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Fundamental properties of borate-modified oriented strandboard manufactured from southern wood species

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FUNDAMENTAL PROPERTIES OF BORATE-MODIFIED ORIENTED STRANDBOARD MANUFACTURED FROM SOUTHERN WOOD SPECIES

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ABSTRACT

In the United States, damages to buildings from termites and decay fungi cost billions of dollars annually. As a result, there is an urgent need for building construction that will withstand the ravages of these biological pathogens. Chemical modification of building products is one of the techniques for developing durable wood-based construction. This study was conducted to examine the effects of powder zinc borate (ZB) and calcium borate (CB) on resin gel time, strength, swelling, leaching, termite, decay, and mold resistance properties of oriented strandboard (OSB). It was found that gel time of phenol formaldehyde (PF) resin decreased with increased amount of ZB, indicating interaction between the borate and the resin. The reduced gel time was partially recovered by using polyethylene glycol (PEG) in combination with ZB. Although panel stiffness was not affected by borate up to a 3.5 percent boric acid (BAE) level, ZB and CB showed a negative effect on the bending and internal bond (IB) strength. Thickness swelling (TS) of treated panels after 24-hour water soaking increased with borate level. ZB OSB displayed less TS than CB OSB at an equivalent BAE level. CB with a larger particle size caused significant TS. However, the chemical with a smaller particle size helped bring TS to a stable and acceptable level. A certain portion of borate leached out from OSB samples under the water-soaking conditions. The leaching rate varied with wood species, borate types, and amount. The use of borate with a smaller particle size helped reduce the leaching rate. The relationship between assayed BAE and leaching

time followed a decaying exponential function for ZB and a decaying power function for CB. Laboratory termite tests showed that wood weight loss decreased and termite mortality increased with the increased BAE level. At the1% BAE or above, there was little damage on wood samples. There were significant correlations among termite mortality, weight loss, and visual damage ratings. Both borate chemicals provided an excellent decay and mold resistance for OSB. The information on various properties of borate-modified OSB is of significant value for developing durable structural panels from southern wood species.

CHAPTER 1

INTRODUCTION

Wood-based composites industry in the United States is one of the most dynamic sectors of the forest products industry. Among many commercial products produced, oriented strandboard (OSB) is one of the engineered structural wood composites widely used for house construction as sheathing, flooring, and I-joist materials. OSB consists of wood flakes glued with an exterior-waterproof resin. The mechanical properties of the board are enhanced by layering and alignment of wood flakes. In 2000, OSB production in North America exceeded 1.93 billion m^2 (on the 0.95cm basis), overtaking that of plywood (Najera and Spelter 2001). The production gap between OSB and plywood is expected to widen in the near future. In the southern United States, low-grade hardwoods are being successfully used to manufacture mixed hardwood OSB, adding significant value to a vast amount of low-value materials.

However, as a biological material, OSB is vulnerable to Formosan subterranean termites (FST) and fungal attack (Schmidt and Nehm 1972). In 1993, the Wood Protection Council of the National Institute of Building Sciences (NIBS) estimated the annual costs of replacing wood damaged by the FST to be $2 billion, up from $750 million in 1988 (Ring 1999). These costs must be greater now. The termites are the most destructive insect in Louisiana and affect significantly the economy of the state.

Decay and mold inside walls and attics thrive under high humidity and temperature conditions in the South, especially in Louisiana. This problem has become more common due to the construction of tighter structures, which do not allow moisture to escape. Common sources of moisture are bathrooms with poor ventilation, leaky roof, leaky water pipes, improperly vented clothes dryers, and flooding (Fogel and Lloyd 2002). Decay fungi are probably the most destructive biological pathogens on wood structures in the United States. Within the last 5 years, huge decay losses occurred as a result of improper installation of exterior insulation finishing systems (Granier and Jorgensen 2001). There are estimated 215,000 homes, which have been built in this country using this technique. Although the exact amount loss due to this process is not known, it is estimated in the billions of dollars.

The presence of moisture also promotes the growth of mold, which has also been of recent concern. Although mold has not been directly linked to health problems scientifically, it is thought to cause illnesses in people sensitive to the toxic gas of molds. These include infants, children, pregnant women, and adults with low immune systems or respiratory conditions (i.e., allergies, asthma, and hay fever). The biggest concern has been the virulent Stackybotrys chartarum, often referred to as toxic black mold. Legal claims resulting from medical problems increase daily, with homes having to be decontaminated or destroyed (Wickell 2002).

One solution against termite, decay, and mold is to use repellent chemicals for wood-based products in residential construction. It has been shown that chromated copper arsenate (CCA) and borate treatments prevent wood materials from termite and fungal attack (Laks 1988). Structural lumber and plywood may be successfully pressure-treated with CCA after their manufacturing. However, OSB cannot be pressure-treated with waterborne preservatives once it is made into panel form, due to its large swelling characteristics. In addition, CCA will be phased out in the next three years.

Zinc borate (ZB), $2ZnO \cdot 3B_2O_3 \cdot 3.5H_2O$, and calcium borate (CB), $Ca_2B_6O_{11} \cdot 5H_2O$, demonstrate very low risks to both mammals and environment. In addition, they offer low cost, ease of handling, and fire retardancy. However, ZB and CB are almost insoluble in water, and it is very difficult to use them in the treatment of solid wood. On the other hand, it is relatively simple to incorporate powder ZB and CB into mat-formed composites during the blending process. This approach is providing an impetus for borate chemicals to play an expanding role within the wood-based composite industry as wood preservatives. Both borates may be applied as a dry powder, and require no use of organic solvents during OSB manufacturing. Technical information on use of these chemicals and their effect on panel properties is highly needed.

This dissertation is composed of seven interrelated chapters to address the aforementioned issues. Chapter 1 (this chapter) serves as an overall introduction to the dissertation.

In Chapter 2, the effects of flake pH and buffer capacity on the resin gel time of phenol formaldehyde (PF) resin in the presence of ZB and polyethylene glycol (PEG) are described.

Chapter 3 presents the effects of borate types (ZB and CB) and borate levels on mechanical and physical properties of ZB- and CB-modified OSB. The effect of PEG on mechanical properties of borate-modified OSB is also discussed.

Chapter 4 describes the leachability of the borate-modified OSB as influenced by wood species, borate types, initial borate content levels, and leaching time. The leaching rate data provide important information for predicting leaching performance of wood composites from various wood species and borate types.

Chapter 5 discusses the effects of ZB and CB on termite resistance for the modified OSB. The correlations among wood species, termite mortality, and damage ratings according to the borate types and levels are analyzed.

Chapter 6 presents the decay and mold resistance properties of borate-modified OSB. The effects of borate levels on decay resistance of the OSB against white and brown rot fungus are discussed. SEM microscopic study provides information about the mode of fungal attack from hyphae and mycelium, ascertaining the effect on the test samples from brown- and white-rot fungi.

Chapter 7 provides overall conclusions for the dissertation.

1.1. REFERENCES

Fogel, J.L., and J.D. Lloyd. 2002. Mold performance of some construction products with and without borate. Forest Prod. J. 52(2): 38-43.

Grenier, D.L., and W.J. Jorgensen. 2001. Exterior Insulation Finish System (EIFS): An Overview. Consultants in Risk Management Homepage. http://www.c-risk.com/Articles/dlg_EIFS_overview.htm.

Laks, P.E., B.A. Haataja, R.D. Palardy, and R.J. Bianchini. 1988. Evaluation of adhesives for bonding borate-treted flakeboards. Forest Prod. J. 38(11/12): 23-24.

Najera, J., and H. Spelter. 2001. Wood-based panels – supply, trade, and consumption. In: UN – ECE/FAO Forest Products Annual Market Review, 2000-2001, Geneva, Switzerland: United Nations Publications, 83-100.

Ring, D. 1999. Need for the integrated pest management of the Formosan subterranean termite. Technical Note, LSU Agricultural Center. pp 3.

Schmidt, V.H., and A.B. Nehm. 1972.Testing of particleboard on termite resistance. Holz Roh-Werstoff. 30(5): 14-16.

Wickell, J. 2002. Toxic Black Mold – Stachybotyrs Chartarum mold control. Home Buying/Selling Homepage. http://homebuying.about.com/library/weekly/aa062302b.htm.

CHAPTER 2

THE INFLUENCE OF FLAKE CHEMICAL PROPERTIES AND ZINC BORATE ON GEL TIME OF PHENOLIC RESIN FOR ORIENTED STRANDBOARD

2.1. INTRODUCTION

Formosan subterranean termites (FST) have rapidly expanded their geographic domain in the southern United States and Hawaii. FST are thought to cause over $1 billion structural damage per year in the country (Ring 1999). It is the most destructive insect in Louisiana. An epidemic destruction by FST causes about $300 million per year in historic and residential buildings in the greater New Orleans metropolitan area alone (Shupe and Dunn 2000). The ultimate solution to termite destruction is to use wood species resistant to termites or to use termite-repellent chemicals for wood-based products in residential construction. It has been shown that both chromated copper arsenate (CCA) and borate treatments prevent termite attack on wood members. Structural lumber and plywood can be successfully treated after their manufacture (e.g., treatments with CCA). Oriented strandboard (OSB), however, cannot be pressure-treated once it is manufactured due to its large swelling characteristics.

Work has been done to incorporate borate chemicals such as zinc borate (ZB) into OSB furnish during the blending process (Laks et al. 1988, Laks et al. 1994, Sean et al. 1999). Panels with good termite-resistant properties have been successfully developed. Borate, however, has an adverse effect on mechanical and physical properties of OSB, especially these bonded with phenol-formaldehyde (PF) resin (Laks et al. 1994). This has presumably been attributed

to the interference of borate with the resin cure process during hot pressing (Laks et. al. 1994, Sean et al. 1999). As a result, a higher resin-loading rate is usually needed to achieve acceptable board strength and durability at high levels of borate addition. The problem associated with potential durability problem of borate-modified OSB has generated controversy in the structural application of the product. This signals the need for studying bonding characteristics and durability of the OSB as influenced by flake chemical properties (i.e., pH and buffer capacity) and levels of borate application.

The importance of wood chemical properties (pH and buffer capacity) and surface activation by oxidizing agents on wood-adhesive bonding has been well studied (Gardner and Elder 1988, Johns and Niazi 1980, Maloney 1977, Stamm 1961). The pH of wood may change the pH of the adhesive at the interface and modify the cure of resin during hot pressing. As a result, too high or too low pH of wood has been reported to be troublesome for achieving good adhesive bonds in wood-based products (Bryant 1968, Campbell and Bryant 1941, Chen 1970). The pH of wood is generally related to its extractive content, which varies from species to species. Although extractives represent only a small portion of wood, they include a wide range of chemical compounds from volatile terpenes, organic solvent-soluble fatty acids and waxes, water-soluble carbohydrates and proteins (Cotton and Wilkinson 1988, Fengel and Wegner 1984). These substances hinder adhesive wetting as well as interfere with the cure process of the adhesives by reducing or prolonging the curing time (Johns and Niazi 1980, Jordan and Wellons 1977). Removal of these extractives represents an effective

means to reduce their effects on wood-adhesive bonding. It was reported that pH of wood from temperate zones are in the weak-to-moderate acidic range of 3.3-6.4 (Gray 1958, Ingruber 1958), while those of tropical woods range from weak acidic to weak alkaline of 3.7-8.2 (Chen 1970). Johns and Niazi (1980) reported that both hardwoods and softwoods are in the pH range of 4.0-5.9, with an inconsistent difference between sapwood and heartwood. The process of hot-water soaking, flaking, and drying in preparing wood flakes for OSB production is likely to change the pH and buffer capacities of wood due to the removal of water-soluble extractives.

Resin gel time is considered a relative measure of the rate of resin cure. It is usually characterized by a sudden, striking increase in the viscosity from liquid to a solid gel, as measured by a suitable gel-time apparatus. It was found that the gel time of urea–formaldehyde (UF) resin was directly correlated to wood pH and inversely correlated with acid-buffer capacity for both hardwood and softwood aqueous extracts (Johns and Niazi 1980). The adverse effect of borate in OSB has been attributed to the interference of borate with the resin cure process during hot pressing (Laks et al. 1994, Laks et al. 1988, Sean et al. 1999). It is believed that boron ions react with the functional methylol groups on resin molecules, which causes the resin to precure prior to consolidation. Sean et al. (1999), in evaluating the effect of borate treatment on the physical and mechanical behavior of OSB, used polyethylene glycol (PEG) as a flow agent to improve resin fluidity during hot-pressing. They reported that the adverse effect of borate on adhesive fluidity could be minimized by the addition of organic flow

agents containing hydroxyl (-OH) groups such as PEG. Additional information regarding the gel process of OSB PF resin may shed more light about the resin cure process in the presence of zinc-borate and wood with different chemical properties.

Currently, very little data on chemical properties of OSB flakes are available. Also, the effect of flake pH and buffer capacity on resin gel time in the presence of chemical additives such as zinc borate is still unknown. The study reported here represents the first part of a comprehensive study on developing chemically-modified OSB with desired strength, durability, and termite resistance using southern wood species. The objective of this work was to study effects of wood flake chemical properties and addition of zinc borate on gel time of the PF OSB resin.

2.2. MATERIALS AND METHODS

2.2.1. Material Selection and Sample Preparation

2.2.1.1. Lumber Selection

Green boards (2.44-m long by 2.54-cm thick by random width) from each of the following eleven species were obtained from the Roy O. Martin Lumber Company in South Louisiana. These species included ash (*Fraxinus* spp.), cottonwood (*Populus* spp.), cypress (*Taxodium distichum* (L.) Rich.), elm (*Ulmus americana* L.), hackberry (*Celtis occidentalis* L.), locust (*R. pseudoacacia* L.), pecan (*Carya* spp.), red oak (*Quercus* spp.), white oak (*Quercus alba* L.), willow (*Salix* spp.), and southern pine (*Pinus taeda* L.). Among the species, plantation loblolly pine is a primary species for the manufacture of southern pine OSB. The

nine hardwood species and cypress are among the most common species used to manufacture mixed hardwood OSB. The specific gravity among all wood species ranges from 0.39 to 0.69 (USDA Forest Service 1986).

2.2.1.2. Wood Flake Preparation

The boards were cross-cut along the length of the board into 152.4-mm long blocks. These blocks were soaked in water prior to making flakes. The soaked blocks were flaked using a laboratory disc flaker to produce 76.2-mm long flakes (0.635-mm thick). The wide surfaces of the flake were parallel to either longitudinal-tangential or longitudinal-radial plane, depending on whether the boards were flat or quarter-sawn. The flakes were dried to 2-3% moisture content using a steam-heated cabinet dryer at a temperature of 95^{o}C. The dry flakes were screened to eliminate fines and stored in polyethylene bags until needed. Approximately one kilogram of dry flake from each species was randomly collected for the measurements of pH, buffer capacity, and gel time described in this study. The rest of the flakes were used for preparing OSB.

2.2.1.3. Wood Meal Preparation

A sufficient amount of dry flakes from each of the eleven species was selected. They were Wiley-milled through a coarse screen (20 mesh per 25.4 mm). The produced wood meal was stored in polyethylene bags until needed. The moisture content of the wood meal at the time of testing was 6% for all species.

2.2.1.4. Resin and Chemical Additives

Unbuffered phenol formaldehyde OSB face resin with a 55% non-volatile content was obtained from Neste Resins Corporation in Winnfield, Louisiana. The pH of the resin was 9.8 and specific gravity (SG) was between 1.1 and 1.3. The resin was kept in a freezer prior to the measurements. Several hours before actual tests, a sufficient amount of resin was removed from the freezer. The resin was allowed to thaw and was then placed in a water bath at 20^{o}C to maintain a constant resin temperature. Zinc borate ($2ZnO \cdot 3B_2O_3 \cdot 3.5H_2O$) was obtained from U.S. Borax Company in Valencia, California. The specific density of borate was 2.79. PEG, purchased commercially, has a general formula of $H(OCH_2CH_2)_nOH$. The average degree of polymerization of the PEG is 76.

2.2.2. Measurements of Wood pH and Buffer Capacity

Flake pH and buffer capacity were determined using the method developed by Johns and Niazi (1980) in order to provide a comparable result between the two studies. In this method, a sample of 26.5 g wood meal was obtained for each measurement, which gave 25 g oven-dry wood weight based on the measured moisture content of wood meal (i.e., 6%). The wood meal was refluxed in 250 g of distilled water for 20 minutes to obtain liquid wood extract. The filtrate was then filtered through Whatman #1 filter paper with an aspirator vacuum. An Orion model 410A Benchtop pH meter was used to determine the pH value of the wood extract solution at room temperature (25^{o}C). The meter was calibrated prior to each measurement. In determining the buffer capacities, 50 ml of the extract solution was titrated to a pH of 7 and 3 with 0.025 N NaOH

and H_2SO_4 solutions, respectively. The pH of the solutions was recorded after adding each ml of acid and alkali solution. Acid, alkali, and total buffer capacities were calculated according to the following formula:

Acid buffer capacity (m_{eq}/g) = Volume of 0.025N NaOH solution required to raise from the starting pH equal to 7 x normality of NaOH (2.1)

Alkali buffer capacity (m_{eq}/g) = Volume of 0.025N H_2SO_4 solution required to lower from the starting pH to pH equal to 3 x Normality of H_2SO4 (2.2)

Total buffer capacity (m_{eq}/g) = Acid buffer capacity + Alkali buffer capacity (2.3)

The mean pH (based on four measurements) and buffer capacity (based on two measurements) values were reported for each wood species.

2.2.3. Measurements of Resin Gel Time

A Sunshine gel timer with water bath (100^oC) was used to measure resin gel time. The measurements were conducted according to the schemes listed in Table 2.1. As shown, all tests were made with 10 grams of the PF resin conditioned to a temperature of 20^oC. Test groups 1, 2, and 3 dealt with the effect of borate and PEG on gel time of neat resin (without wood meal). The borate application rates were 0, 0.5, 1.0, 9.0, and 18% based on solid resin weight of 5.5 grams. Test groups 3, 4, and 5 dealt with the effect of borate and PEG on gel time of PF resin in the presence of wood meal. A constant weight of 5.3 grams of wood meal at 6% MC was used for all species. The ZB application

rates were 0, 5, 10, and 20% based on dry wood weight of 5 grams. Using an average surface area ratio between wood flake and wood meal (-9 +20 Tyler mesh particles) of 3.5 (Gardner and Elder, 1988), the corresponding borate covering rate for wood flakes were 0, 1.5, 3.0, and 6%. The PEG application rate was 40% of the corresponding borate weight for all test runs. Two gel time measurements were conducted at each condition. The difference between the two measurements was on average less than 1.5%.

Table 2.1. Experimental design for gel time measurements.

Test Group Number	Experimental Variables			
	Resin [a]	Zinc Borate [b]	PEG [c]	Wood [d]
1	√			
2	√	√		
3	√	√	√	
4	√			√
5	√	√		√
6	√	√	√	√

[a] Resin: Ten grams of liquid PF resin (55% solid) conditioned at 20 °C for all tests.
[b] Zinc borate: Test groups 2 and 3 had 0.5, 1, 9, and 18% of solid resin weight. Test groups 5 and 6 had 5, 10, and 20% of ovendry solid wood weight.
[c] PEG: One PEG application rate at 40% of the corresponding zinc borate weight.
[d] Wood: 5 grams of dry wood meal (test groups 4 and 5 had eleven single species and one mixture of all species, and test group 6 had only southern pine, red oak, and the mixture of all species).

Each material was weighed to the required amount and mixed in a 13- x 100-mm test tube with a mechanical mixer. After inserting a glass test rod in the tube, the tube was quickly placed in the water bath at 100°C. The glass rod was connected by magnetic force to the meter's spinning head, which was connected to a timer inside the meter. The timer was started immediately after the test tube

was placed in the water bath. The tube was allowed to remain in the bath until the viscosity of PF resin showed sudden increase, indicating completion of each test.

2.3. RESULTS AND DISCUSSION

2.3.1. Wood pH and Buffer Capacity

Measured pH and buffer capacity data are presented in Figure 2.1 (a: low density species, b: medium density species, and c: high density species). Initial pH readings and buffer capacities (acid, base, and total) are summarized in Table 2.2. The pH data from the four replicates were quite consistent as indicated by small standard deviations (Table 2.2). The buffer capacity data are plotted in Figure 2.2 for the eleven species.

The pH of wood extracts decreased (Figure 2.1) with addition of H_2SO_4 and increased with addition of NaOH (i.e., buffering). To achieve a given pH level, the amount of H_2SO_4 and NaOH addition varied significantly from species to species. However, the general trend was the same for all species, similar to those reported by Johns and Niazi (1980). As shown in Figure 2.3, the initial pH values of the southern hardwood and cypress flakes studied were on the acidic side with white oak being the most acidic (pH=4.60) and elm being nearly neutral (pH=6.93). Southern pine flakes had a relatively low pH value (4.98), compared to most of the hardwoods. The alkali buffer capacity was larger than the corresponding acid buffer capacity for most wood species tested (Figure 2.2). The total buffer capacity varied from 0.09 (m_{eq}/g) for cypress to 0.358 (m_{eq}/g) for

Table 2.2. Summary of test data on wood flake pH, buffer capacities, and gel time of phenolic ODB face resin.

Species	SG	pH[a]	Buffer capacities[b] (m_{eq}/g)			Gel time (min.) at various zinc borate covering level (based on dry wood weight)[c]			
			Acid	Alkali	Total	0%	5%	10%	20%
Ash	0.49	5.68	0.038	0.125	0.163	22.40	23.18	22.51	20.40
Cottonwood	0.40	6.88	0.003	0.250	0.250	22.28	22.91	22.47	21.23
Cypress	0.46	5.46	0.015	0.075	0.090	22.43	23.30	22.60	20.65
Elm	0.50	6.93	0.005	0.125	0.125	22.57	23.08	22.40	20.40
Hackberry	0.53	6.00	0.058	0.300	0.358	23.07	23.42	22.52	20.55
Locust	0.69	5.04	0.125	0.075	0.133	22.35	23.12	22.60	21.66
Pecan	0.61	5.73	0.041	0.250	0.291	24.08	22.08	22.21	20.58
Red oak[d]	0.59	5.14	0.075	0.125	0.200	22.19	22.40	22.98	20.50
							23.08	22.23	20.86
White oak	0.68	4.60	0.150	0.075	0.225	23.15	24.61	23.90	21.67
Willow	0.39	6.35	0.014	0.203	0.216	23.30	24.22	23.07	20.55
S. Pine[d]	0.58	4.98	0.043	0.071	0.118	22.96	22.48	22.15	20.46
							22.83	22.15	21.12
Eleven						23.08	22.10	21.33	19.65
Mixture[d]							22.83	22.77	21.17

[a] Average value of four measurements from two extract replications.
[b and c] Average value of two measurements from two extract replications.
[d] Data shown under 5, 10, and 20% borate covering rates was from tests made with 40% PEG of corresponding zinc borate weight.

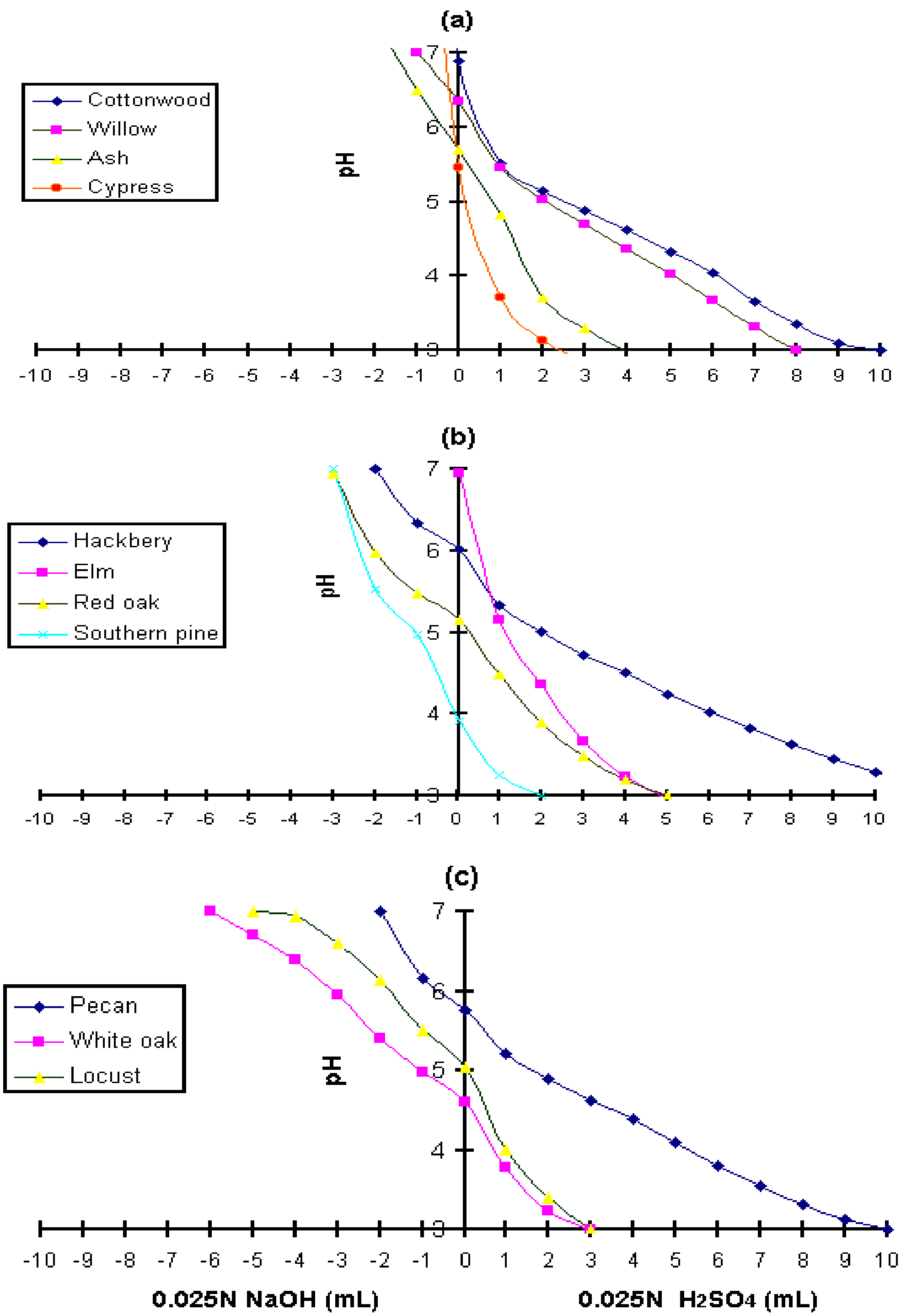


Figure 2.1. The pH, acid, and base buffering potential for (a) low-, (b) medium-, and (c) high-density wood groups.

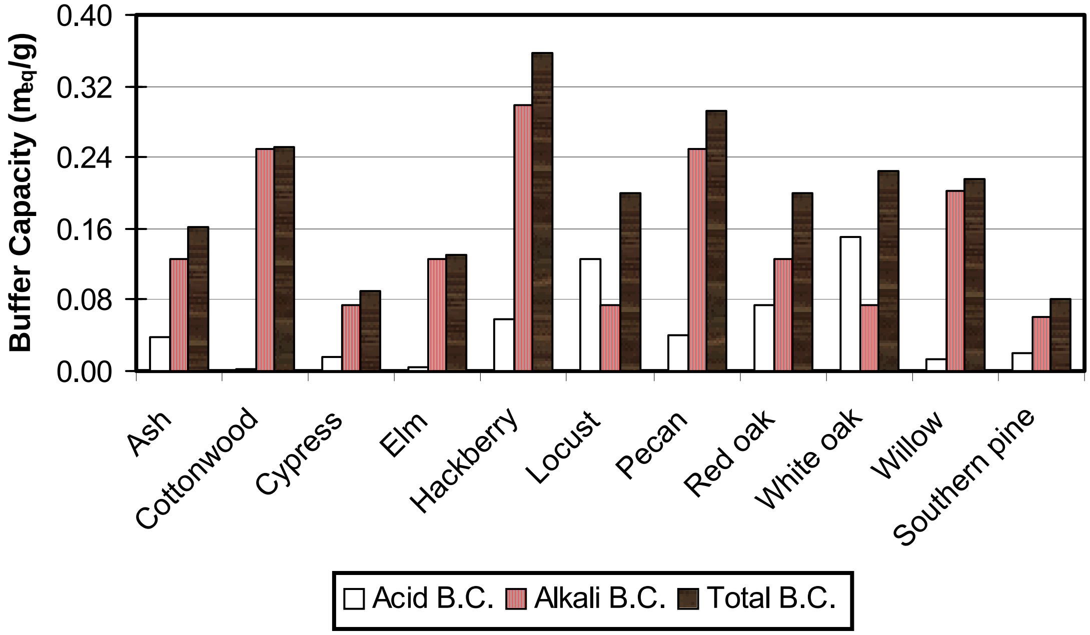


Figure 2.2. The acid, base, and total buffer capacities for eleven southern wood species.

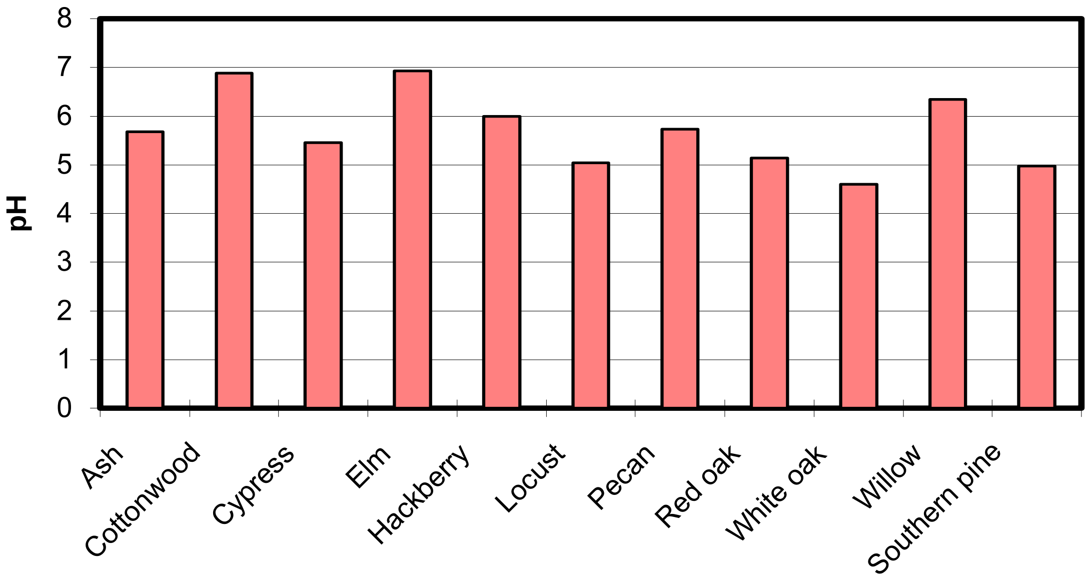


Figure 2.3. The mean pH of eleven southern wood species

hackberry. For the same species, both pH and buffering capacity values from this study were in a range similar to the data reported by Johns and Niazi (1980). However, it is not possible to statistically compare the values from the two studies due to differences in the wood sources and type (solid wood versus wood flakes).

2.3.2. PF Resin Gel Time

Measured gel time for neat PF resin averaged 22.93 minutes (Figure 2.4). The data agreed well with test results made by the resin manufacturer with similar equipment. It should be pointed out that the gel time varies in general with the amount of resin and heating methods used. For example, a water bath at 100^oC tends to give a slightly lower gel time due to the interference effect of water on viscosity development of resin, compared with a silicon oil bath at the same temperature. Thus, the reported resin gel time should be considered as a relative measure among the treatments. Addition of ZB led to a reduced gel time as shown in the graph. At the 0.9% application level, the reduction was slightly over 1% (gel time=22.65 minutes). As the amount of ZB increased, the gel time decreased significantly. At the 18% application level (based on solid resin weight), the gel time was reduced by over 43% (gel time=12.9 minutes). This obviously indicates an interaction between PF resin and ZB. It is believed that boron and oxygen from methyol (CH_2OH) of the PF resin formed the coordinate bonding by donating the lone pair of electrons from oxygen to boron. Such an interaction is known to cause the resin to gel before it is able to develop an effective bond (Sean et al. 1999).

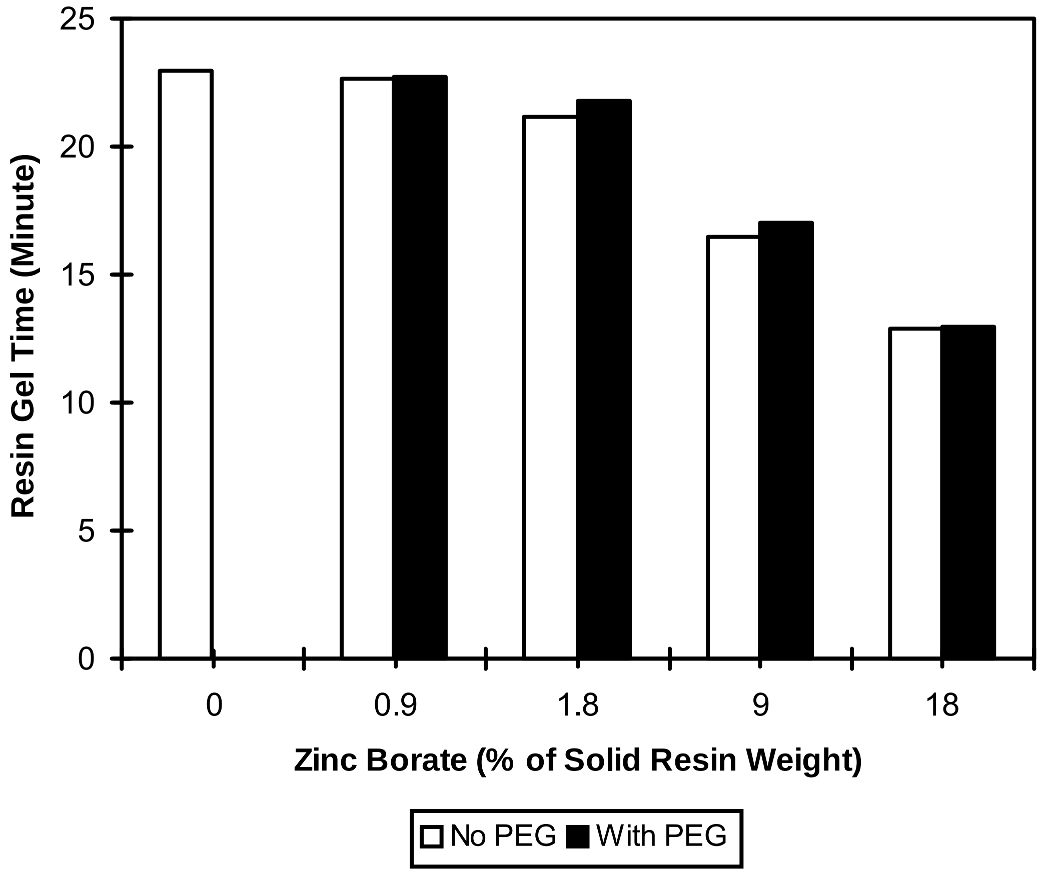


Figure 2.4. Effect of ZB and polyethylene glycol on the gel time of neat phenol-formaldehyde face resin for OSB.

Addition of PEG helped recover some of the lost gel time at a given borate application level (Figure 2.4). At the 40% PEG application rate, gel time was increased by 0.2, 2.7, 3.7, 0.7% at the 0.9, 1.8, 9, and 18% ZB levels based on solid resin weight, respectively. Thus, the effect of PEG appeared to be more pronounced at the intermediate borate application levels. It is believed that the OH functional group of PEG disturbed the linkage between boron and the oxygen ion of CH_2OH in PF resin, making a weak linkage with borate.

The relationship between resin gel time and ZB application rate for various wood species is shown in Figure 2.5 (a: low density species, b: medium density species, and c: high density species). Actual gel time data at various ZB application rates are listed in Table 2.2. At the 0% ZB application level (control), the gel time varied from 22.40 to 24.08 minutes among the species. The mean gel time for all species (22.67 minutes) was not significantly different from that of neat resin (22.93 minutes), indicating little effect of wood species alone. At the 5% ZB loading rate, gel time for most species increased. Further increases in ZB content led to decrease in resin gel time. At the 20% loading rate, the average gel time was reduced by about 8 %.

Plots demonstrating a combined effect of wood (southern pine, red oak, and a mixture of the eleven species), ZB, and PEG on resin gel time are shown in Figure 2.6 (a: 5% ZB, b: 10% ZB, and c: 20% ZB). The effect of borate and PEG on the gel time varied from species to species. At the 5% ZB application rate, the gel time was reduced by 2%, -0.1% (an increase), and 4.2% for

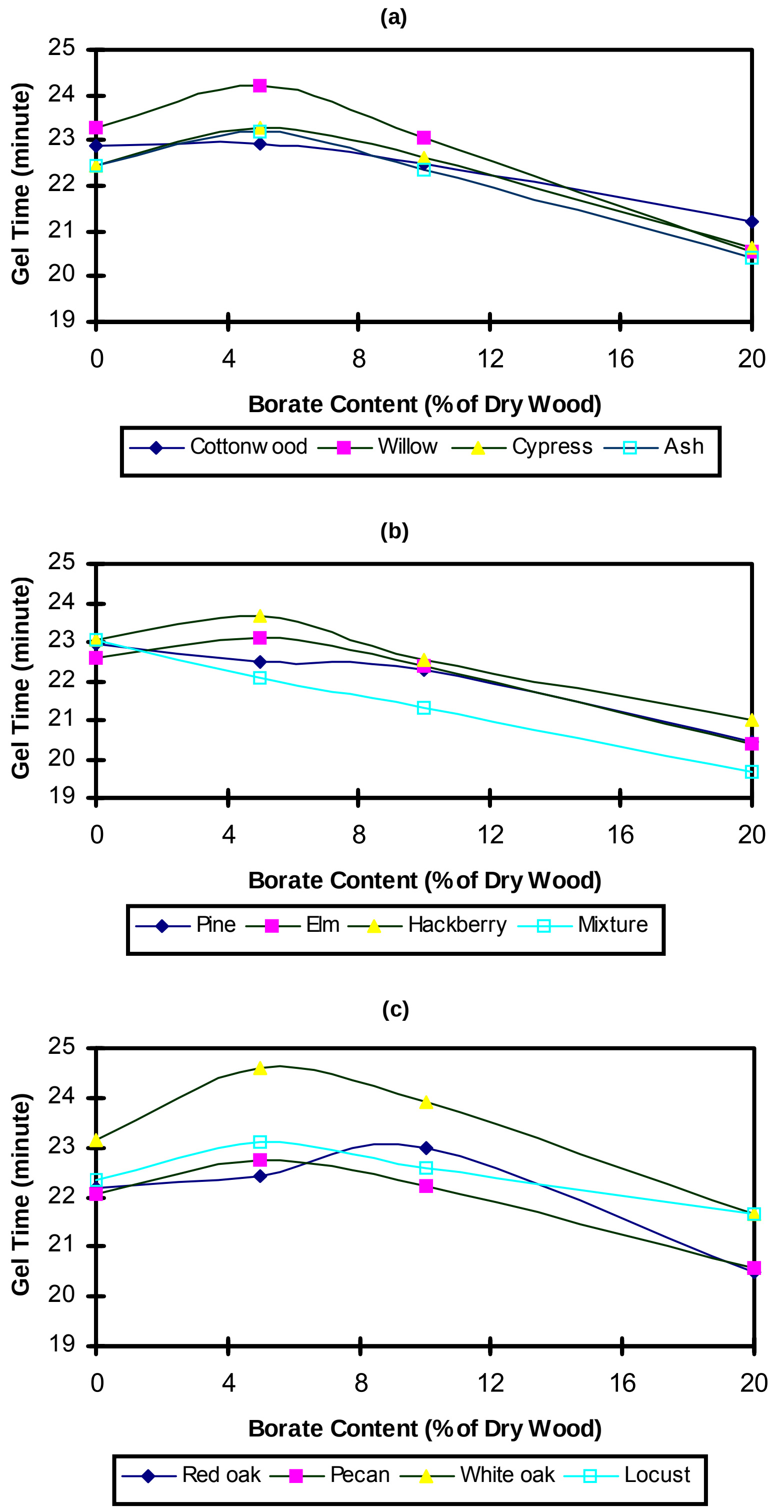


Figure 2.5. Measured PF resin gel time as a function of zinc borate content for (a) low-, (b) medium-, and (c) high-density species groups.

southern pine, red oak, and the mixture, respectively. Adding PEG to the resin-wood-ZB mixture led to an increase in the gel time for all three species groups. At the 10% ZB application level, the gel time was reduced by 3.5% for southern pine, 1% for red oak, and 7.5% for the mixture. Adding 40% PEG at this ZB application level led to a significant recovery of the reduced gel time for the mixture. At the 20% ZB application rate, there was an average of 9% reduction in the gel time for all three species groups. The use of PEG led to some recovery in the gel time, but the extent was smaller compared to the two smaller ZB application levels, especially for the mixture. This indicates that PEG can only help to a certain extent in offsetting the negative effect of ZB on the resin gel process. Once the ZB content reaches a certain level, PEG may not provide significant improvement in the gel time. Sean et al. (1999) used PEG to improve the flow properties of phenol-formaldehyde resin in OSB manufacturing. They found an improvement in resin flow with the addition of the flowing agent. The curing time of PF resin increased markedly with an increased amount of PEG presence, as compared to the controls.

2.3.3. Correlation between Flake Chemical Properties and Resin Gel Time

There was no significant correlation between the gel time of PF resin and flake pH, acid or base buffer capacity (Figure 2.7). Johns and Niazi (1980) found that the gel time of UF resin was directly correlated with acid buffer capacity for both softwood and hardwood extracts. They showed that the gel time of UF resin decreased with a decrease in wood pH and with an increase in acid buffer capacity. The difference may be due to the type of materials (solid

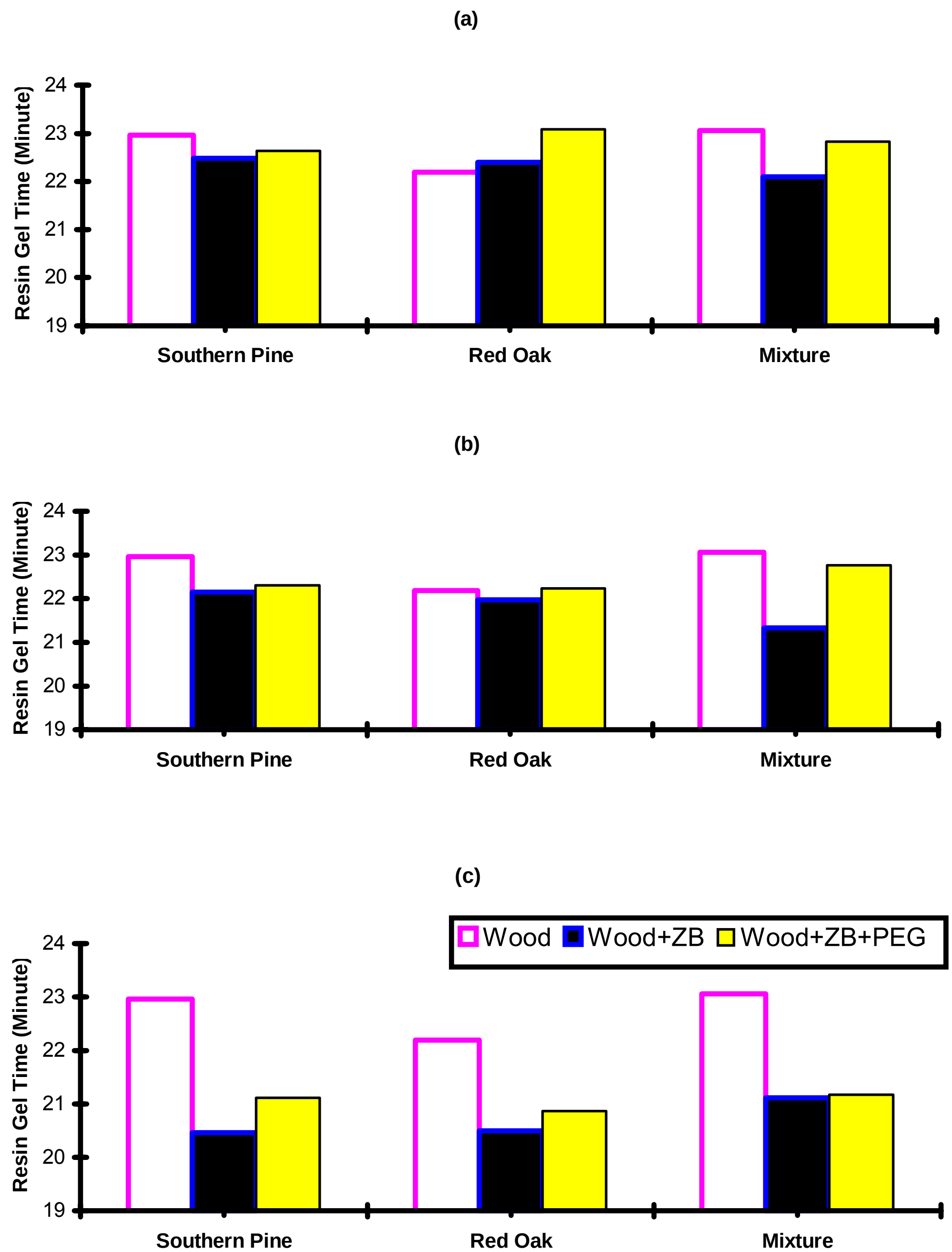


Figure 2.6. A comparison of the PF resin gel time as influenced by zinc borate, PEG, and wood (southern pine, red oak, mixture of eleven wood species). Borate contents were (a) 5%, (b) 10%, and (c) 20% based on 5g of OD wood meal. PEG was 40% based on the borate weight.

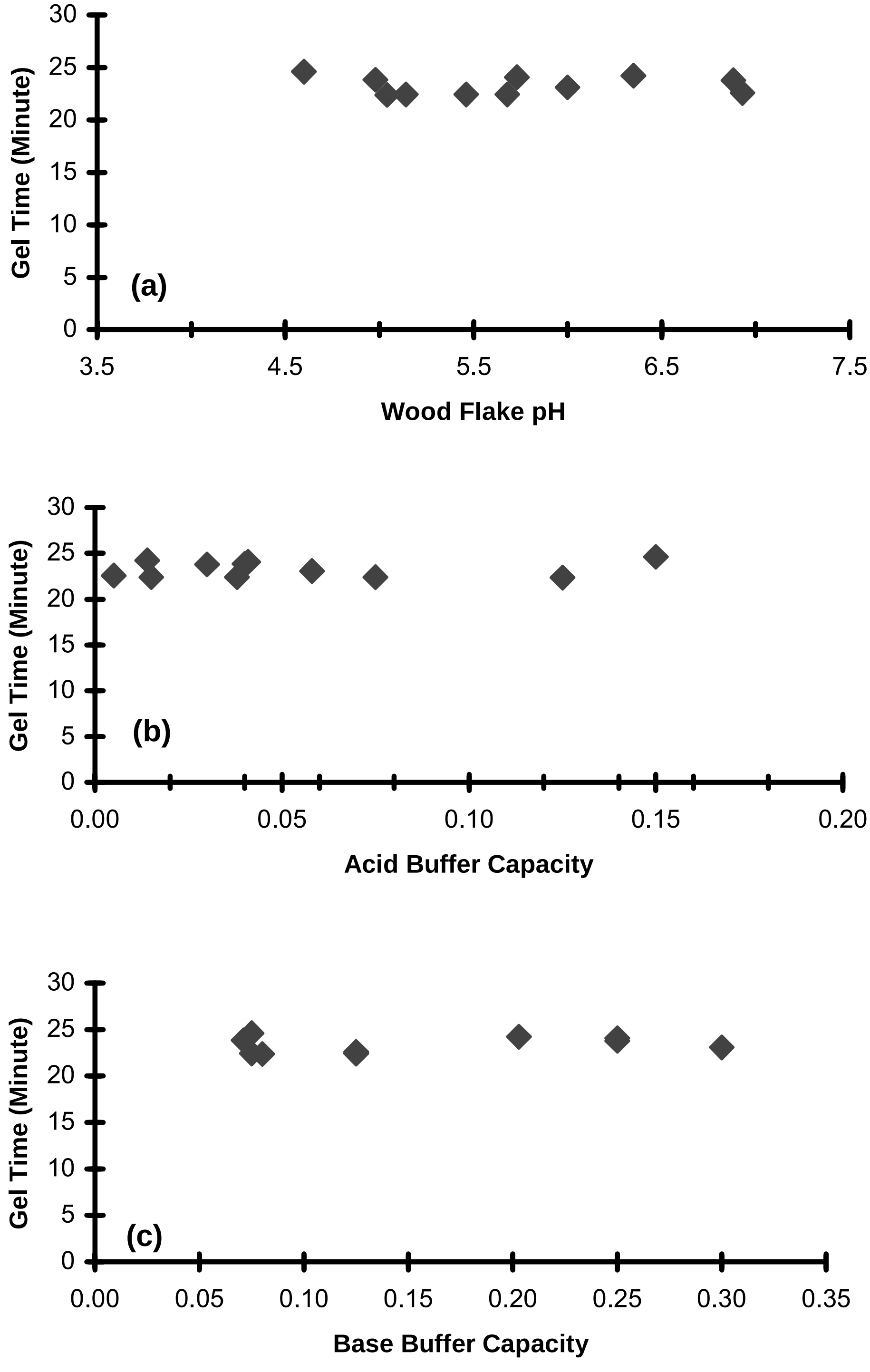


Figure 2.7. Scatter-plot of resin gel time as a function of (a) wood flake pH, wood acid buffer capacity, and (c) wood base buffer capacity.

wood versus wood flakes) and resin type (urea formaldehyde versus phenol formaldehyde) used in the two studies.

2.4. CONCLUSIONS

The chemical properties of wood flakes from eleven southern species and gel time of PF OSB face resin under the influence of wood, ZB, and PEG were investigated, as part of a study with an ultimate goal of developing chemically-modified OSB for residential construction. It was found that the pH of the southern hardwood flakes was acidic, in which white oak was the most acidic (pH=4.60), and elm was nearly neutral (pH=6.93). Flakes from southern pine had a relatively low pH value of 4.98, compared to the southern hardwood flakes. For most species tested, the alkali buffer capacity was larger than the corresponding acid buffer capacity. The total buffer capacity varied from 0.09 for cypress to 0.358 for hackberry. Wood species alone had little effect on the gel time of the PF OSB resin. The measured gel times decreased as the amount of ZB increased. The reduced gel time was partially recovered by using PEG in combination with ZB. The effectiveness of PEG varied with wood species and the level of borate used. The gel time of PF resin-wood mixture had no direct correlation with the pH of wood and buffer capacity for the species studied.

2.5. REFERENCES

Bryant, B.S. 1968. Interaction of wood surface and adhesive variables. Forest Prod. J. 18(6): 57-62.

Campbell, W.G., and S.A. Bryant. 1941. Determination of pH in wood. Nature 47: 357.

Chen, C. 1970. Effect of extractive removal on adhesion and wettability of some tropical woods. Forest Prod. J. 20(1): 36-41.

Cotton, A., and W. Wilkinson. 1988. Advanced Inorganic Chemistry. 5th ed. Wiley-Interscience Publication. John Wiley & Sons. New York, NY.

Fengel, D., and G. Wegner. 1984. Wood chemistry ultrastructure reactions. Walter de Gruyter. New York, NY. 220-221 pp.

Gardner, D.J., and T.J. Elder. 1988. Surface activation treatment of wood and its effect on the gel time of phenol-formaldehyde resin. Wood Fiber Sci. 20(3): 378-385.

Gray, V.R. 1958. The acidity of wood. J. Inst. Wood Sci. 1: 58-64.

Ingruber, O.V. 1958. The behavior of wood and wood constituents as acid-buffering systems. Pulp Paper Mag. Can. 59: 135-141.

Johns, W.E., and K. A. Niazi. 1980. Effect of pH and buffering capacity of wood on the gelation of Urea-formaldehyde resin. Wood Fiber Sci. 12(4): 256-263.

Jordan, D.L., and J.D. Wellon. 1977. Wettability of dipterocarp veneers. Wood Sci. 10(1): 22-27.

Laks, P.E., X.Quan, and R.D. Palardy. 1994. The effects of sodium octaborate tetrahydrate and zinc borate on the properties of isocyanate-bonded waferboard. In: Proc. Symp. Adhesives/Bonded Wood. C.-Y. Hse and B. Tomia, eds. Forest Prod. Soc. Madison, WI. 144-157 pp.

Laks, P.E., B.A. Haataja, R.D. Palardy, and R.J. Bianchini. 1988. Evaluation of adhesives for bonding borate-treated flakeboards. Forest Prod. J. 38(11/12): 23-24.

Maloney, T.M. 1977. Modern particleboard and dry-process fiberboard manufacturing. Miller Freeman Publications, San Francisco, CA.

Philippou, J., E. Zavarin, W. Johns, and T. Nguyen. 1982. Bonding of particleboard using hydrogen peroxide, lignosulfonates, and furfuryl alcohol: effects of chemical composition of bonding materials. Forest Prod. J. 32(5): 55-61.

Ring, D. 1999. Need for integrated pest management of the Formosan Subterranean Termite. Technical Note, LSU Agriculture Center. 3 pp.

Sean, T., G. Brunette, and F. Côtẻ. 1999. Protection of oriented strandboard with borate. Forest Prod. J. 49(6): 47-51.

Shupe, T.F, and M.A. Dunn. 2000. The Formosan subterranean termite in Louisiana: Implications for the forest products industry. Forest Prod. J., 50(5): 10-18.

Stamm, A.J. 1961. A comparison of three methods for determining the pH of wood and paper. Forest Prod. J. 11(3): 310-312.

USDA Forest Service. 1986. Wood Handbook: Wood as an engineering material. Agri. Handbook. No. 72. USDA Forest Prod. Lab., Madison, WI. 466 pp.

CHAPTER 3

MECHANICAL AND PHYSICAL PROPERTIES OF BORATE-MODIFIED ORIENTED STRANDBOARD

3.1. INTRODUCTION

Rapid increase of damages by the Formosan subterranean termites (FST) in wooden structure has accelerated the development of chemically-modified oriented strandboard (OSB). Preliminary work has been done to treat wood flakes with powder borate during the blending operation (Laks et al. 1990a, 1990b, 1991). This approach permits the manufacture of wood composites that contain fixed borate chemicals. Although powder zinc borate (ZB) and calcium borate (CB) are effective in protecting structural wood composites, their effects on the mechanical and physical properties of modified OSB are still not well understood.

Preservatives have the ability to significantly extend the service life of wood materials. However, they typically show an adverse effect on product properties. For example, it has been shown that inorganic waterborne preservatives generally reduce the bending strength of solid wood by 5 to 10 percent, depending on the chemical type, retention of chemical, redrying method, and temperature employed (Winandy 1988). The possibility of such effects must also be considered when treating wood-based composites. In exterior environments, many types of treated wood-based composites suffered serious losses in both mechanical properties and dimensional stabilities when compared

to solid wood which was exposed to similar conditions (Youngquist 1987).

A number of studies have previously reported effects of borate on the properties of treated wood composites. For example, the addition of sodium octaborate tetrahydrate (TIM-BOR®) to isocynate-bonded flakeboard showed little effect on the bending modulus of elasticity (MOE), modulus of rupture (MOR), and internal bond (IB) strength (Laks et al. 1988). However, the use of zinc borate (ZB) at high loading levels led to reductions in both MOE and IB strength (Laks et al., 1991). Sean et al. (1999) reported that MOE of treated OSB panel was not adversely affected by ZB treatment at loading levels up to 5.0%. However, MOR and IB strength correspondingly decreased with the increase of ZB loading levels. This problem is presumably related to the interaction between functional methylol group (CH_2OH) on resin molecules and borate ions, which causes the resin to gel before it is able to develop an effective bond (Sean et al. 1999, Lee et al. 2001). Therefore, the borate may interfere with the development of glue-line strength. In addition, the borate can cause flake furnish and final boards to be more brittle through crystal formations within wood cell walls at higher loading levels (Draganov 1968). It was reported that the adverse effect of borate on the mechanical properties could be reduced by adding organic flow agents containing hydroxyl (-OH) groups such as polyethylene glycol (PEG) (Sean et al. 1999).

Due to its widespread use, OSB is often exposed to various environmental conditions. Although direct water sorption into OSB is a rare occurrence, protection against direct water sorption is required for OSB. It is well documented

that wood-based composites swell significantly in thickness (i.e., thickness swelling, TS) under direct water exposure. Hence, OSB is not generally used in unprotected outdoor applications. A water-soaking test has been applied to evaluate the dimensional stabilities of the board (Biblis 1985, Winistofer and Dicarlo 1988, Generalla et al. 1989, Xu and Winistofer 1995). TS and water absorption (WA) increase in relation to an increase of soaking time for composite materials (Lehmann 1978). A decreased bond efficiency following an increased borate level for borate-modified OSB was reflected by increased TS and WA. The values of TS and WA increased as ZB loading levels increased (Laks et al. 1991, Laks and Manning 1997).

Currently, very few data on mechanical and physical properties of borate modified OSB from southern wood species are available. The study reported in this chapter forms a portion of a comprehensive project on investigating the long-term durability of borate-modified OSB from southern wood species. The specific objective of this chapter was to investigate the effect of borate type, borate level, PEG, and wood species on mechanical (MOE, MOR, and IB) and physical properties (TS) of borate modified OSB. The following three chapters deal with leaching, termite, and decay resistance properties of the borate-modified OSB.

3.2. MATERIALS AND METHODS

3.2.1. Panel Manufacturing

Green boards from each of the following eight species were obtained from the Roy O. Martin Lumber Company in South Louisiana. 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*.). Among the species, southern pine is a primary species for manufacturing southern pine OSB. It was used as a reference for comparison among the hardwood species. The boards were cross-cut and then 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 subsequently used to manufacture single species OSB for zinc borate, and mixed hardwoods and southern pine OSB for calcium borate.

Phenol formaldehyde (PF) resin with a 55% non-volatile content was obtained from Neste Resins Corporation in Winnfield, LA. The panels were fabricated with dry flakes and the PF resin (4.0% based on the oven-dry wood weight). Wax was used at 1.0% level (based on ovendry wood weight). There were one type of zinc borate, $2ZnO\cdot3B_2O_3\cdot3.5H_2O$, and two types of calicium borate (CB), $Ca_2B_6O_{ll}\cdot5H_2O$, with two different particle sizes (Figure 3.1). ZB has a density of 2.79 g/m^3 with a mean particle size of 6.61μm in diameter. ZB presents low acute oral toxicity (LD_{50} (rat)>10g/kg of body weight) and dermal toxicity (LD_{50} (rabbit)>10g/kg of body weight). CB has little or no hazard and low cute oral toxicity (LD_{50} (rat) >1g/kg) and exhibits dermal toxicity (LD_{50} (rabbit) >1g/kg of body weight). The density of CBs is 2.42 g/cm^3 with mean particle sizes of 6.43 and 11.09 μm, respectively.

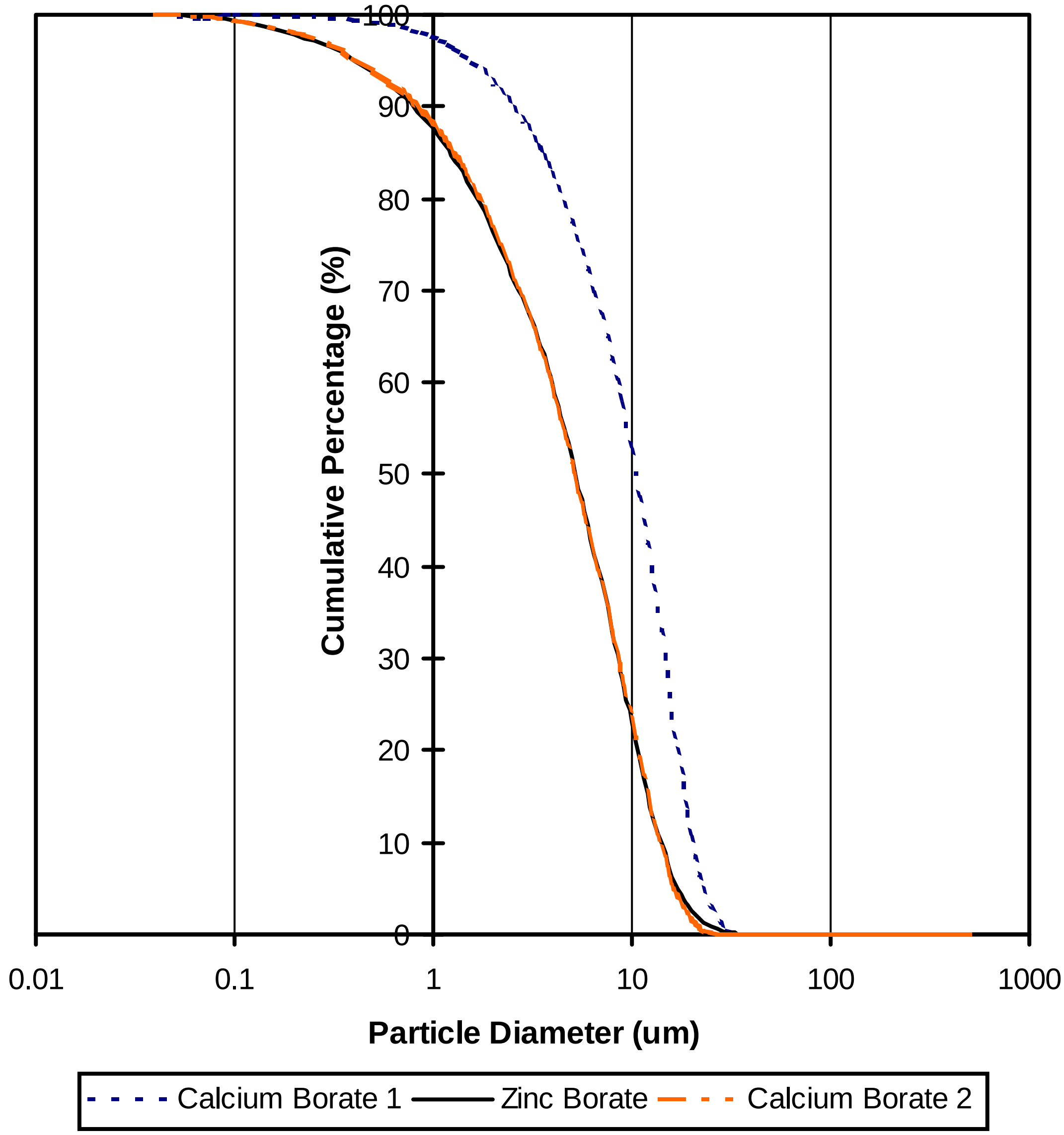


Figure 3.1. Particle size distribution of zinc borate (ZB), calcium borate 1 (CB1), and calcium borate 2 (CB2) used in the study.

Powder ZB and CB were sprayed onto flakes during the blending process. The target loading levels for ZB were 0 (control), 0.5, 1.0, and 3.0% based on the oven-dry flake weight in the panel. The target loading levels for each CB were 0 (control), 0.75, 1.5, 3.0, and 4.5% (based on the oven-dry flake weight). Three single species (ash, locust, and southern pine) panels were made with zinc borate in combination with PEG, $[H(OCH_2CH_2)_{n>4}OH]$, loaded at 40% of the borate weight to study its effect on panel properties.

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 minutes at 1.71MPa pressure and 200^{o}C temperature. The target thickness and panel specific gravity (SG) were 1.27 cm and 0.75, respectively. The resulting boards (55.9- x 50.9- x 1.27-cm) were cooled and conditioned at 22^{o}C and 55% RH prior to testing.

3.2.2. Boron Analysis

For boron chemical analysis, OSB samples (5.08- x 5.08- x 1.27-cm) were cut from each panel. The samples were Wiley-milled to pass through a 20-mesh screen. Five grams of wood meal were selected and placed in a bottom-flat flask with a solution of 100mg 2N HNO_3. The flask was connected to a water-cooled condenser. The flask was heated on a heating mantle for 2 hours at 100^{o}C for digesting. Thereafter, the flask was cooled for 30 minutes while maintaining seals between the flask and the condenser. The digested samples were filtered using Whatman #2 filter paper over a filter funnel, and the analyte was analyzed by

ICP-OES (Inductively Coupled plasma – Optical Emission Spectrometry) to determine actual chemical composition in the sample.

The percentage of boron, zinc, and calcium was 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 boric acid equivalent (BAE). The term "assayed BAE" refers to the amount of boric acid 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 by the following formulas, respectively.

$$\text{\% Boron, Zinc, and Calcium} = [Va \times C \times 100] / W_w \qquad (3.1)$$

$$\% B_{ZB} = \text{\% Boron} / 0.1492 \qquad (3.2)$$

$$\% Zn_{ZB} = \text{\% Zinc} / 0.3 \qquad (3.3)$$

$$\% B_{CB} = \text{\% Boron} / 0.168 \qquad (3.4)$$

$$\% Ca_{CB} = \text{\% Calcium} / 0.3 \qquad (3.5)$$

$$\text{\% BAE (Boric Acid Equivalents)} = [\% B_{ZB} \text{ or } B_{Ca}] / 1.17 \qquad (3.6)$$

where, V_a = The volume of analyte (ml);

C = The concentration of boron, zinc, and calcium (µg x10^{-6}) converted ICP-AES;

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 molecular weight of 3(B_2O_3) to 3(BO_3).

3.2.3. Mechanical Property Testing

For mechanical property testing, two test samples (30.48- x 7.62 x 1.27-cm) were cut from each panel. The samples had two replications at each borate level, chosen randomly for the evaluation of static bending properties. A concentrated load was applied at the center of the specimen, using an INSTRON testing machine according to the ASTM D-1037 (ASTM 1999). Bending MOE and MOR of the OSB were determined from the load and displacement data. The dimensions and weight of each test sample were measured before testing. Each specimen was reweighed immediately after ovendrying. The moisture content (MC) and specific gravity (SG) of each specimen were then calculated. Specific modulus of elasticity (SMOE) and specific modulus of rupture (SMOR) were obtained by dividing MOE and MOR of each specimen by its corresponding SG.

Eight IB specimens (5.08- x 5.08- x 1.27-cm) were cut from each OSB. A total of 328 IB specimens were prepared for the evaluation of IB strength in accordance with the ASTM D-1037 (ASTM 1999). Specific internal bond (SIB) value was obtained by dividing IB values by its SG of each sample.

3.2.4. Measurements of Thickness Swelling Properties

For thickness swelling testing, specimens (15.24- x 15.24- x 1.27-cm) of ZB-modified OSB from six southern wood species (southern pine, ash, locust,

pecan, red oak, and cypress), and of CB-modified OSB from southern pine and mixed hardwoods were prepared with two replications at each borate loading level. Each specimen was labeled on the surface according to species, group number, and replication. Thickness measurements were carried out at the center and at 2.54-cm positions from each edge, according to the ASTM D-1037 (ASTM 1999). Weight and thickness changes from the air-dry condition to 24-hour water soak condition were used to calculate water absorption (WA) and TS.

3.2.5. Data Analysis

Statistical comparisons based on two-way and three-way analyses of variance (ANOVA) were performed to test the effects of wood species, borate levels, borate types, and their interactions on mechanical and physical properties. A linear regression analysis was done to establish the correlations among initial BAE levels, SMOE, SMOR, SIB, WA, and TS for panels with different wood species and borate types (Wozniak and Geaghan 1994).

3.3. RESULTS AND DISCUSSION

3.3.1. Zinc Borate-Modified OSB

3.3.1.1. Static Bending Properties

Averages of SMOE and SMOR for treated and untreated samples from each species are presented in Table 3.1. Cottonwood OSB showed relatively high SMOE and SMOR values, while southern pine OSB had lower values compared with other species. SMOE values for all species ranged from 6.0 GPa for elm at the 1.27% BAE level to 8.95 GPa for cottonwood at the 1.42%

BAE level. ZB treatment did not show a significant effect on panel bending stiffness (Figure 3.2(a)). SMOE for pecan, red oak, and elm decreased with increased BAE levels, whereas the reduction of SMOE was small in southern pine, cypress, and ash. This result indicates that panel stiffness is not affected significantly by the chemical additive. It was also reported that MOE values for OSB panels from aspen flakes were not adversely affected by adding ZB (Sean et al. 1999).

SMOR values for all species ranged from 39.18 MPa for southern pine OSB at the 0.76% BAE level to 69.01 MPa for ash at the 0.28% BAE level. Most of the wood species, except for cypress and red oak, had decreasing trends in SMOR values with increased ZB levels (Figure 3.2(b)). This result indicates that the reduction of SMOR is related to the decreased bonding strength between wood flakes and PF resin due to the addition of ZB. Regression analysis showed that SMOR and SMOE were significantly related (Figure 3.3). There was a positive linear relationship between the two variables. The R-square value indicates that 64.95% of the variation in SMOR was explained by SMOE. According to the two-way ANOVA (Table 3.2), the main effect of wood species at three different levels of ZB was highly significant on SMOE and SMOR of the OSB at the 5% significance level ($P<.0001$). ZB loading levels showed no significant effect on SMOE and SMOR ($P = 0.054$ and $P = 0.6797$, respectively). The interaction effects between wood species and ZB loading levels were also not significant for SMOE and SMOR.

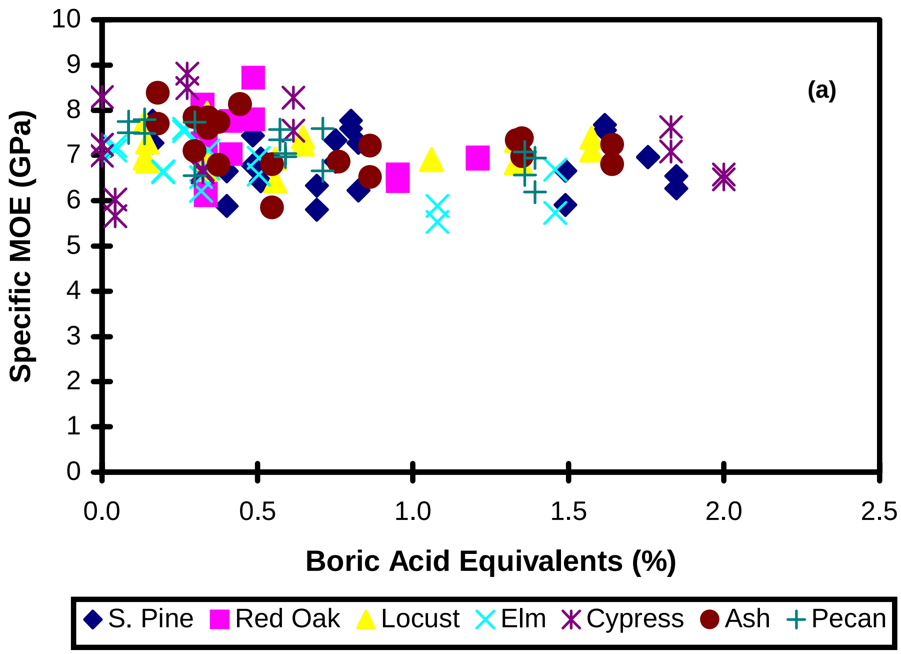
Table 3.1. Summary of static bending and internal bond (IB) properties of ZB-modified OSB panels from southern wood species.

Species	BAE[b] (%)	EMC (%)	Bending Properties SG[c]	SMOE (GPa)	SMOR (MPa)	IB Properties SG[d]	SIB (KPa)
SP	0	5.48	0.77	6.75	49.27	0.70	646.20
	0.50	4.27	0.82	6.89	47.15	0.76	440.74
	0.76	4.02	0.82	6.41	40.17	0.72	218.78
	1.67	3.85	0.86	6.35	42.07	0.75	243.57
PEG[a]	0.91	4.30	0.85	7.39	46.73	0.77	239.01
PEG	2.15	5.05	0.86	7.29	39.18	0.80	261.42
AS	0.28	4.23	0.79	7.66	69.01	0.71	1514.49
	0.32	4.39	0.76	7.60	59.98	0.71	1380.12
	0.50	4.91	0.81	7.23	56.67	0.75	1138.21
	1.50	5.03	0.80	7.10	55.45	0.75	1456.08
PEG	0.69	5.00	0.81	6.87	54.02	0.74	1138.48
PEG	1.14	4.51	0.82	7.10	61.28	0.78	1555.50
LO	0	4.89	0.69	6.21	44.53	0.73	798.88
	0.34	3.61	0.78	7.07	50.52	0.83	932.33
	0.60	3.71	0.79	7.00	53.24	0.84	752.55
	1.34	3.16	0.81	6.96	46.02	0.80	1174.26
PEG	1.06	3.55	0.81	6.91	43.98	0.84	1049.68
PEG	2.51	3.13	0.82	7.25	47.88	0.87	1001.91

Table 3.1. (continued).

Species	BAE[b] (%)	EMC (%)	Bending Properties SG[c]	SMOE (GPa)	SMOR (MPa)	IB Properties SG[d]	SIB (KPa)
EL	0	5.20	0.85	6.31	55.66	0.73	1054.85
	0.30	4.53	0.80	7.23	55.75	0.76	549.28
	0.41	4.65	0.79	6.56	48.18	0.74	869.61
	1.27	4.39	0.80	6.00	43.10	0.74	557.62
RO	0	5.53	0.69	6.61	48.04	0.70	908.43
	0.33	4.66	0.80	6.63	46.68	0.76	808.60
	0.46	4.12	0.82	7.82	60.07	0.75	961.51
	1.08	4.49	0.80	6.72	48.08	0.74	808.18
PE	0	4.57	0.84	7.63	55.32	0.72	908.43
	0.44	4.81	0.82	7.30	53.01	0.75	808.60
	0.65	4.37	0.85	7.07	57.54	0.78	961.51
	1.38	3.97	0.82	6.70	54.66	0.74	808.18
CY	0	5.20	0.72	6.78	51.11	0.73	548.69
	0.16	4.70	0.83	7.25	54.66	0.77	539.04
	0.47	4.55	0.78	7.29	53.17	0.66	338.77
	1.91	3.95	0.83	6.94	60.99	0.76	603.85
CO	0	3.98	0.82	8.76	66.60	0.76	457.23
	0.36	3.56	0.81	8.23	59.70	0.72	279.36
	0.48	3.67	0.80	8.97	68.64	0.71	405.28
	1.42	3.48	0.83	8.95	68.79	0.79	479.59

[a] 40% polyethylene glycol (PEG) is based on the weight of Zinc borate. [b] BAE (%) indicates the Boric Acid Equivalents and average value from 4 specimens from two panels. [c] SG is the average value from 4 specimens from two panels. [d] SG in IB result is the average value from eight specimens from two panels. SMOE and SMOR values are the average values from 4 specimens from two panels. RO-red oak, SP-southern pine, PE-pecan, AS-ash, EL-elm, CO-cottonwood, LO-locust, and CY-cypress.



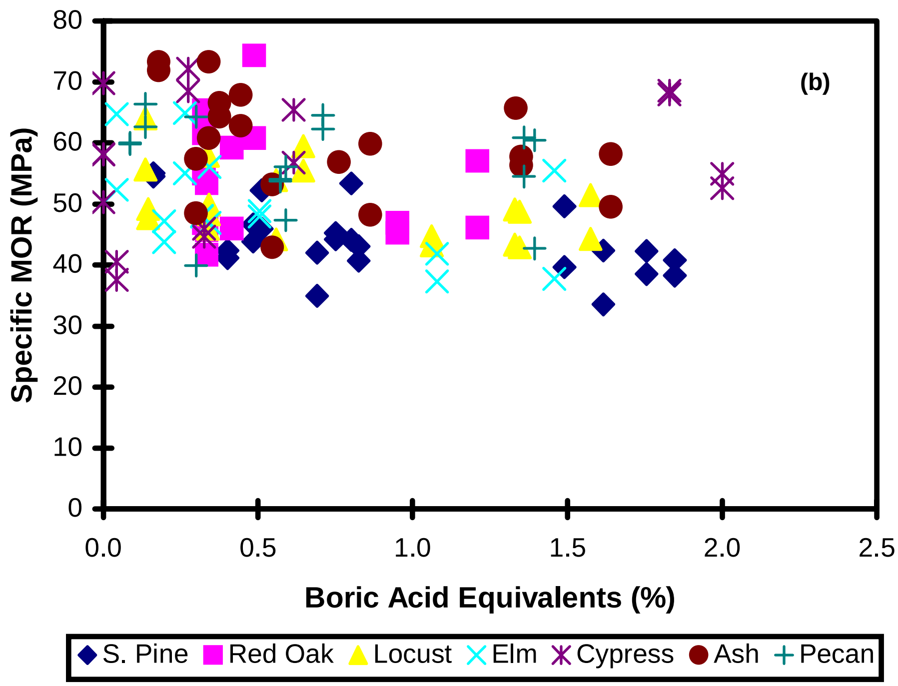


Figure 3.2. Relationship between SMOE (a)/SMOR (b) and assayed BAE from ZB-modified OSB from southern wood species.

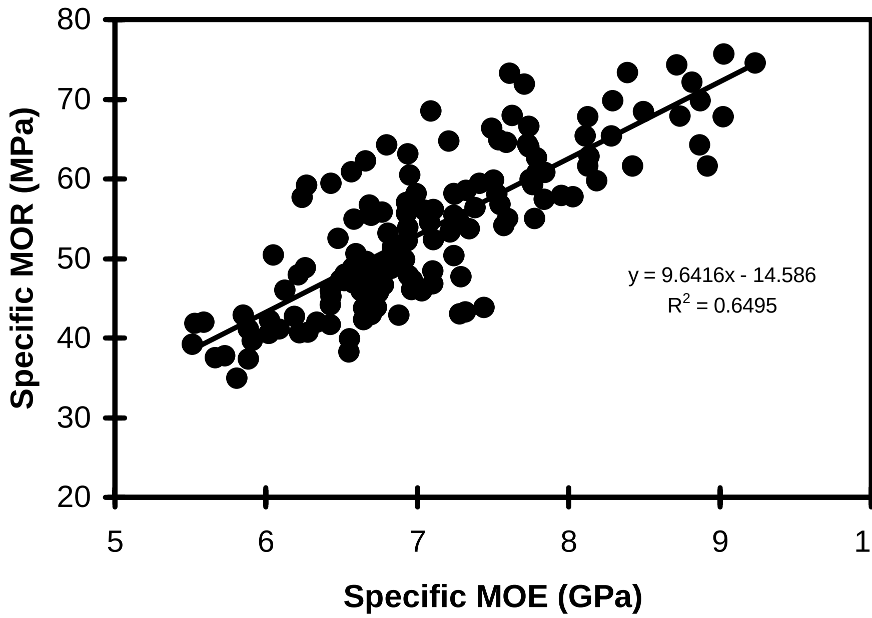


Figure 3.3. Relationship between measured SMOR and SMOE of ZB-modified OSB from combined wood species.

Table 3.2. Results of two-way ANOVA for static bending properties of ZB-modified OSB.

Variable[a]	Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
	Model	31	1095768.4	35347.3	5.00	<.0001
SMOE	Species	7	731567.5	104509.6	14.77	<.0001
	Level	3	56114.5	18704.8	2.64	0.0540
	Species*Level	21	236693.4	11271.1	1.59	0.0687
	Error	90	636809.6	7075.6		
	Model	31	134.4	4.3	3.41	<.0001
SMOR	Species	7	87.8	12.5	9.85	<.0001
	Level	3	1.9	0.6	0.51	0.6797
	Species*Level	21	40.6	1.9	1.52	0.0906
	Error	90	114.5	1.3		

[a] SMOE – Specific modulus of elasticity (GPa) and SMOR – Specific modulus of rupture (MPa).

The effect of PEG on bending properties was significant for OSB made of southern pine, locust, and ash (Table 3.1). For southern pine OSB at the BAE levels of 0.91% and 2.15% with PEG, the SMOE values increased 28 and 14 percent, respectively, compared to untreated southern pine OSB. Ash and locust OSB showed similar effects. For locust OSB at the 0.91% BAE level, the SMOE values increased approximately 4.2%. SMOR from panels with PEG generally increased for southern pine and ash. For southern pine OSB at the 0.91% BAE, the SMOR value with PEG was 16% higher than that at the 0.76% BAE level without PEG. This indicates that the OH- functional group of PEG substituted the covalent bonding between boron and the oxygen ion of CH_2OH in PF resin, thus improving the glueability of the resin.

3.3.1.2. Internal Bond (IB) Properties

Mean SIB values ranged from 0.22 KPa for southern pine OSB at the 0.76% BAE to 1.55 KPa for ash OSB at the 1.14% BAE (Table 3.1). Southern pine and cottonwood OSB had the lowest IB values, whereas ash OSB had the highest IB values. Control panels from each species displayed higher IB values than treated panels. Thus, ZB had negative effects on IB strength for all species (Figure 3.4). The negative effects are presumably related to the interference of ZB with the development of glue-line strength during the curing process. It is also noted that some powdered ZB remained in a powder state on the flake surfaces, thereby reducing the effective bonding area at the interface. Sean et al. (1999) reported that low IB values were related to the increased viscosity of the PF resin

by borate, preventing it from adequate wetting and penetration on the flake surfaces.

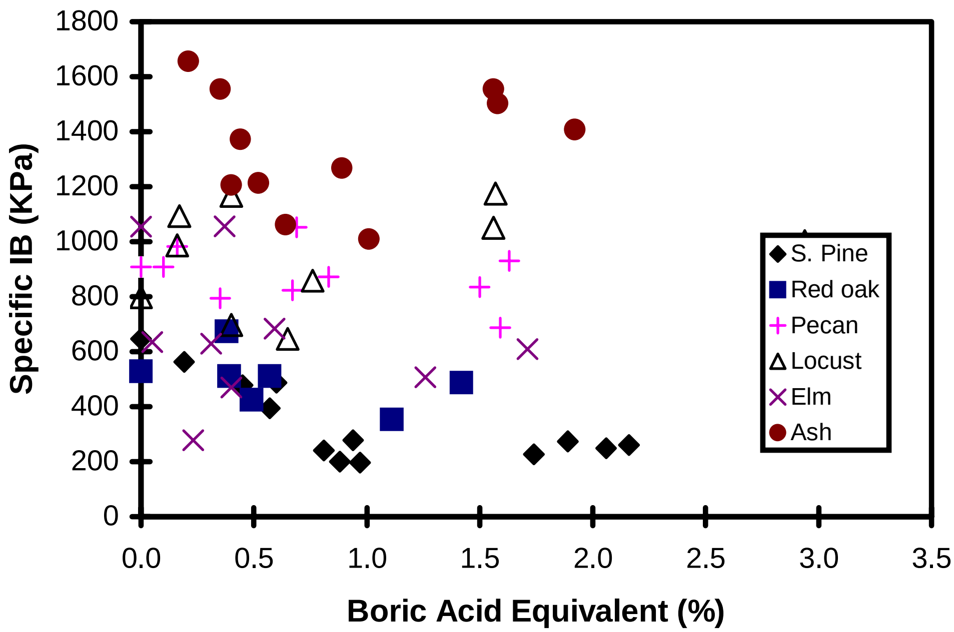


Figure 3.4. Relationship between SIB and assayed BAE of ZB-modified OSB from six wood species.

The results of the two-way ANOVA indicated that the differences among treatment means were significant at the 5% significance level (Table 3.3). The main effects of wood species and ZB loading levels were highly significant on the SIB of the ZB-modified OSB from eight wood species.

Table 3.3. Results of two-way ANOVA for IB properties of ZB-modified OSB.

Variable[a]	Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
	Model	31	633701.38	20441.98	24.00	<.0001
	Species	7	527106.45	75300.92	88.42	<.0001
SIB	ZB	3	20051.98	6683.99	7.85	<.0001
	Species*ZB	21	86542.95	4121.09	4.84	<.0001
	Error	224	190753.90	851.58		

[a]SIB - Specific internal bond strength (KPa).

The IB strength of the borate-treated panels containing 40% PEG (based on the weight of ZB) increased, compared with panels without PEG at similar BAE levels (Table 3.1). For southern pine OSB, the SIB value with PEG was 8% higher than the values from panels without PEG. Thus, PEG can be used to improve the glueability of PF resin in the presence of borate.

3.3.1.3. Thickness Swelling (TS) Properties

WA and TS data of specimens at the center and 2.54-cm positions from the edges are summarized in Table 3.4. There exists a weak inverse linear relationship between water absorption (WA) and board specific gravity (SG). Specimens with lower SG had larger WA than specimens with higher SG. TS values of boards with high SG were relatively smaller than those of boards with low SG. This indicates that boards with smaller SG had a faster rate of WA due to a higher void percentage in the panel compared with boards with a higher SG.

TS-center and TS-edge increased as WA increased. The relationship between WA and TS was fitted well by a linear regression (R^2 = 0.735 for TS-

Table 3.4. Summary of TS and WA of ZB-modified OSB from southern wood species after 24-hour water soaking.

Species	BAE[b] (%)	SG[C]	MC (%)	TS center (%)	TS 2.54-cm (%)	WA (%)
SP	0.28	0.81	4.48	10.18	20.92	24.31
	0.50	0.80	5.33	11.28	17.47	26.09
	0.76	0.80	5.05	10.40	24.28	26.89
	1.67	0.81	4.50	10.81	25.61	30.33
PEG[a]	0.78	0.84	4.67	11.91	29.53	32.68
PEG	1.69	0.69	3.70	14.70	35.63	39.13
AS	0.34	0.81	4.48	8.56	12.99	23.03
	0.40	0.80	5.33	7.19	9.24	22.38
	0.61	0.80	5.05	8.08	14.90	25.11
	1.99	0.81	4.50	7.74	12.58	24.44
PEG	1.07	0.84	4.67	9.02	13.21	24.07
PEG	1.67	0.69	3.70	12.00	13.54	33.88
LO	0.14	0.77	5.06	5.23	5.99	19.67
	0.34	0.81	4.01	4.97	5.18	15.58
	0.60	0.75	6.10	5.86	7.62	21.96
	1.34	0.79	5.01	4.33	6.40	18.16
PEG	1.06	0.73	6.08	3.44	7.11	22.38
PEG	2.51	0.74	5.68	8.06	9.75	25.22

Table 3.4. (continued).

Species	BAE[b] (%)	SG[C]	MC (%)	TS center (%)	TS 2.54-cm (%)	WA (%)
EL	0.12	0.80	6.04	12.93	21.02	35.95
	0.30	0.72	6.47	32.25	39.49	51.14
	0.41	0.83	5.93	7.82	16.68	25.37
	1.27	0.82	6.11	10.31	20.83	34.17
RO	0.32	0.80	5.19	7.93	11.90	20.87
	0.33	0.79	5.28	9.10	14.42	23.26
	0.45	0.76	5.49	9.83	13.83	25.14
	1.08	0.82	4.69	8.21	10.52	20.62
PE	0.11	0.79	6.39	3.80	11.43	25.27
	0.44	0.77	6.29	7.21	12.14	26.29
	0.65	0.79	5.65	8.07	11.60	24.08
	1.38	0.76	5.91	9.42	13.74	27.78
CY	0	0.80	7.16	5.34	8.28	17.00
	0.27	0.81	6.87	4.96	7.40	13.99
	0.47	0.75	6.44	5.63	10.66	16.99
	1.91	0.76	6.17	6.82	9.39	15.69
CO	0	0.74	6.09	8.55	17.65	32.34
	0.42	0.76	6.21	17.69	25.06	47.96
	0.56	0.79	5.55	7.56	11.14	22.25
	1.67	0.73	6.57	12.65	17.78	28.99

[a] 40% polyethylene glycol (PEG) based on the weight of Zinc borate. [b] BAE (%) indicates Boric Acid Equivalents and average value from 4 specimens from two panels.[c] SG is the average value from 4 specimens from two panels. RO– red oak; SP– southern pine; PE – pecan; AS– ash; EL– elm; CO– cottonwood; LO– locust; CY– cypress.

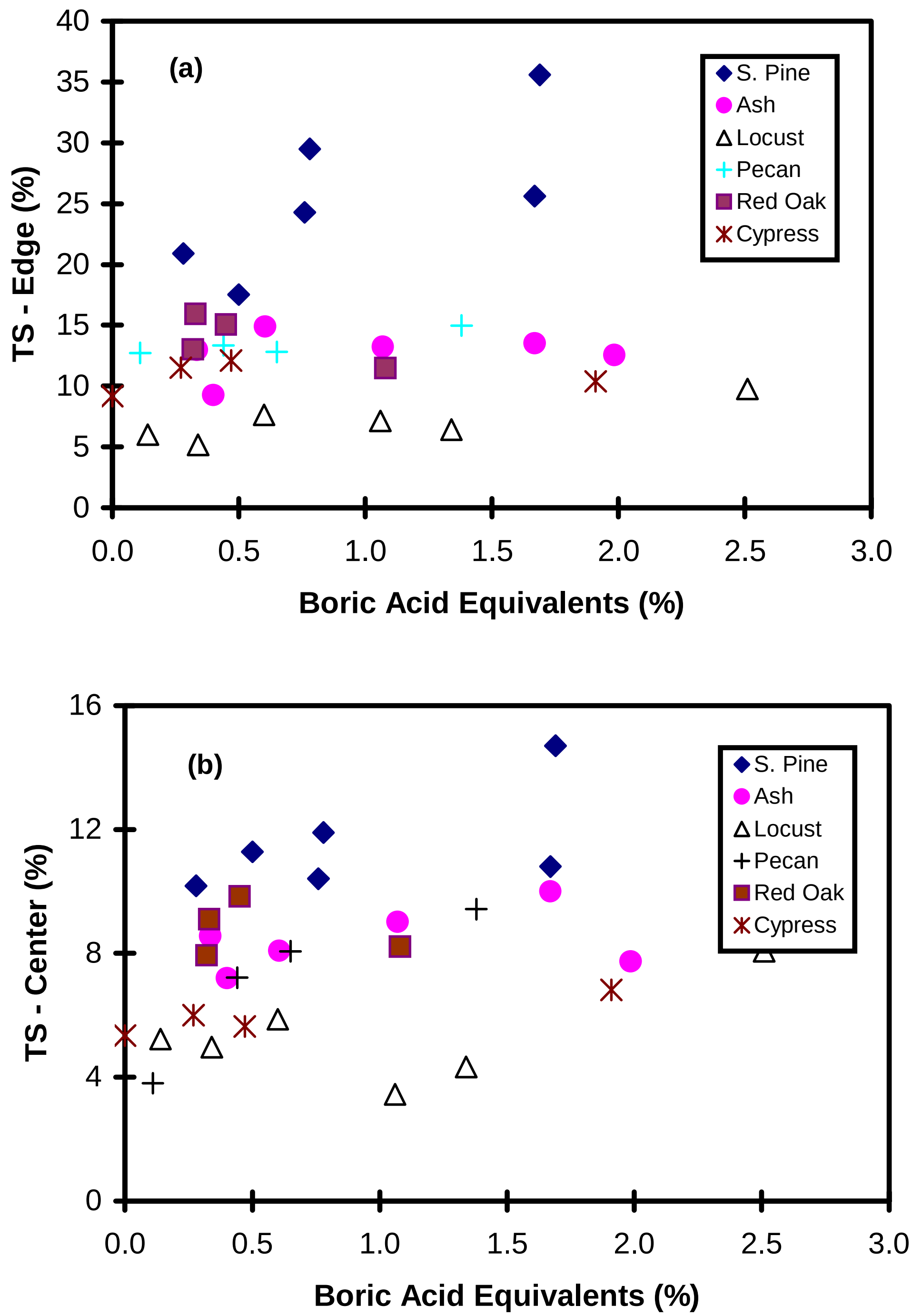


Figure 3.5. Relationship between TS–edge (a)/TS-center (b) and assayed BAE of ZB-modified OSB from southern wood species.

center, and R^2 = 0.715 for TS-edge). This result agreed with that of early studies (Lehmann 1978). TS-edge and TS-center varied with the different wood species as shown in Figures 3.5 a and 3.5 b. Southern pine OSB showed significantly larger TS than OSB from mixed hardwood species. The mean TS-center for all species and BAE levels was within the 15% level. TS varied with BAE levels for various wood species. There was a general increase in TS-center with increased BAE in the sample, especially for southern pine OSB.

According to the two-way ANOVA, the main effect of wood species was highly significant on TS-edge of the OSB from six wood species at the 5.0% significance level (Table 3.5). The effect of ZB levels did not exhibit significant effects on TS-center and TS-edge. There were also no interaction effects of wood species and ZB levels.

Table 3.5. Results of two-way ANOVA for TS-edge and TS-center of ZB-modified OSB at 0, 0.5, 1.0, and 3.0% borate loading levels from 24-hour water soaking.

	Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
TS-edge	Model	31	2918.05	94.13	3.14	0.0022
	Species	7	1706.48	243.78	8.14	<.0001
	ZB	3	138.72	46.24	1.54	0.2278
	Species*ZB	21	784.19	37.34	1.25	0.2964
	Error	25	748.69	29.95		
TS-center	Model	31	1532.96	49.45	1.56	0.1285
	Species	7	478.11	68.30	2.16	0.0744
	ZB	3	239.51	79.84	2.52	0.0810
	Species*ZB	21	630.56	30.03	0.95	0.5456
	Error	25	792.05	31.68		

3.3.2. Calcium Borate-Modified OSB

3.3.2.1. Static Bending Properties

Static bending properties of CB-modified OSB from mixed hardwoods and southern pine are summarized in Table 3.6. The highest SMOE values for all species were obtained without borate treatment. SMOE values for both species groups ranged from 5.3 GPa for CB2-treated southern pine at the 0.75% BAE level to 7.3 GPa for untreated mixed hardwoods OSB. SMOR values ranged from 38.0 MPa for CB1-treated southern pine OSB at the1.94% BAE level to 53.7 MPa for southern pine OSB control. Mixed hardwoods OSB showed relatively higher SMOE and SMOR values than southern pine OSB. Mean SMOE value from CB1-treated mixed hardwoods OSB was 7.11GPa, whereas the value from CB1-treated southern pine OSB was 6.71 GPa. In the case of CB2-modified OSB, mean SMOE value was 6.92 GPa for mixed hardwoods OSB, with 6.26 GPa for southern pine OSB. Mean SMOR value from CB1- and CB2-treated hardwoods OSB was also higher than those from southern pine OSB.

In general, there was no significant difference between mean SMOE values from untreated and borate-treated OSB (Table 3.6). The relationship between SMOE and assayed BAE is shown in Figure 3.6(a). SMOE values from CB1- and CB2-treated mixed hardwoods OSB varied little as the BAE level increased. The corresponding values for CB1- and CB2-modified southern pine OSB showed similar trends.

Table 3.6. Summary of static bending and IB properties of CB1- and CB2-modified OSB from southern wood species.

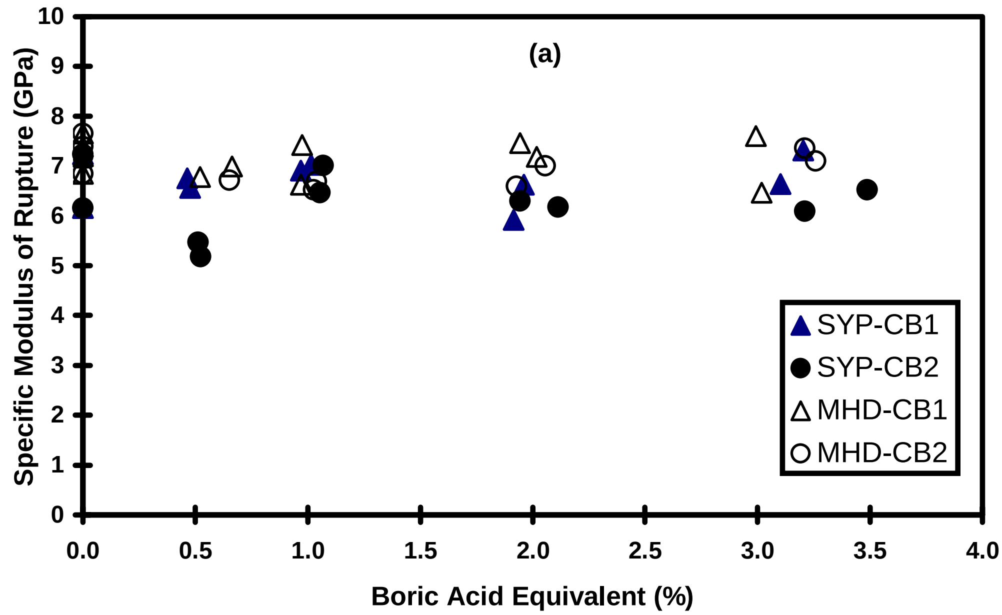
Borate	Species	BAE[a] (%)	MC (%)	Static Bending Properties			IB Properties	
				SG[b]	SMOE (GPa)	SMOR (MPa)	SG[c]	SIB (KPa)
CB1	MHW	0	3.49	0.74	7.27	52.50	0.71	744.07
		0.59	4.27	0.72	6.89	49.28	0.72	563.23
		0.97	4.02	0.74	7.02	42.83	0.80	497.90
		1.98	3.85	0.74	7.32	49.45	0.71	422.70
		3.00	4.30	0.75	7.03	45.77	0.77	517.67
	SP	0	4.23	0.74	6.69	53.74	0.73	547.91
		0.47	4.39	0.73	6.66	39.37	0.76	433.71
		0.99	4.91	0.75	6.97	42.83	0.74	416.48
		1.94	5.03	0.74	6.27	38.00	0.75	330.13
		3.15	5.00	0.71	6.98	46.88	0.74	218.27
CB2	MHW	0	3.71	0.73	7.27	52.50	0.71	744.07
		0.63	3.61	0.71	6.72	47.13	0.79	661.00
		1.03	3.71	0.74	6.61	44.42	0.80	767.99
		1.34	3.16	0.71	6.80	45.58	0.73	541.02
		3.23	3.55	0.75	7.23	44.80	0.71	317.10
	SP	0	3.71	0.73	6.69	53.74	0.73	547.91
		0.52	3.61	0.74	5.33	34.88	0.76	433.71
		1.06	3.71	0.74	6.74	45.96	0.74	420.16
		2.03	3.16	0.75	6.24	41.61	0.77	448.77
		3.35	3.55	0.77	6.31	41.93	0.73	325.83

[a] BAE (%) indicates Boric Acid Equivalents and average value from 4 specimens from two panels. [b] SG is the average value from 4 specimens from two panels. [C] SG in IB result is the average value from eight specimens from two panels. SMOE and SMOR values are the average values from 4 specimens from two panels. MHW-mixed hardwood; SP- southern pine.

There was a significant difference between mean SMOR values from untreated and borate-treated OSB (Table 3.6). Mean SMOR value for untreated southern pine OSB was 28.7% higher than that of CB1-treated southern pine OSB and 31.0% higher than that of CB2-modified southern pine OSB. The SMOR value for untreated mixed hardwoods OSB was 11.4% higher than that of CB1-treated hardwoods OSB, and 15.6% higher than that of CB2-modified hardwoods OSB (Figure 3.6b). SMOE and SMOR at various borate levels had a linear relationship (Figure 3.7).

Comparing ZB and CB-treated panels, mean SMOE and SMOR values for southern pine OSB treated with both ZB and CB were similar. The mean SMOR from CB1- and CB2-mixed hardwoods OSB was smaller than that of ZB-treated single hardwood species OSB. This result indicates that the bonding strength of CB-treated panel was weakened by calcium salts. It needs to be pointed out that panel density affects the strength properties of OSB significantly. Variation of density among various panels prevents an accurate comparison of these properties.

The main effect of wood species (Table 3.7) was highly significant on SMOE of the CB-modified OSB at the 5% significance level (P = 0.0044 and P = 0.0011 for southern pine and mixed hardwoods, respectively). Although CB type showed a significant effect on SMOE, its effect on SMOR was not significant. The interaction effects between wood species, CB types, and CB loading levels were insignificant for all static bending properties.



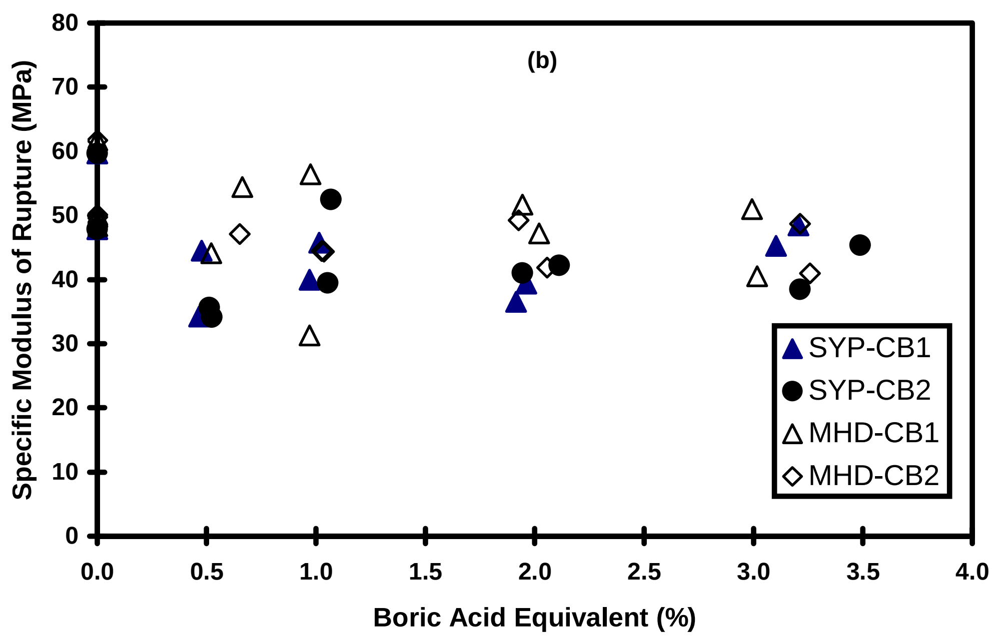


Figure 3.6. Relationship between SMOE (a)/SMOR (b) and assayed BAE of CB-modified OSB from southern wood species.

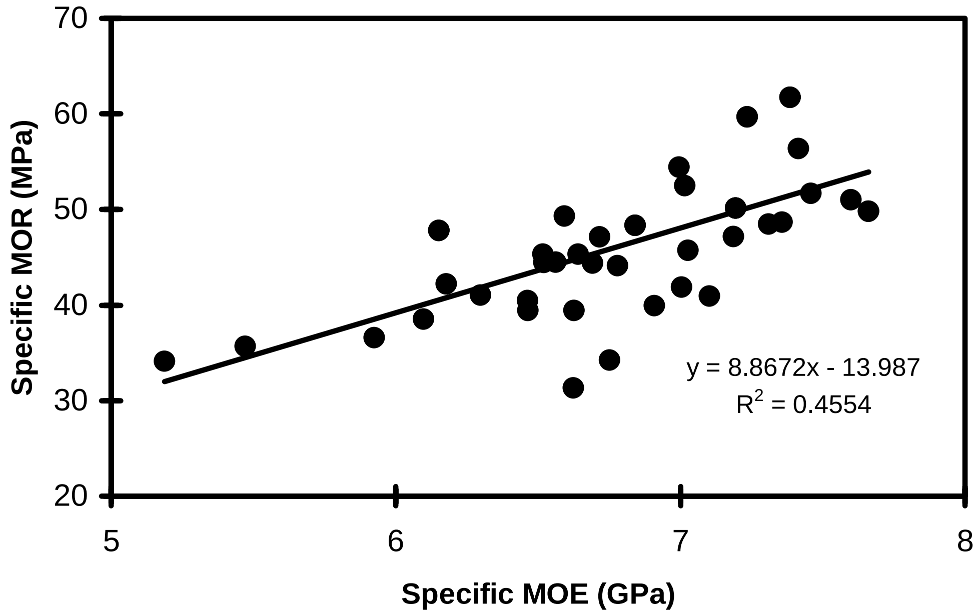


Figure 3.7. Relationship between SMOR and SMOE of CB-modified OSB from combined wood species.

Table 3.7. Results of three-way ANOVA for static bending properties of CB-modified OSB.

	Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
SMOE	Model	17	143528.91	8442.88	2.78	0.0139
	Species	1	43451.54	43451.54	14.33	0.0011
	CB	1	22205.51	22205.51	7.32	0.0132
	Species*CB	1	4028.65	4028.65	1.33	0.2620
	Level	3	19049.18	6349.73	2.09	0.1316
	Species*Level	3	17310.72	5770.24	1.90	0.1601
	CB*Level	3	5394.89	1798.30	0.59	0.6265
	Species*CB*Level	3	16523.20	5507.73	1.82	0.1751
	Error	21	63680.81	3032.42		
SMOR	Model	17	22258360.58	1309315.33	1.47	0.1999
	Species	1	2926435.86	2926435.86	3.28	0.0843
	CB	1	182341.24	182341.24	0.20	0.6557
	Species*CB	1	30390.36	30390.36	0.03	0.8553
	Level	3	345412.98	115137.66	0.13	0.9417
	Species*Level	3	3023643.11	1007881.04	1.13	0.3593
	CB*Level	3	637904.28	212634.76	0.24	0.8684
	Species*CB*Level	3	732930.19	244310.06	0.27	0.8434
	Error	21	18715537.92	891216.09		

3.3.2.2. Internal Bond (IB) Properties

As shown in Table 3.6, the mean SIB values for CB1 treatment ranged from 218.3 KPa at the 3.15% BAE level for CB1-treated southern pine OSB to 744.0 KPa for untreated hardwoods OSB. The SIB values ranged from 317.1 KPa for CB2-treated hardwoods OSB at the 3.23% BAE level to 744.0 KPa for untreated hardwoods OSB. Mean SIB from mixed hardwoods OSB for CB1 was 41.0% higher than that of southern pine OSB. Mean SIB from mixed hardwoods OSB for CB2 was 39.4% higher than that of southern pine OSB.

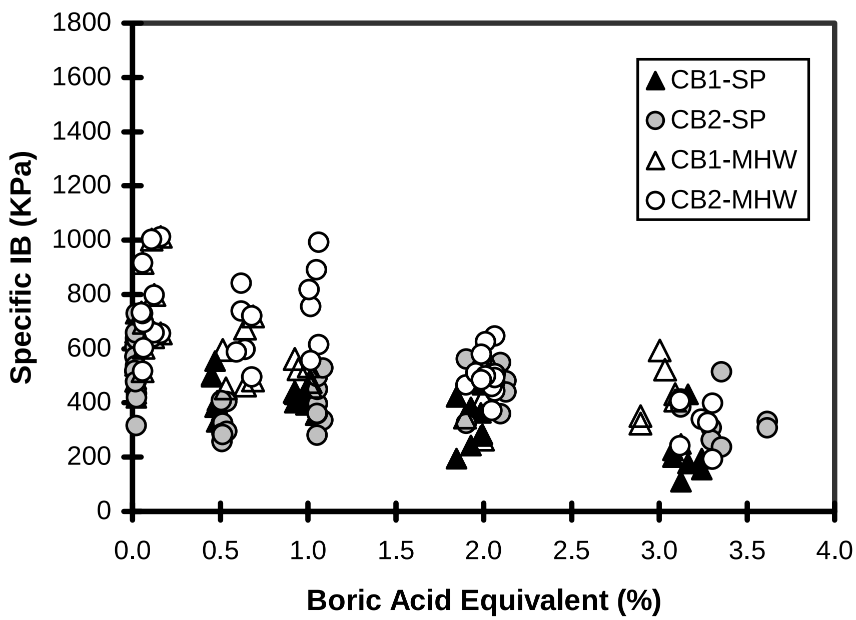


Figure 3.8. Relationship between SIB and the assayed BAE from ZB-modified OSB from southern wood species.

CB treatments on OSB panels had a negative effect on SIB properties for OSB from both wood species groups (Figure 3.8). It was found that the average IB values for the boards without CB were significantly higher than those of the

CB1- and CB2-treated boards. The SIB values at the 3.2% BAE level for CB-treated OSB were 30.5 to 60.0% lower than those of untreated controls.

The results of three-way ANOVA show that the main effects of wood species and CB loading levels were highly significant on the SIB at the 5.0% significance level (Table 3.8). The main effect of borate type was, however, not significant. The interaction effects between wood species and borate types were also not significant. All other interaction effects were significant.

Table 3.8. Results of three-way ANOVA for IB properties of CB-modified OSB.

	Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
	Model	18	61621.73	34.00	15.64	0.0001
	Species	1	18439.66	18439.66	84.22	0.0001
	CB	1	106.71	106.71	0.49	0.4864
SIB	Species*CB	1	4.64	4.64	0.02	0.8845
	Level	4	29549.58	7387.40	33.74	0.0001
	Species*Level	4	3128.07	782.02	3.57	0.0085
	CB*Level	4	5607.12	1401.79	6.40	0.0001
	Species*CB*Level	8	7117.02	2372.34	10.84	0.0001
	Error	130	28462.80	218.94		

3.3.2.3. Thickness Swelling (TS) Properties

WA and TS data on the center and 2.54-cm positions from four edges of test samples of CB-modified OSB are summarized in Table 3.9. Mean SG and initial MC of the OSB samples are in the range of 0.69 to 0.80 and 3.83 to 5.24 percent, respectively. Similar to ZB-modified OSB, a general linear relationship between WA and board SG was observed. This result is related to the high void percentage in the low density boards.

Table 3.9. Summary of TS and WA of CB1- and CB2-modified OSB panels from southern wood species after 24-hour water soaking tests.

Borate	Species	BAE (%)	SG	MC (%)	TS Center (%)	TS 2.54 cm (%)	WA (%)
CB1	MHW	0	0.72	4.08	13.07	18.54	26.80
		0.59	0.74	4.12	8.98	23.17	29.53
		0.97	0.75	4.42	30.58	20.89	28.44
		1.98	0.74	4.60	29.22	49.11	84.25
		3.00	0.72	5.24	19.46	45.41	58.78
	SP	0	0.78	3.83	9.14	15.22	20.94
		0.47	-	-	-	-	-
		0.99	0.75	4.69	13.54	30.59	36.48
		1.94	0.69	5.56	18.39	39.28	57.39
		3.15	0.72	5.76	52.72	66.92	89.57
CB2	MHW	0	0.72	4.08	13.07	18.54	26.80
		0.63	0.76	4.00	6.18	15.87	22.75
		1.03	0.80	3.81	7.90	17.65	22.14
		1.99	0.76	4.02	9.17	21.28	26.42
		3.23	0.76	4.16	12.65	31.24	33.67
	SP	0	0.78	4.08	9.14	15.22	20.94
		0.52	0.73	4.43	11.39	23.01	30.98
		1.06	0.77	4.26	9.00	17.11	23.33
		2.03	0.72	4.28	8.98	17.00	23.95
		3.35	0.74	3.92	8.23	20.01	24.07

TS-edge and TS-center increased positively as WA increased. The regression analysis provided good fits of WA-TS-center (R^2 = 0.691) and WA-TS-edge data (R^2 = 0.943). Both TS-center and TS-edge varied with wood species and borate types. The average TS-center values of CB1-treated OSB from southern pine and mixed hardwoods OSB were 23.44% and 20.3%, respectively, among all borate loading levels. The average TS-edge values of CB1-treated

OSB from southern pine and mixed hardwoods were 31.4% and 22.9%, respectively.

Particle size of CB had a significant effect on the TS properties for treated OSB as shown in Figures 3.8a and b. CB2 with a smaller particle size (6.43 μm) led to good TS resistance for OSB from both species groups, compared with CB1 with a larger particle size (11.09 μm). TS of CB1-treated OSB from both species increased significantly with increase of the CB1 loading, whereas the effect was not clearly seen in CB2-treated OSB.

Comparing TS values of ZB- and CB-modified OSB, CB1-treated southern pine OSB had a 5% to 25% increase of TS-edge and a 5% to 20% increase of TS-center than ZB-treated OSB at similar BAE level. For mixed hardwoods, the CB1 treatment also caused high TS-center and TS-edge values, compared with ZB treatment. On the other hand, CB2 treatment showed almost the same TS values as ZB treatment at an equivalent BAE level, due to similar particle sizes of both borates.

The results of three-way ANOVA (Table 3.10) show that the main effects of wood species, borate type, and CB loading levels were highly significant on TS at the center and edges of calcium borate modified OSB at the 5.0% significance level. All interaction effects among wood species, borate type, and CB loading level were also significant on the TS properties.

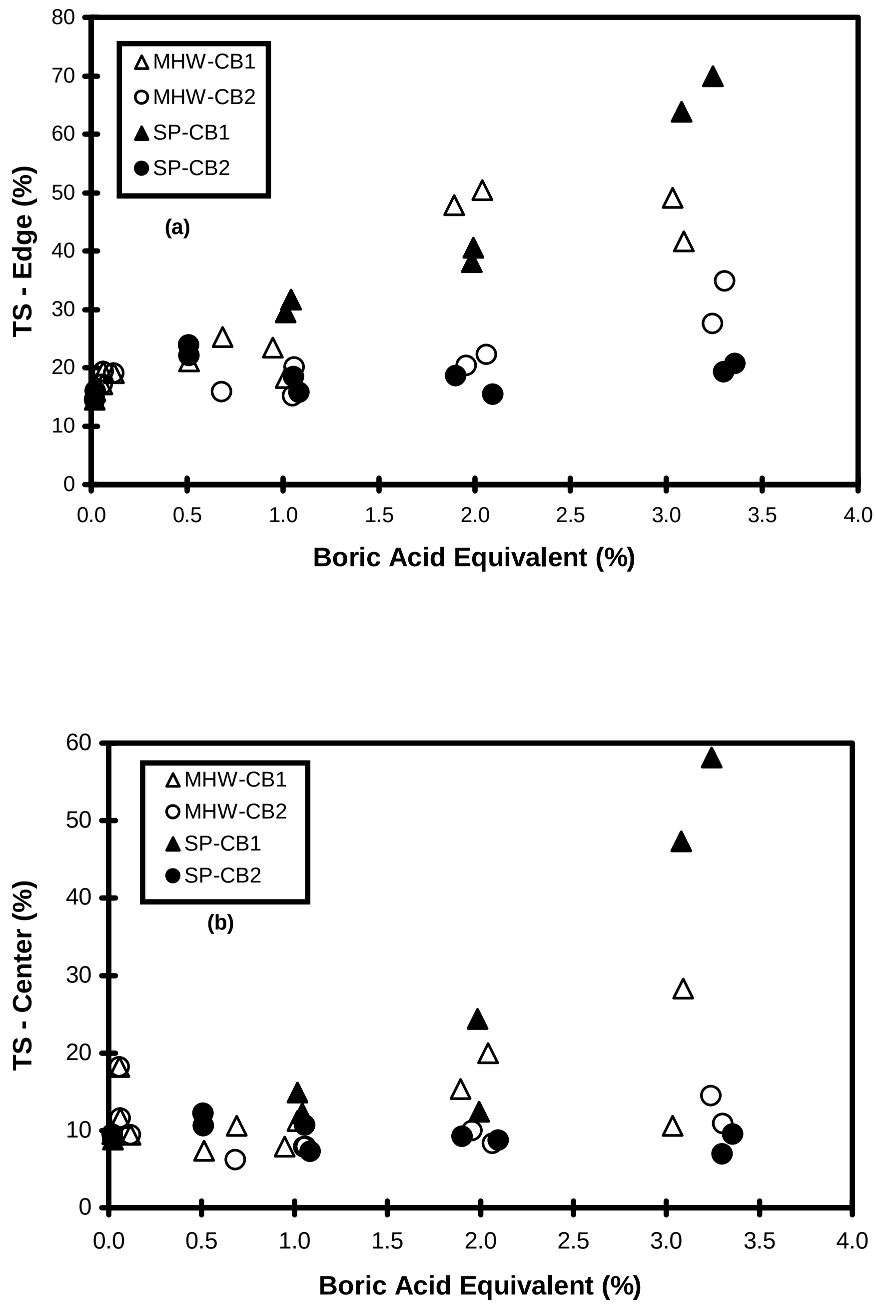


Figure 3.9. Relationship between TS-center (a)/TS-edge (b) and assayed BAE of CB1- and CB2-modified OSB from southern wood species after 24-hour water soaking.

Table 3.10. Results of three-way ANOVA for TS-edge and TS-center of CB modified OSB after 24-hour water soaking.

	Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
	Model	16	6995.30	437.21	66.45	0.0001
	Species	1	32.79	32.79	4.98	0.0382
TS	CB	1	269.28	269.28	40.93	0.0001
-Edge	Species*CB	1	2726.83	2726.83	414.43	0.0001
	Level	3	1548.11	516.04	78.43	0.0001
	Species*Level	3	497.90	165.97	25.22	0.0001
	CB*Level	3	402.83	134.28	20.41	0.0001
	Species*CB*Level	2	533.90	266.95	40.57	0.0001
	Error	20	131.60	6.58		
	Model	16	3713.59	232.10	13.81	0.0001
	Species	1	216.21	216.21	12.86	0.0018
TS	CB	1	281.25	281.25	16.73	0.0006
-Center	Species*CB	1	948.16	948.16	56.41	0.0001
	Level	3	763.11	254.37	15.13	0.0001
	Species*Level	3	295.54	98.51	5.86	0.0048
	CB*Level	3	432.77	144.26	8.58	0.0007
	Species*CB*Level	2	546.89	273.44	16.27	0.0001
	Error	20	336.17	16.81		

3.4. CONCLUSIONS

There was no indication that panels treated with ZB and CB up to 3.5% BAE levels were weaker than untreated panels in terms of stiffness. However, both chemicals showed a negative effect on the panel strength and the IB values. The effect varied with wood species. Some of ZB and CB existed in a powder state on the flake surfaces, thereby reducing the bonding efficiency of the adhesive and contributing to the low property values. The main effect of wood species was significant on the SMOE and SMOR of the ZB-modified OSB. ZB and CB treatment led to a negative effect on IB strength.

TS generally increased with the increase of borate levels in the treated OSB after a 24-hour water soaking. ZB-modified OSB had less TS than CB at an equivalent BAE level. Borate particle size for CB had a significant influence on the TS properties. CB1 with a large mean particle size (11.09 μm) caused significant thickness swelling at high BAE levels, while the smaller particle size of CB2 (6.43 μm) helped bring the TS to a stable and acceptable level. The main effects of wood species, borate type, and CB loading level were highly significant on the TS of CB-modified OSB.

The overall bending SMOE and SMOR values were relatively higher for ZB-modified OSB than the CB-modified OSB. There was no significant difference between CB1- and CB2-modified OSB, in terms of mechanical properties. The overall TS and WA values were significantly higher in the CB-modified OSB (especially CB1-modified OSB), compared with ZB-modified OSB.

3.5. REFERENCES

American Society for Testing and materials. 1999. Standard D-1037, Ann. Book of ASTM Standards. Vol. 04. 09 Wood. ASTM. West Coshohocken, Pa. 170-199 pp.

Biblis, E.J. 1985. Properties of three-layer oriented strandboard from southern hardwoods. Forest Prod. J. 35(2): 28-32.

Canadian Standards Association. 1993. Standard on OSB and Waferboard. 0437-93. CSA, Ontario, Canada.

Draganov, A.M. 1968. Fire retardants in particleboards. In: Second Symp. On Particleboard. Washington State Univ., Pullman, WA. 75-121 pp.

Generalla, N.C., E.J. Biblis, and H.F. Carino. 1989. Effect of two resin levels on the properties of commercial southern OSB. Forest Prod. J. 36(6): 64-68.

Grace, J.K., R.T. Yamamoto, and M. Tamashiro. 1992. Resistance of borate-treated Douglas-fir to the Formosan subterranean termite. Forest Prod. J., 42(2): 61-65.

Grace, J.K., and R.T. Yamamoto. 1994. Natural resistance of Alaska-cedar redwood, and teak to Formosan subterranean termites. Forest Prod. J. 44(3): 41-45.

Sean, T., G. Brunette, and F. CÔTÉ. 1999. Protection of oriented stranboard with borate. Forest Prod. J. 49(6): 47-51.

Laks, P.E., and R.D. Palardy. (1990). Bonding and process consideration for preservative-containing waferboard. Proceedings of "Wood Adhehves 1990", Madison, WI, FPRS. 150-154 pp.

Laks, P.E., X. Quan, and R.D. Palardy. 1990. The development of borate-containing flakeboard. Proceeding of "Wood protection with diffusible preservatives", Nashville, TN, FPRS. 76-79 pp.

Laks, P.E., X. Quan, and R.D. Palardy. 1991. The Effects of sodium octaborate and zinc borate on the properties of isocynate-bonded waferboard. "Adhesives and Bonded Wood Symposium" Proceedings. (C.Y. Hse and B. Tomita, eds.), FPRS. 144-157 pp.

Laks, P.E., and M.J. Manning. 1997. Update on the use of borate as preservatives for wood composites. Proceedings of The Second International Conference on Wood Protection and Diffusible preservatives and Pesticides. Forest Products Society. 62-68 pp.

Lee, S., Q. Wu and B. Strickland. 2001. The influence of flake chemical properties and zinc borate on the gel time of phenolic resin for oriented strandboard. Wood Fiber Sci. 33(3): 425-436.

Lehmann, W.F. (1978). Cyclic moisture conditions and their effect on strength and durability of structural flakeboards. Forest Prod. J. 28(6): 23-31.

Morrell, J.J., and S.T. Lebow. 1991. Borate treatment of seasoned western hemlock and Douglas-fir lumber. Forest Prod. J. 41(1): 27-29.

Murphy, R.J. 1990. Historical perspective in Europe. First International Conference on Wood Protection with Diffusible Preservatives. Proceedings No. 47335. 9-13 pp.

Myles, T.G. 1994. Use of disodium octaborate tetrahydrate to protect aspen waferboard from termites. Forest Prod. J. 44(9): 33-36.

Shupe, T.F., and M.A. Dunn. 2000. The formosan termite in Louisiana: Implications for the forest products industry. Forest Prod. J., 50(5):10-18.

USDA Forest Service. 1986. Wood Handbook: Wood as an engineering material. Agri. Handbook. No. 72. USDA Forest Prod. Lab, Madison, WI. 466 pp.

Winistoffer, P.M., and D. Dicarlo. 1988. Furnish moisture content, resin nonvolatile content, and assembly time effects on properties of mixed hardwood strandboard. Forest Prod. J. 38(11/12): 57-62.

Wozniak, P.J., and J.P. Geaghan. 1994. An introduction to SAS® system for DOS and Wondows™. Department of Experimental Statistics, Louisiana State University. 167 pp.

Xu, W. and P.M. Winistofer. 1995. A procedure to determine thickness swelling distribution in wood composites panels. Wood Fiber Sci. 27(2): 119-125.

Youngquist, A.J. 1987. Wood-based composites: The panel and building components of the future. In: Proceedings of the IUFRO Wood Protection Subject Group. Dalawana Inn, Honey Harbor, Ontario, Canada.

CHAPTER 4

LEACHABILITY OF BORATE-MODIFIED ORIENTED STRANDBOARD

4.1. INTRODUCTION

Work has been done to combine powder borate with wood flakes during the manufacturing of oriented standboard (OSB) to provide termite resistance to the finished products (Laks et al. 1991, Laks et al. 1994, Sean et al. 1999). One of the concerns for any treated products is the leaching of the chemicals under the service conditions. However, information on the effect of wood species, borate type, borate particle size, initial borate content level, and other processing variables on the leachability of borate-treated OSB is still missing.

Leaching tests of wood preservatives provide a relative measure of the leaching losses from treated wood products in service. 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 and placed in landfills (Lebow 1996). Chromated copper arsenate (CCA) is of particular interest because of its extensive use in residential construction. Whereas CCA is considered to be highly resistant to leaching losses, small amounts of contaminant elements can be measured in the leached water and soil. Their potential effects on public health and environment are being assessed. The rate of fixation of wood preservatives depends highly on temperature and pH of wood (Dahlgren 1975), exposed surface area of the products and time (Fowlie et al. 1990), and leaching site factors (Evans 1987,

Cooper and Ung 1992). Although boron-based preservatives have many advantages (Barnes et al. 1989, Myles 1994), boron does not adequately protect wood that has ground contact because of the chemical's susceptibility to leaching (Williams and Amburgey 1987). Various techniques have been tried to fix water-soluble borates. For example, Gezer et al. (1999) incorporated polyethylene glycol (PEG) into either boric acid or sodium borate solution. However, they found little or no effect on the resistance of boron to leaching. Both zinc and calcium borates are considered water insoluble at room temperature. However, when combined into a composite material, leaching under direct water exposure can still occur (Laks et al. 1991, Sean et al. 1999).

Currently, very little data on the leachability of borate-modified OSB under service conditions are available. This work forms part of a larger project on investigating long-term durability of borate-modified OSB from southern wood species. The specific objective of this work was to investigate the leachability of the modified OSB as influenced by wood species, borate types, initial borate levels, and other panel processing variables.

4.2. MATERIALS AND METHODS

4.2.1. Panel Manufacturing

Green boards from eight southern wood species were selected from a local sawmill in south Louisiana. These species included ash (*Fraxinus* spp.), cottonwood (*Populus* spp.), cypress (*Taxodium distichum* (L.) Rich.), elm (*Ulmus americana* L.), locust (*R. pseudoacacia* L.), pecan (*Carya* spp.), red oak

(*Quercus* spp.), and southern pine (*Pinus taeda* L.). The boards were cross-cut into 152-mm sections, which were flaked to produce 76-mm long flakes using a disk flaker. The flakes were dried to 2-3% moisture. They were screened to eliminate fines and stored in polyethylene bags until needed. The wood flakes were used to manufacture single species of OSB for zinc borate (ZB) and mixed hardwood and southern pine OSB for calcium borate (CB).

During the panel manufacturing, certain amounts of dry wood flakes, liquid phenol formaldehyde resin, wax, and borate were blended together. The loading rates for resin and wax were 4 and 1%, based on the oven-dry wood weight. There were one type of ZB ($2ZnO \cdot 3B_2O_3 \cdot 3.5H_2O$) with a particle of 6.61μm and two types of CB ($Ca_2B_6O_{11} \cdot 5H_2O$) with two different particle sizes of 6.43 and 11.09μm. Both types of borate are considered as water insoluble at room temperatures. The loading rates for ZB were 0 (control), 0.5, 1.0, 3.0% based on dry flake weight in the panel. The loading rates for CB were 0 (control), 0.75, 1.5, 3.0, and 4.5%. Several single species panels with ZB were made with the addition of PEG, $H(OCH_2CH_2)_{n>4}OH$, to study its effect on panel properties.

The formed mats were hot pressed in a single opening press with the regulated platen temperature of 200^{o}C for 6 minutes. The target thickness and panel specific gravity were 12.7mm and 0.75, respectively. Two replicate panels at each borate were made.

4.2.2. Leaching Experiments

Leaching experiments were conducted according to a modified AWPA eaching standard (Laks et al.1991). OSB specimens (5.08- x 5.08- x 1.27-cm) were prepared according to borate type, wood species, initial borate level, target leaching time, 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 10-30mmHg. After vacuum was released, the specimens were kept in running tap water (pH = 6.7 and 31.1^{o}C) for 8, 24, 72, and 216 hours. After leaching, the specimens were removed from water sink and oven-dried. They were finally Wiley-milled to pass through a coarse screen (20 mesh per 25.4 mm). The same grinding procedure was applied to the un-leached samples from each group.

An equivalent of five grams oven-dry wood meal from each sample was weighed and put into a CHEMGLASS bottom-flat flask (300ml). One hundred ml 1N hydrochloric acid for ZB or 2N nitric acid for CB was added into the flask. After 2-hour digestion, the flask was removed from the heating mantle and cooled for 30 minutes while maintaining the seal between the flask and the condenser. The wood meal solution was filtered using Whatman #2 filter paper over a filter funnel. The leachate solution was analyzed with an ICP-AES. From

the analysis, the percent of boron, zinc, and/or calcium was determined based on the oven-dry wood weight. The percent of boron was finally converted to boric acid equivalent (BAE), using equations shown in Chapter 3.

4.2.3. Data Analysis

Regression analyses were performed to establish the correlations between the assayed BAE and leaching time, and between boron/zinc or boron/calcium ratio and leaching time. 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).

<u>4.3. RESULTS AND DISCUSSION</u>

4.3.1. Leachability of ZB-Modified OSB

4.3.1.1. Assayed BAE

Experimental results on sample specific gravity, assayed BAE, and boron/zinc ratios for ZB-modified OSB at three different ZB levels are summarized in Table 4.1. The BAE data as a function of time are shown in Figure 4.1 for the selected four species (i.e., southern pine, red oak, ash, and cottonwood). There was an initial larger leaching rate (up to 24-hour leaching time) and the rate decreased as the leaching time increased. 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

Table 4.1. Summary of assayed BAE and B/Zn ratio at various leaching times for ZB-treated OSB panels.

Species	0hr[d]					24hr				
	SG[a]	BAE[b] (%)	B (%)	Zn (%)	B/Zn (%)	SG	BAE (%)	B (%)	Zn (%)	B/Zn (%)
SP	0.86	0.50	0.58	0.60	0.97	0.77	0.37	0.43	0.61	0.72
	0.85	0.76	0.89	0.94	0.95	0.86	0.64	0.75	0.96	0.78
	0.90	1.67	1.95	2.08	0.94	0.80	1.46	1.71	1.99	0.86
PEG[c]	0.89	0.78	0.91	0.94	0.96	0.72	0.52	0.61	0.86	0.71
PEG	0.90	1.69	1.97	2.08	0.95	0.75	1.44	1.69	2.13	0.79
AS	0.79	0.42	0.38	0.40	0.94	0.77	0.29	0.34	0.40	0.85
	0.85	0.50	0.50	0.53	0.93	0.86	0.36	0.42	0.56	0.76
	0.84	1.07	1.75	1.90	0.92	0.80	1.09	1.28	1.55	0.83
PEG	0.87	0.81	0.85	1.07	0.89	0.72	0.63	0.74	0.89	0.83
PEG	0.90	1.33	1.56	1.67	0.93	0.75	1.18	1.38	1.53	0.90
LO	0.81	0.34	0.40	0.43	0.92	0.80	0.35	0.41	0.40	1.01
	0.82	0.60	0.70	0.76	0.92	0.83	0.63	0.74	0.75	0.99
	0.83	1.34	1.57	1.63	0.96	0.76	1.27	1.49	1.59	0.94
PEG	0.84	1.06	1.24	1.29	0.96	0.72	0.74	0.87	0.93	0.93
PEG	0.85	1.57	1.84	1.94	0.95	0.78	1.17	1.37	1.49	0.92
EL	0.84	0.30	0.35	0.37	0.97	0.72	0.21	0.25	0.34	0.74
	0.83	0.41	0.48	0.50	0.97	0.74	0.50	0.58	0.66	0.88
	0.84	1.27	1.48	1.63	0.91	0.86	1.42	1.66	1.73	0.96
PE	0.86	0.44	0.51	0.52	0.98	0.77	0.31	0.46	0.49	0.94
	0.88	0.65	0.76	0.79	0.96	0.73	1.09	1.65	1.73	0.95
	0.86	1.38	1.61	1.93	0.83	0.78	1.09	1.65	1.73	0.95
RO	0.86	0.33	0.39	0.39	1.00	0.69	0.16	0.18	0.33	0.56
	0.84	0.45	0.53	0.56	0.95	0.69	0.23	0.27	0.49	0.56
	0.86	1.08	1.26	1.37	0.92	0.82	0.93	1.09	1.33	0.82
CY	0.87	0.16	0.19	0.19	1.00	0.81	0.27	0.32	0.35	0.91
	0.81	0.47	0.50	0.57	0.88	0.74	0.43	0.51	0.57	0.89
	0.86	1.91	2.24	2.38	0.94	0.83	2.08	2.44	2.51	0.97
CO	0.84	0.42	0.49	0.52	0.95	0.79	0.26	0.31	0.37	0.85
	0.83	0.56	0.49	0.52	0.95	0.79	0.26	0.31	0.37	0.85
	0.86	1.67	1.95	1.79	1.08	0.71	1.50	1.76	1.82	0.97

Table 4.1. (continued).

Species	72hr SG	72hr BAE (%)	72hr B (%)	72hr Zn (%)	72hr B/Zn	216hr SG	216hr BAE (%)	216hr B (%)	216hr Zn (%)	216hr B/Zn
SP	0.71	0.33	0.38	0.65	0.60	0.77	0.16	0.19	0.59	0.32
	0.80	0.56	0.65	0.99	0.66	0.80	0.34	0.39	0.93	0.43
	0.76	1.43	1.67	2.13	0.79	0.88	1.04	1.21	1.94	0.63
PEG[c]	0.74	0.49	0.57	0.92	0.62	0.75	0.28	0.33	0.86	0.38
PEG	0.79	1.36	1.59	1.99	0.80	0.78	1.10	1.29	2.08	0.60
AS	0.71	0.22	0.25	0.39	0.66	0.77	0.18	0.21	0.41	0.51
	0.80	0.31	0.37	0.53	0.69	0.80	0.21	0.25	0.56	0.45
	0.76	1.03	1.21	1.54	0.78	0.88	0.87	1.02	1.60	0.64
PEG	0.74	0.45	0.52	0.83	0.63	0.75	0.38	0.45	0.86	0.52
PEG	0.79	1.09	1.27	1.52	0.84	0.78	0.86	1.01	1.54	0.66
LO	0.70	0.25	0.29	0.40	0.71	0.82	0.29	0.34	0.44	0.76
	0.83	0.54	0.63	0.73	0.87	0.80	0.47	0.56	0.81	0.69
	0.63	1.07	1.26	1.56	0.80	0.83	1.15	1.35	1.71	0.79
PEG	0.76	0.68	0.80	0.91	0.88	0.79	0.65	0.76	1.06	0.71
PEG	0.85	1.17	1.36	1.55	0.88	0.71	0.80	0.94	1.50	0.62
EL	0.73	0.16	0.19	0.31	0.60	0.74	0.08	0.09	0.32	0.28
	0.85	0.43	0.50	0.60	0.84	0.80	0.34	0.40	0.67	0.59
	0.77	1.10	1.28	1.55	0.83	0.79	0.95	1.12	1.56	0.71
PE	0.71	0.31	0.36	0.43	0.82	0.82	0.26	0.31	0.47	0.66
	0.74	0.50	0.58	0.69	0.84	0.71	0.33	0.39	0.58	0.57
	0.70	1.09	1.28	1.53	0.84	0.74	0.95	1.11	1.59	0.70
RO	0.72	0.13	0.15	0.34	0.45	0.74	0.04	0.05	0.19	0.26
	0.85	0.26	0.31	0.52	0.60	0.78	0.11	0.13	0.49	0.26
	0.68	0.62	0.73	1.23	0.59	0.73	0.41	0.48	1.28	0.38
CY	0.78	0.52	0.61	0.70	0.87	0.78	0.20	0.23	0.38	0.61
	0.76	0.37	0.43	0.55	0.78	0.77	0.34	0.40	0.61	0.65
	0.82	1.72	2.01	2.39	0.84	0.75	1.73	2.03	2.50	0.81
CO	0.87	0.21	0.25	0.33	0.74	0.73	0.15	0.18	0.38	0.47
	0.75	0.50	0.59	0.70	0.84	0.79	0.42	0.49	0.73	0.68
	0.82	1.31	1.53	1.72	0.89	0.77	1.18	1.38	1.85	0.74

[a] SG=specific gravity of borate treated specimens. [b] BAE = 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] Leaching time under running water. RO-red oak, SP-southern pine, PE-pecan, AS-ash, EL-elm, CO-cottonwood, LO-locust, and CY-cypress.

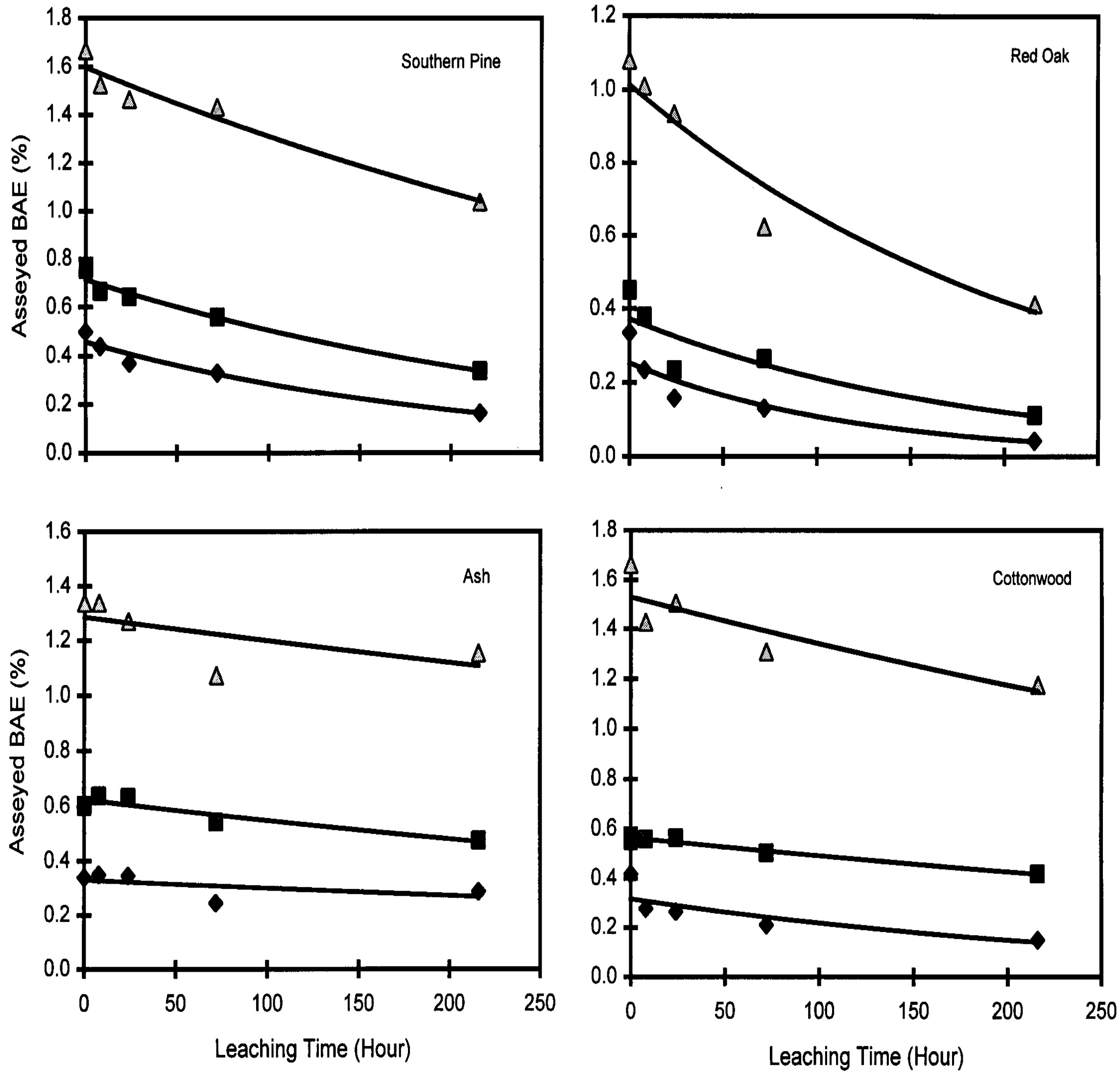


Figure 4.1. Relationship between assayed BAE and leaching time for zinc borate-modified OSB from southern pine, red oak, ash, and cottonwood. Lines show the regression fit.

test, OSB from several wood species (e.g., ash and pecan) held the borate fairly well.

The water leaching experiment with small samples (e.g., 50.4 mm by 50.4 mm) is a severe test for wood-based composite materials. This process leads to a significant thickness swelling even with samples having their edge sealed. 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 was simply washed out under running water. After the 24-hour water exposure, thickness swelling and washing effect were stabilized, leading to a reduced leaching rate. Thus, the thickness swelling properties of the OSB affected the leaching rate significantly. Since the thickness swelling of wood composite varies from place to place within a composite panel, this variability may significantly affect the leaching results.

According to the two-way ANOVA (Table 4.2), 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, however, not significant.

Table 4.2. Results of two-way ANOVA for the leachability of ZB-modified OSB [a].

	Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
	Model	39	0.9099	0.0233	1.82	0.0031
0.5%	Species	7	0.3465	0.0495	11.55	0.0002
ZB	Time	4	0.3050	0.0762	5.95	0.0007
	Species*Time	28	0.2583	0.0092	0.72	0.8175
	Error	40	0.1541			
	Model	39	1.4692	0.0376	5.46	0.0001
1.0%	Species	7	0.8406	0.1200	17.42	0.0001
ZB	Time	4	0.4543	0.1135	16.47	0.0001
	Species*Time	28	0.1742	0.0062	0.90	0.6065
	Error	40	0.1541			
	Model	39	5.6595	0.1451	7.55	0.0001
3.0%	Species	7	3.4312	0.4901	25.11	0.0001
ZB	Time	4	1.6941	0.4235	22.04	0.0001
	Species*Time	28	0.5341	0.0190	0.99	0.4999
	Error	40	0.1541			

[a] Leachability of eight single species OSB measured under running water (88^{o}F temperature) for 0 (control), 8, 24, 72, and 216 hours.

4.3.1.2. Boron/Zinc Ratio

The measured B/Zn ratios of the modified OSB are shown in Table 4.1 and are plotted in Figure 4.2 for the selected species. 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, which indicates 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-

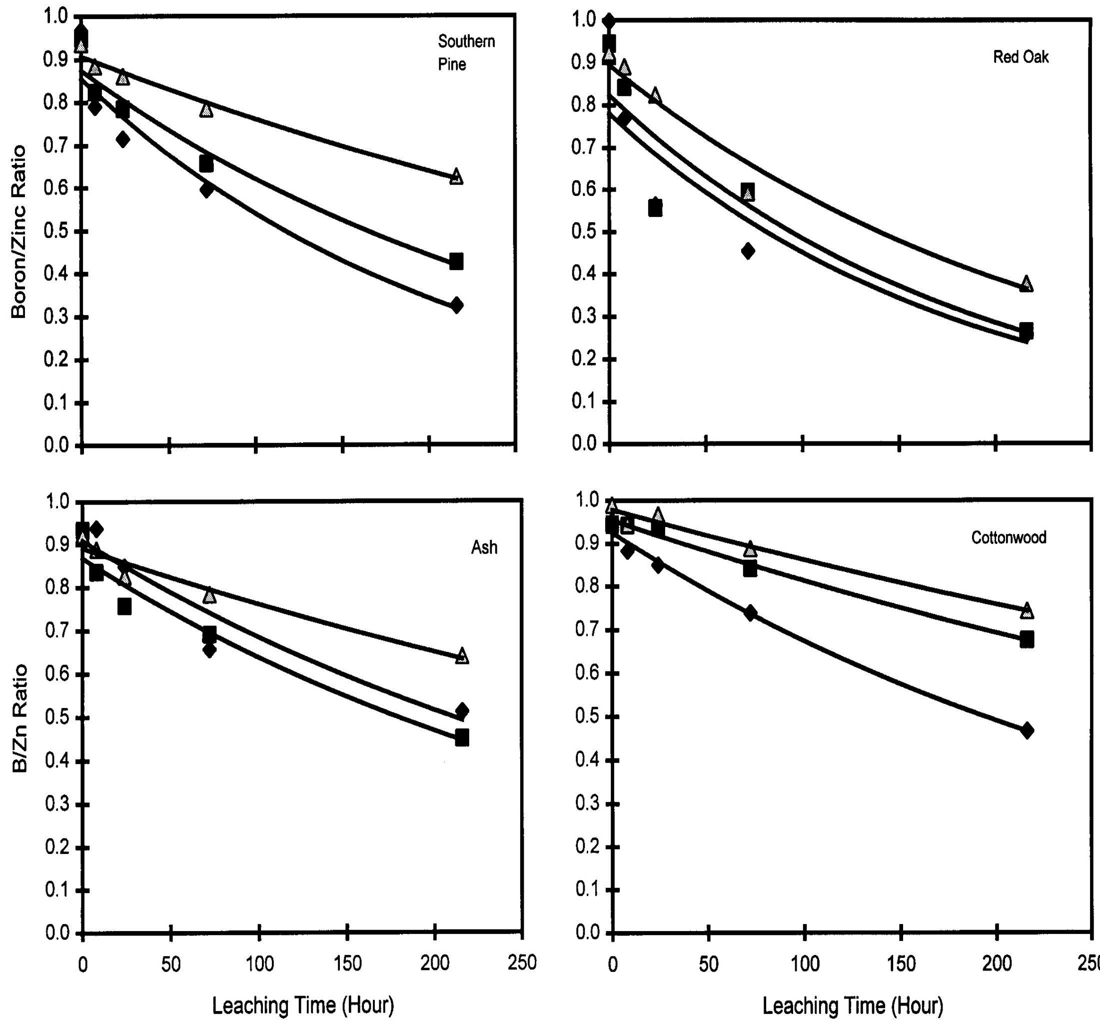


Figure 4.2. Relationship between assayed boron/zinc ratio and leaching time for ZB-modified OSB from southern pine, red oak, ash, and cottonwood. Lines show the regression fit.

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.

4.3.1.3. Regression Analysis

The leaching kinetics between leachability and leaching time at the initial BAE levels is shown in Table 4.3. The data of assayed BAE and B/Zn ratio as a function of time were well fitted with a decaying exponential function (lines in Figures 4.1 and 4.2):

$$Y= a\, e^{-bX} \qquad (4.1)$$

where, Y = BAE (%) or B/Zn ratio, a = regression constant representing the initial BAE level, b = regression constant representing boron leaching rate, and x = leaching time (hour).

A comparison of the normalized BAE (Y/a) predicted by Equation 4.1 for various species is shown in Figure 4.3(a) at the 3% target BAE level (actual BAE level varying 1.08 and 1.91%). Figure 4.3(a) clearly shows red oak OSB had the smallest Y/a value, whereas locust and cypress had the highest Y/a values. A comparison of the leaching coefficient, b, is shown in Figure 4.3(b). Red oak and

Table 4.3. Model parameters for the relationship between assayed BAE and leaching time of ZB-modified OSB [a].

Species	Target ZB (%)	Initial BAE (%)	a	b	R^2
Ash	0.5	0.42	0.3193	0.0029	0.822
	1.0	0.50	0.3987	0.0030	0.979
	3.0	1.07	1.2898	0.0020	0.745
PEG[b]	1.0	0.81	0.6871	0.0031	0.797
PEG	3.0	1.33	1.2713	0.0018	0.964
Locust	0.5	0.34	0.3305	0.0010	0.311
	1.0	0.60	0.6250	0.0013	0.893
	3.0	1.34	1.2852	0.0007	0.405
PEG	1.0	1.06	0.8258	0.0014	0.382
PEG	3.0	1.57	1.3431	0.0024	0.805
S. Pine	0.5	0.50	0.4579	0.0048	0.977
	1.0	0.76	0.7151	0.0035	0.985
	3.0	1.67	0.5979	0.0020	0.858
PEG	1.0	0.99	0.9095	0.0040	0.905
PEG	3.0	1.69	0.9261	0.0017	0.909
Cypress	0.5	0.16	0.3267	0.0016	0.155
	1.0	0.47	0.4122	0.0010	0.795
	3.0	1.91	1.9742	0.0007	0.550
Cottonwood	0.5	0.42	0.3180	0.0038	0.792
	1.0	0.56	0.5649	0.0014	0.974
	3.0	1.67	0.5292	0.0013	0.789
Elm	0.5	0.30	0.2442	0.0054	0.913
	1.0	0.41	0.4622	0.0014	0.700
	3.0	1.27	1.3187	0.0016	0.802
Pecan	0.5	0.44	0.4138	0.0023	0.879
	1.0	0.65	0.6373	0.0031	0.987
	3.0	1.38	1.3803	0.0019	0.878
Red oak	0.5	0.33	0.2533	0.0085	0.938
	1.0	0.45	0.3724	0.0056	0.869
	3.0	1.08	1.0148	0.0044	0.944

[a] Model: BAE = a $\exp^{[-b*(\text{Leaching time})]}$. Coefficients a and b represent initial BAE level and leaching rate, respectively. [b] PEG=polyethylene glycol, which was loaded at 40% of the zinc borate weight.

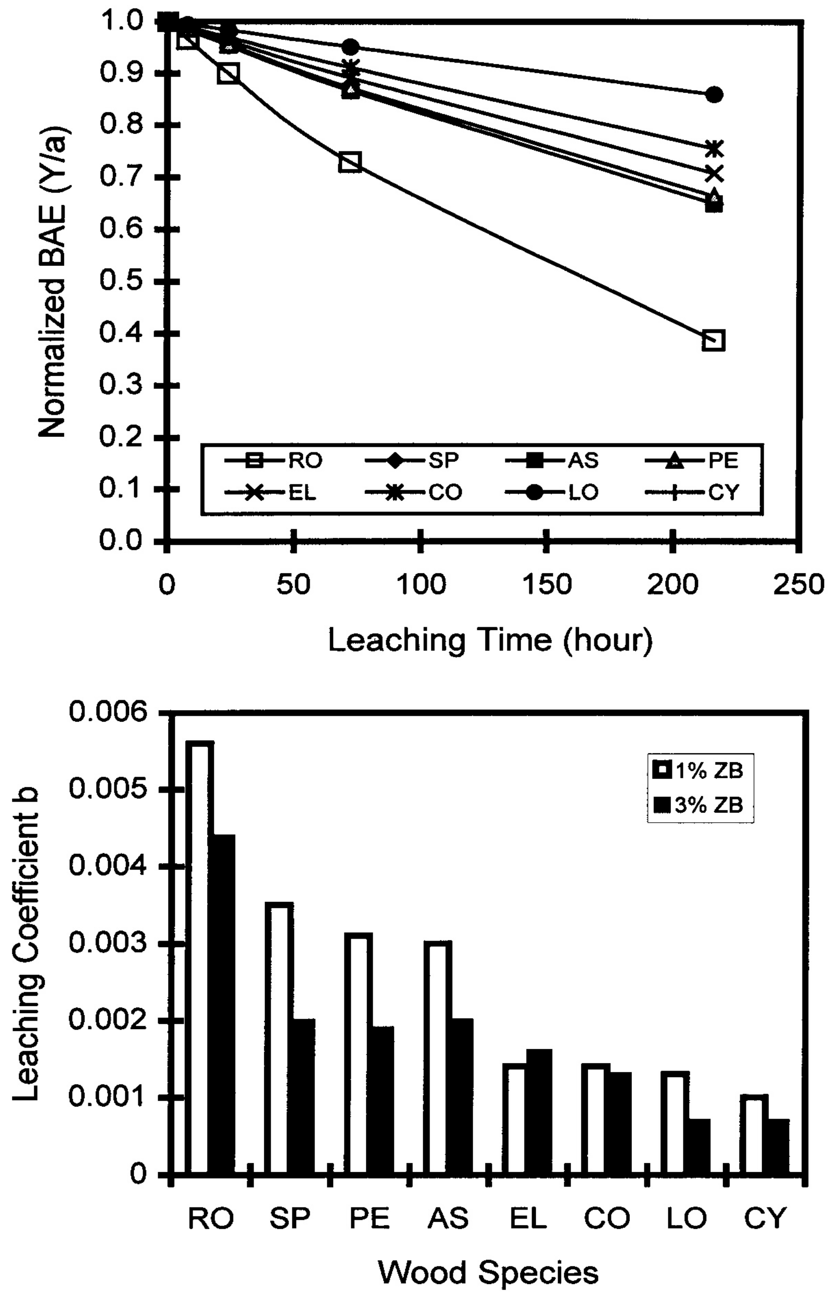


Figure 4.3. A comparison of leachability of ZB-modified OSB from the eight single wood species. Top: normalized BAE as a function of time (3% target BAE level). Bottom: leaching coefficients from various species at the two target BAE levels. RO-Red oak, SP-southern pine, PE-pecan, AS-Ash, EL- Elm, CO-cottonwood, LO-locust, CY-Cypress.

southern pine OSB showed a significantly larger leaching coefficient compared to OSB from locust and cypress. This variability of species effect is presumably related to the surface smoothness, porosity, presence of extractives, and wettability of wood flakes.

4.3.1.4. Effect of Polyethylene Glycol (PEG)

It was found that adding PEG (40% based on ZB weight) helped increase the boron retention for southern pine, ash, and locust. Similar results have been reported for boric acid and sodium borate (Gezer 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% ZB level, however, little effect of PEG on the leachability was observed. 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 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.

According to the three-way ANOVA, the main effects of wood species and leaching time at two different levels of ZB were significant on the leachability of ZB-modified OSB from PEG-added species at the 5% significant level. There was a significant effect of PEG on the leachability of boron at the 1.0% target ZB level (Table 4.4). At the 3.0% ZB level, however, little effect of PEG on the leachability was seen. 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 4.4. Results of three-way ANOVA for leachability of ZB/PEG-modified OSB[a]

	Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
1.0% ZB	Model	29	1.5632	0.0539	10.49	0.0001
	Species	2	0.1186	0.0593	11.55	0.0002
	Time	4	0.7432	0.1858	36.16	0.0001
	Species*Time	8	0.1127	0.0140	2.74	0.0213
	PEG	1	0.2134	0.2134	41.54	0.0001
	Species*PEG	2	0.1589	0.0794	15.47	0.0001
	Time*PEG	4	0.1468	0.0367	7.14	0.0004
	Species*Time*PEG	8	0.0693	0.0086	1.69	0.1430
	Error	30	0.1541	0.0051		
3.0% ZB	Model	29	2.8835	0.0994	6.08	0.0001
	Species	2	0.6207	0.3103	18.98	0.0001
	Time	4	1.7458	0.4364	26.69	0.0001
	Species*Time	8	0.0537	0.0067	0.41	0.9052
	PEG	1	0.0248	0.0248	1.52	0.2272
	Species*PEG	2	0.0081	0.0040	0.25	0.7815
	Time*PEG	4	0.2533	0.0633	3.87	0.0118
	Species*Time*PEG	8	0.1768	0.0221	1.35	0.2571
	Error	30	0.4905	0.0163		

[a] Leachability of the three single species OSB (ash, locust, and southern pine) was measured under running water (88^{o}F) for 0 (control), 8, 24, 72, and 216 hrs. PEG (polyethylene glycol) was loaded at the 40% application level based on zinc borate weight.

4.3.2. Leachability of CB-Modified OSB

4.3.2.1. Assayed BAE

Experimental results on assayed BAE and B/Ca ratios for CB-modified OSB are summarized in Table 4.5. The assayed BAEs as a function of time are shown in Figure 4.4 for both southern pine and mixed hardwood OSBs. The extreme leachability from CB-modified OSB occurred after 8-hour leaching under the running water. This is indicated by a large initial drop of the assayed BAE. The effect of borate particle size on the leachability is clearly seen from Figure 4.4. For CB1, which had a larger particle size, the BAE reduction after the first 8-hour leaching varied from 37 to 64% for mixed hardwoods OSB and 19 to 69% for southern pine OSB at the various initial BAE levels. Samples with a higher initial BAE level had a larger reduction rate. The leaching continued at a reduced rate after the first 8 hours. After 216 hour leaching, the reduction of boron from CB1-modified OSB was over 80% for OSB samples from both species. Thus, a majority of borate (CB1) leached out under the particular test conditions due to the large thickness swelling in the samples. For CB2, which had a smaller particle size, the BAE reduction after the first 8-hour leaching varied from 33 to 48% for mixed hardwoods and from 42 to 55% for southern pine. However, the leaching rate stabilized significantly after the first 8-hour leaching. The loss of boron from CB2-modified OSB after 216 hour leaching was about 60% for both

Table 4.5. Assayed BAE and Boron/Calcium ratio from CB-modified OSB panels after various leaching periods.

Species	CB	0hr[c]					24hr				
		SG[a]	BAE[b] (%)	B (%)	Ca (%)	B/Ca	SG	BAE (%)	B (%)	Ca (%)	B/Ca
MHW	CB1[d]	0.86	0.59	0.69	0.71	0.97	0.82	0.34	0.40	4.50	0.27
		0.85	0.97	1.13	1.19	0.95	0.81	0.52	0.61	1.77	0.35
		0.90	1.98	2.31	2.46	0.94	0.80	0.59	0.68	2.15	0.32
		0.89	3.01	3.51	3.66	0.96	0.83	0.80	0.94	2.63	0.36
	CB2[e]	0.79	0.63	0.73	0.78	0.94	0.85	0.46	0.54	1.35	0.41
		0.85	1.03	1.19	1.28	0.93	0.83	0.67	0.79	1.64	0.48
		0.84	1.99	2.31	2.51	0.92	0.87	1.30	1.52	2.75	0.55
		0.87	3.23	3.75	4.21	0.89	0.84	1.73	2.02	3.82	0.53
SP	CB1	0.81	0.48	0.56	0.61	0.92	0.84	0.28	0.33	0.77	0.43
		0.82	0.99	1.15	1.25	0.92	0.84	0.52	0.61	1.26	0.48
		0.83	1.94	2.25	2.34	0.96	0.81	0.76	0.89	1.93	0.46
		0.84	3.15	3.65	3.80	0.96	0.86	0.90	1.06	2.14	0.49
	CB2	0.84	0.52	0.60	0.62	0.97	0.92	0.30	0.35	0.63	0.55
		0.83	1.06	1.23	1.27	0.97	0.84	0.70	0.82	1.08	0.76
		0.84	2.03	2.35	2.23	0.91	0.79	1.25	1.47	1.92	0.55
		0.86	3.35	3.89	3.97	0.98	0.80	1.60	1.88	2.59	0.72

Table 4.5. (continued).

Species	CB	72hr SG	BAE (%)	B (%)	Ca (%)	B/Ca	216hr SG	BAE (%)	B (%)	Ca (%)	B/Ca
MHW	CB1	0.79	0.24	0.28	1.45	0.19	0.78	0.14	0.17	1.31	0.11
		0.87	0.43	0.50	2.10	0.25	0.87	0.21	0.25	1.57	0.16
		0.81	0.49	0.57	2.11	0.27	0.77	0.15	0.18	1.23	0.14
		0.84	0.68	0.79	2.69	0.29	0.81	0.32	0.37	2.61	0.14
	CB2	0.83	0.33	0.38	1.33	0.28	0.83	0.22	0.26	1.45	0.18
		0.85	0.57	0.67	1.59	0.42	0.79	0.31	0.35	1.60	0.22
		0.85	0.87	1.02	2.30	0.43	0.82	0.68	0.79	2.51	0.31
		0.84	1.44	1.69	3.55	0.47	0.82	1.06	1.25	3.25	0.38
SP	CB1	0.87	0.21	0.25	0.77	0.32	0.77	0.08	0.10	0.86	0.11
		0.88	0.34	0.40	1.21	0.32	0.82	0.13	0.15	1.53	0.13
		0.84	0.46	0.53	1.61	0.32	0.82	0.14	0.16	1.18	0.14
		0.91	0.64	0.75	1.97	0.38	0.80	0.15	0.18	1.38	0.13
	CB2	0.85	0.16	0.18	0.28	0.31	0.78	0.24	0.28	1.26	0.22
		0.83	0.49	0.57	1.12	0.51	0.83	0.35	0.41	1.16	0.35
		0.84	0.98	1.16	1.83	0.63	0.85	0.83	0.97	2.01	0.48
		0.83	1.40	1.64	3.13	0.65	0.81	1.31	1.54	2.81	0.55

[a] SG = specific gravity of borate-treated specimens.
[b] BAE = Boric acid equivalent (i.e. BAE = %CB / 1.17).
[c] Leaching time under running water.
[d] CB1 – particle size = 11.03 µm in diameter.
[e] CB2 – particle size = 6.43 µm in diameter.
MWH-mixed hardwood and SP- southern pine.

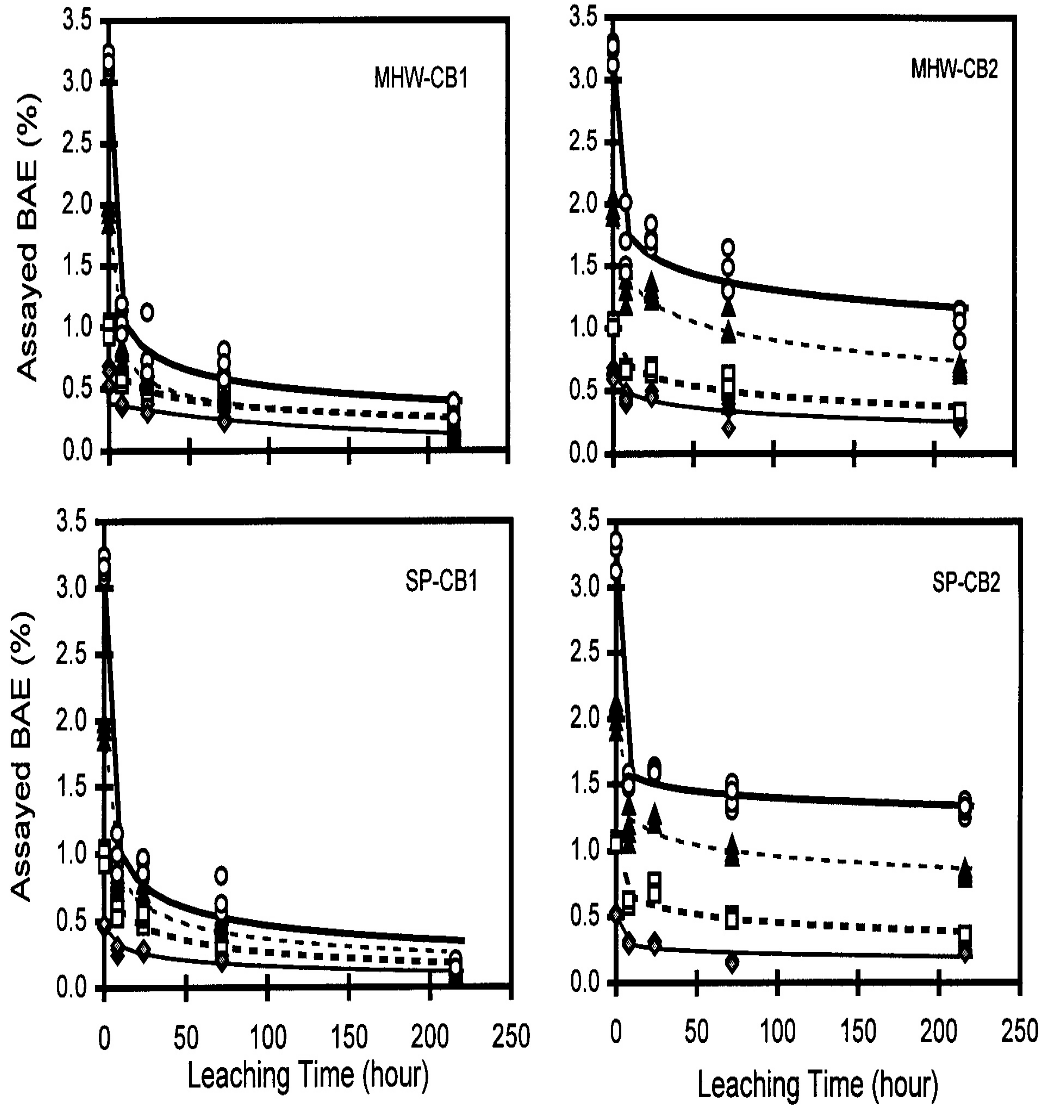


Figure 4.4. Relationship between assayed BAE and leaching time for CB1-and CB2-modified OSB from mixed hardwood and southern pine. Lines show the regression fit.

groups of the OSB. Therefore, CB with a smaller particle size helped reduce its leachability significantly. OSB panels made with CB2 had physical and mechanical properties comparable to these of ZB-modified OSB, offering an alternative treating method for the OSB products. The effect of wood species on the boron leachability was insignificant at various initial BAE levels.

According to the three-way ANOVA (Table 4.6), the main effects of wood species, leaching time, and CB type among the four different levels of CB were highly significant on the leachability of the CB-modified OSB at the 5% significant level. The interaction effects between wood species and CB type, and wood species and leaching time were not significant at higher BAE levels. The results shown in Figures 4.4 and 4.5 are verified by this statistical analysis of ANOVA.

4.3.2.2. Boron/Calcium Ratio

The corresponding boron/calcium ratios are shown in Figure 4.5. The trend of boron/calcium ratio from mixed hardwoods and southern pine OSB was similar to that of the assayed BAE. The initial B/Ca ratios from the unleached control groups were close to unity for both species. As the leaching time increased, however, the ratio decreased significantly, which indicates that boron element leached out at a larger rate than calcium. This indicates decomposition of CB during OSB manufacturing and/or under the water exposure, leading to the subsequent formation of calcium hydroxide, $Ca(OH)_2$ and boric acid, H_3BO_3. Calcium hydroxide is less water-soluble than boric acid.

Table 4.6. Results of three-way ANOVA for leachability of CB-modified OSB[a].

CB	Source	DF	Sum of Squares	Mean Squares	F Values	Pr >F
0.75%	Model	19	9.2219	0.4853	198.55	0.0001
	Species	1	0.3991	0.3991	163.27	0.0001
	Time	4	2.1018	0.5254	214.95	0.0001
	Species*Time	4	1.5681	0.3920	160.37	0.0001
	CB	1	1.4980	1.4980	612.80	0.0001
	Species*CB	1	0.9186	0.9186	375.78	0.0001
	Time*CB	4	1.3713	0.3428	140.24	0.0001
	Species*Time*CB	4	1.3647	0.3411	139.57	0.0001
	Error	60	0.1466	0.0024		
1.5%	Model	19	5.1210	0.2695	225.54	0.0001
	Species	1	0.0329	0.0329	27.58	0.0001
	Time	4	4.8267	1.2066	1009.77	0.0001
	Species*Time	4	0.0250	0.0062	5.23	0.0011
	CB	1	0.1723	0.1723	144.25	0.0001
	Species*CB	1	0.0000	0.0000	0.02	0.8947
	Time*CB	4	0.0417	0.0104	8.72	0.0001
	Species*Time*CB	4	0.0222	0.0055	4.65	0.0025
	Error	60	0.0717	0.0011		
3.0%	Model	19	25.1414	1.3232	144.72	0.0001
	Species	1	0.0034	0.0034	0.38	0.5417
	Time	4	20.7166	5.1791	566.45	0.0001
	Species*Time	4	0.0780	0.0195	2.13	0.0876
	CB	1	2.9386	2.9386	321.4	0.0001
	Species*CB	1	0.0144	0.0144	1.58	0.2135
	Time*CB	4	1.2352	0.3088	33.77	0.0001
	Species*Time*CB	4	0.1550	0.0387	4.24	0.0043
	Error	60	0.5489	0.0091		
4.5%	Model	19	66.1030	3.4791	256.71	0.0001
	Species	1	0.0772	0.0772	5.70	0.0201
	Time	4	57.1012	14.2251	1053.31	0.0001
	Species*Time	4	0.1227	0.0306	2.26	0.0727
	CB	1	6.5249	6.5249	481.44	0.0001
	Species*CB	1	0.0003	0.0003	0.02	0.8815
	Time*CB	4	2.0524	0.5131	37.86	0.0001
	Species*Time*CB	4	0.2240	0.0560	4.13	0.0051
	Error	60	0.8131	0.0135		

[a] Leachability test was performed under running water (88^{o}F) for 0 (control), 8, 24, 72, and 216 hrs (southern pine and mixed hardwoods).

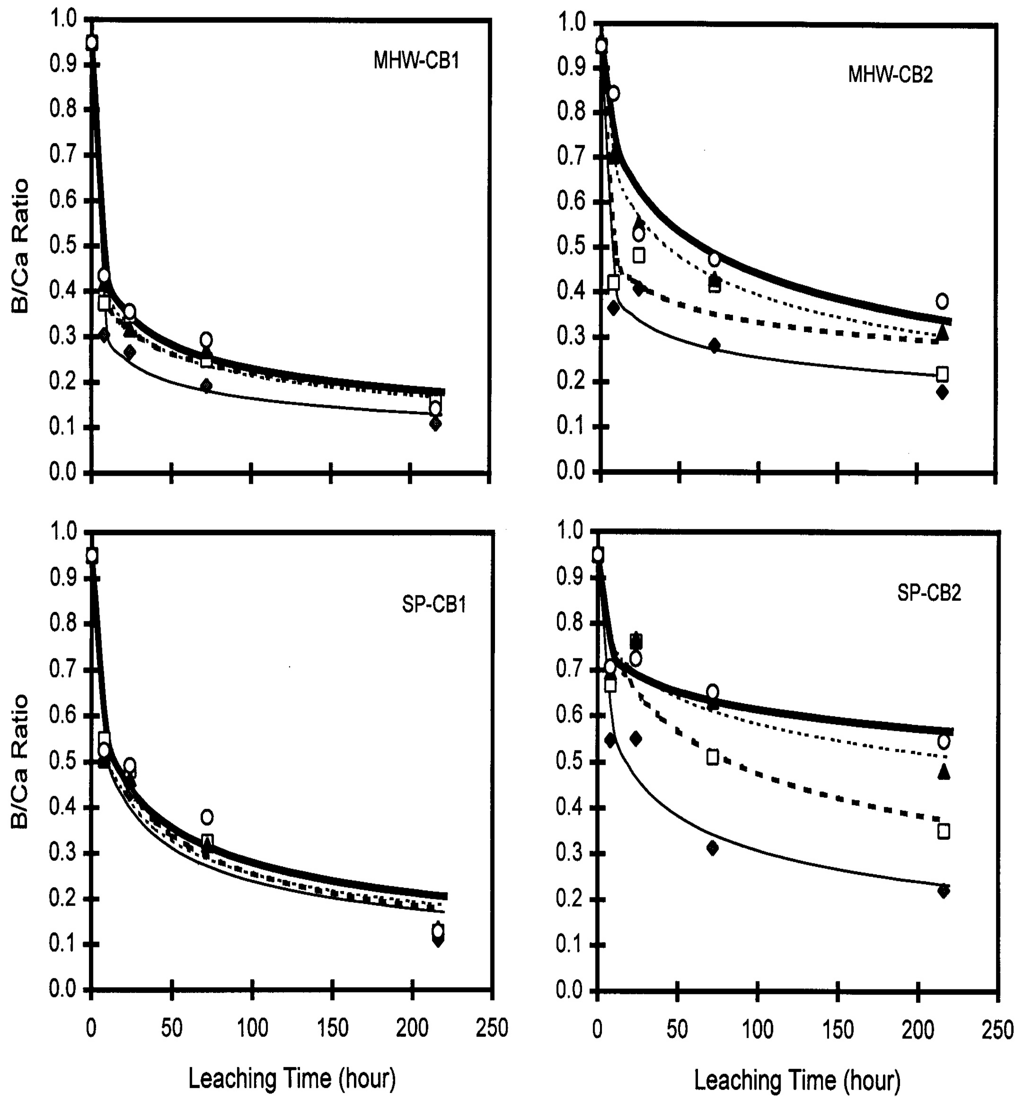


Figure 4.5. Relationship between assayed B/Ca ratio and leaching time for CB1- and CB2-modified OSB from mixed hardwood and southern pine. Lines show the regression fit.

As a result, boron element leached out faster than calcium, leading to the decreased boron/calcium ratios.

The effect of borate particle size on the B/Ca ratio is clearly seen in Figure 4.5. The ratios from OSB with a larger thickness swelling (made with CB1) were significantly lower than those with a smaller thickness swelling (made with CB2).

4.3.2.3. Regression Analysis

The data of assayed BAE and B/Ca ratio as function of time were well fitted with a Harris decaying power function (Table 4.7):

$$Y = 1 / (a + b\,x^{c}) \qquad (4.2)$$

where, Y = BAE (%), a, b, and c = regression constants, X = leaching time (hour). A comparison of the fitted BAE and B/Ca ratios with the measured data is shown in Figures 4.4 and 4.5. The analysis allows predicting the leachability of boron at different CB levels and leaching time for various OSB products.

4.4. CONCLUSIONS

Water leaching tests were conducted in this work to study the leachability of borate-modified OSB. Boron leaching from both ZB- and CB-modified OSB occurred upon the initial water exposure, and the rate decreased as the leaching time increased. Borate type, initial BAE level, and wood species significantly influenced the boron leachability. There was no consistent effect of PEG on ZB leaching. A smaller particle size for CB helped reduce its leachability. The glue-line washing due to thickness swelling of the test samples under water and

decomposition of the borate to form less water-soluble boric acid are two possible causes for the observed leaching. The relationship between assayed

Table 4.7. Model parameters for relationship between fixed BAE and leaching time of CB-modified OSB [a].

Species	CB	Target CB (%)	BAE (%)	a	b	c	R^2	STD
MHW	CB1	0.75	0.59	2.611	0.011	1.115	0.979	0.025
		1.5	0.97	1.012	0.248	0.444	0.975	0.062
		3.0	1.98	0.517	0.289	0.459	0.989	0.099
		4.5	3.01	0.317	0.263	0.392	0.992	0.134
	CB2	0.75	0.48	1.597	0.157	0.504	0.950	0.046
		1.5	0.99	0.977	0.150	0.449	0.913	0.099
		3.0	1.94	0.504	0.079	0.441	0.973	0.108
		4.5	3.15	0.309	0.151	0.239	0.975	0.183
S. Pine	CB1	0.75	0.63	2.149	0.276	0.584	0.964	0.036
		1.5	1.03	1.015	0.159	0.618	0.981	0.061
		3.0	1.99	0.517	0.211	0.513	0.985	0.112
		4.5	3.23	0.317	0.245	0.437	0.989	0.164
	CB2	0.75	0.52	1.930	0.898	0.232	0.937	0.046
		1.5	1.06	0.946	0.252	0.345	0.958	0.076
		3.0	2.03	0.436	0.180	0.152	0.974	0.102
		4.5	3.35	0.299	0.277	0.089	0.990	0.117

[a] Model: $Y = 1 / (a + b x^c)$, where x = leaching time, y = leachability (BAE) of CB, a, b, and c are the regression constants.

BAE and leaching time followed a decaying exponential function for ZB and a Harris decaying power function for CB. The material constants of the regression models allow comparing the leachability of the modified OSB for various wood species. The results provide a relative measure of the leachability of the OSB panels treated with different types of borate. In order to reduce the influence

of the sample thickness swelling on its leachability, a unified leaching method detailing sample size and exposure conditions for treated composite materials is highly needed.

4.5. REFERENCES

Barnes, H.M., T.L. Amburgey, L.H. Williams, and J.J. Morrell. 1989. Borates as wood preserving compounds. The status of research in the United States. IRG/WP/3542. International Research Group on Wood Preservation, Stockholm, Sweden.

Copper, P.A. 1990. Leaching of CCA from treated wood. Proc. Can. Wood Preserv. Assoc. 11: 144-169.

Copper, P.A., and Y.T. Ung. 1992. Accelerated fixation of CCA treated poles. Forest Prod. J. 42(9): 27-32.

Dahlgren, S.E. 1975. Kinetics and mechanism of fixation of preservatives. Part V. Effect of wood species and preservative composition on leaching during storage. Holtzforshung. 29: 84-95.

Evans, F.G. 1987. Leaching from CCA-impregnated wood to food, drinking water, and silage. International Research group on Wood preservation. DOC. No. IRG/WP/3433. Stockholm, Sweden.

Fowlie, D.A., A.F. Preston, and A.R. Zahora. 1990. Additives: an example of their influence on the performance and properties of CCA-treated Southern Pine lumber. In: Proceedings, American Wood Preserver's Association, 86, 11-21.

Gezer, E.D., J.H. Michael, and J.J. Morrell. 1999. Effects of glycol on leachability and efficacy of boron wood preservatives. Wood Fiber Sci. 31(2): 136-142.

Laks, P.E., B.A. Haataja, R.D. Palardy, and R.J. Bianchini. 1988. Evaluation of adhesives for bonding borate-treated flakeboards. Forest Prod. J. 38(11/12): 23-24.

Laks, P.E., X. Quan, and R.D. Palardy. 1991. The effects of sodium octaborate and zinc borate on the properties of isocyanate-bonded waferboard. "Adhesives and Bodnded Wood Symposium" Proceedings. (C.Y. Hse and B. Tomita, eds.) FPRS. 144-157 pp.

Lebow, S.T. 1996. Leaching of wood preservative components and their mobility in the environment-Summary of pertinent literature. Gen. Tech. Rep. FPL-GLT-93. Madison, WI. 36 pp.

Sean, T., G. Brunnett, and F. CÔTÉ. 1999. Protection of oriented strandboard with borate. Forest Prod. J. 49(6): 47-51.

Williams, L.H., and T.L. Amburgey. 1987. Integrated protection against lyctic beetle infestations: IV. Resistance of boron-treated wood to insect and fungal attack. Forest Prod. J. 37(2): 10-17.

Wozniak, P.J., and J.P. Geaghan. 1994. An introduction to SAS® system for DOS and Wondows™. Department of Experimental Statistics, Louisiana State University. pp. 167.

CHAPTER 5

TERMITE-RESISTANCE OF BORATE-MODIFIED ORIENTED STRANDBOARD

5.1. INTRODUCTION

The Formosan subterranean termite (FST) is 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 soaked by condensation from roofs, siding, floors, and plumbing leaks, or by drainage overflow (Radcliffe 1999).

Soil chemical barriers and termite baits have provided the promising technique to prevent the attack by the FST. However, these methods are under scrutiny by the public and their use may become more restricted (French and La Fage 1989, Su and Scheffrahn 1990). One simple solution to the FST destruction is by using wood species that are resistant to termite attack. Red wood and western red cedar are more resistant to the FST attack than Douglas-fir, ponderosa pine, Englemann spruce, and western hemlock (Su and Tamashiro 1986). Grace and Yamamoto (1994) stated that the FST damaged pine and Douglas-fir equally, but damages were significantly less on Alaska cedar and redwood. The content of extractives in heartwood shows a significant relationship to the toxicity of those species against termites (Behr 1972).

As an ultimate solution against FST deterioration, the potential for employing termite-repellent 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 is such an treatment that has been proven to be a very effective chemical element against insects and decay fungi (Barnes et al. 1989, Laks et al. 1988, Lloyd 1993). Powder form zinc borate (ZB) and calcium borate (CB) are described a 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 OSB 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. The treatment with disodium octaborate tetrahydrate (DOT) has been shown to provide good protection against the FST, showing only trivial cosmetic damage. In a laboratory study on the FST, Williams et al. (1990) found that 0.54% BAE showed high termite mortality with only a 1.0% weight loss in banak (V*irola 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, 0.54% BAE for DOT dramatically protected southern pine wood from significant damage by the FST for two years (Preston et al. 1986). OSB panels with 1.0% ZB were shown to provide good termite protection, having the highest rating of 10 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 termites attack on aspen waferboard treated with 3.0% ZB and 3.0% DOT showed no termite attack (damage rating of 10) after one year of exposure in a field site in Florida.

Preston et al. (1996) reported that the DOT treatment on Douglas-fir interior structural lumber was subject to attack at all retention levels. A non-linear regression analysis of the data predicted the protection threshold retention in excess of 1.5 pcf (24 kg/m^3). In another study (Archer et al. 1991), Douglas-fir samples, treated with 25% and 30% BAE solutions of DOT and kept for an 8-week diffusion period, were found to be subject to severe degradation from termite attack. Wafers from Douglas-fir 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).

Currently, little data on chemically-modified OSB against FST attack are available. In addition, the effects of ZB and CB on termite resistance are still unknown for southern mixed hardwoods and southern pine OSB panels. The objectives of this study, therefore, 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 damage ratings.

5.2. MATERIALS AND METHODS

Termite test specimens were cut from test panels following the procedure described in Chapters 3 and 4. The samples were stored in an air-conditioned room at 55% relative humidity (RH) and 22^{o}C before termite testing.

5.2.1. 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 Segnette State Park in Louisiana on July 10, 2002. The crates, built with wood squares, were buried under ground for several months to attract the termites. The crates then were removed and transported to Baton Rouge in large plastic bins. They were stored in a termite lab until needed. The FSTs were collected from the wood squares 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 worker and soldier termites in an air-conditioned room at 29 $\pm$ 0.5^{o}C and 90% RH.

OSB specimens (1.78- x 1.78- x 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 (2x3x2x5 CRD 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 blocks of untreated southern pine solid wood were added as controls in this study. Prior to the termite test, all blocks were oven-dried at 105^{o}C for 24 hours. Sample weight (W_1) and dimension were measured prior to testing.

Each test bottle (80 mm in diameter x 100 mm in height) was autoclaved for 30 minutes 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 termite workers were determined after weighing five groups of over 100 termites each and determining the average weight of an individual termite.

Four hundred termites (approximately 360 workers and 40 soldiers) were added to the opposite side of the test block in the container. All containers were maintained at 29^{o}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 or rinsing with distilled water. Each block was ovendried again at 105^{o}C for 24 hours, and its oven-dry weight measured (W_2). The weight loss in each sample was calculated as follows:

$$\text{Weight loss (\%)} = [(W_1 - W_2) / W_1] \times 100 \quad (5.1)$$

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 dead termite number to the initial termite number (400). Test blocks were visually rated using 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 termite testing were determined following the procedure described in Chapter 3.

5.2.2. 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 percent significance level was used to compare the difference among treatment means (Wozniak and Geaghan 1994).

5.3. RESULTS AND DISCUSSION

Test data on termite mortality, sample weight loss, and damage ratings of the ZB- and CB-modified OSB from mixed hardwoods and southern pine are summarized in Table 5.1. Data on actual BAE in OSB samples before and after termite tests are also presented in Table 5.1.

Table 5.1. Summary of BAE, damage ratings, weight loss, and termite mortality in ZB and CB-modified OSB from mixed hardwoods and southern pine from a 28-day FST test[a].

Borate Type	Wood Species	Actual BAE (%) A[g] / B[h]	SG[b]	MC (%)	Ratings[c]	WL[d] (%)	TM[e] (%)
ZB	MHW	0/0	0.74	7.0	2.96 c	16.48 a	17.50 b
		0.97/0.97	0.69	6.8	8.54 b	4.58 b	34.95 a
		1.72/1.86	0.59	6.8	8.52 b	4.17 b	40.05 a
		3.00/2.96	0.71	6.6	9.54 a	3.08 b	37.95 a
	S. Pine	0/0	0.74	7.0	2.36 c	21.02 a	19.50 b
		1.04/1.02	0.72	7.3	9.80 a	2.70 b	32.45 a
		1.78/1.76	0.70	7.6	8.86 b	3.84 b	32.25 a
		3.02/2.81	0.67	7.4	9.18 ab	3.51 b	37.00 a
CB	MHW	0/0	0.75	6.3	2.98 c	21.32 a	27.70 b
		0.95/0.90	0.79	7.0	7.01 b	7.58 b	33.70 ab
		1.87/1.82	0.80	6.7	8.00 a	5.24 bc	42.60 ab
		3.02/3.06	0.81	6.6	8.68 a	4.20 c	46.45 a
	S. Pine	0/0	0.78	7.1	3.76 c	18.99 a	19.00 c
		0.99/0.94	0.73	7.0	6.76 b	5.88 b	31.95 b
		1.86/1.84	0.76	7.1	8.46 a	4.54 b	37.60 b
		3.07/3.00	0.70	6.9	8.12 a	3.57 b	50.95 a
N/A[f]	SPwood	-	-	7.1	1.00	31.15	11.70

[a] Each mean 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).
[b] SG – Specific gravity based oven-dry weight and volume at about 7% moisture content.
[c] Ratings – Based on 1-10 scale with 1 denoting the most damages.
[d] WL – Wood weight loss expressed as percentage of the original calculated ovendry weight.
[e] TM – Termite mortality expressed as percentage of initial input of 400 termites
[f] N/A – Southern pine solid wood were untreated.
[g] A – Actual BAE before the termite test.
[h] B – actual BAE after the termite test.

Southern pine solid wood samples without borate treatment were used as control for comparison with the treated OSB samples. The overall average SG 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.

5.3.1. 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 5.1 and in Figure 5.1. 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 after termite testing at each ZB and CB loading level (Figure 5.1). This indicates that there was little decomposition of the borates under high humidity exposures. Harrow (1959) stated that the preservatives must be soluble in water, and liquid water must penetrate the wood in order for leaching to occur.

5.3.2. 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 higher termite mortality, compared with southern pine OSB. The termite survival rate with southern pine solid wood was about 88.3%, slightly higher than those of OSB. The difference was probably due to the presence of resin and wax in the OSB sample.

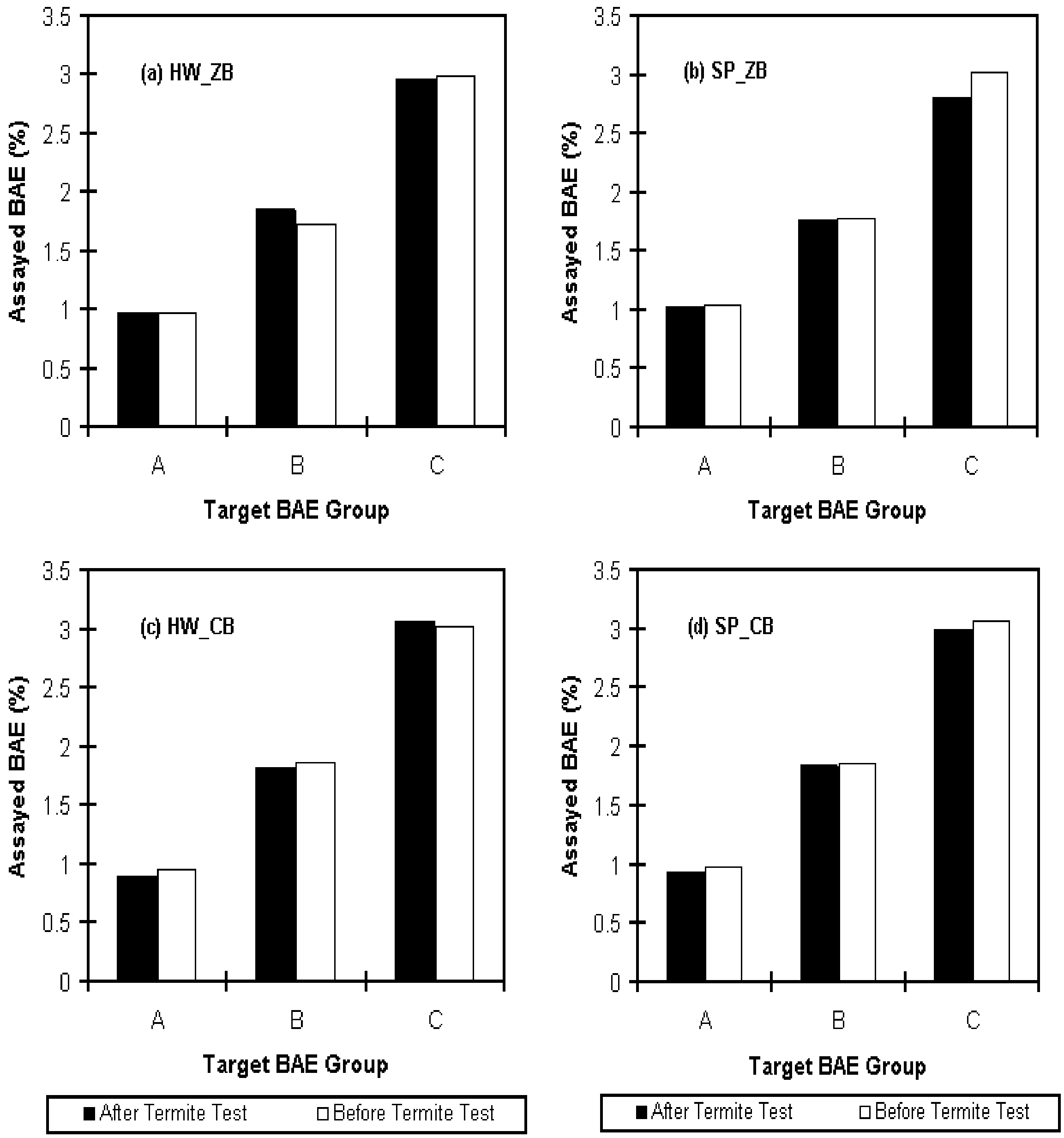


Figure 5.1. Assayed BAE of ZB- and CB-modified OSB from mixed hardwoods and southern pine before and after 28-day termite test. A – 1.5%; B – 3.8%; C – 4.5% borate level. (a) HW-ZB, (b) SP-ZB, (c) HW-CB, and (d) SP-CB.

Significant termite mortality resulted from feeding on treated samples with both ZB and CB (Table 5.1). 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 0.125% BAE. Williams and Amburgey (1987) reported that the retention of 0.17% BAE 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.

A linear regression analysis was performed to establish a correlation between termite mortality and BAE for both ZB- and CB-modified OSB. The results are summarized in Table 5.2 and are plotted in Figure 5.2. 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 are summarized in Table 5.3. Both borate levels and wood species showed a significant effect on termite mortality ($P<.0001$) at the 5% significance level. The borate types show no significant effect on the 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 ($P=0.0009$).

Table 5.2. Model parameters for the relationship between BAE and termite mortality, weight loss, or damage ratings of ZB- and CB-modified OSB by the FST.

	Species	TM[a]			WL[b]				RT[b]			
		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	0.94
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 beginning termites. The relationship between TM and BAE was fitted with the linear regression function, TM (%) = A + B*BAE (%). A and B are regression coefficients.

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

Table 5.3. Results of three-way ANOVA for the termite mortality of the FST feed by ZB- and CB-modified OSB.

Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
Model	15	6222.149	414.809	10.60	<.0001
Level	3	3388.164	1129.388	28.87	<.0001
Borate	1	8.288	8.288	0.21	0.6468
Level*Borate	3	334.277	111.425	2.85	0.0443
Species	1	889.444	889.444	22.74	<.0001
Level*Species	3	489.246	163.082	4.17	0.0093
Borate*Species	1	379.538	379.538	9.70	0.0028
Level*Borate*Species	3	733.189	244.396	6.25	0.0009
Error	64	2503.350	39.114		

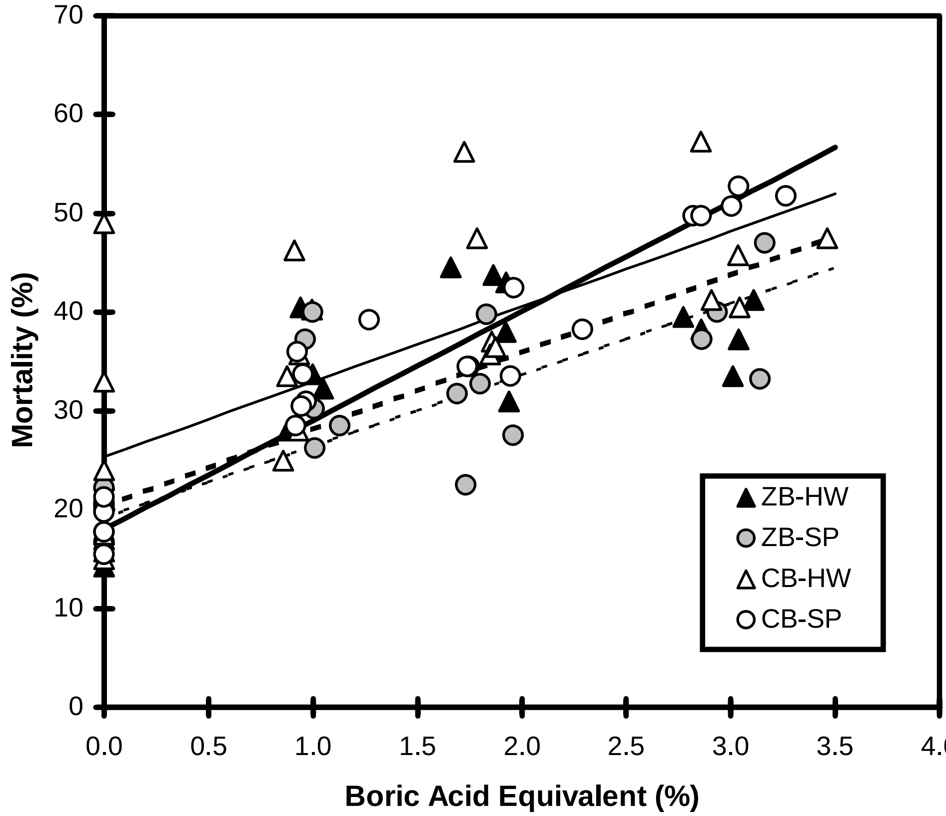


Figure 5.2. Relationship between the termite mortality and BAE for ZB- and CB-modified OSB from southern pine and mixed hardwood after 28-day termite test. Lines show the regression fit.

5.3.3. Weight Loss

Wood weight loss data generally agreed with termite mortality data (Table 5.1). Untreated southern pine wood, used as control, showed a weight loss of 31.2%. This led to an approximately 65% higher weight loss than that of untreated southern pine OSB (Table 5.1). At the 1.0% BAE level for ZB, 4.58% and 3.84% weight losses were obtained 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.

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-modified OSB (Table 5.2 and Figure 5.3). There were large weight losses at the 0% BAE level (control samples) for the OSB. The weight loss was significantly smaller 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 results of statistical analysis on weight loss caused by the FST are shown in Table 5.4. 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 ($P<.0001$) on the weight loss. ZB led to a smaller weight loss (2.7 to 4.6%) than

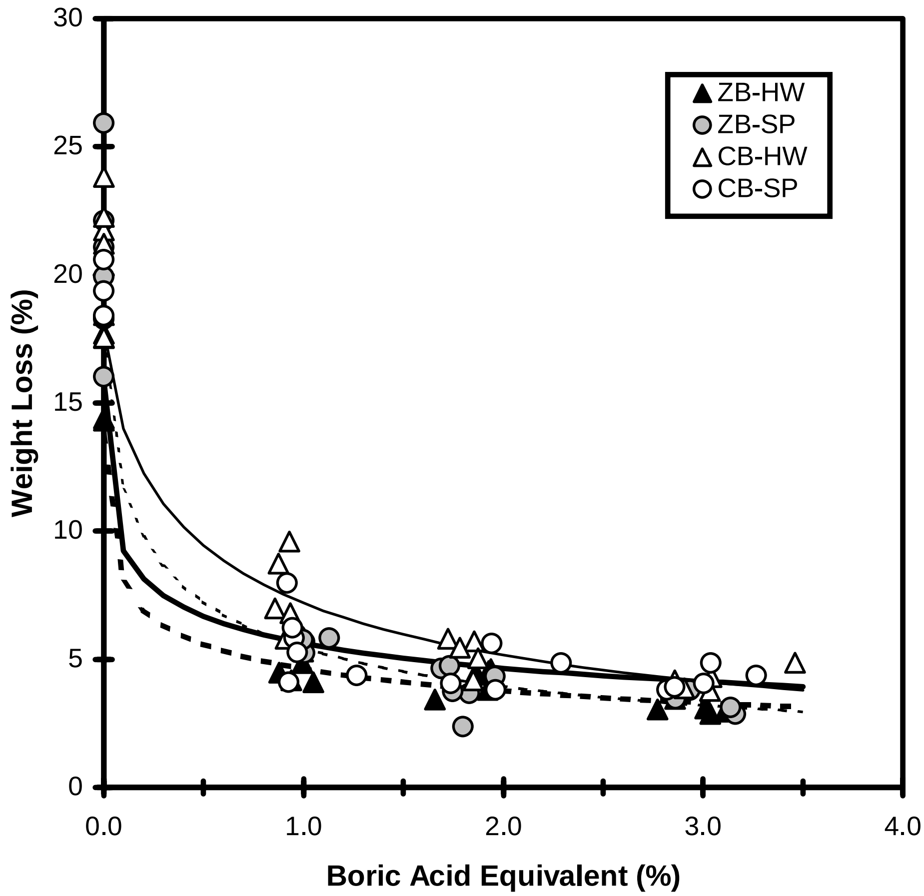


Figure 5.3. Relationship between the weight loss and BAE for ZB- and CB-modified OSB from southern pine and mixed hardwood after 28-day termite test. Lines show the regression fit.

CB (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 ($P<.0001$). Wood species alone showed no significant effect on sample weight loss ($P>0.1554$).

Table 5.4. Results of three-way ANOVA for weight loss of ZB- and CB- modified OSB by the FST.

Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
Model	15	3467.262	231.151	100.39	<.0001
Level	3	3162.257	1054.085	457.78	<.0001
Borate	1	106.281	106.281	46.16	<.0001
Level*Borate	3	29.014	9.671	4.20	0.0089
Species	1	4.758	4.758	2.07	0.1554
Level*Species	3	68.465	22.821	9.91	<.0001
Borate*Species	1	0.804	0.804	0.35	0.5566
Level*Borate*Species	3	95.680	31.893	13.85	<.0001
Error	64	147.365	2.302		

5.3.4. 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 a perfect condition, whereas a rating of 0 means that the sample is completely damaged. The mean damage ratings from this test are shown in Table 5.1 and are plotted as a function of BAE in Figure 5.4. 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 (Figure 5.4).

The increasing Harris power function showed excellent fits of damage ratings and BAE data for both ZB- and CB-modified OSB (Table 5.2 and Figure

5.4). Damage ratings showed an opposite trend with the weight loss data in relation to BAE.

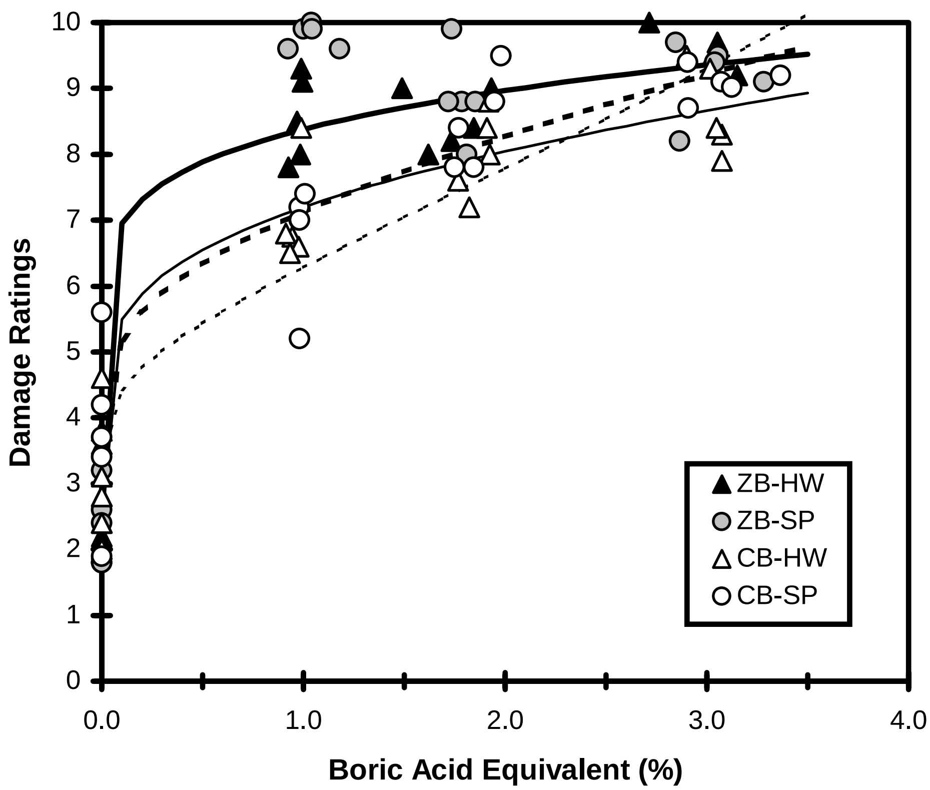


Figure 5.4. Relationship between damage ratings and BAE for ZB- and CB-modified OSB from southern pine and mixed hardwoods after 28-day termite test. Lines show the regression fit.

The results of the three-way ANOVA for the termite damage ratings of the ZB- and CB-modified OSB are shown in Table 5.5. Except for wood species, both borate types and borate levels showed important effects on the damage

ratings (P<.0001). All interactions among borate levels, borate types, and wood species significantly affected the rating by the FST (P<.0001).

Table 5.5. Results of three-way ANOVA for the damage ratings of the FST feed by ZB- and CB-modified OSB.

Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
Model	15	2473.264	164.884	95.04	<.0001
Level	3	2080.746	693.582	399.77	<.0001
Borate	1	105.576	105.576	60.85	<.0001
level*Borate	3	150.437	50.146	28.90	<.0001
Species	1	2.175	2.176	1.25	0.2635
Level*Species	3	70.687	23.562	13.58	<.0001
Borate*Species	1	9.456	9.456	5.45	0.0201
Level*Borate*Species	3	54.187	18.062	10.41	<.0001
Error	384	3139.484	1.735		

5.3.5. Correlation Analysis

The results of correlation analysis among weight loss, termite mortality, and damage ratings of ZB and CB-modified OSB are summarized in Table 5.6. The regression equations are plotted in Figure 5.5, Figure 5.6, and Figure 5.7, in comparison with the experimental data. The relationship between weight loss and damage ratings of borate-modified OSB from both wood species were expressed well by a decaying exponential function (Figure 5.5). An increasing exponential function provided the best fit for termite mortality and damage rating data (Figure 5.6). A decaying power function provided the best fit for weight loss and termite mortality data (Figure 5.7).

Table 5.6. The correlation among the weight loss, termite mortality, and damage ratings of ZB and CB-modified OSB by the FST according to the regression analysis.

	WL (%) = a x $e^{-b \times RT}$				TM (%) = a x $e^{b \times RT}$			WL (%) = a x TM^{-b}		
	Species	a	b	R^2	a	b	R^2	a	b	R^2
ZB	MHW	32.395	0.239	0.943	12.382	0.123	0.808	1571.3	1.647	0.845
	SP	39.192	0.268	0.976	16.116	0.078	0.682	1448.6	2.354	0.677
CB	MHW	44.258	0.263	0.919	13.373	0.137	0.705	1304.9	1.465	0.759
	SP	43.096	0.271	0.818	16.527	0.109	0.333	2458.3	1.703	0.905

TM – termite mortality expressed as percentage of the beginning termites.
RT – damage rating based on 1-10 scale with 1 denoting the most damages.
WL – Wood weight loss expressed as percentage of the original weight.

The inter-relationships among termite mortality, wood weight loss, and damage ratings from the 3-way nonlinear regression analysis had the following form, according to borate type and wood species.

$$RT_{HW,ZB} = -3.4283 + 0.2962 \times TM + 0.7370 \times WL - 0.0253 \times TM \times WL + 0.00471 \times TM^2 - 0.0088 \times WL^2 \quad (R^2 = 0.99) \qquad (5.2)$$

$$RT_{SP,ZB} = 4.5712 - 0.2051 \times TM + 0.3680 \times WL - 0.0174 \times TM \times WL + 0.0081 \times TM^2 - 0.0044 \times WL^2 \quad (R^2 = 0.96) \qquad (5.3)$$

$$RT_{HW,CB} = 5.6979 - 0.0918 \times TM + 0.1674 \times WL - 0.0098 \times TM \times WL + 0.0013 \times TM^2 - 0.0011 \times WL^2 \quad (R^2 = 0.93) \qquad (5.4)$$

$$RT_{SP,CB} = 4.1724 + 0.3209 \times TM - 0.0391 \times WL + 0.0028 \times TM \times WL + 0.0214 \times TM^2 + 0.0026 \times WL^2 \quad (R^2 = 0.77) \qquad (5.5)$$

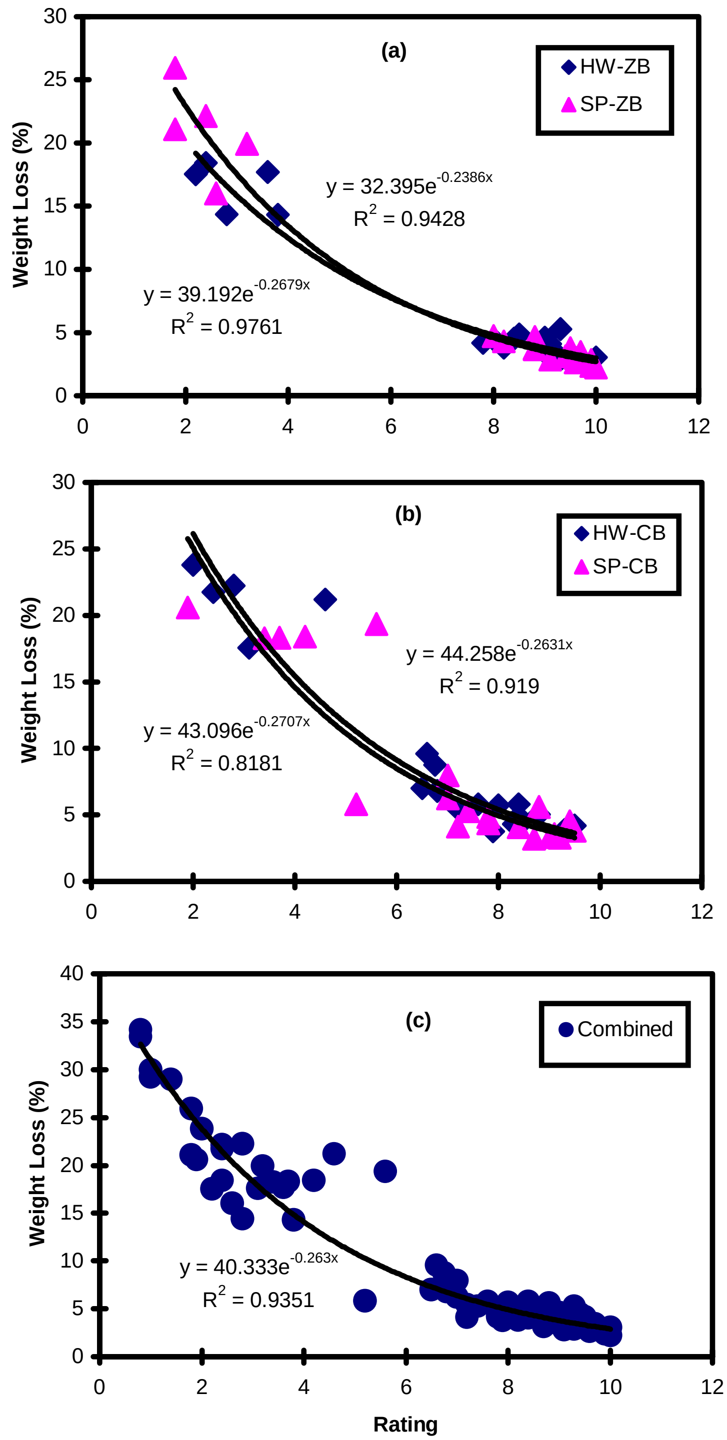


Figure 5.5. The correlation between damage rating and sample weight losses of borate modified OSB from mixed hardwoods and southern pine after 28-day termite test. (a) ZB, (b) CB, and (c) combined data.

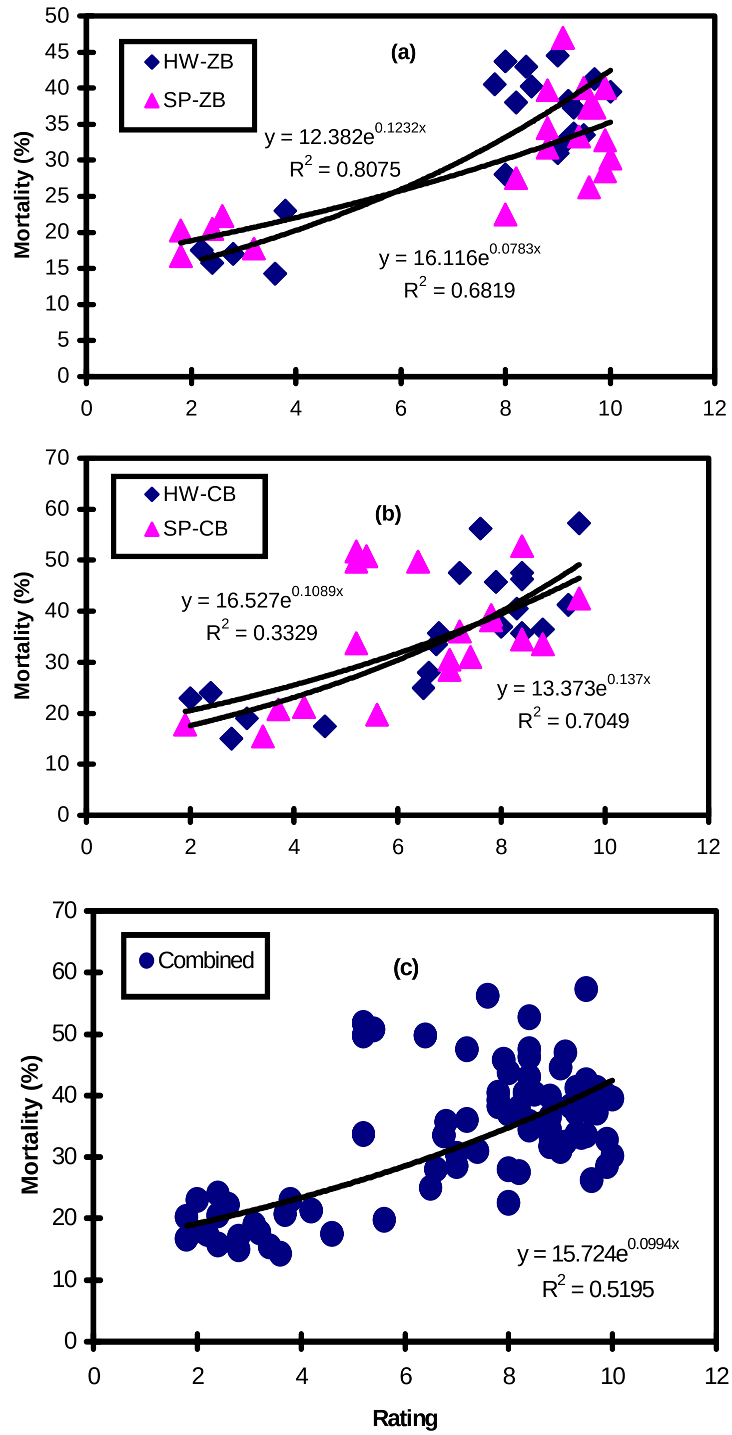


Figure 5.6. The correlation between damage rating and termite mortality of borate-modified OSB from mixed hardwoods and southern pine after 28-day termite test. (a) ZB, (b) CB, and (c) combined data.

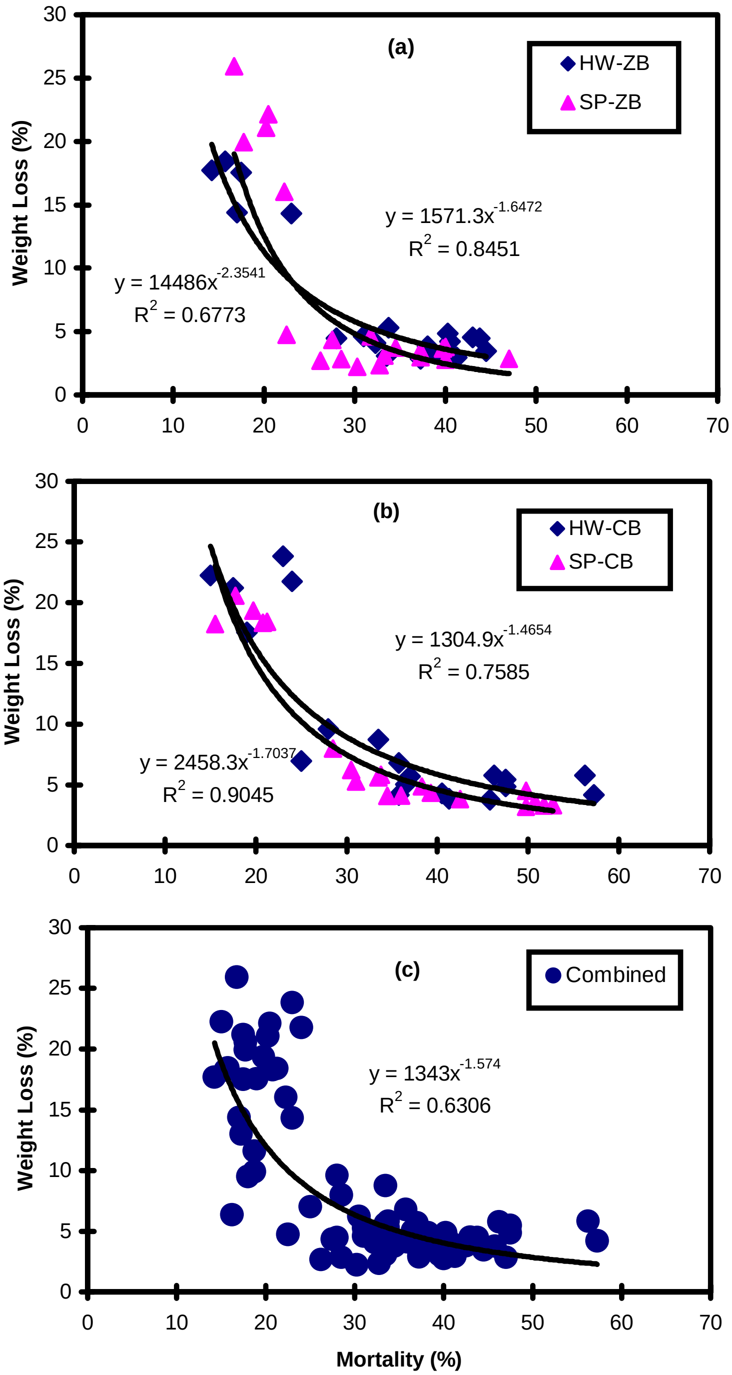


Figure 5.7. The correlation between weight loss and termite mortality of Borate-modified OSB from mixed hardwoods and southern pine after 28-day termite test. (a) ZB, (b) CB, and (c) combined data.

5.4. CONCLUSIONS

FST laboratory tests showed that both zinc and calcium borate used in OSB resisted Formosan subterranean termites well. The borate levels showed a significant effect on weight loss, termite morality, 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 showed no significant effect on termite resistance properties.

The decaying power relationship in weight loss, with an increase of ZB and CB levels, was observed. 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 correlations between weight loss and damage ratings, and between damage ratings and termite mortality from both wood species, were perfectly fitted by decaying exponential regression function. The correlation between termite percent mortality and weight loss was best fitted using a decaying power regression analysis. The correlations among termite mortality, wood weight loss, and wood ratings were best fitted by the 3-way nonlinear regression analysis.

Our results suggest that boron retention above 1.0% BAE can increasingly minimize the potential damage to OSB by FST, but the retention level does not completely eliminate the damage. This information can help more OSB producers manufacture chemically-modified OSB to meet increasing market demands.

5.5. REFERENCES

American Wood Preserver's Association. 1999. Standard method for laboratory evaluation to determine resistance to subterranean termites. E1-97. AWPA Book of standards.

Archer, K.J., D.A. Fowlie, A.F. Preston, and P.J. Walcheski. 1991. A termite field test with diffusion treated lumber. 22nd annual meeting of the Inter. Res. Group on Wood Preservation. Working Group III. Preservatives and Methods of Treatment, Tokyo, Japan. IRG Secretarist, Stockholm, Sweden.

Barnes, H.M., T.L. Amburgey, L.H. Williams, and J.J. Morrell. 1989. Borates as wood preserving compounds, the status of research in the United States. International Research Group on Wood Preservation. Document No. IRG/WP/3542. 1-16 pp.

Behr, E.A. 1972. Decay and termite resistance of medium density fiberboards made from wood residue. Forest Prod. J. 22(12): 48-51.

French, J.R., and J.P. La Fage. 1989. Termite standards questionnaire survey-second report. 20th International Research Group on Wood Preservation, Lappeeranta, Finland, Document No. IRG/WP/1395. 6 pp.

Grace, J.K., R.T. Yamamoto, and M. Tamashiro. 1992. Resistance of borate-treated Douglas-fir to the Formosan subterranean termite. Forest Prod. J. 42(2): 61-65.

Grace, J.K., R.T. and Yamamoto. 1994a. Natural resistance of Alaska-cedar, redwood, and teak to Formosan subterranean termites. Forest Prod. J. 44(3): 41-45.

Grace, J.K., and R.T. Yamamoto. 1994b. Repeated exposure of borate-treated Douglas-fir lumber to Formosan Subterranean termites in an accelerated field test. Forest Prod. J. 44(1): 65-67.

Harrow, K. 1959. Conditions for leaching. New Zealand Timber Journal and Wood Products. 6(1): 71.

Laks, P.E., B.A. Haataja, R.D. Palardy, and R.J. Bianchini. 1988. Evaluation of adhesives for bonding borate-treated flakeboards. Forest Prod. J. 38(11/12): 23-24.

Laks, P.E., and M.J. Manning. 1997. Update on the use of borates as preservatives for wood composites. Proceedings of The Second International Conference on Wood Protection and Diffusible Preservatives and Pesticides. Forest Products Society. 62-68 pp.

Laks, P.E., X. Quan, and B.A. Haataja. 1991. The effects of sodium octaborate tetrahydrate and zinc borate on the properties of isocynate-bonded waferboard. Forest Prod. Soc. Madison, WI. 144-157 pp.

Lloyd, J.D. 1993. The mechanisms of action of boron-containing wood preservatives. Ph.D. Thesis. Imperial College of Science, Technology of Medicine, Department of Biology. 352 pp.

Mauldin, J.K., and B.M. Kard. 1996. Disodium octaborate tetrahydrate treatments to slash pine for protection against Formosan subterranean termite and eastern subterranean termite (*Isoptera: Rhinotermitidae*). J. Economic Entomology. 89(3): 682-687.

Preston, A.F., L. Jin, and K.J. Archer. 1996. Testing treated wood for protection against termite attack in buildings. American Wood Preserver's Assoc. Proc. AWPA, Granbury, Tex. 205-220 pp.

Preston, A.F., P.A. Mckaig, and P.J. Walcheski. 1986. Termite resistance of treated wood in an above ground field test. International Research Group on Wood Preservation. Document No. IRG/WP/1300. 1-5 pp.

Radcliffe, M. 1999. Fighting termites with good design and detailing. The Construction Specifier. 47-51 pp.

Schefrahn, R.H., R.C. Hsu, N.Y. Su, J.B. Hoffman, S.L. Modland, and J.J. Sim. 1988. Alleochemical resistance of bald cypress *Taxidium distichum*, heartwood to the subterranean termite, Coptotermes formosanus. J. Chem. Ecol., 14, 765-776.

Schmidt, V.H., and A.B. Nehm. 1972. Testing of particleboard on termite resistance. Holz Roh-. Werstoff. 30(5): 14-16.

Sean, T., G. Brunnette, and F. CÔTÉ. 1999. Protection of oriented strandboard with borate. Forest Prod. J. 49(6): 47-51.

Su, N.Y., and M. Tamashiro. 1986. Wood-consumption rate and survival of the Formosan subterranean termite when fed one of six woods used in commercially in Hawaii. Proc. Hawaiian Entomol. Soc. 26:109-113.

Su, N.Y., and R.H. Scheffrahn. 1990. Economically important termites in the United States and their control. Sociobiology. 17: 77-94.

Su, N.Y., and R.H. Scheffrahn. 1991. Laboratory evaluation of disodium octaborate tetrahydrate (TIM-BOR) as a wood preservative or a bait-toxicant against the Formosan and eastern subterranean termites (*isoptera: Rhinotermitidae*). Inter. Res. Group Wood Preserv. Doc. No. IRG/WP/1513:1-12.

Williams, L.H., and T.L. Amburgey. 1987. Integrated protection against Lyctid beetle infestation IV. Resistance of boron-treated wood (Virola spp.) to insect and fungal attack. Forest Prod. J. 37(2): 10-17.

Williams, L.H., T.L. Amburgey, and B.R. Parresol. 1990. Toxic thresholds of three borates and percent wood weight loss for two subterranean termite species when feeding on treated wood: In: First Inter. Conf. On Wood Protection with Diffusible Preservatives. Forest Prod. Res. Soc., Madison, WI. 129-133 pp.

Wozniak, P.J., and J.P. Geaghan. 1994. An introduction to SAS® system for DOS and Wondows™. Department of Experimental Statistics, Louisiana State University. 167 pp.

CHAPTER 6

DECAY AND MOLD RESISTANCE OF BORATE-MODIFIED ORIENTED STRANDBOARD

6.1. INTRODUCTION

Chemical treatment for wood-based composites against biodeterioration is an actively growing sector in the forest products industry. Composite panels need to be treated with appropriate chemicals to prevent biological attack (Lea and Bravery 1986). Like other wood materials, oriented strandboard (OSB) is susceptible to biodeterioration by a variety of microorganisms. For example, it is often exposed to wood-decay fungi, which can severely affect its economic value and usefulness. Therefore, it is desirable to find means for imparting more permanent protection during OSB manufacture.

Decay resistance of wood-based composites, including particleboard containing decay-resistant wood species, medium density fiberboard (MDF), and regular particleboards, has been studied (Behr and Wittrup 1969, Clark 1960, Evans 1997). Wood-destroying organisms such as T*. versicolor* and G. *trabeum* degrade insoluble wood components to soluble products and finally to simple chemical components. Treated products generally show a greater resistance to decay than untreated wood (Toodle and Barnes 1974, Curling and Murphy 1999). Several factors other than the natural decay resistance of wood species have been shown to influence the durability of wood composites. It was reported that the strength reduction in particleboard caused by fungi was considerably greater than the losses from 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 a greater 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). Increasing the amount of UF resin in the panel improved its resistance (Hann et al. 1962). Clark (1960) reported that the change of board specific gravity had no significant effect on decay resistance. However, the small particle size in a dense board interfered with the growth of decay fungi (Willeitner 1965).

The use of borate chemicals in preventing decay fungal attack has been previously investigated. In terms of weight loss of wood, Murphy et al. (1995) found that a boric acid equivalent (BAE) level of 0.07% from a sodium borate and boric acid mixture showed an 18.5% weight loss in southern pine sapwood caused by *G. trabeum*. The weight loss was reduced to 4.4% as the content of the borate increased to the 0.74% BAE level. Laboratory soil block tests with brown- and white-rot fungus 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 waferboard containing ZB were lower compared to the sodium borate boards at an equivalent loading level (Laks et al. 1991). The weight losses for ZB-treated panels were under 2.0% compared to 40 to 50% for the untreated panels. Fungal growth on the treated panels was also undetected (Sean et al.1999). Verhey et al. (2001) reported that 1.0% target ZB loading effectively prevented fungal attack on wood fiber and thermoplastic composites.

Hence, borate chemicals are effective to prevent wood composites from fungal attack.

The decay resistance mechanism of borate chemicals is still not well known. Lloyd et al. (1990) reported that tetrahydroxyborate ion [$B(OH)_4^-$] acts by complexation with polyols and probably attacks decay fungi through extra- and inter-cellular substrate sequestration, enzyme inhibition, and change in membrane function. They also stated that the syntheses of proteins, carbohydrates, ATP, and DNA/RNA do not occur when altering the metabolism, electron transport, and phosphate metabolism.

Airborne mold spores spoil indoor air quality and mold growth on wood products is harmful to human health. Although mold fungi generally do not decay or weaken wood materials, the growth of toxic mold fungi from poor moisture management, culminating in high indoor temperature, home dampness, and flooding in structural materials, is a significant problem (Laks et al. 2002). The indoor mold exposure has been found to induce asthma, causing chronic sinus infection and respiratory infection (Zock et al. 2001). Mold growth may be found on many domestic and commercial construction materials in service due to poor design or maintenance. *Cladosporium*, *Penicilium*, and *Alternaria*, toxic mold fungi, have been detected in homes, hotels, schools, and other structural buildings (Fogel and Lloyd 2002).

Studies have been done on the relative susceptibility of borate-treated wood products to mold fungi. The addition of 0.56% BAE from ZB to 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 zinc borate displayed a better mold resistance than disodium octaborate tetrahydrate (DOT). Gypsum boards treated with 0.3% boric acid showed sparse mold growth, which was significantly lower than the untreated boards. The boards with 1.0% boric acid showed the best results, indicating little to no growth after a 6-week period. Laks et al. (1991) also reported that zinc borate showed better mold resistance than DOT.

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-modified OSB against biodeterioration. This study was undertaken to investigate the effect of wood species, fungus type, borate types, and borate levels on the resistance of PF-bonded OSB against decay and mold.

6.2. MATERIALS AND METHODS

Experimental materials for the decay and mold tests were obtained from the panels used previously for testing of mechanical, physical, leaching, and termite resistance properties described in the previous chapters. For simplicity, the detailed description of the panel manufacturing process is omitted in this chapter.

6.2.1. Decay Resistance Test

Decay resistance tests were conducted in accordance with the modified ASTM D 2017-81 (ASTM 1998) method. Brown rot fungus, *Gloeophyllum trabeum*, and white-rot fungus, *Trametes versicolar*, were used in the study. Cultures of the test fungi consisted of a nutrient medium containing two weight percent malt extract and 1.5 weight percent agar. The medium was sterilized at 105 KPa for 30 min at 125^{o}C, and cooled down before inoculation.

To prepare test bottles, one hundred grams of silt loam screened through a U.S. No. 6 sieve were placed in each bottle with a screw cap. The average pH of the soil substrate was 7.76. Distilled water was subsequently added to bring water-holding capacity of the soil to 130 percent. The filled bottles were then loosely capped, and autoclaved twice at 105 KPa for 30 min at 125^{o}C in two days.

After cooling the bottles, untreated southern pine (*Pinus taeda L.*) and ash (*Fraxinus spp.*) feeder strips (3.4 x 2.8 x 0.3 cm) were placed on the top of soil in each bottle. Each feeder strip was then inoculated diagonally at opposite corners with a mycelial plug. The plug was cut from the actively growing edge of a 7-day old malt culture of either white or brown rot fungus. Each inoculated bottle was then incubated at 25^{o}C and 75% relative humidity until the feeder strip was heavily colonized by the test fungus.

All decay tests were done with 1.40- x 1.40- x 1.27-cm specimens from each group of OSB. There were two borate types (ZB and CB), two wood

species groups (southern pine and mixed hardwoods), four BAE levels (0, 1.5, 3.0, and 4.5%), and five replications. The labeled test blocks were placed in a screen tray and conditioned at 40°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 a feeder strip colonized by fungus, one in each bottle. To avoid losing the identity of the blocks, both bottles and OSB blocks were labeled accordingly. The bottles for brown rot fungus were incubated at 25°C and 75% RH for 8 weeks, while the bottles for white rot fungus were stored at the same conditions for 12 weeks. The lids of the jars were slightly loosened by unscrewing.

At the end of the exposure period, the test blocks were removed from the bottles. The block surfaces were carefully brushed. Finally, the blocks were dried to a constant weight at 40°C in the oven. The blocks were weighed to the nearest 0.01 g to obtain their weight after test (W_2). Weight loss was calculated as percentage of the initial sample weight as follows:

$$\text{Weight loss (\%)} = [(W_1 - W_2)/W_1] \times 100 \qquad (6.1)$$

where, W_1 = Conditioned block weight (gram) before decay test; and

W_2 = Conditioned block weight (gram) after decay test.

Microscopic analysis of the decayed test blocks was performed using Scanning Electron Microscopy (SEM). Wood samples (0.1- x 0.1- x 0.05-cm),

removed from the decay test, were conditioned at 40^{o}C for 7 days. Prior to the SEM analysis, the samples were carefully sawn under a light microscope. For SEM analysis, the prepared test blocks were mounted on stubs and coated with nickel using a EDWARD S150 Sputter Coater. The samples were then scanned using an EDWARD S150 SEM operated at 20KV.

6.2.2. Mold Resistance Test

OSB test blocks (7.62- x 10.16- x 1.27-cm) were cut from various panels for mold resistance tests. There were two species (southern pine and mixed hardwoods), 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 southern pine with resin type and content level unknown.

The mold test assembly is shown in Figure 6.1. The system consists of a metal chamber with a lid, a heating belt with temperature control unit, a sample and soil support frame, a plastic soil holder, and external insulation. The chamber was filled with water to a 7.62-cm depth. Test samples were hanged over unsterilized potting soil with their lower edges about 7.6-cm above the soil. Water temperature was controlled at 32.5 $\pm$ 1^{o}C during test. The total exposure time was 6 weeks. After the test, specimens were examined visually and rated by five people according to ASTM D 5590-94 (Table 6.1).

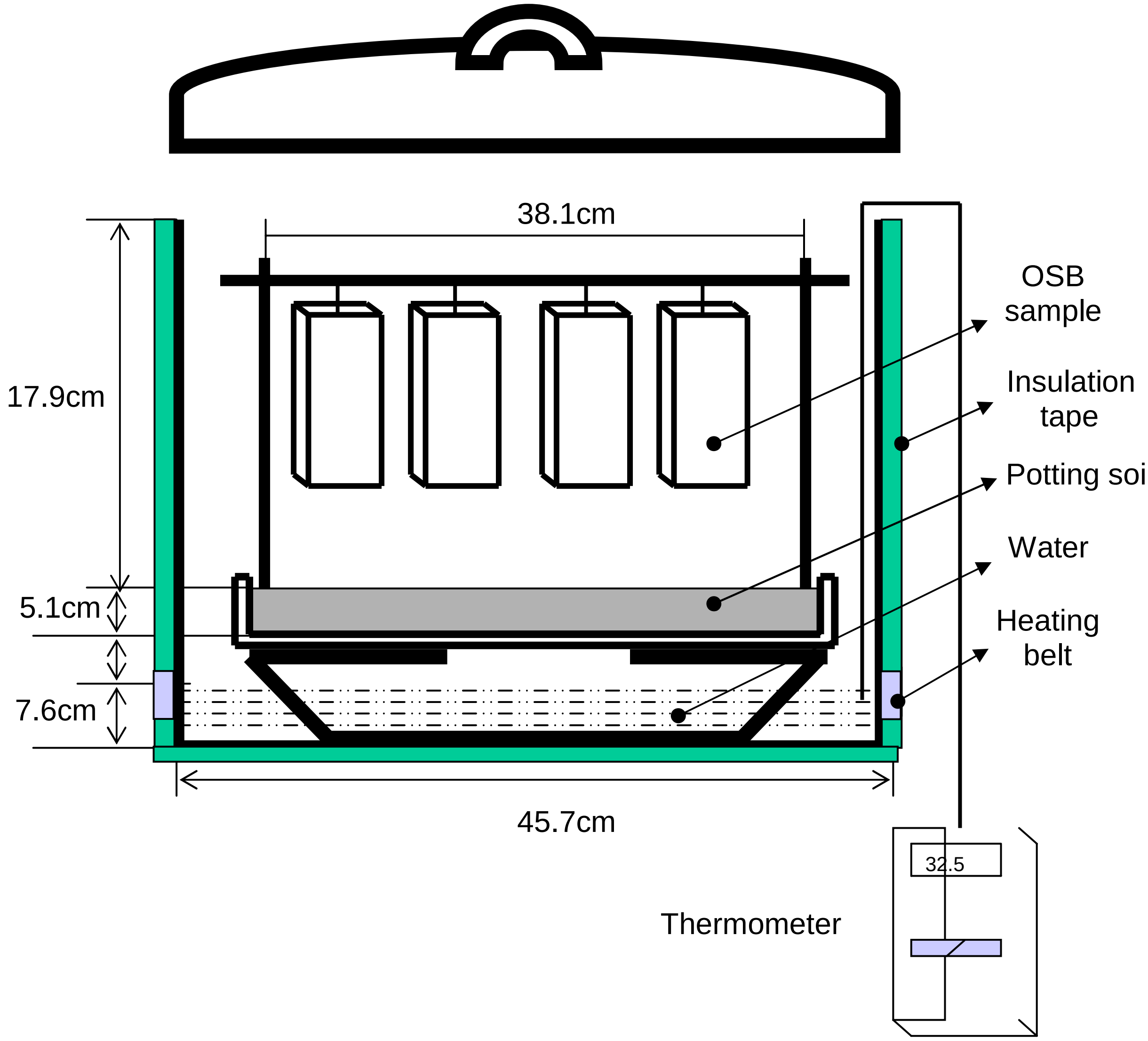


Figure 6.1. Schematic of test apparatus for mold resistance evaluation.

Table 6.1. Evaluation method for microbial growth on OSB sample surface.

Observed growth on specimens	Ratings
None	0
Traces of growth (<10%)	1
Light growth (10-30%)	2
Moderate growth (30-60%)	3
Heavy growth (60% to complete coverage)	4

6.2.3. 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 CRD factorial experiment). The effect of various factors on mold resistance properties of the treated OSB was also tested using three-way ANOVA (2x2x4x2 CRD factorial experiment). Tukey's Studentized-Range test was employed to determine whether weight loss and visual ratings were significantly different for panels at various borate content levels at the 5% significance level.

6.3. RESULTS AND DISCUSSION

6.3.1. Decay Resistance Properties

6.3.1.1. Main Effects

Average weight losses for ZB- and CB-modified OSB samples and controls exposed to white rot fungus (*T. versicolar*) and brown rot fungus (*G. trabeum*) are presented in Table 6.2. Mean specific gravity (SG) and BAE data for each group are also shown in Table 6.2. The SG for all samples varied from

Table 6.2. Average weight losses of borate-modified OSB from mixed hardwood and southern pine caused by *T. versicolar* and *G. trabeum* in a soil block test [a].

Borate [b]	Fungi	Species	SG	BAE [c] (%)	Weight loss [d] (%)
ZB	T. *versicolor*	MHW	0.64	0	5.62 (0.74) a
			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
		SP	0.73	0	7.57 (1.01) a
			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	0.73	0	22.35 (7.49) a
			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
		SP	0.70	0	39.24 (4.53) a
			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
CB	T. *versicolor*	MHW	0.79	0	5.62 (0.74) a
			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
		SP	0.77	0	7.57 (1.01) a
			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	0.79	0	22.35 (7.49) a
			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
		SP	0.81	0	39.24 (4.53) a
			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

[a] Each mean (± SD) represents five replicates of borate-modified OSB. Means within each column followed by the different letter are significantly different (ANOVA, Tukey's Studentized-Range Test, *P* = 0.05). [b] ZB and CB indicate zinc borate and calcium borate, respectively. [c] BAE – boric acid equivalents.
[d] Negative values in weight loss indicate weight gain.

0.64 to 0.82. The BAE varied from 0 (control) to about 3 percent. The weight loss data are plotted in Figures 6.2 and 6.3.

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 6.2). Clark (1960) found that increasing board SG from 0.53 to 0.60 had no effect on biodeterioration of wood. Willeitner (1965) also reported that density changes in medium density boards had no effect on decay resistance.

There were significant differences in sample weight losses between untreated OSB from mixed hardwoods and southern pine (Table 6.2). It was found that southern pine control samples were highly attacked by both fungi, compared with mixed hardwoods OSB. For white rot, the average weight loss for untreated southern pine OSB was 7.57%, whereas the average weight loss for untreated mixed hardwoods OSB was 5.62%. For brown rot, the average weight loss of southern pine OSB was 39.24%, while the weight loss for the hardwood samples was 22.35%. The results reveal that wood species had an important effect on decay resistance. Mixed hardwoods OSB showed much better decay resistance against both white rot and brown rot fungi. 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, Haygreen and Bowyer 1989). OSB specimens

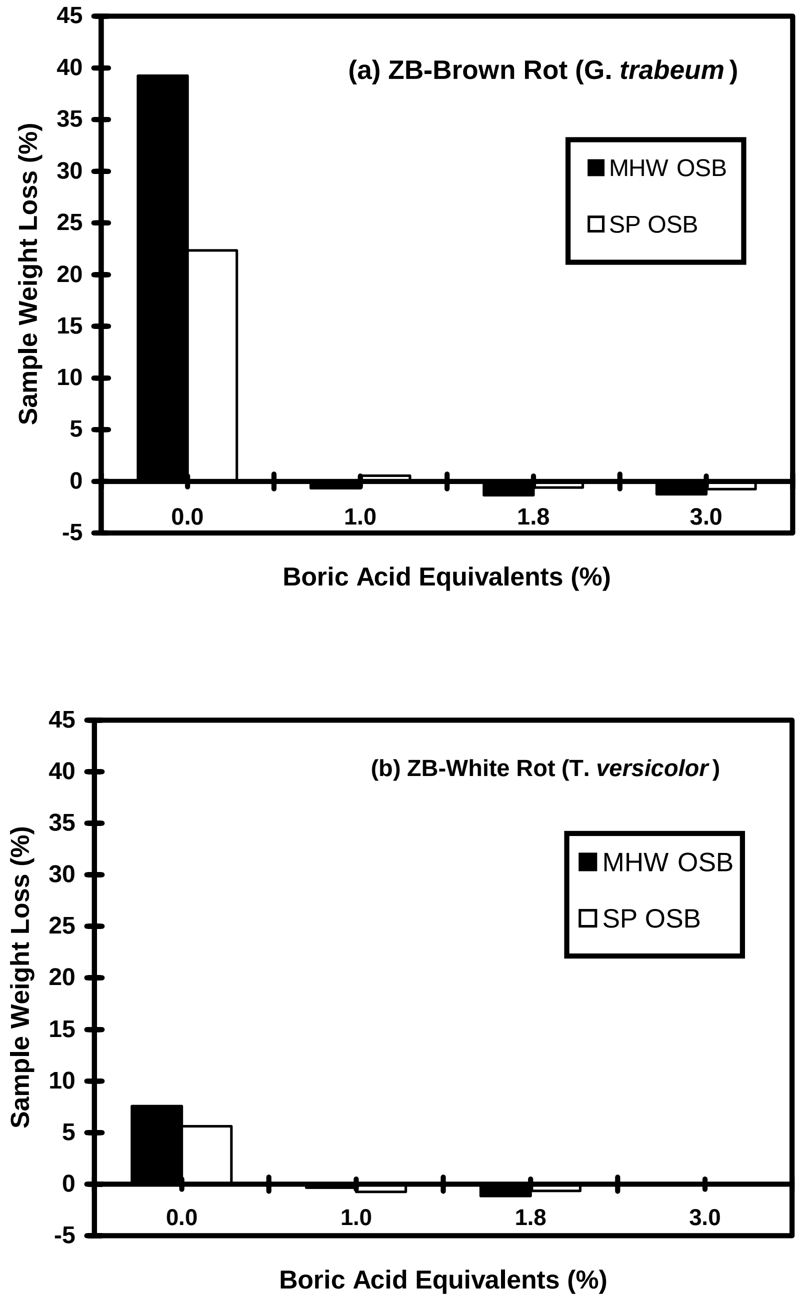


Figure 6.2. Mean weight loss caused by brown-rot fungus (a) in 8 weeks and white-rot fungus (b) in 12 weeks for ZB-modified OSB from mixed hardwoods and southern pine.

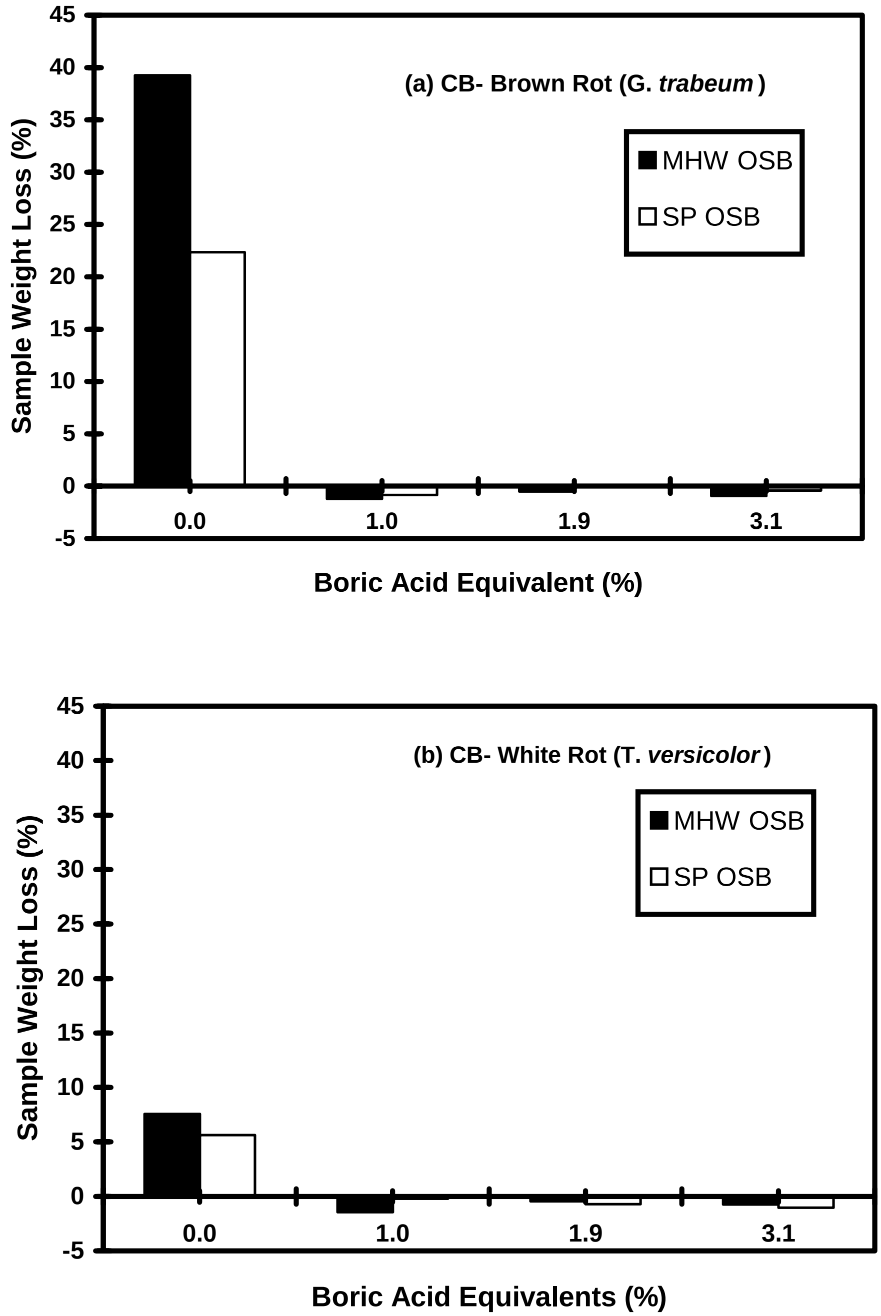


Figure 6.3. Mean weight loss caused by brown-rot fungus (a) in 8 weeks and white-rot fungus (b) in 12 weeks for CB-modified OSB from mixed hardwoods and southern pine.

produced from hardwood species such as red oak may be highly resistant to decay due to high tannin content in heartwood portions. The blocking cell cavities by tyloses in the vessel may also explain the greater durability of oak heartwood (Panshin and Zeeuw 1980).

Brown rot fungus caused significantly more decay on untreated OSB from both mixed hardwoods and southern pine, compared with white rot fungus (Figures 6.2 and 6.3). For untreated mixed hardwoods OSB samples, weight loss in the sample was 5.62% and 22.35% for white and brown rot, respectively. For the southern pine control samples, the weight loss for white and brown rot was, respectively, 7.57% and 39.24%. The primary reason for this behavior is that the decay mechanism for brown rot is characterized by both enzyme activity and non-enzyme decay agents (Fe^{+++}/H_2O_2), while the white-rot mechanism is operated by the enzyme activity only (Green and Highley 1997).

The addition of borate at 1.0% BAE or above levels into OSB completely prevented fungal attack on wood components (Figures 6.2 and 6.3). The average weight loss of ZB- and CB-treated OSB showed close to zero percent for panels at higher ZB and CB levels (1.8 and 3.0% BAE). The experimental data indicate that ZB and CB are very effective wood preservatives against both types of decaying fungi. This suggests that only relatively small ZB and CB loadings are needed to provide adequate panel protection against decay. There were some weight gains for some treated OSB samples. The weight gain may be attributed

to the moisture content variation of the test blocks before and after conditioning to a constant weight at 40°C.

According to the four-way ANOVA (Table 6.3), the main effects of fungi, borate types, and borate levels were highly significant on 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 fungus type and wood species (P > 0.6994). The main effect of wood species was insignificant (P > 0.6088).

Table 6.3. Results of four-way ANOVA on the weight loss of ZB- and CB-modified OSB attacked by *T. versicolar* and *G. trabeum*.

Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
Model	31	12513.85	403.67	84.62	<. 0001
Fungus	1	703.30	703.30	147.42	<. 0001
Species	1	1.25	1.25	0.26	0.6088
Fungus*Species	1	0.71	0.71	0.15	0.6994
Borate	1	97.97	97.97	20.54	<. 0001
Fungus*Borate	1	92.63	92.63	19.42	<. 0001
Species*Borate	1	170.18	170.18	35.67	<. 0001
Fungus*Species*Borate	1	166.90	160.90	34.99	<. 0001
Level	3	7393.28	7393.28	516.58	<. 0001
Fungus*Level	3	2096.51	698.83	146.49	<. 0001
Species*Level	3	49.03	16.34	3.43	0.0192
Fungus*Species*Level	3	0.40	0.13	0.03	<. 0001
Borate*Level	3	279.53	93.17	19.53	<. 0001
Fungus*Borate*Level	3	318.18	106.06	22.23	<. 0001
Species*Borate*Level	3	572.12	190.70	39.98	<. 0001
Fung*Species*Bora*Level	3	550.52	183.50	38.47	<. 0001
Error	128	610.64	4.77		

6.3.1.2. SEM Analysis

Small sections (0.1- x 0.1- x 0.05-cm) of solid wood (ash and southern pine) and treated OSB samples that were decayed by *G. trabeum* with up to a 40% weight loss in 8 weeks were examined with SEM. The appearances of both un-decayed tracheid cells of southern pine wood and undecayed OSB samples are shown in Figure 6.4. Decayed OSB samples from southern pine and mixed hardwoods are displayed in Figure 6.5.

Figure 6.4 (a and b) shows a severe erosion pattern of tracheid cell wall for southern pine wood due to decay. 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 et al. 1961). Figures 6.4(c) and (d) show a general view of undecayed southern pine OSB with multi-layered flakes. Large voids existed between the OSB flakes due to different characteristics of the raw furnish. The voids promote the penetration of fungal hyphae and provide more susceptibility to microorganisms compared with solid wood (Chung et al. 1999).

The extent of deterioration by *G. trabeum* fungus was severe in OSB from both southern pine and mixed hardwoods (Table 6.2 and Figures 6.5a to 6.5d).

(a) (b)

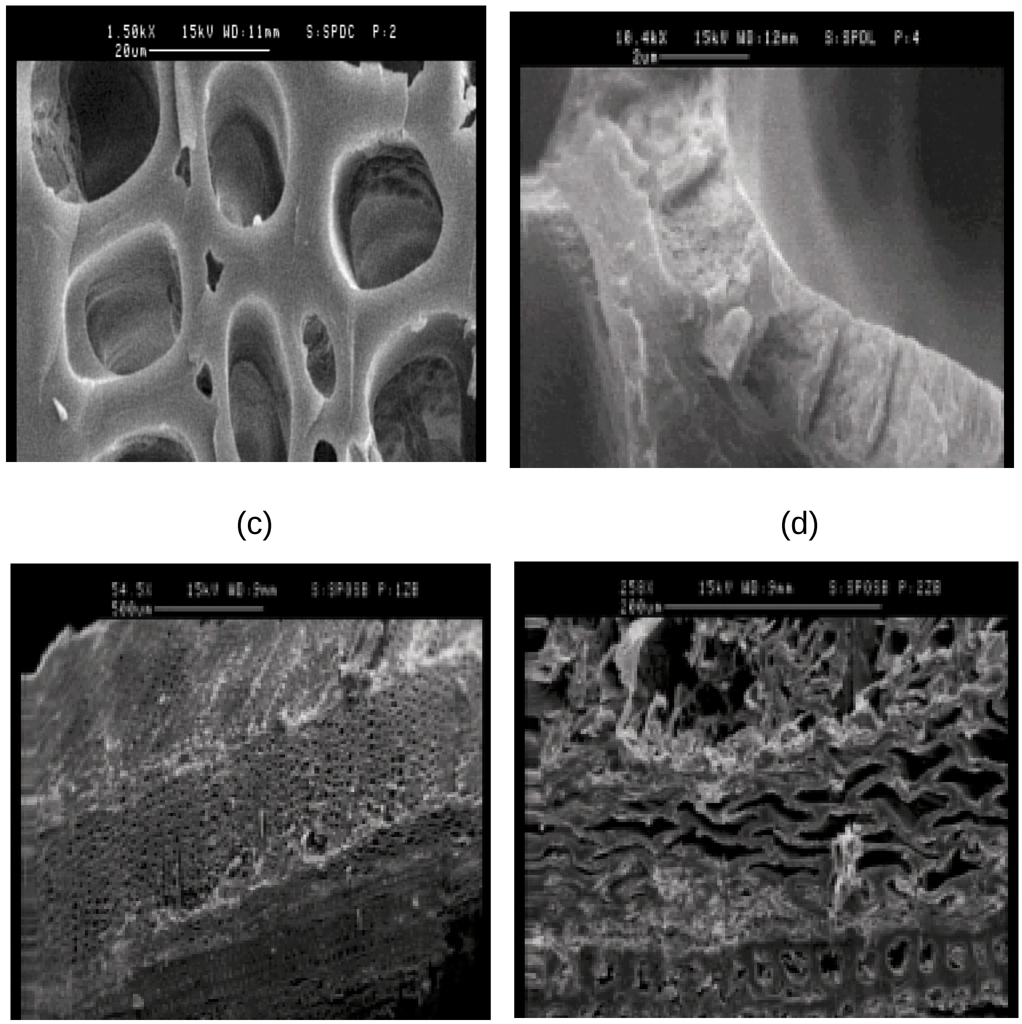


Figure 6.4. Scanning electron micrographs of southern pine wood and OSB samples exposed to wood-decay fungi *G. trabeum*. Typical views of undecayed (a) and decayed (b) southern pine tracheid cells; and typical views of undecayed southern pine OSB (c and d).

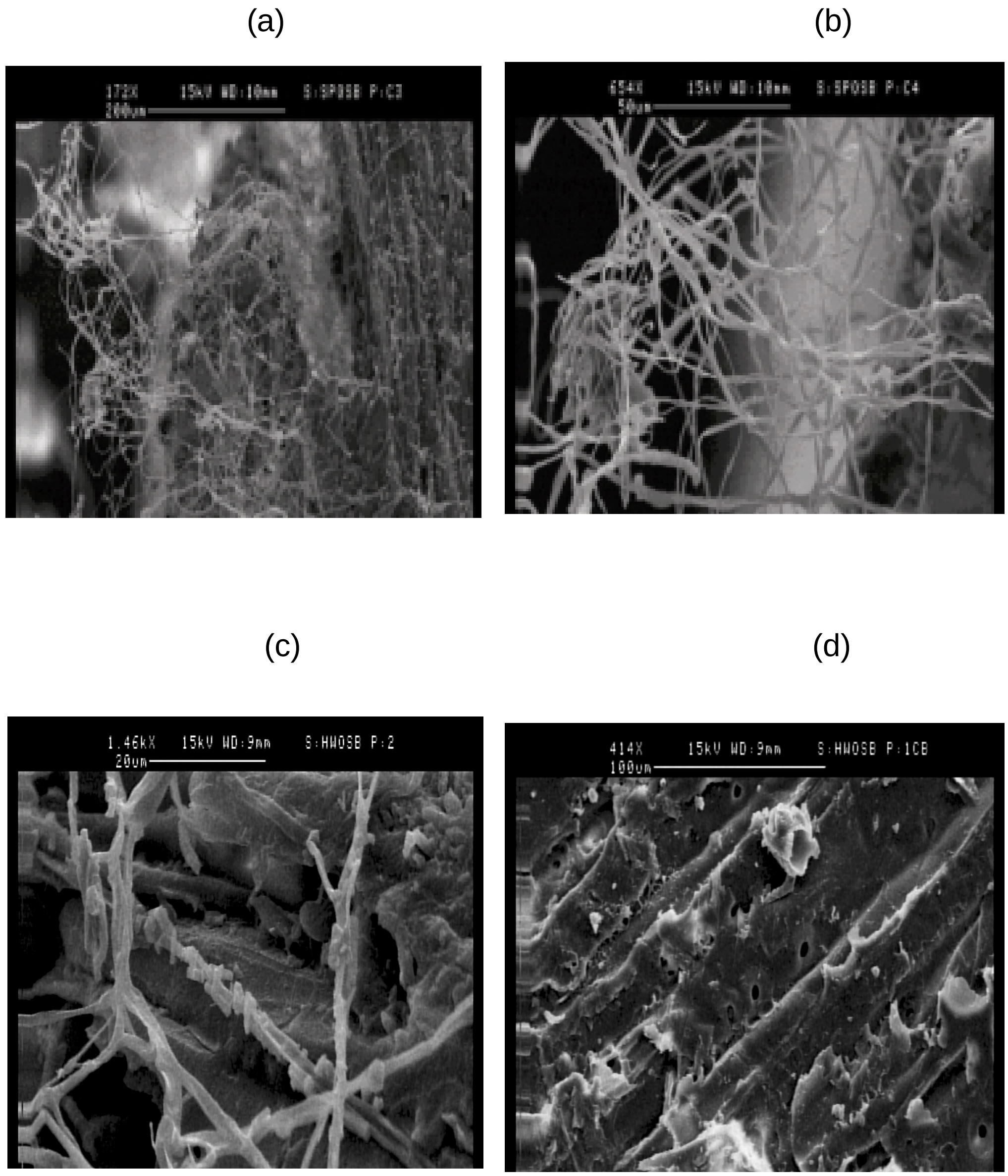


Figure 6.5. Scanning electron micrographs of southern pine and mixed hardwood oriented strandboard (OSB) samples exposed to the wood-decay fungi *G. trabeum*. (a) and (b) Hypha growth of *G. trabeum* on tracheid cell of untreated southern pine OSB, (c) hypha growth of *G. trabeum* on untreated mixed hardwoods OSB, (d) no hypha growth of *G. trabeum* on CB-treated OSB from mixed hardwoods (1.0% BAE).

Figures 6.5a and b show the appearance of the control southern pine OSB after decaying by *G. trabeum* with a 39.24% weight loss. Mycelium heavily covered the sample during the 8-week period. The appearance of the control mixed hardwoods OSB sample, decayed by brown rot fungi with a 22.35% weight loss, is shown in Figure 6.5c. 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 vessel and tracheid lumen helped fungal hyphae penetrate into OSB.

No apparent fungi of *G.trabeum* were observed from treated OSB samples (Figure 6.5d). Pits were clearly seen along the longitudinal surface of cell walls. *G. trabeum* did not grow on the surface of the OSB sample and penetrate into the inner cell through pit pairs.

6.3.3. Mold Resistance Properties

Mold resistance data are summarized in Table 6.4. The rating data are plotted in Figure 6.7 as a function of BAE level for various products. As shown in Figure 6.7, untreated OSB samples from mixed hardwoods OSB and commercial OSB were most susceptible to mold growth (ratings of 3.82 and 4.0, respectively). Borate-modified OSB from both mixed hardwoods and southern pine prevented the mold growth effectively (ratings of 0.50 to 2.75, respectively). Greater protection of the OSB was achieved with an increase in borate retention levels. This result is consistent with data produced by Fogel and Lloyd (2002).

Table 6.4. Average visual ratings of borate-modified OSB after exposure to mold fungi for 6 weeks.

Species	Borate	BAE (%)	SG	Ratings[a]
MHW	ZB	0	0.774	3.82 (0.26)a
		1.05	0.784	2.00 (0.00)b
		2.00	0.749	1.90 (0.64)b
	CB	0	0.778	3.82 (0.26)a
		1.03	0.790	2.75 (0.46)b
		1.96	0.753	2.13 (0.83)b
SP	ZB	0	0.772	1.50 (0.46)a
		1.1	0.805	0.63 (0.52)a
		2.0	0.786	0.75 (0.46)a
	CB	0	0.776	1.50 (0.46)a
		1.03	0.805	0.50 (0.53)b
		1.99	0.787	0.63 (0.52)b
Commercial OSB panel		0	0.653	4.00 (0.00)

[a]Data with the same letter within a group show no significant difference at the 5% significance level.

Mixed hardwoods OSB showed a higher susceptibility to mold growth than southern pine OSB with and without borate treatment (Figure 6.6). 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 (Beall 1970, Wanggard 1966). It was reported that there was significant relationship between mold growth and carbohydrate content (Terziev 1996, Terziev and Boultelje 1998). It was also found that carbohydrates with low molecular weight and nitrogen content of wood showed great effect on the susceptibility of wood to mold attack (Theander, 1993).

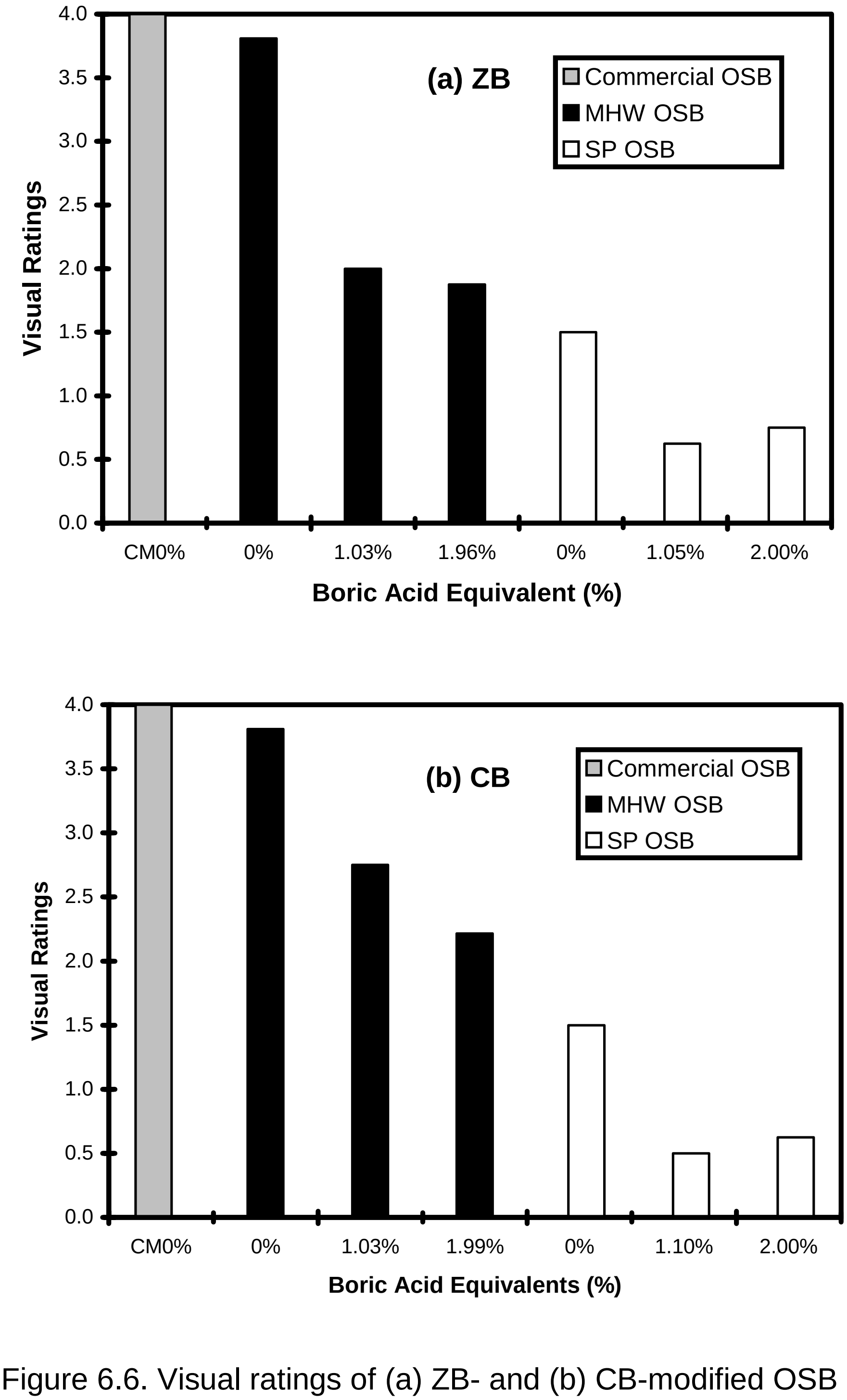


Figure 6.6. Visual ratings of (a) ZB- and (b) CB-modified OSB exposed to mold fungi for 6 weeks.

According to the three-way ANOVA (Table 6.5), the main effects of wood species, borate types, and borate levels were significant on mold growth rating of 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, however, not significant (Table 6.5).

Table 6.5. Results of three-way ANOVA on mold resistance properties of borate-modified OSB.

Source	DF	Sum of Squares	Mean Squares	F Values	Pr>F
Model	11	128.61	11.69	45.95	<.0001
Species	1	78.84	78.84	309.84	<.0001
Borate	1	4.59	4.59	18.05	0.014
Species*Borate	1	0.01	0.01	0.04	0.840
Level	2	33.58	16.79	65.99	<.0001
Species*Level	2	4.00	2.00	7.86	0.007
Borate*Level	2	3.25	1.63	6.39	0.003
Species*Borate*Level	2	4.35	2.17	8.51	0.001
Error	84	21.38	0.25		

6.4. CONCLUSIONS

Weight loss in OSB caused by both brown- and white-rot fungi was directly related to borate level, wood species, and fungus type. Decay by brown-rot fungus was evident for untreated southern pine and mixed hardwoods OSB

controls. The white-rot samples did not show significant weight loss in either wood species group. The incorporation of ZB and CB into OSB provided a suitable protection against both fungi. No significant weight loss was observed from samples treated with ZB and CB, even at the low loading level (i.e., 1.0% BAE).

SEM analysis showed distinct evidence of the 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 a sparcity of bore-holes. Bore-holes became progressively more numerous and larger in samples with a 30% or more weight loss.

Untreated OSB from both mixed hardwoods and commercial OSB were most susceptible to mold growth. However, borate treatment for OSB from both mixed hardwoods and southern pine effectively prevented the mold growth. Mold resistance was further achieved with the increase of borate retention level. Mixed hardwoods OSB with and without borate treatment showed a higher susceptibility to mold growth than southern pine OSB. This was attributed to the content of nutrient and other low molecular weight carbohydrates of the different wood species.

6.5. REFERENCES

American Society for Testing and Materials. 1997. Standard test method for resistance to growth of mold on the surface of interior coatings in an environmental chamber. ASTM D 3273-94. Annual Book of ASTM Standards. Vol. 6.01. Paint-Tests for Chemical, Physical, and Optical Properties; Appearance. ASTM, West Conshohocken, PA. 338-340 pp.

American Society for Testing and Materials. 1997. Standard test method for determining the resistance of paint films and related coating to fungal defacement by accelerated four-week agar plate assay. ASTM D 5590-94. Annual Book of ASTM Standards. Vol. 6.01. Paint-Tests for Chemical, Physical, and Optical Properties; Appearance. ASTM. West Conshohocken, PA. 622-625 pp.

American Society for Testing and Materials. 1998. D 2017-81. Standard method of accelerated laboratory test of natural decay resistance of wood. In: ASTM Annual Book of Standards, Vol. 4.10. Wood, American Society for Testing and Materials. West Conshohocken, PA. 312-316 pp.

Beall, F.C. 1971. Differential calometric analysis of wood and wood components. Wood Sci. Tech. 5: 159-175.

Behr, E.A., and B.A. Wittrup. 1969. Decay and termite resistance of two species particleboars. Holzforshung 23: 166-170.

Chung, W.Y., S.G. Wi, H.J. Bae, and B.D. Park. 1999. Microscopic observation of wood-based composites exposed to fungal deterioration. J. of Wood Science. 45: 64-68.

Clark, J.W. 1960. Decay resistance of experimental and commercial particleboard. USDA For. Prod. Lab., Rept. No. 2196. Madison, WI.

Cowling, E.B. 1961. Comparative biochemistry of the decay of sweetgum sapwood by white-rot and brown-rot fungi. Technical Bulletin No. 1258. Forest Products Laboratory Forest service, Madison, WI.

Curling, S.F., and R.J. Murphy. 1999. The effect of artificial ageing on the durability of wood-based boards materials against basidiomycete decay fungi. Wood Sci. Tech. 33: 245-257.

Evans, P.D., J.W. Creffield, J.S. Conroy, and S.C. Barry. 1997. Natural durability and physical properties of particleboard composed of white cypress pine and radiata pine. Forest Prod. J. 47(6): 87-94.

Fengel, D., and G. Wegner. 1984. Wood chemistry ultrastructure reactions. Walter de Gruyter, New York, N.Y. 373-406 pp.

Fogel, J.L., and J.D. Lloyd. 2002. Mold performance of some construction products with and without borate. Forest Prod. J. 52(2): 38-43.

Green, F., and T.L. Highley. 1997. Brown-rot wood decay-insight gained from a low-decay isolate of *Postia Placenta*. Trends in Plant Pathology. 1:1-17.

Hann, R.A., J.M. Black, and R.F. Blomquist. (1962). How durable is particleboard. Forest Prod. J. 12(12): 577-584.

Haygreen, J.G., and J.L. Bowyer. 1989. An Introduction: Forest products and Wood Science (2nd ed.). Iowa State University press, Ames, Iowa.

Laks, P.E., B.A. Haataja, R.D. Palardy, and R.J. Bianchini. 1988. Evaluation of adhesives for bonding borate-treated flakeboards. Forest Prod. J. 38(11/12): 23-24.

Laks, P.E., X. Quan, and R.D. Palardy. 1991. The effects of sodium octaborate and zinc borate on the properties of isocyanate-bonded waferboard. “Adhesives and Bodnded Wood Symposium” Proceedings. (C.Y. Hse and B. Tomita, eds.) FPRS. 144-157 pp.

Laks, P.E., D. Richiter, and G.M. Larkin. 2002. Fungal susceptibility of interior commercial building panels. Forest Prod. J. 52(5): 41-44.

Lea, R.G., and A.F. Bravery. 1986. Laboratory assessment of the fungal resistance of wood-based board materials. Mat. U. Org. 21(2): 101-122.

Lloyd, J.D., D.J. Dickinson, and R.J. Murphy. 1990. The probable mechanisms of action of boric acid and borates as wood preservatives. Intl. Res. Group on Wood Preserv. Doc. No.: IRG/WP/1450. Stockholm, Sweden.

Murphy, R.J., H.M. Barnes, and S.M. Gray. 1995. Decay and soil depletion studies with polymer/boron preservative systems. Forest Prod. J. 45(9): 77-81.

Panshin, A.Z., and C. Zeeuw. 1980. Text Book of Wood technology. McGraw-Hill Book Company, New York. 720 pp.

Schmidt, E.L., D.W. French, R.O. Gerthejensen, J. Hermann, and H. Hall. 1978. Strength reductions in particleboard caused by fungi. Forest. Prod. J. 28(2): 26-31.

Sean, T., G. Brunette, and F. CÔTÉ. 1999. Protection of oriented strandboard with borate. Forest Prod. J. 49(6): 47-51.

Terview, N., N. Bjurman, and J. Boutelje. 1996. Effect of planning on mould susceptibility of Kiln- and air-dried Scots Pine (pinus sylvestris L.) lumber. Mat. and Org. 30(2): 95-103.

Terview, N., and J. Boutelje. 1998. Effect of felling time and kiln-drying on time and susceptibility of wood to mould and fungal stain during an above-ground field test. Wood Sci. Tech. 30(4): 360-367.

Theander, O., N. Bjurman, and J. Boutelje. 1993. Increase in the content of low-molecular weight carbohydrates at lumber surface during drying and correlation with nitrogen content., yellowing, and mould growth. Wood Sci. Tech. 27: 381-389.

Toole, E.R., and H.M. Barnes. 1974. Biodeterioration of particleboard. Forest Prod. J. 24(10): 55-57.

Verhey, S., P. Laks, and D. Richiter. 2001. Laboratory decay resistance of woodfiber/themoplastic composites. Forest Prod. J. 51(9): 44-49.

Wanggard, F.F.1966. Resistance of wood chemical degradation. Forest Prod. J. 16(2):53-64.

Wellietner, H. 1965. On the mycological testing of wood particleboards. Materialprufung. 7(4): 129-134.

Wozniak, P.J., and J.P. Geaghan. 1994. An introduction to SAS® system for DOS and Wondows™. Department of Experimental Statistics, Louisiana State University. 167 pp.

Zock, J.P., D. Jarvis, C. Luczynska, J. Sunyer, and P. Burney. 2002. Housing characteristics, reported mold exposure, and asthma in the European Community Respiratory Health Survey. J. of Allergy and Clinical Immunology 110 (2):285-292.

CHAPTER 7

CONCLUSIONS

This study was done to examine the effects of powder zinc borate (ZB) and calcium borate (CB) on resin gel time, strength, swelling, leaching, termite, and decay resistance properties of oriented strandboard (OSB). Based on the results from the study, the following conclusions can be derived.

1. The pH of southern hardwood flakes was acidic. White oak flakes were the most acidic (pH=4.60), while elm flakes were nearly neutral (pH=6.93). Flakes from southern pine showed a relatively low pH value of 4.98, compared to southern hardwood flakes. The alkali buffer capacity was larger than the corresponding acid buffer capacity. The gel time of PF resin decreased with the increase of ZB content. The reduced gel time was partially recovered by using PEG in combination with ZB. The effectiveness of PEG varied with wood species and borate levels. The main effect of wood species was not significant on the gel time of the PF resin. The gel time of the PF resin-wood mixture had no direct correlation with either pH or buffer capacity of the wood for those species.
2. Panel stiffness was not significantly affected by borate to a 3.5 percent boric acid equivalent (BAE) level. However, zinc and calcium borate showed some negative effects on bending strength and internal bond (IB) strength values for both mixed hardwood and southern pine OSB. The main effect of wood species at various ZB levels was highly significant on

both bending strength and stiffness for ZB-modified OSB. TS after a 24-hour water soaking generally increased with the increase of borate level in the panel. However, ZB-modified OSB had less TS than CB-modified OSB at an equivalent BAE level. Borate particle size had a significant influence on the TS properties. CB with a large mean particle size (11.09 μm) caused significant thickness swelling at high BAE levels. CB with a smaller particle size (6.43 μm) helped bring the TS into a stable and acceptable level.

3. A portion of boron in the treated OSB leached out under a water-soaked condition. Boron leaching from both ZB- and CB-modified OSB occurred during the initial water exposure. The leaching rate decreased as the leaching time increased. Types of borate, BAE levels, and wood species significantly influenced the boron leachability. A smaller particle size of CB (6.43 μm) helped reduce its leachability. Glue-line washing due to TS of the test samples under water and borate decomposition to form more water-soluble boric acid are two possible causes for the observed large leachability. The relationship between BAE and leaching time followed a decaying exponential function for ZB and a decaying power function for CB. Material constants of the regression models allowed a direct comparison of OSB's leachability from various wood species. A boron fixation with other chemical agents may be necessary for borate-modified OSB under the extreme water exposure conditions.

4. High termite mortality and low wood weight loss of borate-modified OSB from both mixed hardwoods and southern pine were observed with the increase of ZB and CB loading levels. At higher borate levels, there was little damage on wood samples. The treatment of OSB with ZB and CB at BAE levels equal or greater than 1.0% provided adequate protection from serious structural damages, although some surface termite feeding still occurred. Wood species showed an insignificant effect on termite resistance. ZB-modified OSB showed a relatively lower weight loss than CB-modified OSB under similar conditions. There were significant correlations among termite mortality, weight loss, and visual damage ratings.

5. Decay tests with brown- and white-rot fungus revealed that wood weight loss was significantly related to wood species and fungus type. White-rot fungi did not cause significant weight losses for OSB control samples from both species, compared to the brown-rot fungi. No significant weight loss was observed from the samples that were treated with ZB and CB at a loading level of 1.0% BAE or above. The SEM analysis showed distinct evidence toward fungal colonization and the general thinning pattern of the cell wall material due to the fungal attack. In the OSB and solid wood controls that were decayed by *G. trabuem*, the hyphae were abundant only in the wood rays. In the early stages of decay, the wood cell walls were penetrated almost exclusively through bordered and simple pit pairs.

This caused sparse bore-holes in the sample. However, bore-holes became progressively more numerous and larger when the samples reached a weight loss above 30 percent.

6. Mold resistance of treated OSB was achieved with an increase of borate level with both mixed hardwood and southern pine. The mixed hardwoods and commercial OSB exhibited a higher susceptibility to mold growth than southern pine OSB with and without borate treatment. The mold susceptibility is presumably related to three factors: sample surface nutrient content, low molecular weight carbohydrate content, and sapwood content.

The information developed from this study can help OSB industry to produce chemically-modified OSB to resist termite, decay, and mold for meeting the increased market demand of treated structural panels.

VITA

Sunyoung Lee was born in Seoul, the capital city of South Korea. In 1988, he received his bachelor of science degree in forest resources from Korea University, Korea. He received his master of science degree with an emphasis in the wood chemistry, pulp, and paper in 1990. After graduation, he engaged in compulsory military service as a second Lieutenant in Youngchon, Korea. He received his second master of science degree from University of Washington with an emphasis on paper science and engineering in 1995. He studied at the University of Minnesota in a doctoral program in wood and paper science for two years from 1996 to 1998. He transferred from University of Minnesota to Louisiana State University for studying in the forest products program. Now he is pursuing his doctor of philosophy degree in the School of Renewable Natural Resources, Louisiana State University. He plans to complete his doctoral studies in December of 2002 and to continue his research career in academic fields in Korea.