-97 (AWPA 1999). Actual BAE, B/Zn, and B/Ca ratios for the OSB samples before and after

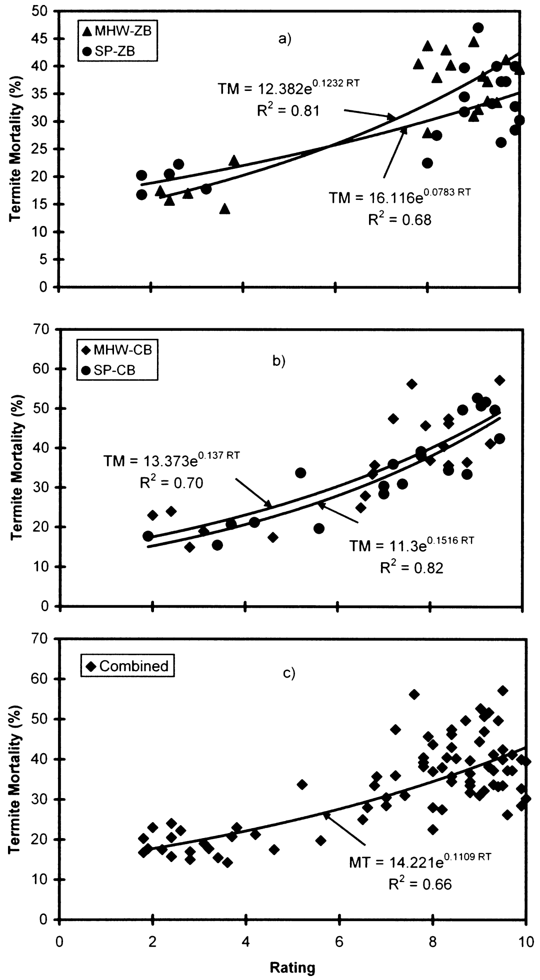

FIG. 4. Correlation between termite mortality and damage rating for ZB (a), CB (b), and combined data (c) from southern pine and mixed hardwoods OSB after a 28-day laboratory termite test.

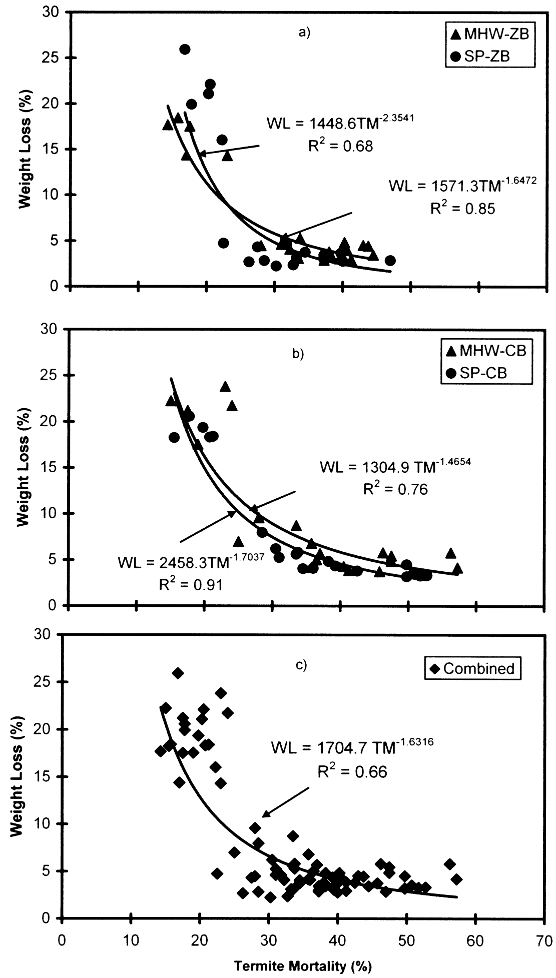

FIG. 5. Correlation between sample weight loss and termite mortality for ZB (a), CB (b), and combined data (c) from southern pine and mixed hardwoods OSB after a 28-day laboratory termite test.

termite testing were determined. Southern pine solid wood samples without borate treatment were used as control for comparison with the treated OSB samples.

Data analysis

A regression analysis was performed to establish the correlations among weight loss of test samples, termite mortality, visual damage ratings, and BAE levels. Statistical comparisons, based on three-way ANOVA, were performed to test the effects of wood species, borate types, borate levels, and their interactions on sample weight loss, termite mortality, and damage ratings. Tukey's studentized-range test at the 5% significance level was used to compare the difference among the treatment means (Wozniak and Geaghan 1994).

RESULTS AND DISCUSSION

Test data on termite mortality, sample weight loss, and damage ratings of the ZB-

TABLE 2. *Regression analysis for the relationship between BAE and weight loss, termite mortality, and damage rating of ZB- and CB-modified OSB.*

		TM[a]			WL[b]				RT[b]			
	Species	A	B	R^2	A	B	C	R^2	A	B	C	R^2
ZB	MHW	20.3	7.8	0.55	0.07	0.14	0.43	0.63	0.41	−0.29	0.04	0.92
	SP	19.2	7.2	0.58	0.06	0.13	0.66	0.64	0.30	−0.14	0.29	0.84
CB	MHW	25.4	7.6	0.38	0.06	0.08	0.73	0.61	0.40	−0.26	0.08	0.88
	SP	18.0	11.0	0.92	0.06	0.11	0.40	0.62	0.32	−0.18	0.15	0.83

[a] TM—Termite mortality as percentage of the initial termite number. The relationship between TM and BAE was fitted by a linear regression function, TM (%) = A + B·BAE (%) with A and B as regression coefficients.

[b] WL—Wood weight loss expressed as percentage of the original weight. RT—Damage ratings based on 0–10 scale with 1 denoting the most damage. The relationships between WL or RT and BAE were fitted by the Harris power regression function, WL or RT = $1/(A+B\cdot BAE^{C})$ with A, B, and C as the regression coefficients.

and CB-treated OSB from mixed hardwoods and southern pine are summarized in Table 1. Data on actual BAE in OSB samples before and after termite tests are also presented in Table 1. The overall average specific gravity for OSB panels from both wood species was approximately 0.75. There were some SG variations within and between test groups. This was due to the inherent SG variations for flake-type composites. The MC of the test samples averaged about 7.0% at the time of termite testing.

BAE before and after termite test

BAE analyses were made on all OSB samples before and after testing. Assayed BAE values remained constant throughout the 28-day termite testing as shown in Table 1 and in Fig. 1. These analyses show that boron leaching did not occur under the high RH exposure conditions. In addition, the B/Zn and B/Ca ratios did not change significantly after termite testing at each ZB and CB loading level (Fig. 1). This indicates that there was little decomposition of the borates under high humidity exposures. Harrow (1959) stated that the preservatives must be both soluble in water and liquid water must penetrate the wood in order for leaching to occur.

Termite mortality

After the 28-day test, termites with the control samples survived well. The survival rates were 81% for southern pine OSB and 77% for mixed hardwoods OSB. Thus, the mixed hardwoods OSB caused slightly higher termite mortality, compared with southern pine OSB. The termite survival rate with the southern pine solid wood control was about 88.3%, slightly higher than those for OSB. The difference may have been due to the presence of resin and wax in the OSB samples, but the specific cause was not determined.

Significant termite mortality resulted from feeding on treated samples with both ZB and CB (Table 1). At the BAE levels of 1.0% or above, both ZB and CB provided excellent protection against termites for OSB. This result is in accordance with the conclusions from a comparable laboratory test by Williams et al. (1990). They demonstrated that FST failed to survive for 7 weeks with banak wood samples treated with Tim-Bor® at the 0.125% BAE level. Williams and Amburgey (1987) reported that the retention of 0.17% BAE (Tim-Bor®) in banak wood species was toxic to eastern subterranean termites (*R. flavipes*). Su and Scheffrahn (1991) reported similar reductions in FST feeding, even though there was less termite mortality in tests with DOT-treated pine blocks. Jones (2002) reported that the addition of CB only slightly deterred FST damage. The performance difference of CB against FST between Jones' and current studies was attributed to the difference of the type of CB used.

A linear regression analysis was performed to establish a correlation between termite mor-

TABLE 3. *Correlation coefficients for regression analysis of weight loss, termite mortality, and damage ratings of ZB and CB-modified OSB.*[a]

	Species	WL (%) = a $e^{-b\ RT}$			TM (%) = a $e^{b\ RT}$			WL (%) = a TM^{-b}		
		a	b	R^2	a	b	R^2	a	b	R^2
ZB	MHW	32.395	0.239	0.94	12.382	0.123	0.81	1571.3	1.647	0.85
	SP	39.192	0.268	0.97	16.116	0.078	0.68	1448.6	2.354	0.68
CB	MHW	44.258	0.263	0.91	13.373	0.137	0.71	1304.9	1.465	0.76
	SP	43.096	0.271	0.82	16.527	0.109	0.33	2458.3	1.703	0.91

[a] TM—Termite mortality expressed as percentage of the initial number of termites. RT—Damage rating based on 0–10 scale with 0 denoting the most damage. WL—Wood weight loss expressed as percentage of the original dry weight.

tality and BAE for both ZB- and CB-treated OSB. The results are summarized in Table 2 and are plotted in Fig. 2a. Termite mortality increased with BAE level increase in the sample. The degree of the correlations varied with type of panels. Results of the three-way ANOVA on termite mortality as influenced by wood species, borate types, and borate levels showed that both borate levels and wood species had a significant effect on termite mortality ($P < 0.0001$) at the 5% significance level. The borate types showed no significant effect on mortality ($P = 0.6468$). Therefore, there was no distinct effect of ZB and CB on termite mortality. The interactions of borate levels, wood species, and borate types revealed significant effects on termite mortality ($P = 0.0009$).

Weight loss

Wood weight loss data generally agreed with termite mortality data (Table 1). Untreated southern pine wood used as control showed a weight loss of 31.2%, indicating that the termites were active. Untreated southern pine OSB had less weight loss of 19%–21% (Table 1). At the 1.0% BAE level for ZB, there were 4.58% and 3.84% weight losses from mixed hardwoods and southern pine OSB, respectively. For CB at the 1.0% BAE level, 7.58% and 5.88% weight losses were shown from mixed hardwoods and southern pine OSB, respectively. This seems to indicate that more CB is needed to achieve the same protection level for OSB compared with ZB. However, further investigation is required to reach a definite conclusion on this.

From these results, it can be seen that both borates at an application level of 1.0% BAE or above showed excellent termite resistance in terms of wood weight loss. This result agrees with the observation of Grace et al. (1992) that feeding by termites was significantly reduced at borate levels above 1.5% BAE and surface feeding was significantly reduced at a concentration of 0.98% BAE. In a later paper, Grace and Yamamoto (1994b) reported minor surface nibbling by the FST in concentrations as high as 2.1% DOT.

The Harris decaying power function provided a good fit of the weight loss and BAE data for both ZB- and CB-treated OSB (Table 2 and Fig. 2b). There were large weight losses at the 0% BAE level (control samples) for the OSB. The weight loss was significantly less in the treated OSB samples as the BAE level increased. The trend leveled off significantly after the 1.0% BAE level, as shown in the graph. The small amount of weight loss in treated blocks at high BAE levels indicates that some surface termite feeding still occurred.

The relationships among weight loss and borate types, borate levels, and wood species were statistically analyzed by the three-way ANOVA. The borate types and borate levels showed significant effects ($P < 0.0001$) on weight loss. The ZB treatment led to less weight loss (2.7 to 4.6%) than the CB treatment (4.5 to 7.6%). As the borate levels increased, the wood weight loss decreased.

There were significant correlations between borate levels and wood species ($P < 0.0001$), and among borate levels, borate types, and wood species ($P < 0.0001$). Wood species alone showed no significant effect on sample weight loss ($P > 0.1554$).

Visual damage rating

An alternative interpretation of the termite test is the visual damage rating. A rating of 10 indicates that the sample is in excellent condition with permission of surface nibbles, whereas a rating of 0 means that the sample is completely damaged. The mean damage ratings from this test are shown in Table 1 and are plotted as a function of BAE in Fig. 2C. Control samples from mixed hardwoods OSB had an average damage rating of 3.0 after the 28-day termite test, whereas the control samples from southern pine OSB had an average damage rating of 3.1. The results show that the samples were heavily damaged, and wood species did not affect the damage rating significantly (Fig. 2c).

The increasing Harris power function showed excellent fits of damage ratings and BAE data for both ZB- and CB-treated OSB (Table 2 and Fig. 2c). Damage ratings showed an inverse trend with the weight loss data in relation to BAE. Results of the three-way ANOVA for the termite damage ratings of the treated OSB demonstrated that, except for wood species, both borate types and borate levels had significant effects on the damage ratings ($P < 0.0001$). All interactions among borate levels, borate types, and wood species significantly affected the rating by the FST ($P < 0.0001$).

Correlation analysis

The results of correlation analysis among sample weight loss, termite mortality, and sample damage ratings of ZB and CB-treated OSB are summarized in Table 3. The regression equations are plotted in Figs. 3, 4, and 5 in comparison with the experimental data. The relationships between weight loss and damage ratings of borate-modified OSB from both wood species were expressed well by a decaying exponential function (Fig. 3). An increasing exponential function provided the best fit for termite mortality and damage rating data (Fig. 4). A decaying power function provided the best fit for the weight loss, and termite mortality data (Fig. 5). The interrelationships among termite mortality, wood weight loss, and damage ratings from the three way nonlinear regression analysis had the following form, according to borate type and wood species:

$$RT_{MHW,ZB} = -3.4283 + 0.2962TM + 0.7370WL - 0.0253TM\,WL + 0.00471TM^2 - 0.0088WL^2 \quad (R^2 = 0.99) \tag{8}$$

$$RT_{SP,ZB} = 4.5712 - 0.2051TM + 0.3680WL - 0.0174TMWL + 0.0081TM^2 - 0.0044WL^2 \quad (R^2 = 0.96) \tag{9}$$

$$RT_{MHW,CB} = 5.6979 - 0.0918TM + 0.1674WL - 0.0098TMWL + 0.0013TM^2 - 0.0011WL^2 \quad (R^2 = 0.93) \tag{10}$$

$$RT_{SP,CB} = 4.1724 + 0.3209TM - 0.0391WL + 0.0028TM\,WL + 0.0214TM^2 + 0.0026WL^2 \quad (R^2 = 0.77) \tag{11}$$

where, RT = rating (0–10); TM = termite mortality (%), and WL = weight loss (%). The correlations can be used to predict sample damage ratings from the wood sample weight loss and termite mortality data.

CONCLUSIONS

FST laboratory tests showed that both zinc- and calcium borate-treated OSB resisted attack by Formosan subterranean termites. The borate levels showed a significant effect on weight loss, termite mortality, and damage ratings. As the borate loading level increased, wood sample weight loss decreased and termite mortality increased. Borate levels over 1.0% BAE led to a low weight loss. Wood species used to manufacture the OSB showed no significant effect on termite resistance properties.

There was a linear relationship between termite mortality and assayed BAE for both ZB and CB-treated OSB. The relationship between sample weight loss and BAE followed a decaying power relationship with increasing effect of ZB and CB levels. The increasing power function provided excellent fits between damage ratings and BAE levels. There were strong correlations among visual damage ratings, wood sample weight loss, and termite mortality. The results suggest that boron retention above 1.0% BAE can increasingly minimize the potential damage to OSB by FST. However, the retention level does not completely eliminate the damage. This information can help more OSB producers manufacture chemically-treated OSB to meet increasing market demands.

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