Borate-Treated Strand Board from Southern Wood Species: Resistance Against Decay and Mold Fungi

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Combined decay and mold resistance of zinc borate-(ZB) and calcium borate-(CB) treated oriented strand board (OSB) from southern mixed hardwood (MHW) and southern yellow pine (SYP) was investigated. Tests were done with a brown-rot fungus, *Gloeophyllum trabeum*, and a white-rot fungus, *Trametes versicolor,* for 8 and 12 weeks, respectively. Wood species and fungus type had significant influence on the decay resistance. Decay caused by the brown-rot fungus was evident for all untreated SYP and mixed MHW controls. White-rot fungus did not cause significant sample weight loss for either species group. In the SYP OSB control inoculated with *G. trabeum*, the hyphae were abundant in wood rays and cell walls where they primarily penetrated through bordered and simple pits. The incorporation of ZB and CB into OSB provided significant protection against the fungi with no significant weight loss observed in the treated OSB. Microscopic analysis showed distinct evidence of fungal colonization and a thinning pattern of cell wall material. Untreated OSB samples from MHW and commercial OSBs were most susceptible to mold growth after 6 weeks. The borate-modified OSB from MHW and SYP effectively prevented the mold growth.

Keywords: Zinc borate; Calcium borate; Strandboard, Decay; Mold

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INTRODUCTION

Oriented strand board (OSB) is susceptible to biodeterioration by wood-decay fungi, which can severely affect its economic value and usefulness. It is important to develop methods for the long-term protection of OSB that can be applied during the manufacturing process (Ayrilmis *et al.* 2005, Smith and Wu 2005). Decay resistance of wood-based composites, including particleboard containing decay-resistant wood species, medium density fiberboard (MDF), and particleboards, has been studied (Evans *et al.* 1997). Wood-destroying organisms, such as *T. versicolor* and *G. trabeum*, degrade insoluble wood components to soluble products, and finally to simple chemical components. Several factors other than the natural decay resistance of wood species have been shown to influence the durability of wood composites. It has been reported that the strength reduction in particleboard caused by fungi is considerably greater than the losses in fungus-free samples submerged in water for extended periods, primarily due to the weakening of the glue-line by the fungi (Schmidt et al. 1978). Phenol formaldehyde (PF) resin provided more resistance to fungal degradation than urea formaldehyde (UF) resin due to its high pH and the presence of non-condensed phenols (Schmidt *et al.* 1978). Increased amount of UF resin in the panel improved its resistance (Hann *et al.* 1962)

The role of borate compounds in preventing fungal decay has been well documented. In terms of loss of wood mass, Murphy *et al.* (1995) found that treatment with a mixture of sodium borate and boric acid, adjusted to a boric acid equivalent (BAE) level of 0.07%, resulted in an 18.5% reduction of southern pine sapwood mass when inoculated with *G. trabeum*. Laboratory soil block tests with brown- and white-rot fungi showed that the threshold for decay resistance was about 0.5% BAE for zinc borate (ZB) and sodium borate. The weight losses for isocyanate-bonded wafer board containing ZB were lower compared to that of the sodium borate boards at an equivalent loading level (Laks *et al.* 1991). The weight losses of ZB-treated panels were under 2.0% as compared to 40-50% losses for the untreated panels, and fungal growth on the panels was not detected (Sean 1999). Verhey *et al.* (2001) reported that 1.0% target ZB loading effectively prevented fungal attack on wood fiber and thermoplastic composites. Borate compounds are effective in protecting wood composites from fungal colonization. The addition of calcium borate (CB) to southern yellow pine flakeboard was studied by Jones (2002). It was shown that CB provided certain protection against decay fungi and termites, but higher loading levels were needed to provide adequate protection. Physical and mechanical properties were negatively impacted with the addition of CB, and higher loadings resulted in lower property values (Jones 2002). The size of CB particles used played an important role in the balanced biological and mechanical performance of the manufactured flakeboards. Panels made with large-sized CB particles had poor mechanical performance compared with these made with small-sized CB particles.

Airborne mold spores spoil indoor air quality, and mold growth is harmful to human health. In general, mold fungi do not significantly decay or weaken wood materials, but they can utilize the wood as a substrate, particularly in a cool and moist environment, creating a health problem (Laks *et al.* 2002). Indoor mold exposure has been found to induce asthma, chronic sinus infection, and respiratory tract problems (Zock 2002). Mold growth may be found on many domestic and commercial construction materials in situations where poor design or maintenance leads to a cool and moist environment. *Cladosporium*, *Penicilium*, *Alternaria*, as well as the toxic mold fungus, *Stachybotrys chartarum*, were detected in homes, hotels, schools, and other structural buildings (Fogel and Lloyd 2002). Studies have been conducted on the relative susceptibility of borate-treated wood products to mold fungi. The addition of 0.56% BAE from ZB to Polymeric Diphenyl Methane Diisocyanate (pMDI)-glued OSB and gypsum boards decreased the growth of mold fungi. Even greater protection was achieved with 1.76% BAE from zinc borate (Fogel and Lloyd 2002). Research also found that ZB provided better mold resistance than disodium octaborate tetrahydrate (DOT). Gypsum boards treated with 0.3% boric acid had significantly less mold growth than untreated boards. Boards treated with 1.0% boric acid showed the best results with little or no mold growth after a 6-week period. Laks *et al.* (1991) also reported that ZB had better mold resistance than DOT on wafer board. Very limited work has been done dealing with mold resistance of CB on wood composites.

Durability improvement through preservative treatment is seen as an effective method by which the range of uses of wood-based composites such as OSB may be extended. To achieve this goal, more information is needed to understand the resistance properties of borate-treated OSB against biodeterioration. The objective of this study was to investigate the effect of wood species, fungus type, borate types (*i.e.*, ZB *vs.* CB), and borate levels on the resistance of PF-bonded OSB against decay and mold.

MATERIALS AND METHODS

Panel Manufacturing

Unseasoned (green) boards from several southern hardwood species including 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.) were obtained from a local saw mill in Louisiana. 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), and were used to manufacture mixed hardwood (MHW) and southern yellow pine (SYP) OSB. Zinc borate (ZB, $2ZnO•3B_2O_3•3.5H_2O$; density = 2.79 g/cm^3, and a mean particle size = 6.61 μm) was obtained from US Borax Inc. (Valencia, Ca) and calcium borate (CB, $Ca_2B_6O_{11}•5H_2O$, density = 2.42 g/cm^3, and a mean particle size = 6.46 μm) was obtained from a supplier in China. The flakes were placed in a rotary blender, and 4.0 wt% PF resin, 1.0 wt% wax, and ZB or CB powder (based on oven-dry wood weight) were sprayed on the flakes through different spray nozzles. The target loading levels for ZB and CB were 0 (control), 0.5, 1.0, 3.0, and 4.5 wt%.

Random mats were formed by hand with the blended flakes. Two replicate panels at each borate level were fabricated. The pressing time was 6 minutes at 1.71 MPa pressure and 200 ^oC temperature. The target thickness and panel specific gravity (SG) were 1.27 cm and 0.75, respectively. The resulting boards (55.9 cm x 50.9 cm x 1.27 cm) were cooled and conditioned at 22 ^oC and 55% relative humidity (RH) prior to testing. Chemical analysis with ICP-OES (Inductively Coupled Plasma – Optical Emission Spectrometry) was done to determine the actual loading level of ZB and CB for each panel.

Decay Resistance Test

Decay resistance tests were conducted in accordance with the AWPA E22 standard (AWPA E22-07, 2007) using the brown-rot fungus *Gloeophyllum trabeum* and the white-rot fungus *Trametes versicolor* obtained from the USDA Forest Products Laboratory, Madison, Wisconsin. The test fungi were grown on 2% malt extract agar (MEA) in 100 mm plastic petri dishes for the purposes of this study. One hundred grams of silt loam soil with an average pH of 7.8 were screened through a U.S. No. 6 sieve and were placed in 250 ml size Pyrex® brand bottles. The water-holding capacity of the soil was then adjusted to 130% with distilled water.

Untreated southern pine (*Pinus taeda* L.) or ash (*Fraxinus* spp.) feeder strips (3.4 x 2.8 x 0.3 cm) were placed on the top of the soil in each bottle. The filled bottles were then loosely capped and autoclaved on two successive days at 105 KPa for 30 min. at 125 ^oC. After cooling the bottles, each feeder strip was inoculated diagonally at opposite corners with a mycelial plug cut from the actively growing edge of a 7-day old MEA culture of either the white- or brown-rot fungus. Each inoculated bottle was incubated at 25 ^oC and 75% relative humidity (RH) until the feeder strip was heavily colonized by the test fungus.

All decay tests were done with 1.40 cm x 1.40 cm x 1.27 cm specimens from each group of OSB. There were two borate types (ZB and CB), two wood species groups (SYP and MHW), four BAE levels (0, 1.5, 3.0, and 4.5 wt%), and five replications. The labeled test blocks were placed in a screen tray and conditioned at 40 ^{o}C in an oven to reach constant weight. The samples were weighed to the nearest 0.01 g after conditioning and their weight was recorded as W_1. The test blocks were then placed on the surface of an inoculated feeder strip in each bottle. To avoid losing the identity of the blocks, both bottles and OSB blocks were labeled. The bottles were incubated at 25 ^{o}C and 75% RH for 8 weeks for the brown-rot fungus, and 12 weeks for the white-rot fungus. At the end of the exposure period, the test blocks were removed from the bottles, carefully brushed, and dried to a constant weight at 40 ^{o}C in the oven. The blocks were weighed to the nearest 0.01 g to obtain their weight after testing (W_2). Weight loss was calculated as a percentage of the initial sample weight as: weight loss (%) = $[(W_1 - W_2)/W_1]$ x 100.

Sub-samples (0.1 cm x 0.1 cm x 0.05 cm) were removed from the dried blocks for Scanning Electron Microscopy (SEM). The sub-samples were mounted on stubs, and nickel-coated with an EDWARD S150 Sputter Coater, and examined with an EDWARD S150 SEM at 20KV.

Mold Resistance Test

OSB test blocks (7.62 cm x 10.16 cm x 1.27 cm) were cut from various panels for mold resistance test according to a modification of the AWPA E24 standard (AWPA E24-07, 2007). There were two species (SYP and MHW), two borate types (ZB and CB), three borate levels, and two replications for the experimental panels. For comparison, four commercial OSB samples were also included in the experiment. The commercial OSB was made of SYP with unknown resin type and content level. The mold test assembly consisted of a test chamber with a lid, a heating belt with a temperature control unit, a sample and soil support frame, and a plastic soil holder. The chamber was filled with water to a 7.62-cm depth. Test samples were suspended over non-sterile potting soil with their lower edges about 7.6-cm above the soil. Water temperature was maintained at 32.5 ± 1^{o}C during the 6-week test period.

Molds and their spores were obtained from the USDA Forest Products Laboratory, Madison, Wisconsin. They consisted of *Aureobasi-dium pullulans* (d. By.) Arnaud ATCC 9348, *Aspergillus niger* v. Tiegh. ATCC 6275, *Penicillium citrinum* Thom ATCC 9849, and *Alternaria tenuissima* group (Kunze) Wiltshire Ftk 691B. The spore inocula collected from Petri dishes of individual mold fungi were dispersed in distilled water and distributed on potting soil in the mold chambers by spraying the mixture on the top surface of the soil bed. After the test, specimens were examined visually and rated by five people as none (0), traces of growth (<10%, 1), light growth (10 to 30%, 2), moderate growth (30 to 60%, 3), and heavy growth (60% to complete coverage, 4).

Data Analysis

Statistical comparisons, based on the four-way ANOVA, were performed to test the effects of wood species, borate type, borate level, decay fungi, and their interaction on decay resistance properties of borate-modified OSB (2x2x4x2x5 factorial experiment). The effects of various factors on mold resistance properties of the treated OSB were tested using three-way ANOVA (2x2x4x2 factorial experiments). Tukey's studentized-range test was employed to determine whether weight loss and visual ratings were significantly different for various panels at the 5% significance level.

RESULTS AND DISCUSSION

Decay Resistance Properties

Sample weight loss

Average weight losses, mean SG and BAE data for ZB- and CB-modified OSB samples and controls exposed to the decay fungi are presented in Table 1. The SG for all samples varied from 0.64 to 0.82, and the BAE varied from 0 (control) to about 3 percent. The weight loss data are plotted in Fig. 1. The test specimens were covered with fungal mycelium in both brown- and white-rot culture bottles after 8- and 12-week tests. The sample SG of the OSB had no direct effect on decay resistance (Table 1).

Table 1. Average Weight Losses of Borate-Treated MHW and SYP Caused by *T. versicolor* and *G. trabeum* in Soil Block Tests[1].

Borate Type	Fungi Type	Species Group	Specific Gravity	BAE[2] (%)	Weight loss[3] (%)
Control	*T. versicolor*	MHW	0.64	0	5.62 (0.74) a
		SYP	0.73	0	7.57 (1.01) a
	G. trabeum	MHW	0.73	0	22.35 (7.49) a
		SYP	0.70	0	39.24 (4.53) a
Zinc Borate	*T. versicolor*	MHW	0.74	0.97	-0.76 (0.43) b
			0.71	1.72	-0.67 (0.48) b
			0.65	3.00	0.04 (0.11) b
		SYP	0.63	1.04	-0.35 (0.48) b
			0.79	1.78	-1.14 (0.30) b
			0.67	3.02	-0.77 (0.40) b
	G. trabeum	MHW	0.71	0.97	0.53 (0.92) b
			0.70	1.72	-0.59 (0.25) b
			0.69	3.00	-0.75 (0.25) b
		SYP	0.61	1.04	-0.68 (0.22) b
			0.79	1.78	-1.35 (0.19) b
			0.67	3.02	-1.26 (0.23) b
Calcium Borate	*T. versicolor*	MHW	0.75	0.95	-0.21 (0.58) b
			0.77	1.87	-0.71 (0.21) b
			0.74	3.02	-1.03 (0.50) b
		SYP	0.77	0.99	-1.45 (0.36) b
			0.72	1.86	-0.46 (0.42) b
			0.76	3.07	-0.74 (0.31) b
	G. trabeum	MHW	0.77	0.95	-0.83 (0.19) b
			0.82	1.87	-0.05 (0.38) b
			0.73	3.02	-0.42 (0.54) b
		SYP	0.78	0.99	-1.22 (0.27) b
			0.76	1.86	-0.50 (0.06) b
			0.74	3.07	-0.93 (0.06) b

[1] Each mean (± standard deviation) weight loss represents five replicates of borate-modified OSB. The ranking was done in relation to the corresponding control group. Means within ZB and CB treated groups followed by the same letters are not significantly different (ANOVA, Tukey's Studentized-Range Test, P = 0.05); [2] BAE – boric acid equivalents; [3] Negative values in weight loss indicate weight gain.

Untreated MHW OSB showed much better decay resistance against both white-rot and brown-rot fungi (Table 1). The average white-rot loss for untreated SYP OSB was 7.57%, but only 5.62% for untreated MHW OSB. The average weight loss attribu-table to brown-rot was 39.24% in the SYP OSB as compared to 22.35% in the MHW OSB.

In general, wood species displaying high natural decay resistance contains a high percentage of heartwood and extractives. Examples of the commercially available wood species with natural decay resistance include white oak, red oak, cypress, and locust (Fengel and Wegner 1984). OSB specimens produced from hardwood species such as red oak may be highly resistant to decay due to high tannin content in heartwood portions. The blocking of cell cavities by tyloses in the vessel may also explain the greater durability of oak heartwood (Panshin and Zeeuw 1980).

The incorporation of ZB or CB at the 1.0% BAE level or above in OSB completely prevented decay of wood components by either fungus (Table 1). The experimental data indicate that ZB and CB were very effective wood preservatives against brown-rot decay fungus for OSB. However, the performance against the white-rot fungus was less effective. The white-rot isolate was not virulent, and low weight loss in the control OSB was observed.

There were some weight gains for some treated OSB samples, which may be attributed to the moisture content (MC) variation of the test blocks before and after conditioning to a constant weight at 40 ^oC. According to the four-way ANOVA, the main effects of fungi, borate types, and borate levels were significant relative to OSB weight loss at the 5% significance level. The interaction effects between and among the independent variables were also significant except for the interaction between and among fungus type and wood species ($P > 0.6994$). The main effect of wood species was insignificant ($P > 0.6088$).

SEM analysis

Figures 1a and 1b show a severe erosion pattern of tracheid cell wall for SYP wood due to decay in comparison with unexposed wood. The S2 layer of the cell wall was heavily damaged by *G. trabeum*, revealing a distinct increase in porosity of the secondary walls. Because this layer has a comparatively lower lignin content than the S1 and S3 layers, the polysaccharides are more accessible to biodegradation. In the S2 layer, *G. trabeum* preferentially utilized holocellulose in the amorphous regions of wood cell walls, catalyzing a rapid depolymerization of the wood polysaccharides by a random mechanism (Cowling 1961).

Figures 1c and 1d show a general view of undecayed SYP OSB with multi-layered flakes. Large voids existed between the OSB flakes due to different characteristics of the raw furnish. During decay testing, moisture penetrated into the samples and caused certain delamination between flakes, leading to more void spaces. The voids promoted the penetration of fungal hyphae and provided more susceptibility to microorganisms compared with solid wood (Chung *et al.* 1999).

The extent of deterioration by *G. trabeum* was severe in both untreated SYP and MHW OSB (Table 1 and Fig. 2). Mycelium heavily covered the sample during the 8-week period.

The appearance of the control MHW OSB sample, decayed by brown-rot fungi with a 22.35% weight loss, is shown in Fig. 2c. The hyphae penetrated the entire block, largely through bordered and simple pit pairs. Bore-holes became progressively denser and larger in the sample. Large voids between OSB flakes or exposed vessels and tracheid lumen helped fungal hyphae penetrate into OSB. *G. trabeum* hyphae could not be seen on treated OSB samples (Fig. 2d).

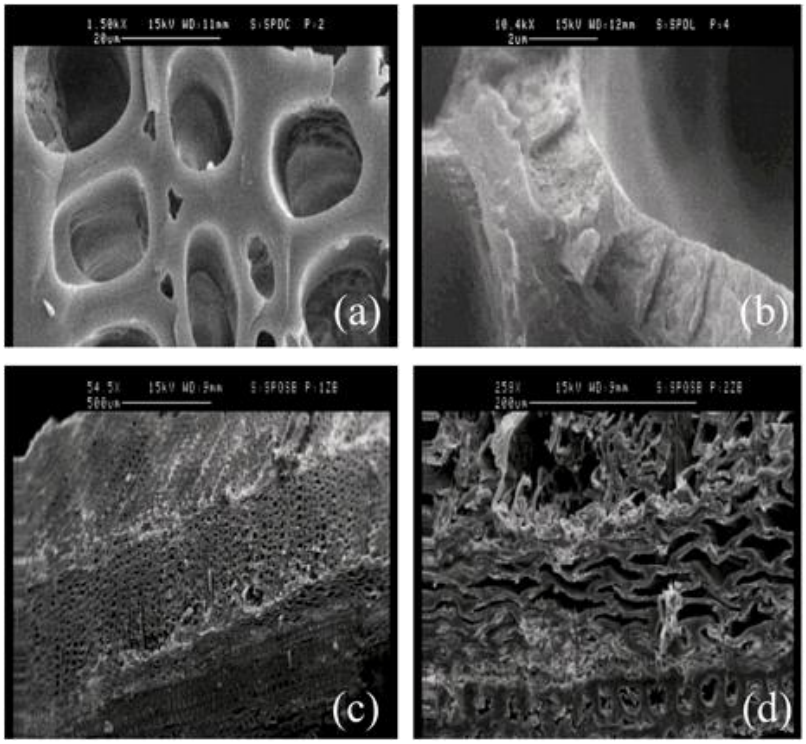

Fig. 1. Scanning electron micrographs of SYP wood and OSB samples unexposed and exposed to the fungi *G. trabeum*. Typical views of undecayed (a) and decayed (b) SYP tracheid cells; and typical views of undecayed (c) and decayed (d) SYP OSB.

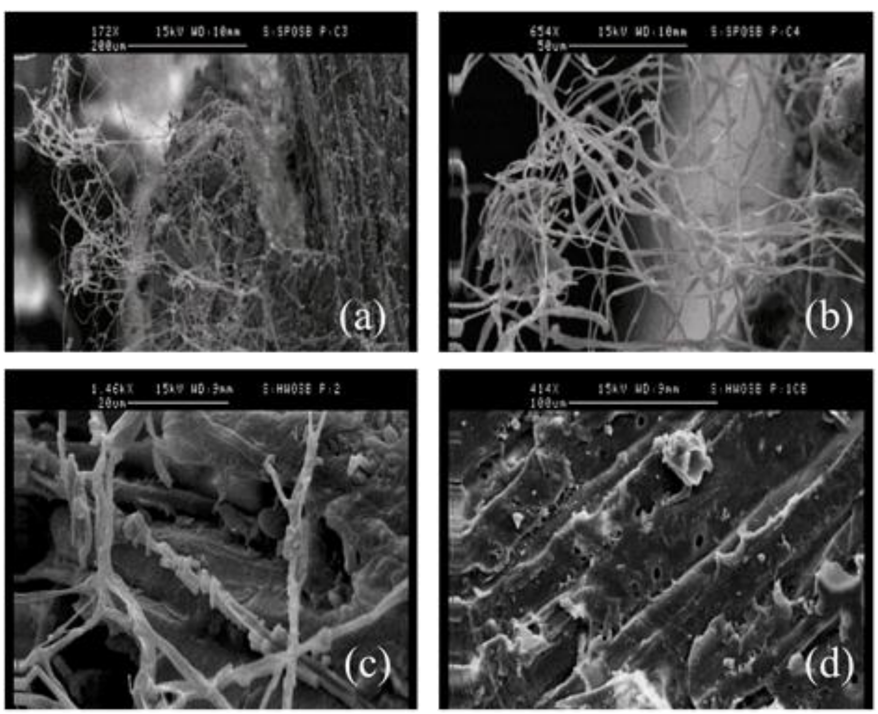

Fig. 2. Scanning electron micrographs of MHW and SYP OSB exposed to the fungi *G. trabeum*. (a) and (b) hyphal growth on tracheid cell of untreated SYP OSB, (c) hyphal growth on untreated MHW OSB, (d) no hyphal growth on CB-treated MHW OSB (1.0% BAE).

Mold Resistance Properties

Mold resistance data are summarized in Table 2. The rating data are plotted in Fig. 3 as a function of the BAE level for various products. As shown in Fig. 3, untreated MHW and commercial OSB samples were most susceptible to mold growth (ratings of 3.8 and 4.0, respectively). Borate-treated MHW and SYP OSB reduced the mold growth (ratings of 0.50 to 2.75, respectively). Greater protection of the SYP OSB was achieved with an increase in borate retention levels. This result is consistent with data presented by Fogel and Lloyd (2002). MHW OSB showed a higher susceptibility to mold growth than SYP OSB with and without borate treatment (Fig. 3). Thus, borate treatment for MHW OSB did not effectively prevent mold growth. The difference between two different wood species groups is presumably related to the content of nutrients and other low molecular weight carbohydrates available on the OSB surfaces. Hardwood hemicelluloses are rich in pentosan (xylan), which is generally the least thermally stable hemicellulose, with a decomposition temperature around 200 ^{o}C. It was reported that there was a significant relationship between mold growth and carbohydrate content (Terviev and Boutelje 1998). It was also found that low molecular weight carbohydrates and low nitrogen content of wood had a significant impact on the susceptibility of wood to mold attack (Theander *et al.* 1993). According to the three-way ANOVA, the main effects of wood species, borate types, and borate levels significantly affected mold growth on borate-treated OSB at the 5% significance level. The interaction effects between borate types and borate levels and between wood species and borate levels were also significant. The main effects of wood species and the interaction between wood species and borate types were not significant.

Table 2. Average Visual Ratings of Borate-treated OSB after Exposure to Mold Fungi for 6 Weeks

Species Group	Borate Type	BAE (%)	Specific Gravity	Mold Ratings [1]
MHW	Zinc Borate	0 1.05 2.00	0.77 0.78 0.75	3.82 (0.26)a 2.00 (0.00)b 1.90 (0.64)b
	Calcium Borate	0 1.03 1.96	0.78 0.79 0.75	3.82 (0.26)a 2.75 (0.46)b 2.13 (0.83)b
SYP	Zinc Borate	0 1.1 2.0	0.77 0.81 0.79	3.50 (0.46)a 0.63 (0.52)b 0.75 (0.46)b
	Calcium Borate	0 1.03 1.99	0.78 0.81 0.79	3.50 (0.46)a 0.50 (0.53)b 0.63 (0.52)b
Commercial OSB Panel		0	0.65	4.00 (0.00)

[1] Mold rating data with the same letter within a group show no significant difference at the 5% significance level.

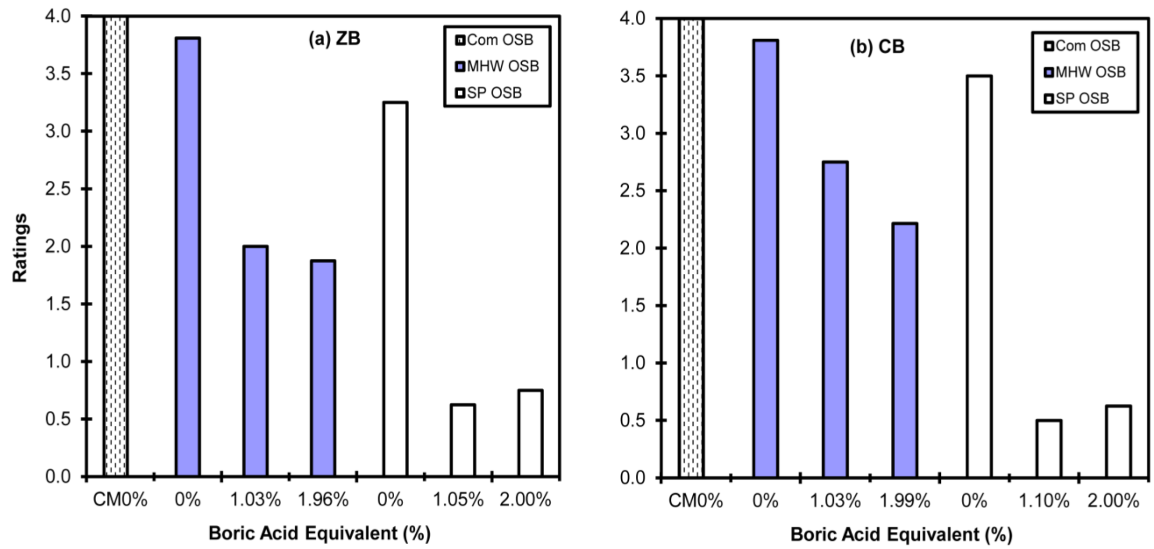

Fig. 3. A comparison of visual ratings of (a) ZB- and (b) CB-treated OSB exposed to mold fungi for 6 weeks

CONCLUSIONS

1. Weight loss in OSB caused by both brown- and white-rot fungi was directly related to borate level, wood species, and fungus type. Brown-rot decay was evident for both untreated SYP and MHW OSB controls.
2. The incorporation of ZB and CB into OSB provided a suitable protection against brown-rot fungus. No significant weight loss due to brown-rot attack was observed from samples treated with both ZB and CB, even at the low loading level (*i.e.*, 1.0% BAE). However, the performance against the white-rot fungus was less effective. The white-rot isolate was not virulent, and low weight loss in the control OSB was observed.
3. SEM analysis showed distinct evidence of fungal colonization with bore-hole formation and erosion in the cell wall material. For untreated OSB and solid wood controls decayed by *G. trabuem*, the hyphae ramified through the wood elements, usually as individual filaments. The hyphae penetrated the entire block from the sample with a 40% weight loss, largely through bordered and simple pit pairs. At the early stage of decay, the cell walls were penetrated almost exclusively through bordered and simple pit pairs, leaving few bore-holes. Bore-holes became progress-sively more numerous and larger in samples with a 30% or more weight loss.
4. Untreated OSB from both MHW and commercial OSB were most susceptible to mold growth. However, borate treatment for SYP OSB effectively prevented the mold growth, and the effect increased with the increase of borate retention level. MHW OSB with and without borate treatment showed a higher susceptibility to mold growth than SYP, which can be attributed to nutrients and other low molecular weight carbohydrates in the different hardwood species. Borate treatment for MHW OSB did not effectively prevent mold growth.

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