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Properties of borate-treated strandboard bonded with pMDI resin

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PROPERTIES OF BORATE-TREATED STRANDBOARD BONDED WITH PMDI RESIN

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Random strandboards from mixed southern wood species were manufactured using calcium borate (CB) and zinc borate (ZB) as chemical additives and polymeric methylene diphenylmethane disocyanate (pMDI) as resin. There were four target levels of borate loading and two levels of resin content. Panel properties, including modulus of elasticity (MOE), modulus of rupture (MOR), internal bond (IB) strength, linear expansion (LE), thickness swelling (TS), leachability, and swelling and strength retention properties under cyclic relative humidity, were measured. The influence of borate content, borate type, and resin content on various properties was analyzed.

It was found that the addition of borate negatively impacted the mechanical and physical properties of the boards. The influence of ZB and CB on both mechanical and physical properties was similar. The increase of resin content improved the properties significantly, especially TS. A certain portion of borate leached out from test samples under the water-soaking conditions. There was a higher initial leaching rate and the leaching rate decreased with the lapse of leaching time. Panels with higher initial borate loading level had higher leaching rate for all panel types. The leaching rates of ZB and CB treated samples were similar. The increase of resin content helped reduce TS and boron leaching. Compared with PF-bonded boards, leaching rate was significantly reduced for the pMDI-bonded panels. Under cyclic humidity exposure condition, the addition of borate negatively influenced the maximum TS, residual TS, and mechanical properties. The effects of ZB and CB on the maximum TS, residual TS, and mechanical properties were similar. The increase of resin content significantly reduced residual TS, but had no influence on maximum TS and mechanical properties. The addition of borate

did not have significant influence on the strength retention of the boards under long term cyclic humidity exposure condition.

CHAPTER 1

INTRODUCTION

Oriented strandboard (OSB) is a performance-rated structural panel engineered for uniformity, strength, versatility, and workability. It is utilized internationally in a wide array of applications including commercial residential construction and renovation, packaging, furniture, and shelving. Because it is engineered, OSB can be manufactured to meet specific requirements in thickness, density, panel size, surface texture, strength, and rigidity. This engineering process makes OSB one of the most widely accepted and preferred structural panels (Biblis 1985).

Oriented strandboard can be manufactured using residue of wood mills or small-diameter logs that are previously under-utilized. In the southern United States, low-grade hardwoods are being successfully used to manufacture mixed hardwoods OSB, adding significant value to a vast amount of low-value materials. OSB has a viable potential in time of curtailed timber supplies due to reducing forest, demand from conservation groups and public for saving the environment, and more stringent logging regulations. Production trends in the forest products industry indicate less production of structural plywood and increased production of composite wood panels like OSB (Barnes and Amburgey 1993). 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).

However, as a biodegradable material, OSB is vulnerable to Formosan subterranean termites (FST) and fungal attack. In 1993, the Wood Protection Council of the National Institute of Building Sciences (NIBS) estimated the annual costs of replacing wood damage by the FST to be $2 billion, up from $750 million in 1988 (Ring 1999). The

termites are the most destructive insect in Louisiana and significantly affect the economy of the state.

Decay fungi are probably the most destructive biological pathogens on wood structures in the United States. 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). Within the last 5 years, huge decay losses occurred as a result of improper installation of exterior insulation finishing systems (Granier and Jorgensen 2001).

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, 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 because water has an adverse effect on the adhesive bond resulting in high thickness swelling and water absorption in wood composite products (Currie 1997).

One of the most promising chemicals for treating OSB furnish is boron compounds or borates. Borates are odorless, colorless, and noncorrosive. They have a low mammalian toxicity, but high toxicity to insects and fungi (Manning and Arthur 1995). Early attempts to treat OSB with borates were unsuccessful because most borates are highly soluble in water. Highly soluble borates inhibit the ability of phenol-formaldehyde (PF) resins to penetrate the wood and limit the effectiveness of the glue bond (Knudson and Gnatowski 1990). Zinc borate (ZB), $2ZnO \cdot 3B_2O_3 \cdot 3.5H_2O$, and calcium borate (CB), $Ca_2B_6O_{11} \cdot 5H_2O$, are almost insoluble in water. In addition, they offer low cost, ease of handling, and fire retardancy. 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 (Barnes and Amburgey 1993).

However, the properties of OSB may decrease with the addition of ZB and CB. Lee (2003) demonstrated that mechanical and swelling properties of borate-treated strandboard bonded with PF resin were negatively impacted with the increase of borate content, especially with CB. The leaching rate also increased due to large thickness swelling of the test samples. The initial leaching rate was much larger, especially with panels at higher borate loading levels, and the rate decreased as the leaching time increased. The boron element leached out at a higher rate compared to zinc and calcium

(Lee 2003). The problem is presumably related to the interaction between functional methyl 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). The leaching of boron for PF-bonded strandboard containing water insoluble borate has significantly limited its direct exterior applications such as sidings.

Resin type and content significantly influence the properties of wood based composites. The use of higher resin loading levels and more advanced resin systems (such as pMDI) can directly improve strength and dimensional stability of the wood composite panels (Wilson 1980, Galbraith 1986). It was shown that bond strengths of PF-bonded waferboard containing biologically-effective levels of sodium borates or boric acid was unacceptable low. In contrast, there was little or no effect by water soluble borates on the bonding efficiency of pMDI resin (Laks et al. 1991). However, the properties of borate-treated OSB bonded with pMDI resin are still lacking. Therefore, a systematic study on the properties of pMDI-bonded strandboard with different borate systems can provide useful information for better design, fabrication, and field uses of such a valuable structural product.

1.1 Objectives

The general goal of this research was to study the influence of borates on the properties of strand panels bonded with pMDI resin. Specific objectives were:

1) to study the effect of borate type, borate loading level, and resin content on short term bending strength and modulus, internal bond strength, linear expansion, and thickness swelling;

2) to study the boron leachability of the panels as influenced by borate type, leaching time, and resin contents; and
3) to study long-term swelling and strength retention properties of the panel under cyclic humidity exposure conditions.

1.2 Outline of Thesis

This thesis is divided into five chapters. Chapter 1 and Chapter 2 provide introduction and background to the research problems addressed in the thesis. Chapter 3 presents material selection, experiment procedure, and data analysis methods. The results are summarized in chapter 4. Finally, Chapter 5 provides the conclusions to the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 OSB as a Structural Composite Panel

Wood composites have long been the building materials of choice for home construction in the United States. The wood-frame construction system has a solid history of producing housing of the highest standards. The system is easy to build, delivers economic value, has excellent strength in earthquake or high-wind conditions, is energy efficient, and is derived from a renewable resource. Modern wood-frame construction includes several types of engineered wood composites that are economically viable in multi-story residential buildings and non-residential projects. Oriented strandboard (OSB) is one of the engineered structural wood composites widely used for house construction as sheathing, flooring, and I-joist materials. OSB, as an engineered structural use panel developed in 1954 (Lowood 1997), is a mat-formed panel product made of strands, flakes or wafers sliced from small diameter, round wood logs and bonded with an exterior-type binder under heat and pressure. Strand dimensions are predetermined and have a uniform thickness. OSB panels consist of layered mats. Exterior or surface layers are composed of strands aligned in the long panel direction; inner-layers consist of cross- or randomly-aligned strands. These large mats are then subjected to intense heat and pressure to become a "master" panel and are cut to size. The mechanical properties of the board are enhanced by layering and alignment of wood flakes. The strength of OSB comes mainly from the uninterrupted wood fiber, interweaving of the long strands or wafers, and degree of orientation of strands in the surface layers. Waterproof resin

binders are combined with the strands to provide internal strength, rigidity, and moisture resistance (Najera and Spelter 2001).

The physical and mechanical properties of OSB make it suitable for a wide range of structural and non-structural applications. It is widely used in residential construction and is also gaining recognition in the commercial construction industry. Applications include sub- flooring, underlayment, roof sheathing, wall sheathing, and exterior siding. OSB is increasingly used in engineered components such as webs of wood I-beams, components for floor trusses, stressed skin panels, and structural foam core panels. It is also suitable for applications such as crating, pallets, bins, furniture frames, display racks, and store fixtures (Lowood 1997).

Today, all model building codes in the U.S. and Canada recognize OSB panels for the same uses as plywood on a thickness-by-thickness basis. Production trends in the forest products industry indicate less production of structural plywood and increased production of composite wood panels like OSB (Barnes and Amburgey 1993). OSB has captured more than half of the structural panel market in the last two decades (Schuler *et al.* 2001). OSB and similar composite products allow forest products companies to better utilize their resources and obtain a faster return on their investment.

2.2 The Need for Protecting OSB

Because the flakes in OSB are a natural and organic material, OSB is at the risk of biodeterioration in certain circumstance—for example, in wet conditions or in the areas with a high termite hazard. In the United States, particularly in the south, damages to buildings from termites and decay fungi cost billions of dollars per year. The Formosan subterranean termites (FST) are the most destructive insect in Louisiana and affect

significantly the economy of the state. FST were accidentally introduced to the southern United States (US) in the early 1960's. This insect thrives in climates with mild winters and high rainfall. The states along the Gulf Coast have a climate that is ideal for the Formosan termites to thrive. In the greater New Orleans metropolitan area, the Formosan termites are believed to cause $300 million of damages annually. The abundance of food and ideal climate for the termite have led to a greater need for treated wood products in these geographic areas (Shupe and Dunn 2000).

Decay and mold inside walls and attics thriving under high humidity and heat conditions were common in the South, especially in Louisiana. This problem has become more serious due to the construction of tighter structures, which do not allow high moisture to escape. Common sources of moisture are bathrooms with poor ventilation, roof leaks, leaky water pipes, improperly vented clothes dryers, and flooding (Fogel and Lioyd 2002). Decay fungi are probably the most destructive biological pathogens on wood structures in the United States. Within the last 5 years, there were huge losses due to decay occurred and improper installation of exterior insulation finishing systems (Granier and Jorgensen 2001). And, the growth of mold has also been concern recently. Although mold has not been directly linked to health problems scientifically, it is thought to cause illness 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)

In order to prevent the damage of FST, mold and decay, the factors that allowed them to colonize wood including oxygen, water, favorite temperature and source of food have been extensively studied. It should be noted that, although the methods focused on the first three factors have significant results, they will not prevent reinfestation. It is becoming increasingly evident that the only certain method of providing protection for the wood products is to remove the wood as a food resource. Repellent chemicals are used in wood composites based on this idea. It has been shown that the chromate copper arsenate (CCA) and borate chemical treatments prevent wood materials from termite and fungal attack (Laks and Palardy 1993).

2.3 Protection Techniques and Chemicals

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 is being phased out from the market (Archer et al. 1993).

One of the most promising preservatives for treating OSB is boron. Boron is a ubiquitous element, present naturally in sea water, fresh water, rocks, soil, and all plants. Boron neither accumulates in any environmental compartment nor bioaccumulates, but is transported into the oceans which have a high natural environmental background level of borate (Morrel et al. 1998). Boron is an essential micronutrient for healthy growth of all plants, and borate fertilizers are used in agriculture to improve yields and to correct the symptoms of boron deficiency in crops. At the concentrations generally detectable in rivers, borate causes no adverse effects to either land plants by irrigation or water plants and aquatic life. Similarly, borate levels generally detected in soil cause no effects to land

plants or soil organisms. Organisms in fresh water are the most sensitive to borate. The safe, no-effect concentration of borate to all freshwater aquatic life is at least 1mg/l (Drysdale 1994).

Boron has been used for soil treatments, baits for termite traps, insecticide dusts, remedial treatments for lumber, and for protection of solid wood and wood composites (Grace 1997). Changing building practices, the discontinuation of soil poisoning for termite control, trends towards value-added production at the source, public perception of the need to conserve valuable forest resources, and product development in the composites industry will lead to a further use of preservatives like boron (Vinden 1990). Borates have a low mammalian toxicity, are effective in protecting wood from termites and fungi, are odorless and colorless, reduce the susceptibility to fire, are non-volatile, and are noncorrosive (Currie 1997). Borates have been used to protect wood from damage by termites and fungi in North America since the 1930s (McNamara 1990).

At the same time, borates are found as mineral deposits around the world, with a particularly large storage in the United States (i.e., in the deserts of California). Because they are considered benign for human health, borates are perhaps the most suitable wood preservatives for interior construction components. Borates are also inorganic, and contain no volatile organic component (VOC). VOCs are air pollutants sometimes associated with various health and odour complaints. Borate-treated wood looks and handles just like untreated wood. Borate-treated wood is colorless, although some treating facilities add a colorant for identification. It can be drilled, sawn, glued and finished as with any other wood (Drysdale 1994).

There are many kinds of borates. Zinc borate (ZB, $2ZnO \bullet 3B_2O_3 \bullet 3.5H_2O$) and calcium borate (CB, $Ca_2B_6O_{11} \bullet 5H_2O$) are two common kinds of borates. They are easy of handing and offer low cost. ZB and CB are almost insoluble in water, which can reduce their leaching under the wet condition. Although they are difficult to be used in the solid wood, it is relatively simple to incorporate powder ZB and CB into mat-formed composites during the blending process. Both borates may be applied as dry powder and require no use of organic solvents during OSB manufacturing. These characters provide an impetus for borate components to play an expanding role in the wood-based panel industry as wood preservatives (Hashim et al. 1992).

2.4 Previous Work on Borate Treated OSB

Significant work has been done to study the properties of ZB and CB treated strandboards from southern wood species boned with phenol formaldehyde resin (Lee 2003). It was shown that the panels treated with ZB and CB at the levels used were not significantly weaker than the untreated samples in terms of specific MOE and MOR (i.e., MOE and MOR divided by sample specific gravity). ZB and CB showed the negative effect on IB strength. The ZB level did not show significant effect on thickness swelling. CB treated panels had large TS and the property can be improved by using CB with a smaller particle size.

The leaching of the chemicals under the service conditions is another important problem for PF-bonded OSB containing borate. Laboratory leaching tests of wood preservatives provide a relative measure of the leaching losses from treated wood products in service. Leachability studies have been done on CB and ZB boards bonded with PF resin. It was found that boron leaching from both ZB and CB modified OSB

occurred upon the initial water exposure, and the leaching rate decreased as the leaching time increased. Borate type, initial boric acid equivalent (BAE) level, wood species, and sample thickness swelling significantly influenced the 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 reasons 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 condition (Lee 2003, Lee and Wu 2002).

It is believed that the interference with the glue bond caused by the addition of borates to the wood particles prior to formation of a consolidated board occurs. During the pressing operation, steam is generated and condenses on the surface of the wood particles. This condensing steam dissolves the borates and facilitates reaction with the adhesive, thereby impairing the bonding efficiency of the adhesive and significantly limiting the quantity of borates that may be incorporated in the wood particles if an adequate bond is to be maintained (Knudson and Gnatowski 1989).

The type of the resin is one of the most important factors that influence the properties of panels. Bond strengths of PF-bonded waferboard containing biologically-effective levels of sodium borates or boric acid are unacceptable low. In contrast, there is little or no effect by water soluble borates on the bonding efficiency of pMDI resin (Laks et al. 1998). The properties of borate-modified (ZB and CB) strandboards with phenol

formaldehyde resin were studied extensively. However, the properties of borate-modified strandboards bonded with pMDI resin are still missing. Therefore, this study was designed to examine the effects of powder zinc and calcium borate on the mechanical and physical prosperities including modulus of elasticity (MOE) and modulus of rupture (MOR), internal bond, thickness swelling, linear expansion and leaching of borate-modified OSB bonded with polymeric methylene pMDI resin.

2.5 The Need for Understanding Long Term Swelling and Strength Retention Properties of Treated OSB

Long-term structural performance of borate-treated structural composites is one of the major concerns for structural application. It was shown that boards bonded with both phenolic and isocyanate adhesives displayed a reduction in bending strength upon the incorporation of borate (Lehmann 1978, Lee 2003). Thus, durability issues of borate-treated composites will arise both in load-bearing (e.g., OSB shear wall, roof, and I-beams) and non-load-bearing (e.g., OSB siding and sheathing) situations. It has been reported that high temperatures that occur within roof structures can cause a degradation in the wooden roof components that is probably catalyzed by acids derived from the chemical (LeVan and Winandy 1990). Also, the influence of cyclic environmental exposure can affect the extent of degrade. Because the borate is inorganic salts, it diffuses throughout the wood with moisture movement. In some situations, such as roofs, elevated temperatures and humidity changes cause shifts in the equilibrium moisture content of the wood. As the moisture moves, so do the inorganic salts. This cycling could cause migration of the salts within the wood. At each new site, the acidic salt can cause further degradation (Sean et al. 1999). The study reported by Wu and Lee (2002) demonstrated creep performance of zinc and calcium borate-treated OSB under both constant and

varying moisture conditions. In the study, the influence of initial borate content, wood species, and stress level on the creep deformation was studied. Under the constant moisture condition, there was practically no difference in creep for boards at various borate levels for both types of borate. The creep data were fitted well with a spring-dashpot model. Predicted fractional creep validated the current adjustment factor up to a 30-year duration under a constant moisture content level. Under the varying moisture condition, however, large creep deflection developed due to the mechano-sorptive effect. The effect of borate on wood deformation became significant for both zinc and calcium borate treated OSB, indicating a reduced load carrying capacity of the OSB at higher borate levels. This result indicates the necessary to study long-term durability properties of the modified OSB under combined mechanical and moisture loadings for panels with different combinations of resin, wood, and chemical loading.

CHAPTER 3

MATERIALS AND METHODS

3.1 Wood Flake Preparation

Green boards from each of the following eight species were obtained from the Roy O. Martin Lumber Company in South Louisiana. These species include 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, plantation loblolly pine is a primary species for manufacturing southern pine OSB and the hardwoods are being used to manufacture mixed hardwood OSB. The boards were flaked to produce 76.2-mm long flakes (0.635-mm thick) by a laboratory disc flaker. The flakes were dried to 2-3% moisture content by a steam-heated cabinet dryer at a temperature of 95°C. The dry flakes were screened to eliminate fines and stored in polyethylene bags until needed.

3.2 Resin, Wax, and Borate

Polymeric methylene diphenylmethane disocyanate (pMDI) from the DOW Chemical Company and wax emersion from Borden Chemical Inc. were used in this study. The pMDI resin was brown liquid with a specific gravity of 1.24 at 20 °C. Before the experiment, pMDI resin was stored under the condition of 60% relative humidity and 25 °C. The wax had a solid content of 55% and was stored in a refrigerator prior to use. Zinc borate ($2ZnO\text{-}3B_2O_3\text{-}3.5H_2O$) used had a density of 2.79 g/m^3 with a mean particle size of 6.61 μm in diameter. The density of calcium borate ($Ca_2B_6O_{11}\text{-}5H_2O$) is 2.42 g/cm^3 with mean particle size of 6.43 μm (Figure 3.1). ZB presented low acute oral toxicity (LD_{50}>10g/kg of body weight) and dermal toxicity (LD_{50} >10 g/kg of body

weight). CB had little or no hazard and low cute oral toxicity (LD_{50}>1g/kg of body weight) and exhibits dermal toxicity (LD_{50} >1 g/kg of body weight).

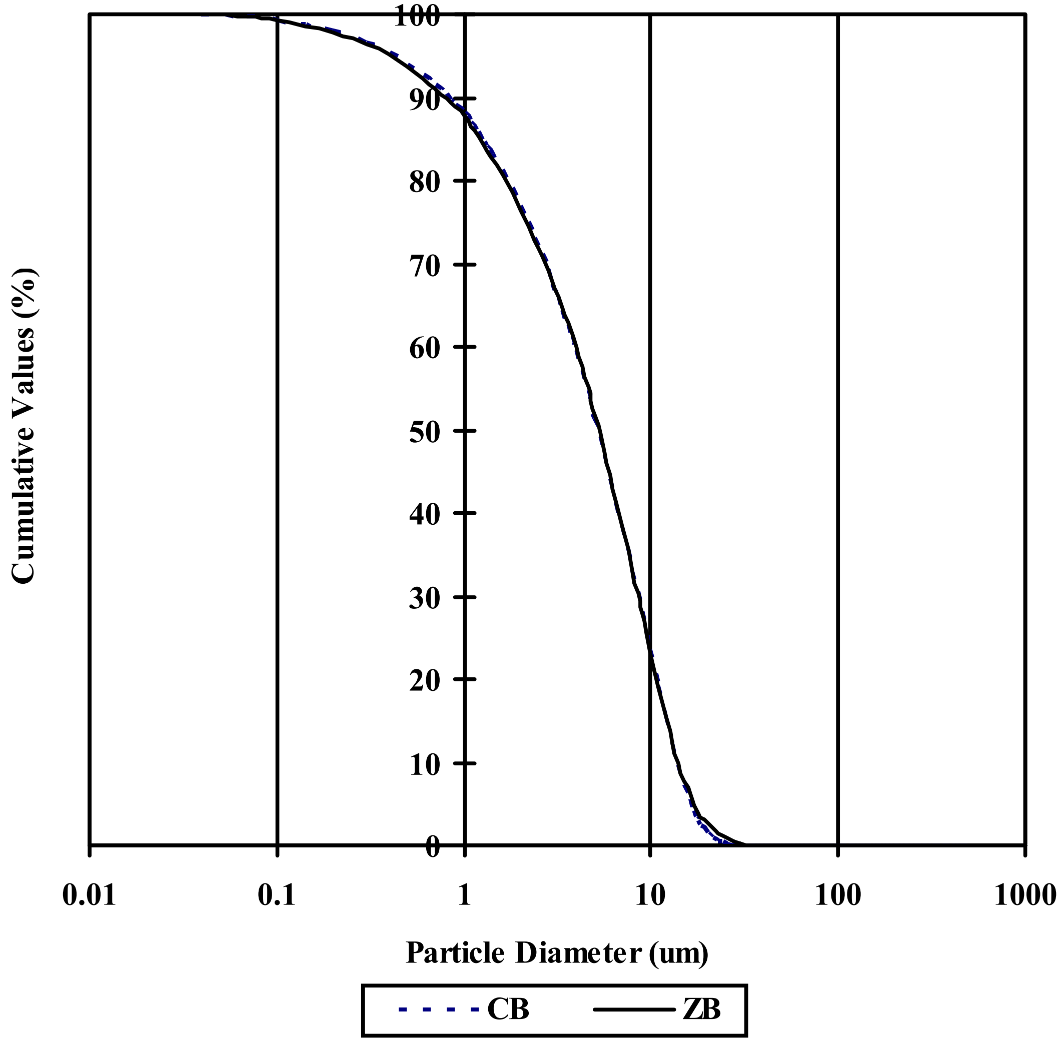


Figure 3.1 Particle size distribution of zinc borate (ZB) and calcium borate (CB) used in this study.

3.3 Panel Manufacturing

The design of experimental panels for the study is shown in Table 3.1. There were totally 16 independent panels. Two replications were made for each panel type, leading to

a total of 28 panels with only four control panels (i.e., 0% chemical loading) made for both chemicals.

Table 3.1 Design of experimental panels bonded with pMDI resin

Variables	Number of Variables
Wood Species	Mixed southern pine and hardwoods (1)
Resin Content (%) [a]	2.5% and 5% (2)
Wax (%)[b]	1 (1)
Panel Density (g/cm^3)	0.75 g/cm^3 (1)
Chemical Type	Calcium Borate and Zinc Borate (2)
Chemical Loading (%) [c]	0, 1.5%, 3%, 4.5% (4)
Panel Dimension (mm)	558mm × 508mm × 12.7mm (1)
Replications	Two

[a] Solid pMDI resin content in percentage based on oven dry wood weight.
[b] Solid wax content in percentage based on oven dry wood weight.
[c] Percentage of calcium and zinc borate based on oven dry wood weight.

The required raw material and additive were calculated by the following formulas:

$$BW = \text{Target Length} \times \text{Target width} \times \text{Target thickness} \times \text{Target density} \quad [1]$$

$$OBW = BW / BMC \quad [2]$$

$$DFW = OBW \times (1+ FMC) / (1+ RL + WL) \quad [3]$$

$$FW = DFW \times (1+FMC) \quad [4]$$

$$RW = DFW \times RL \quad [5]$$

$$ZB \text{ (or CB) weight} = DFW \times ZBL \quad [6]$$

$$CB \text{ weight} = DFW \times CBL \quad [7]$$

$$\text{Wax weight} = DFW \times WL \quad [8]$$

where, BW = board weight (g), OBW = oven dry board weight (g), BMC = board moisture content (%); DFW = dry flake weight (g); RL = resin loading level (%);

WL = wax loading level (%); FW = flake weight (%); FMC = flake moisture content (%); RW = resin weight (%); ZBL = ZB loading level (%); and CBL = CB loading level (%).

During panel manufacturing, flakes from southern pine and various hardwood species were mixed evenly prior to blending. The target amount of wood flakes was measured for each panel and loaded in the blender. The target amount of wax, resin, and chemical was then sprayed onto the flakes through separate spray lines when the flakes were being rotated. After blending, wood flakes were removed from the blender and random mats were formed by hand. The mat was loaded into the press and was pressed 5 minutes at a pressure of 1.71MPa and a temperature of 200°C. The press closing time was 1 minute for all panels. The manufactured boards were then cooled and conditioned at 25°C and 55% relative humidity (RH) prior to testing.

3.4 Panel Testing

3.4.1 Chemical Analysis

Actual boron content in the boards was analyzed. One OSB sample (50.8 mm × 50.8 mm × 12.7 mm) was cut from each panel, leading to two samples for each panel type. Each sample was Wiley milled to pass through a 20-mesh screen. Wood meal from two samples of each panel type was mixed and oven-dried. Five grams of the mixture were selected and placed into a flat-bottom flask with a solution of 100ml 2N HNO_3. The flask was connected to a water-cooled condenser (Figure 2.2). The flask was heated on a heating mantle for 2 hours at 100°C for digesting. The flask was then cooled for 30 minutes while maintaining seals between the flask and the condenser. The digested samples were filtered using a piece of Whatman#2 paper over a filter funnel. The solution was analyzed by ICP-OES (Inductively Coupled Plasma-Atomic Emission Spectrometry)

to determine the actual chemical composition in the sample. The percentage of boron, zinc, and calcium was determined on the basis of molecular weight of ZB and CB. The boron/zinc (B/Z) 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” was referred to the amount of boric comes from boric acid.

The percentage of B, Zn, and Ca in ZB and CB was determined by the following formulas, respectively.

$$\%\text{Boron, Zinc and Calcium} = V \times C \times 100 / Ww \quad [9]$$

$$\%B_{ZB} = \%\text{Boron}/0.1492 \quad [10]$$

$$\%Zn_{ZB} = \%\text{Zinc}/0.3 \quad [11]$$

$$\%B_{CB} = \%\text{Boron}/0.1578 \quad [12]$$

$$\%Ca_{CB} = \%\text{Calcium}/0.2 \quad [13]$$

$$\%BAE = \%B_{CB} (\text{or } \%B_{ZB})/1.17 \quad [14]$$

where, V = the volume of the analytic solution (ml);

C = the concentration of boron, zinc and calcium ($\mu g \times 10^{-6}$) converted ICP-AES;

Ww = the weight of oven-dry wood meal (g);

0.1492 = the ratio of molecular weight of boron to ZB;

0.1578 = the ratio of molecular weight of boron to CB;

0.3 = the ratio of molecular weight of Zinc to ZB;

0.20 = the ratio of molecular weight of Ca to CB; and

1.17 = the transform constant.

Figure 3.2 Chemical analysis experiment (Top: wood meal under digestion and Bottom: ICP analysis).

3.4.2 Mechanical Properties

3.4.2.1 Sample Preparation and Testing

For the bending test, one sample (355.6 mm × 76.2 mm × 12.7 mm) was cut from each panel. Totally, there were two samples for each panel type. Each specimen was labeled on the surface according to the resin level, borate type and content, and replication. The specimens were conditioned at 25°C and 55% RH prior to testing. After conditioning, the length, width, thickness, and weight of each sample were measured. During testing, concentrated load was applied at the center of the specimen, using an INSTRAN testing machine according to the ASTM-1037 (ASTM 1999). Modulus of elasticity (MOE) and modulus of rupture (MOR) were determined from the load and displacement data. After the bending test, the samples were oven dried and reweighed for moisture content determination.

Five internal bond (IB) specimens (50.8 mm × 50.8 mm × 12.7 mm) were cut from each panel according to the ASTM D-1037 (ASTM 1999). Totally, there were ten samples for each panel type. Each specimen was labeled on the surface according to the resin level, borate type and content, and replication. The specimens were conditioned at 25°C and 55% RH prior to testing. After conditioning, the length, width, thickness, and weight of each sample were measured. Each sample was bonded with hot melt glue to the loading fixtures and then attached to the INSTRAN testing machine. The specimens were pulled by separation of the heads of the testing machine until failure. IB strength was calculated based measured peak load and sample cross-section area.

3.4.2.2 Data Analysis

The influence of borate type, borate loading level, and resin content level on the mechanical properties were investigated. The details of the analysis are shown as follows.

(1) Contrast of measured mechanical properties (MOE, MOR, and IB) from ZB or CB boards under the same resin loading level but different borate content levels.

The purpose of this contrast was to investigate the influence of borate loading level on the mechanical properties. The contrasted treatments had the same resin content and

Table 3.2 List of SAS program for mechanical property comparison

```
OPTIONS NONUMBER NODATE;
TITLE 'MOE CONTRAST UNDER 2.5% pMDI, CB BOARDS';
DATA ONE;
INPUT TRT MOE;
CARDS;
0       1360.04
0       1077.21
.
1.5     972.54
1.5     1098.93
.
3       1134.78
3       820.85
.
4.5     986.19
4.5     973.64
.
PROC GLM; CLASS TRT;
MODEL MOE=TRT;
LSMEANS TRT/STDERR PDIFF;
CONTRAST '0&1.5, CB' TRT -1 1 0 0;
CONTRAST '0&3, CB' TRT -1 0 1 0;
CONTRAST '0&4.5, CB' TRT -1 0 0 1;
CONTRAST '1.5&3, CB' TRT 0 -1 1 0;
CONTRAST '1.5&4.5, CB' TRT 0 -1 0 1;
CONTRAST '3&4.5, CB' TRT 0 0 -1 1;
RUN;
```

borate type, but different borate loading levels. A SAS program was developed to perform the analysis (Table 3.2). The P-Value, which indicates whether the difference between the contrasted treatments was significant, was obtained from each analysis. The program shown in Table 3.2 contrasted the MOE data of CB boards with 5% pMDI. There were four treatments (i.e., CB loading levels): 0, 1.5, 3, and 4.5%. Each of them was contrasted with the rest. A similar program was used to perform contrast analysis for boards at other conditions (e.g., 2.5% resin level and ZB boards).

(2) Contrast of the mechanical properties between ZB and CB boards under the same borate loading and resin level.

Table 3.3 List of SAS program for testing the effect of borate type*

```
OPTIONS NONUMBER NODATE;
TITLE 'same borate level, ZB VS CB';
DATA ONE;
INPUT TRT MOE;
CARDS;
1        1219.06
.
.
2        871.04
.
.
PROC GLM; CLASS TRT;
MODEL MOE=TRT;
LSMEANS TRT/STDERR PDIFF;
CONTRAST '1&2' TRT 1 -1;
RUN;
```

*There were two treatments in this contrast. The number “1” indicates the samples of CB boards and the number “2” indicates the samples of ZB boards.

The purpose of this contrast was to investigate the influence of borate type on the mechanical properties. The contrasted treatments had the same borate and resin content

levels, but different borate types. A SAS program was developed and P-Value was obtained to indicate whether the properties of ZB and CB boards under the same resin level were significantly different. A sample program for MOE contrast of CB and ZB boards with 2.5% pMDI is shown in Table 3.3.

(3) Contrast of the mechanical properties under different resin levels (2.5% and 5%)

The purpose of this contrast was to investigate the influence of resin loading level on the mechanical properties. The contrasted treatments had the same borate type and borate loading level, but different resin loading levels.

Table 3.4 List of SAS program for testing the effect of resin loading level*

```
OPTIONS NONUMBER NODATE;
TITLE '2.5% VS 5% RESIN CONTENT, MOE OF CB';
DATA ONE;
INPUT TRT MOE;
CARDS;
1       905.62
.
2       1182.34
.
PROC GLM; CLASS TRT;
MODEL MOE=TRT;
LSMEANS TRT/STDERR PDIFF;
CONTRAST '1&2' TRT 1 -1;
RUN;
```

* There were two treatments in this contrast. The number “1” indicates the samples with 2.5% pMDI and the number “2” indicates the samples with 5% pMDI.

A SAS program was developed and P-Value was obtained to indicate whether the properties of the boards with different resin levels were significantly different. A sample program for MOE contrast of CB boards under 2.5% and 5% resin loading levels is listed in Table 3.4.

3.4.3 Physical Properties

3.4.3.1 Thickness Swelling Test

For thickness swelling test, one sample (15.24 cm $\times$ 15.24cm $\times$ 0.635cm) was cut from each panel. Each specimen was labeled on the surface according to the resin level, borate type and content, and replication. The initial thickness at marked positions (25.4-mm to the edge positions and the center of the sample), length, width, and weight of each sample was measured. The specimens were then oven-dried at 105 °C for 24 hours and the weight and thickness were measured again. The specimens were then submerged 25.4 mm below the surface of water at room temperature. After soaking for 24 hours, the specimens were removed from the water tank and surface water was wiped off. The soaked weight and thickness at the 25.4-mm to the edge positions and the center of the sample were measured according to the ASTM D-1037 (ASTM 1999). The average thickness of these five points was used as the soaked thickness.

Thickness changes from the air-dry condition to 24-hour water soak condition were used to calculate TS:

$$TS = \frac{ST - OT}{OT} \times 100\% \qquad [15]$$

where, ST = soaked thickness (mm) and OT = OD thickness (mm).

Water absorption (WA, %) was calculated as follows:

$$WA_{TS} = \frac{SW - OW}{OW} \times 100\% \qquad [16]$$

where, SW = soaked weight (g), and OW = OD weight (g).

3.4.3.2 Linear Expansion Test

For linear expansion (LE) test, one sample (250 mm $\times$ 50 mm $\times$ 12.5mm) was cut from each panel. Two holes (1.1-mm diameter), 254-mm apart, were drilled along the long dimension of each specimen. A small rivet (1-mm diameter), dipped in epoxy glue, was plugged into each of the two holes. A reference cross was carefully cut on the tip of each rivet using a sharp razor blaze.

Measurements, including specimen weight, length, width, thickness, and reference dimension between the two rivets of each specimen, were performed at the room condition. All specimens were oven-dried at 105 °C for 24 hours, and the measurements were repeated at the dry condition. The specimens were then placed into a pressure vessel filled with water. The vessel was kept at -0.19-MPa (vaccum) for 1 hour and then 0.69-MPa for 2 hours. After treatment, the specimens were removed from the vessel and the measurements (i.e., weight, length, width, thickness, and reference dimension between the two rivets) were performed again.

LE was calculated according to the following formula:

$$LE = \frac{SL - DL}{DL} \times 100\% \qquad [17]$$

where SL = soaked length (mm), and DL = dry length (mm).

Water absorption (WA, %) from the LE test was calculated as follows:

$$WA_{LE} = \frac{SW - OW}{OW} \times 100\% \qquad [18]$$

where, SW = soaked weight (g) and OW = OD weight (g).

Data analysis of physical properties was similar as those for mechanical properties. The influence of the borate type, borate loading level, and resin loading level on the measured properties were investigated.

3.4.4 Leaching Test

Leaching experiments were conducted according to a modified AWPA leaching standard (Laks et al. 1991). Two OSB specimens (50.8 mm × 50.8 mm × 12.5mm) were prepared according to borate type, initial borate content level, target leaching time, and replication with each group. Four sides of each specimen were coated using several layers of waterproof paint. The paint was allowed to dry at room temperature (Figure 3.2). Six specimens were stacked together with thin wood sticks between individual samples and each stack was secured using rubber bands. The prepared samples were first vacuum-soaked for 25 minutes at 10-30 mmHg. They were then kept under running tap water (PH=6.7) for 8, 24, 72 and 216 hours for individual groups. After leaching, the specimens were removed from water sink and oven dried. They were finally analyzed for BAE content using the chemical analysis methods discussed in section 3.4.1.

The influence of borate type, borate loading level, and resin loading level on the leaching rate were investigated. The detail contrasts are listed as follows.

(1) Contrast of leaching rate under different borate types

This contrast investigated the influence of borate type on the leaching rate. The contrast treatments had the same resin content and borate loading level, but different borate types. Graphs were drawn to compare the leaching rate of different kinds of samples over 216 hours. A SAS program was developed to compare the difference between ZB and CB boards under the same pMDI resin level and borate content. A

sample program, which contrasted the leaching ability between ZB and CB boards with 2.5% pMDI and 1.5% borate content, is shown in Table 3.5.

Table 3.5 List of SAS program on the effect of borate types on leaching rate*

```
OPTIONS NONUMBER NODATE;
TITLE 'Leaching contrast, ZB VS CB';
DATA ONE;
INPUT TRT BAE;
CARDS;
1       1.09
.
2       1.24
.
PROC GLM; CLASS TRT;
MODEL BAE=TRT;
LSMEANS TRT/STDERR PDIFF;
CONTRAST '1&2' TRT 1 -1;
RUN;
```

*There were two treatments in this contrast. The number "1" indicates the samples of CB boards and the number "2" indicates the samples of ZB boards.

(2) Contrast of leaching rate under different resin levels

This contrast investigated the influence of resin level on the leaching rate. The contrast treatments had the same borate type and borate loading level. A SAS program was developed and a sample program is listed as follows (Table 3.6) to contrast the leaching rate of the boards with 1.5% CB at 2.5% and 5% pMDI resin levels.

3.4.5 Swelling and Strength Retention under Cyclic Humidity Exposure Condition

Thickness swelling and bending property of borate modified strandboard bonded with pMDI resin were measured under cyclic humidity exposure conditions. Table 3.7 shows the experimental design. Four samples ($304.8 \times 64 \times 12.7$ mm) from each type of panel were used in the experiments, giving a total of 56 samples (only one control group for

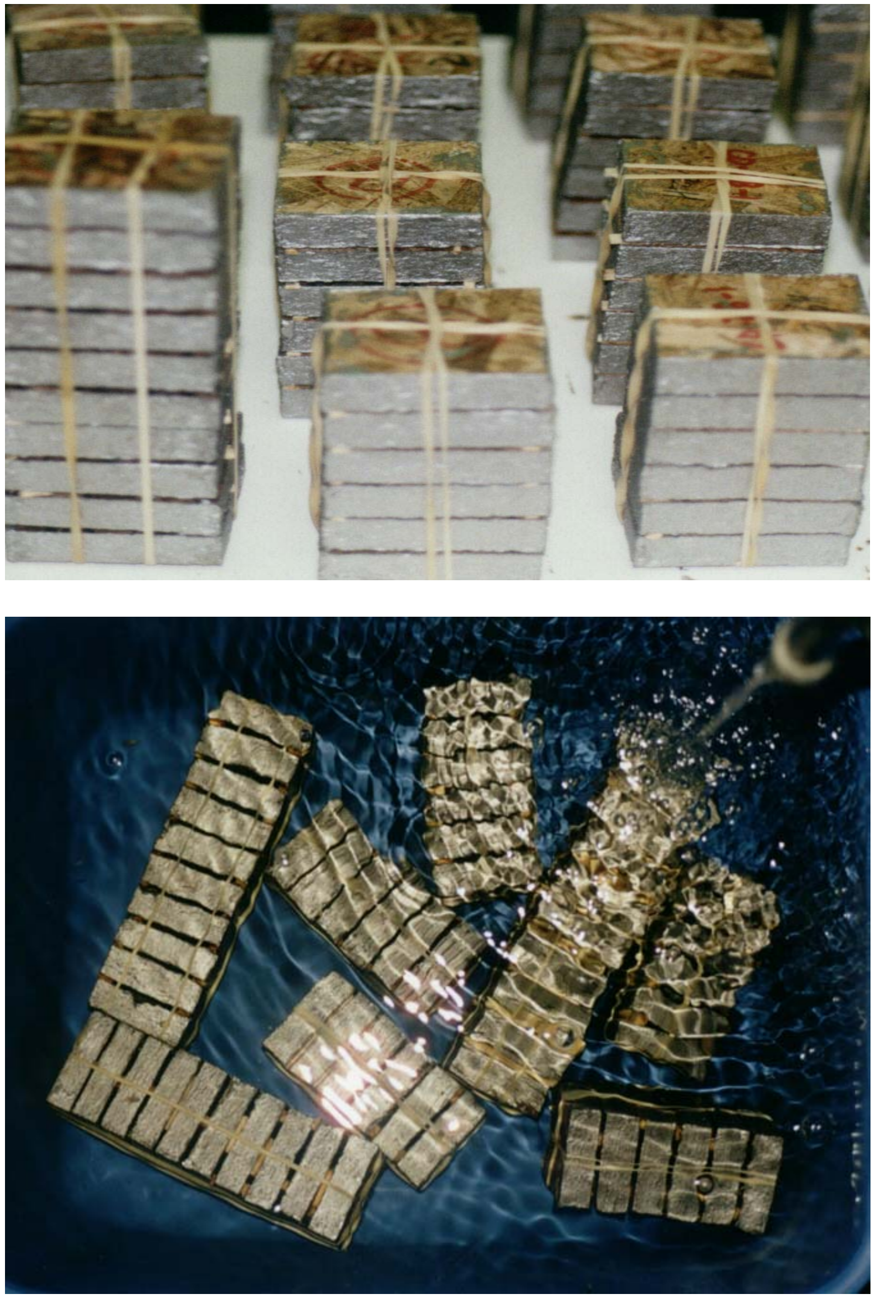


Figure 3.3 Leaching experiments (Top: samples with edges coated, and Bottom: samples under leaching).

Table 3.6 List of SAS Program on the effect of resin level on leaching rate*

```
OPTIONS NONUMBER NODATE;
TITLE 'Leaching contrast, 1.5% CB';
DATA ONE;
INPUT TRT BAE;
CARDS;
1         1.48
.
2         1.09
.
PROC GLM; CLASS TRT;
MODEL BAE=TRT;
LSMEANS TRT/STDERR PDIFF;
CONTRAST '1&2' TRT 1 -1;
RUN;
```

*There were two treatments. The number "1" indicates the samples of CB boards with 2.5% pMDI; and the number "2" indicates the samples of CB boards with 5% pMDI.

Table 3.7 Experimental design for long-term durability tests

Variables	Number of Variables
Resin Content (%)	2.5 and 5 (2)
Chemical Type	Calcium Borate and Zinc Borate (2)
Chemical Loading (%)	0, 1.5, 3, 4.5 (4)
Sample Dimension (mm)	305 x 64 $\times$ 12.7 (1)
Exposure Condition	Control and Treated (2)
Replications	Two

both chemicals). The samples were randomly separated into two equal groups. One group was control, and the other group was under treatment.

Measurements for the treatment group, including specimen weight, length, width, and thickness, were performed at the room condition. All specimens were dried at 70 °C to reach a constant weight and the measurements were repeated at the dry state. The specimens were then conditioned to reach equilibrium according to the following scheme: Dry -> 75% RH -> 93% RH->75% RH->OD in a conditioning chamber. At each RH condition, five samples were removed periodically from the conditioning

chamber and were weighed until the samples reached a constant weight. The measurements (i.e., specimen weight, length, width, and thickness) were repeated. Finally, all specimens were oven-dried for 24 hours at 105°C to determine their oven-dry weight and dimension. Measured sample thickness at various RH levels was used to calculate TS according to the following formula:

$$TS(RH,\%) = \frac{TK(RH) - TK(DRY)}{TK(DRY)} \times 100\% \quad [19]$$

where TK (RH) = sample thickness (mm) at a given RH level; and TK (DRY) = sample thickness (mm) at the initial dry condition.

Measured sample weight at various levels of RH condition was used to calculate MC change according to the following formula:

$$\Delta MC(RH,\%) = \frac{W(RH) - W(DRY)}{W(DRY)} \times 100\% \quad [20]$$

where W (RH) = sample weight (g) at a given RH level; and W (DRY) = sample weight (g) at the initial dry condition (70°C until constant weight).

Finally, both control and treated groups were reconditioned to reach equilibrium at 25 °C and 60% RH and all samples were tested under static bending to determine their MOE and MOR. The strength and modulus retention values were calculated as a ratio between treated and control values. The effects of processing variables and moisture treatments on the retention properties were analyzed statistically.

A SAS program was developed and P-value was obtained to compare the difference of mechanical properties between the cyclic-humidity-treated boards and control boards. There are eight treatments in this contrast (Table 3.8). Treatments 1, 2, 3, and 4

contrasted with treatments 5, 6, 7, and 8 respectively. A sample program for MOR contrast is shown in Table 3.9.

Table 3.8 Treatment list for MOR contrast in SAS program

	Treated				Control			
Borate	CB		ZB		CB		ZB	
% pMDI	2.5	5	2.5	5	2.5	5	2.5	5
Treatment	1	2	3	4	5	6	7	8

Table 3.9 List of SAS program for contrasting MOR between cyclic humidity treated and control boards

```
OPTIONS NODATE NONUMBER;

TITLE 'CONTRAST BETWEEN TREATED AND CONTROL';
DATA ONE;
INPUT TREATMENT MOR pMDIpMDI;
CARDS;
1       22.93
.
.
2       29.92
.
.
8       53.99

;

PROC GLM;
CLASS TREATMENT;
MODEL MOR=TREATMENT;
CONTRAST 'CB, 2.5%pMDI'
TREATMENT  1 0 0 0 -1 0 0 0;
CONTRAST 'CB, 5%pMDI'
TREATMENT  0 1 0 0 0 -1 0 0;
CONTRAST 'ZB, 2.5%pMDI'
TREATMENT  0 0 1 0 0 0 -1 0 ;
CONTRAST 'ZB, 5%pMDI'
TREATMENT  0 0 0 1 0 0 0 -1 ;
RUN;
QUIT;
```

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Borate Retention

Figure 4.1 shows measured BAE as a function of target borate loading levels for both CB and ZB treated panels with combined data from the two resin content levels. Measured BAE increased with the increase of borate loading level following a rough linear relationship. Due to chemical loss during the blending process, measured BAEs were smaller than the target loading levels, especially at higher loading levels (Tables 4.1 and 4.2).

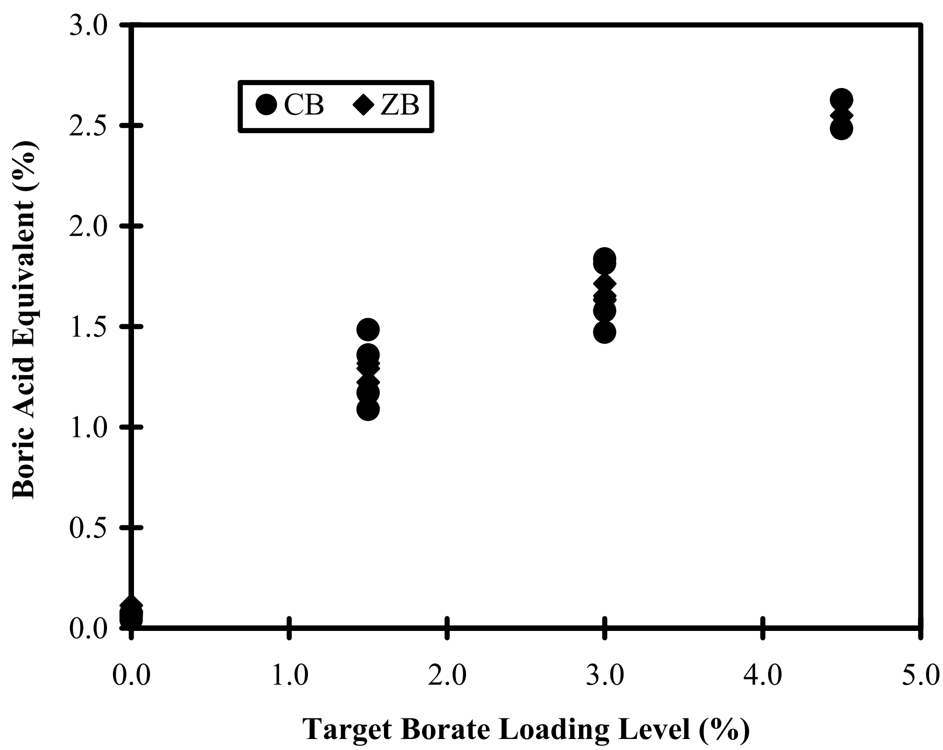


Figure 4.1 Measured BAE as a function of target borate loading levels.

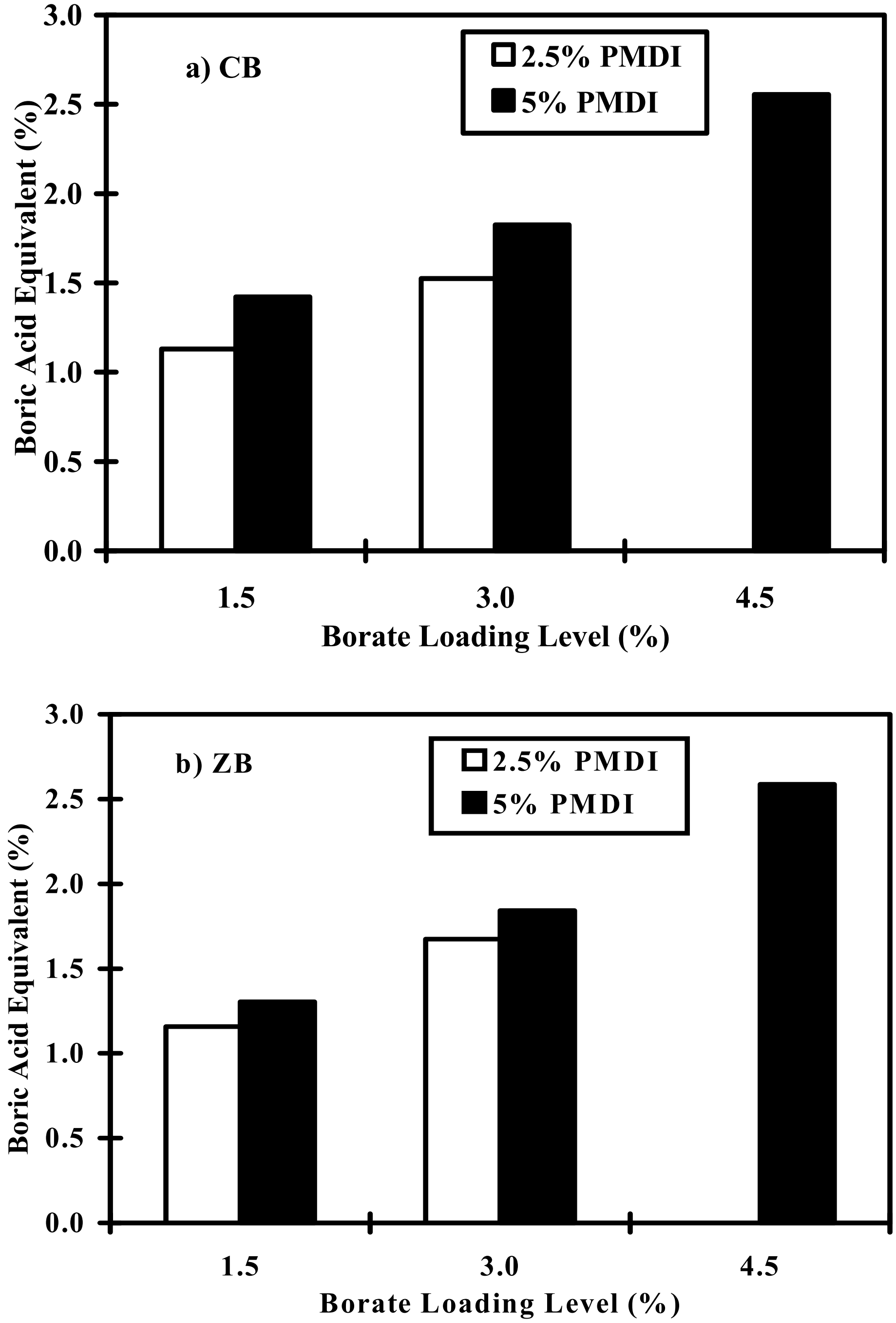


Figure 4.2 Relationship between target borate loading level and actual BAE. a) CB and b) ZB

Figure 4.2 shows the effect of resin content on borate retention in the panel at various chemical loading levels. At the same borate loading level, measured BAEs from the panels with 5% pMDI resin were higher than those from the panels with 2.5 % pMDI resin. The powder borate was sprayed into the blender during the blending and conglutinated on the surface of the wood flakes. High resin content on the flake surface helped make the flakes sticker and increased chemical retention rate.

4.2 Mechanical Properties

Measured data on BAE, moisture content (MC), density, MOE, MOR, and IB strength for the test panels are listed in Table 4.1s and 4.2 for CB and ZB-treated panels, respectively. The actual density of all panels was close to the target density level (i.e., 0.75 g /cm^3). MOE, MOR, and IB values with 5% pMDI were higher than those with 2.5% pMDI. Figure 4.3 to Figure 4.8 show the plots of various properties in relation to measured BAE under the two resin content levels (i.e., 2.5% and 5%). Statistical analysis of the data is presented in the following sections.

Table 4.1 Summery of mechanical properties of CB-treated strandboard

pMDI (%)	BAE (%)	Bending Properties				IB Strength [a]	
		MC (%)	Density (g/cm^3)	MOE (GPa)	MOR (MPa)	Density (g /cm^3)	IB (KPa)
2.5	0.05	3.94	0.74	5.02	35.05	0.72	841.81 (133.67)
2.5	1.13	3.76	0.75	4.24	32.35	0.74	807.60 (233.67)
2.5	1.52	3.39	0.76	3.48	28.62	0.75	654.58 (153.35)
5	0.07	3.97	0.78	6.21	55.76	0.75	1301.68 (169.97)
5	1.42	3.79	0.75	5.53	51.09	0.72	1103.49 (334.22)
5	1.83	3.82	0.76	5.07	40.56	0.78	975.42 (226.01)
5	2.56	3.98	0.77	4.3	36.80	0.76	949.24 (234.59)

[a]. Values in parenthesis are standard deviations based on ten specimens.

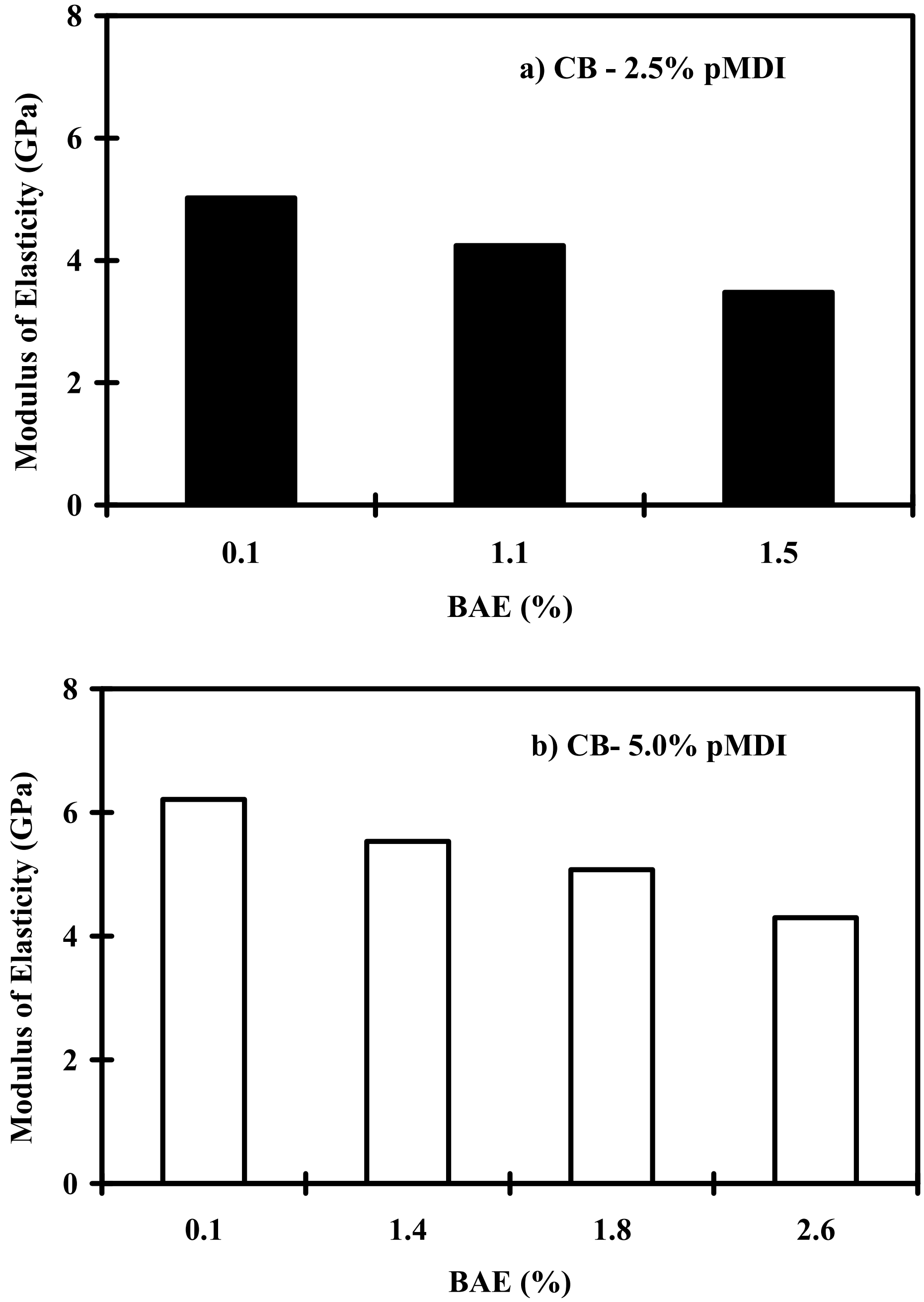


Figure 4.3 MOE in relation with BAE for CB-treated strandboard. a) CB - 2.5% pMDI and b) CB - 5.0% pMDI.

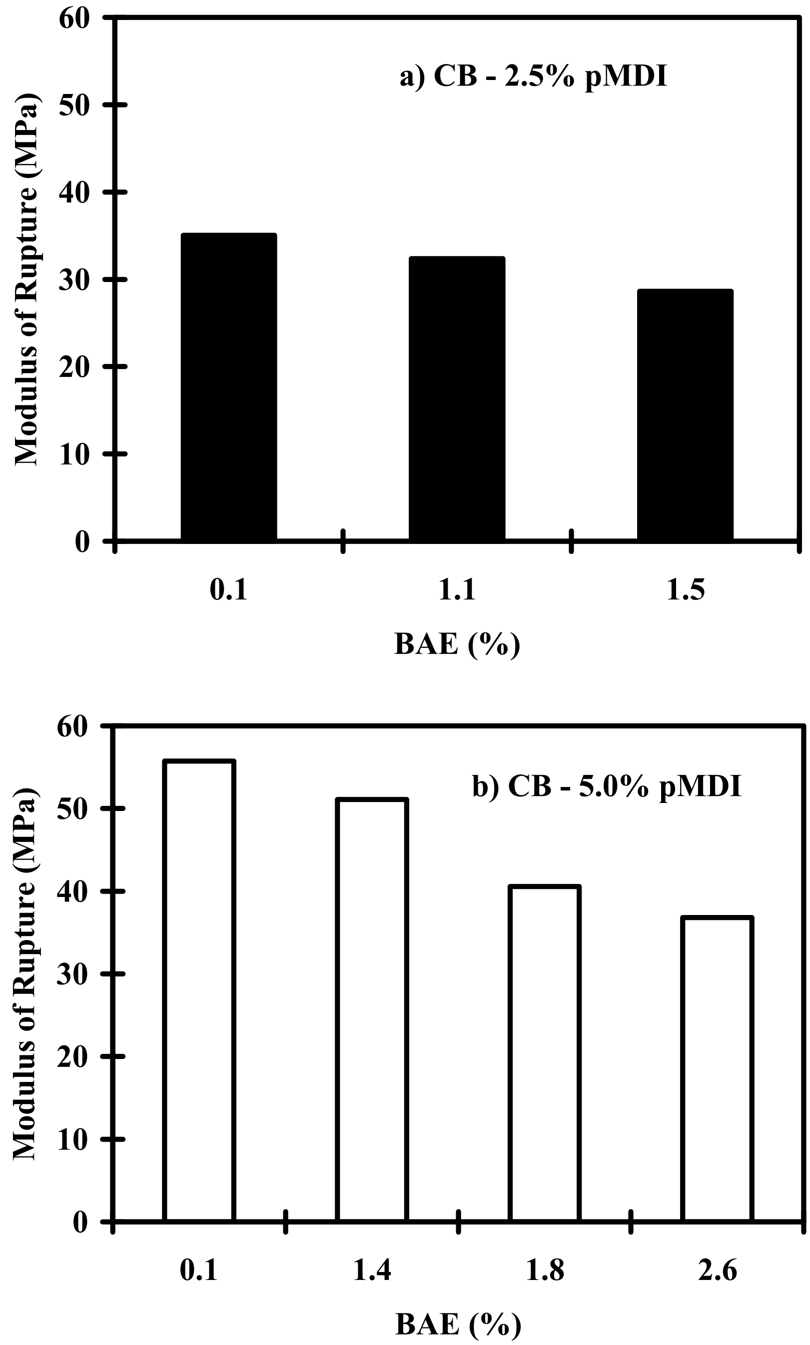


Figure 4.4 MOR in relation with BAE for CB-treated strandboard. a) CB - 2.5% pMDI and b) CB - 5.0% pMDI.

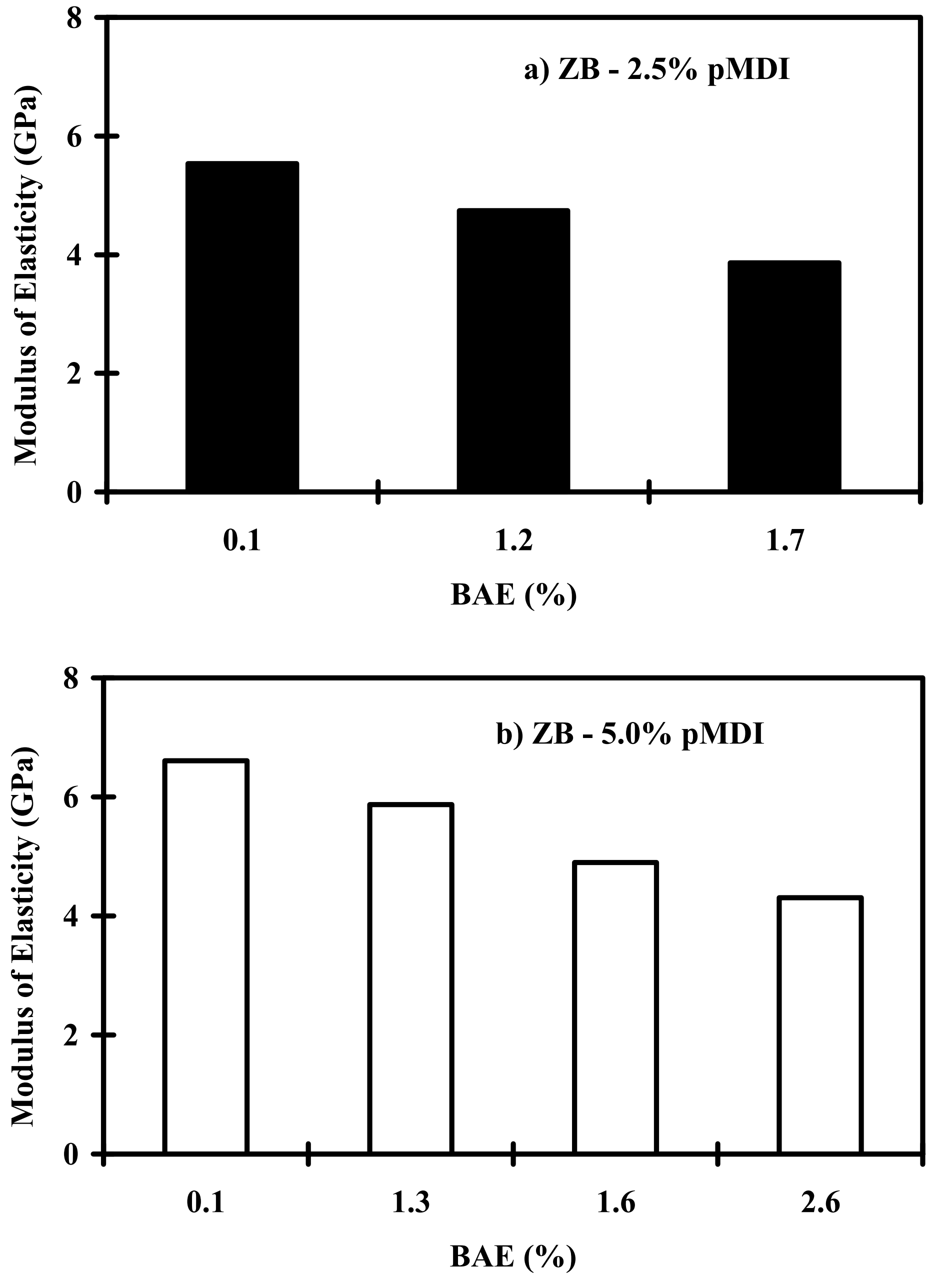


Figure 4.5 MOE in relation with BAE for ZB-treated strandboard. a) ZB - 2.5% pMDI and b) ZB - 5.0% pMDI.

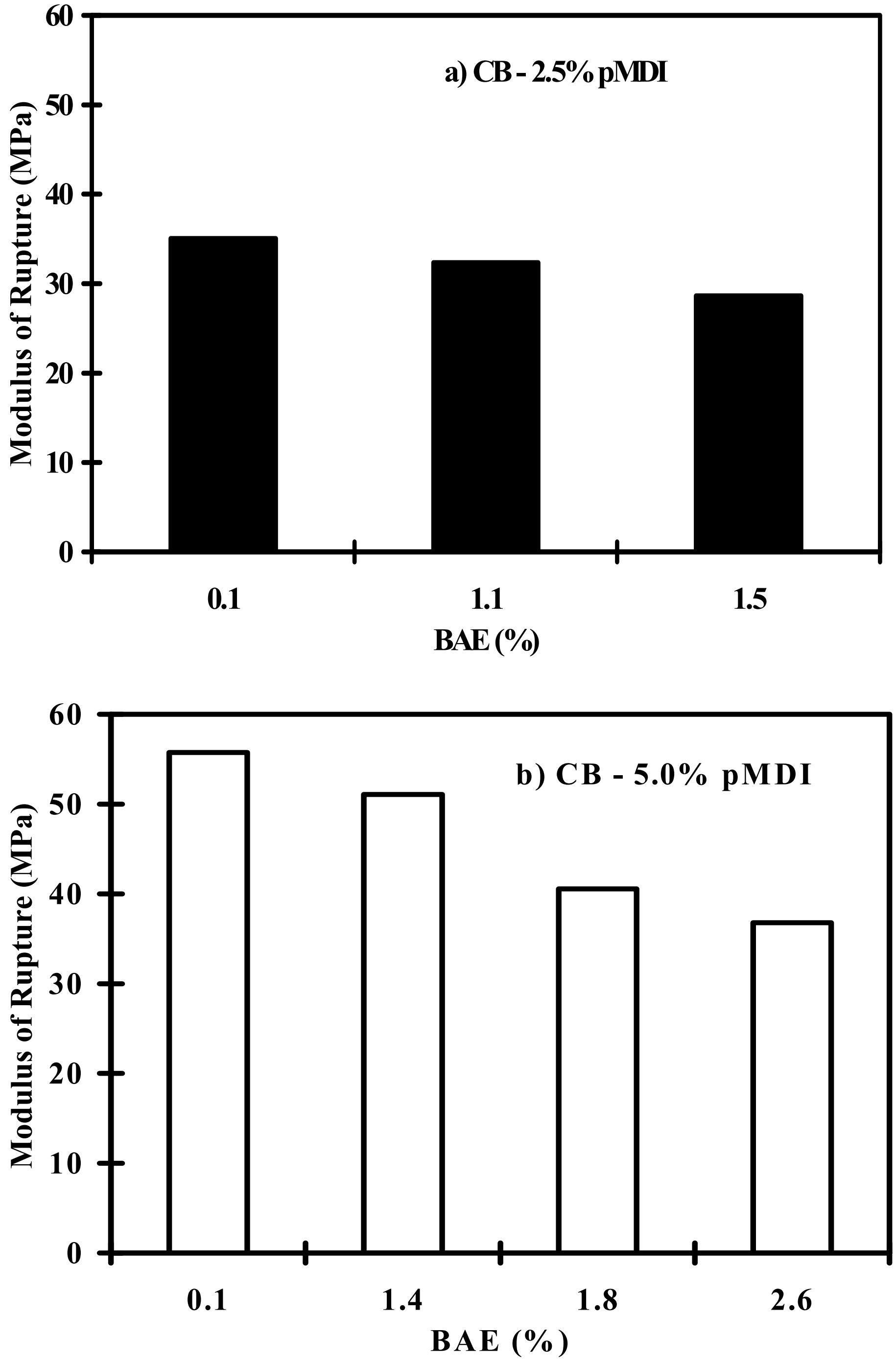


Figure 4.6 MOR in relation with BAE for ZB-treated strandboard. a) CB - 2.5% pMDI and b) CB - 5.0% pMDI.

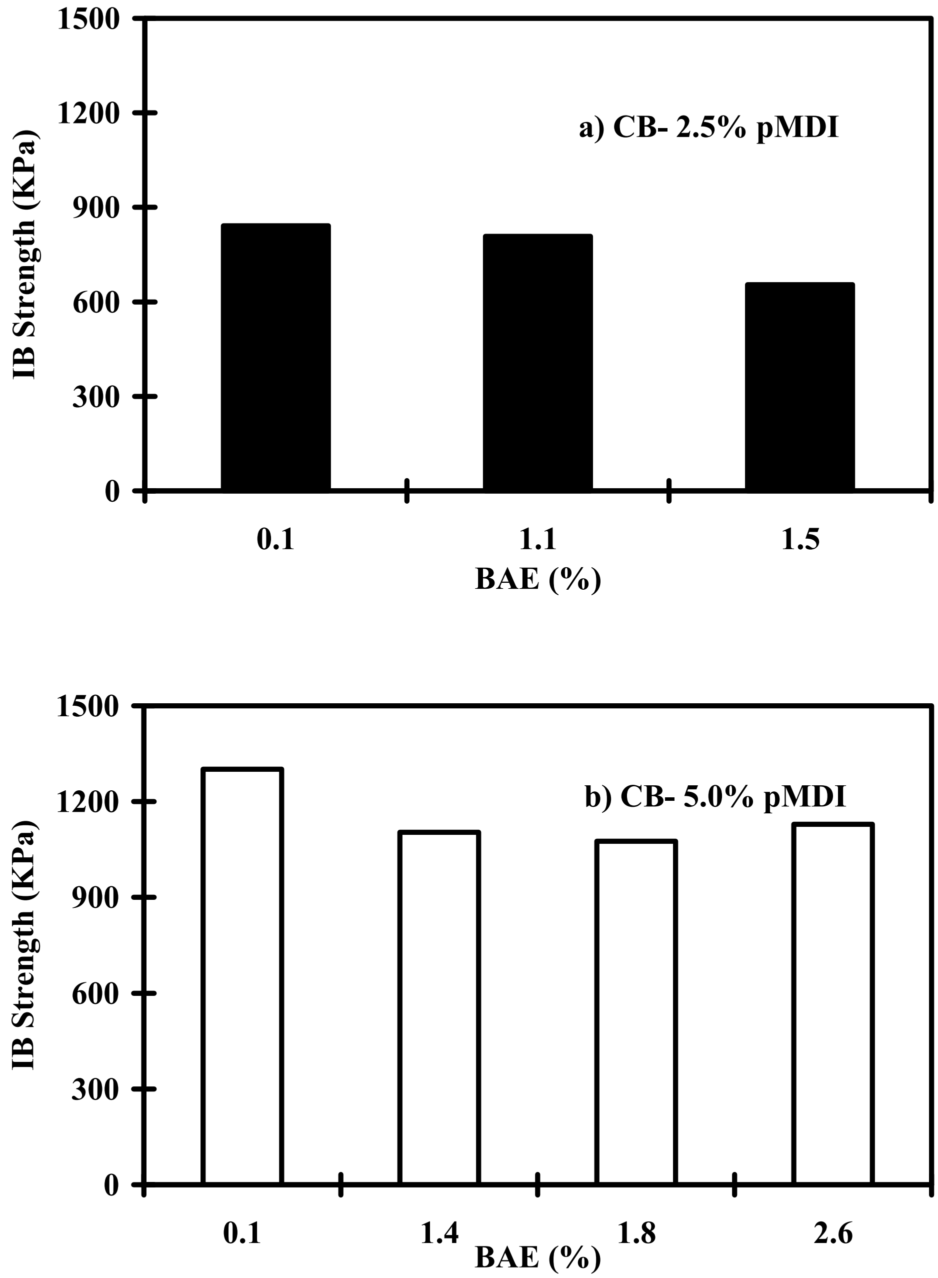


Figure 4.7 IB strength in relation with BAE for CB-treated strandboard. a) CB - 2.5% pMDI and b) CB - 5.0% pMDI.

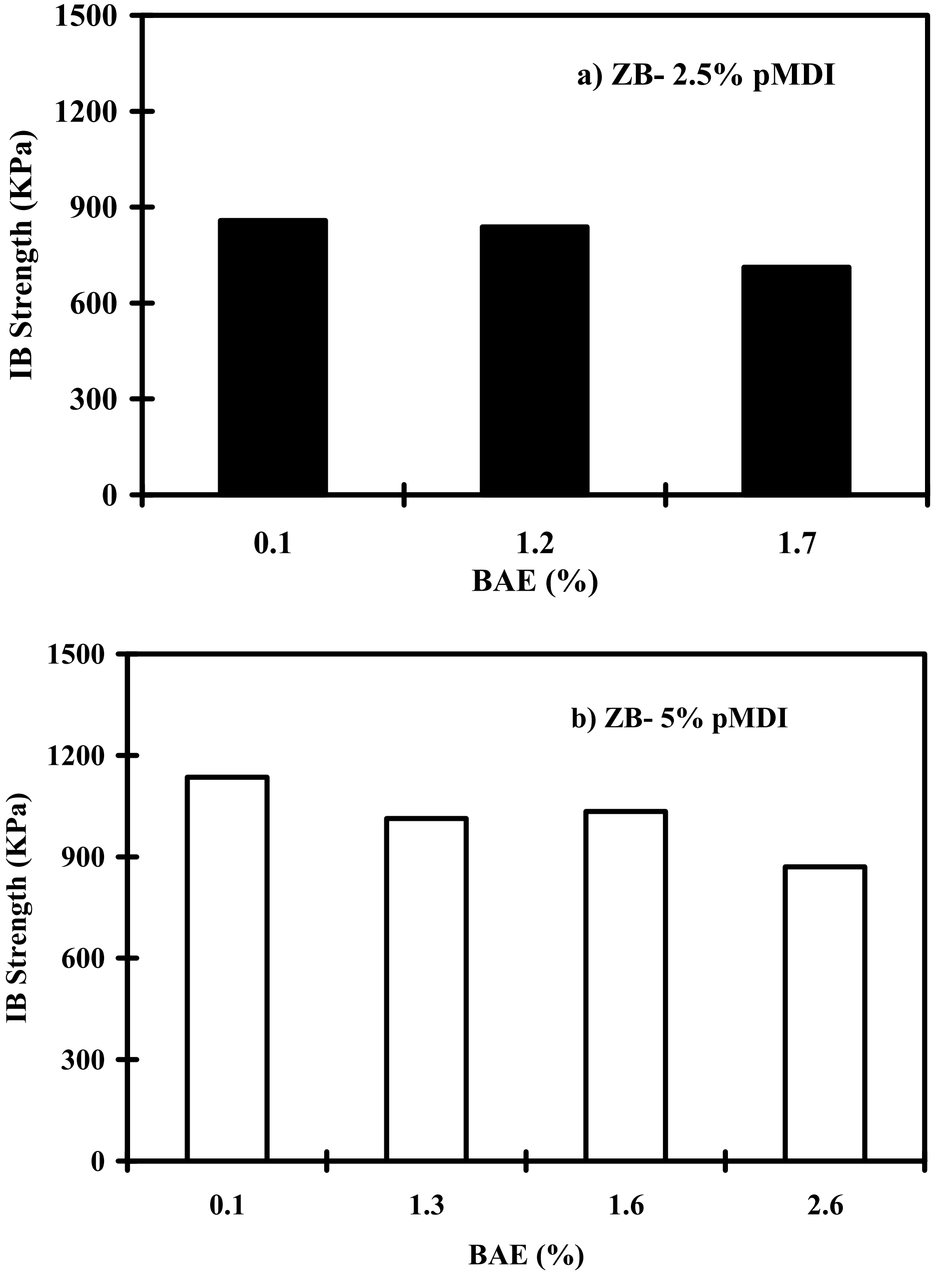


Figure 4.8 IB strength in relation with BAE for ZB-treated strandboard. a) ZB - 2.5% pMDI and b) ZB - 5.0% pMDI.

Table 4.2 Summery of mechanical properties of ZB-treated strandboard.

pMDI (%)	BAE (%)	Bending Properties				IB Strength [a]	
		MC (%)	Density (g/cm^3)	MOE (GPa)	MOR (MPa)	Density (g/cm^3)	IB (KPa)
2.5	0.07	4.22	0.79	5.54	42.73	0.76	857.73 (98.11)
2.5	1.18	3.89	0.78	4.74	38.10	0.77	838.10 (217.38)
2.5	1.67	3.82	0.79	3.86	30.43	0.76	712.27 (280.46)
5	0.10	3.87	0.78	6.61	55.36	0.74	1135.54 (205.90)
5	1.49	3.90	0.75	5.87	50.70	0.73	1012.92 (228.52)
5	1.64	3.83	0.79	4.90	44.22	0.75	953.84 (199.18)
5	2.59	3.93	0.80	4.31	40.37	0.77	870.15 (125.09)

[a] Values in parenthesis are standard deviations based on ten specimens.

4.2.1 Effect of Borate Content on Mechanical Properties

Mechanical properties (e.g., MOE, MOR, and IB) decreased with the increase of BAE (Figures 4.3 -- 4.8). This trend was consistent with previous study using PF resin as a binder (Lee 2003). This problem is presumably related to the interaction between functional methyl 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). The results of statistical analysis proved the negative influence of borate on the mechanical properties. For MOE, at the 2.5% pMDI level, MOE of the samples with 3% CB was significantly lower than that of the samples with 0% CB. MOE of the samples with 0% ZB was significantly lower than that of the samples with 3% and 1.5% CB. At the 5% pMDI level, MOE of the samples with 4.5% CB was significantly lower than that of the samples with 0% and 1.5% CB. MOE of the samples with 3% and 4.5% ZB were significantly lower than that of the samples with 0% and 1.5% ZB (Table 4.3). For MOR, there was significant difference between the samples with different borate contents

except between the samples with 3% and 4.5% ZB bonded with 5% pMDI resin (Table 4.4).

For IB test, CB boards with 5% pMDI had the highest IB value and CB boards with 2.5% pMDI had the lowest IB value (Tables 4.1 and 4.2). IBs of ZB boards with 5% pMDI was much higher than these of ZB boards with 2.5% pMDI (Figures 4.7 and 4.8). At the 2.5% pMDI level, IB of the boards with 0% CB was significantly higher than that of the boards with 3% CB. At the 5% pMDI level, IB values of boards with 0% CB and ZB were significantly higher than those of boards with 4.5% CB and ZB (Table 4.5). All these results indicate that the addition of borate significantly reduced IB strength. This result was consistent with the report of OSB bonded with PF resin by Lee (2003).

Table 4.3 MOE contrast at different borate loading levels

Borate Type	pMDI (%)	Contrast Level	Mean Square	F Value	Pr > F
CB	2.5	0 VS. 1.5%	0.6241	2.69	0.1452
		0 VS. 3%	2.387025	10.28	0.015
		1.5% VS. 3%	0.570025	2.45	0.1612
	5	0 VS. 1.5%	0.455625	1.96	0.2041
		0 VS. 3%	1.2996	5.59	0.05
		0 VS. 4.5%	3.6481	15.7	0.0054
		1.5 VS. 3%	0.216225	0.93	0.3668
		1.5 VS. 4.5%	1.525225	6.57	0.0374
		3 VS. 4.5%	0.5929	2.55	0.1542
ZB	2.5	0 VS. 1.5%	0.632025	5.53	0.051
		0 VS. 3%	2.805625	24.55	0.0016
		1.5% VS. 3%	0.7744	6.78	0.0353
	5	0 VS. 1.5%	0.5476	4.79	0.0648
		0 VS. 3%	2.9241	25.58	0.0015
		0 VS. 4.5%	5.313025	46.48	0.0002
		1.5 VS. 3%	0.9409	8.23	0.024
		1.5 VS. 4.5%	2.449225	21.43	0.0024
		3 VS. 4.5%	0.354025	3.1	0.1218

Table 4.4 MOR contrast at different borate loading levels

Borate Type	pMDI (%)	Contrast Level	Mean Square	F Value	Pr > F
CB	2.5	0 VS. 1.5%	4.831567	10.92	0.013
		0 VS. 3%	47.96377	108.45	<.0001
		1.5% VS. 3%	22.34931	50.53	0.0002
	5.0	0 VS. 1.5%	21.77785	49.24	0.0002
		0 VS. 3%	230.8638	521.99	<.0001
		0 VS. 4.5%	359.4532	812.73	<.0001
		1.5 VS. 3%	110.8288	250.59	<.0001
		1.5 VS. 4.5%	204.2777	461.88	<.0001
		3 VS. 4.5%	14.1756	32.05	0.0008
ZB	2.5	0 VS. 1.5%	21.40843	7.13	0.032
		0 VS. 3%	151.1516	50.35	0.0002
		1.5% VS. 3%	58.78974	19.58	0.0031
	5.0	0 VS. 1.5%	21.72222	7.24	0.0311
		0 VS. 3%	124.2197	41.38	0.0004
		0 VS. 4.5%	224.7468	74.87	<.0001
		1.5 VS. 3%	42.05106	14.01	0.0072
		1.5 VS. 4.5%	106.7264	35.55	0.0006
		3 VS. 4.5%	14.79302	4.93	0.0619

4.2.2 Effect of Borate Type on Mechanical Properties

The effect of borate type on mechanical properties of panels was investigated. Specimens with the same resin and borate loading level but different borate types were contrasted. The mechanical properties (MOE, MOR, and IB) of ZB boards were close to those of CB boards under the same resin loading level and similar BAE (Figures 4.3 -- 4.8). This indicates that the effect of ZB and CB on the mechanical properties was similar. This effect was also demonstrated from the statistic analysis (Table 4.6). It is attributed that ZB and CB have some similar chemical properties and both of the chemicals are almost insoluble in water and the boron content in their molecules is similar. By weight, there is 15% boron in $2ZnO{\cdot}3B_2O_3{\cdot}3.5H_2O$ and18% boron in $Ca_2B_6O_{11}{\cdot}5H_2O$. This indicates that if there is equal weight of CB and ZB in a given

board, CB has 3% more boron than ZB. However, based on the result mentioned above (i.e., borate content had no significant influence on mechanical properties), this small difference in borate content cannot significantly influence on the mechanical properties of the boards at the resin content level used.

Table 4.5 IB contrast at different borate loading levels

Borate Type	pMDI (%)	Contrast Level	Mean Square	F Value	Pr>F
CB	2.5	0 VS. 1.5	6934.86	0.15	0.7036
		0 VS. 3	175258.5	3.69	0.0492
		1.5 VS. 3	119173.2	2.51	0.1181
	5.0	0 VS. 1.5%	196394.4	4.14	0.0861
		0 VS. 3%	255965.7	5.39	0.0734
		0 VS. 4.5%	148684.7	3.13	0.0416
		1.5 VS. 3%	3939.625	0.08	0.7742
		1.5 VS. 4.5%	3314.025	0.07	0.7925
		3 VS. 4.5%	14480.27	0.3	0.5827
ZB	2.5	0&1.5	0.6956	0	0.9967
		1.5&3	78694.79	1.93	0.1697
		0&3	79163.43	1.94	0.1684
	5.0	0 VS. 1.5%	75173.42	1.84	0.1794
		0 VS. 3%	51711.4	1.27	0.2644
		0 VS. 4.5%	352161.9	8.64	0.0046
		1.5 VS. 3%	2188.023	0.05	0.8176
		1.5 VS. 4.5%	101923.5	2.5	0.1189
		3 VS. 4.5%	133978.6	3.29	0.0747

4.2.3 Effect of Resin Content on Mechanical Properties

The mechanical properties (MOE, MOR, and IB) of CB and ZB boards bonded with 5% pMDI resin were higher than those of the boards bonded with 2.5% pMDI resin (Figures 4.3 -- 4.8). The statistic data analysis proved this point (Table 4.8). Modulus of elasticity of CB boards with 5% pMDI was significantly higher than that with 2.5% pMDI (Figure 4.3, Tables 4.1and 4.8). MOE of ZB boards with 5% pMDI was higher

Table 4.6 Contrast of mechanical properties of ZB and CB boards under the same resin and borate loading level

Variable	pMDI (%)	Borate (%)	Mean Square	F Value	Pr> F
MOE	2.5	1.5	0.01	0.04	0.86
		3	1.65	4.3	0.17
	5	1.5	0.07	0.1	0.78
		3	0.22	0.51	0.55
		4.5	0.01	0.02	0.91
MOR	2.5	1.5	33.12	0.86	0.45
		3	116.75	6.38	0.13
	5	1.5	129.95	0.53	0.54
		3	13.38	0.21	0.69
		4.5	73.55	2.46	0.26
IB	2.5	1.5	1888.77	0.13	0.75
		3	19319.97	12.2	0.07
	5	1.5	8202.17	1.71	0.32
		3	1728.63	0.45	0.57
		4.5	67125.82	8.32	0.10

Table 4.7 Mechanical property contrast for boards with 2.5% and 5% pMDI resin levels

Property	Borate Type	Mean Square	F Value	Pr>F
MOE	CB	95091.96086	8.27	0.0139
	ZB	42.91492917	0.01	0.9143
MOR	CB	18761460.04	9.6	0.0092
	ZB	1400215.152	6.04	0.0301
IB	CB	536144.3310	44.41	<.0001
	ZB	741.5732	13.99	0.0028

than that with 2.5% pMDI (Figure 4.5 and Table 4.1). However, the difference between them was not significant (Table 4.8). MOR of the boards with 5% pMDI was significantly higher than that with 2.5% pMDI for both CB and ZB boards (Figures 4.4 and 4.6, Tables 4.1 and 4.7). IBs of boards with 5% pMDI are significantly higher than those with 2.5% pMDI (Figures 4.7 and 4.8, Tables 4.1 and 4.7).

4.3 Physical Properties

Test data of BAE, TS, LE, and WA are listed in Tables 4.8 and 4.9. The difference of the water absorption from TS and LE samples was significant (Tables 4.8 and 4.9, Figures 4.10, 4.12, 4.14, and 4.15). One of the reasons was the different experiment procedure. The TS specimens were simply submerged 25.4 mm under the surface of the water at room temperature. However, the LE specimens were placed into a pressure vessel filled with water. The LE specimens were kept under – 0.19 MPA for 1 hour and then 0.69 MPa for 2 hours. The vacuum and pressure condition affected the water absorption of LE specimens heavily. The other reason was that the dimension of the TS samples (15.24 cm $\times$ 15.24cm $\times$ 1.27cm) and LE samples (25 cm $\times$ 5cm $\times$ 1.27cm) was different. When the sample was cut, the glue line at the edge of the sample was damaged by the vibration and strike of cutter, which can increase the thickness swelling and water absorption. This influence was much more significant when the sample was small or slim. The width of LE sample (5cm) was much smaller than the width of TS samples (15.24cm). As a result, the water absorption of LE sample was much higher than that of TS samples (Table 4.8).

Table 4.8 Summery of physical properties of CB panels [a]

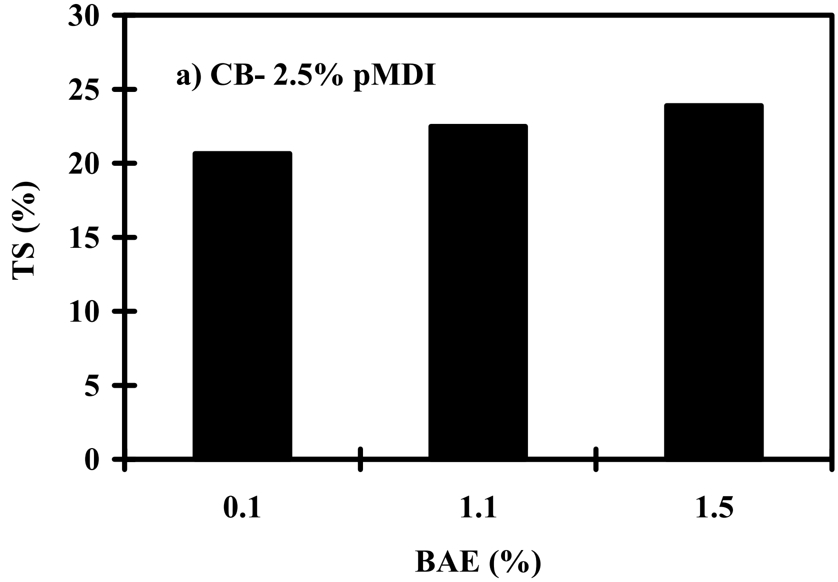
		Thickness Swelling			Linear Expansion		
pMDI (%)	BAE (%)	Density (g/cm^3)	TS (%)	WA [b] (%)	Density (g/cm^3)	LE (%)	WA [c] (%)
2.5	0.05	0.73	20.66 (3.31)	30.14	0.73	0.21	69.62
2.5	1.13	0.74	22.49 (6.07)	31.84	0.73	0.25	69.99
2.5	1.52	0.74	23.89 (4.97)	34.60	0.73	0.27	76.34
5.0	0.07	0.72	9.32 (3.11)	16.38	0.72	0.23	33.85
5.0	1.42	0.73	10.67 (2.23)	17.48	0.72	0.25	35.58
5.0	1.83	0.74	10.94 (2.87)	18.38	0.74	0.27	37.07
5.0	2.56	0.75	11.06 (2.19)	19.09	0.73	0.29	38.01

[a]. Values in parenthesis are standard deviations based on five points.
[b]. indicates the water absorption of TS specimens.
[c]. indicates the water absorption of LE specimens.

Table 4.9 Summery of physical properties of ZB panels [a]

		Thickness Swelling			Linear Expansion		
pMDI (%)	BAE (%)	Density (g/cm^3)	TS (%)	WA [b] (%)	Density (g/cm^3)	LE (%)	WA [c] (%)
2.5	0.07	0.72	19.55 (3.03)	26.45	0.72	0.27	43.70
2.5	1.18	0.73	20.02 (4.07)	27.47	0.73	0.28	48.15
2.5	1.67	0.73	22.78 (3.97)	30.95	0.73	0.31	55.19
5.0	0.10	0.74	8.62 (2.57)	17.15	0.74	0.24	22.36
5.0	1.30	0.73	11.29 (1.49)	17.63	0.74	0.29	26.14
5.0	1.64	0.74	11.90 (1.74)	19.98	0.72	0.29	26.27
5.0	2.59	0.74	11.94 (2.69)	22.77	0.73	0.32	30.28

[a]. Values in parenthesis are standard deviations based on five points.
[b]. indicates the water absorption of TS specimens.
[c]. indicates the water absorption of LE specimens.



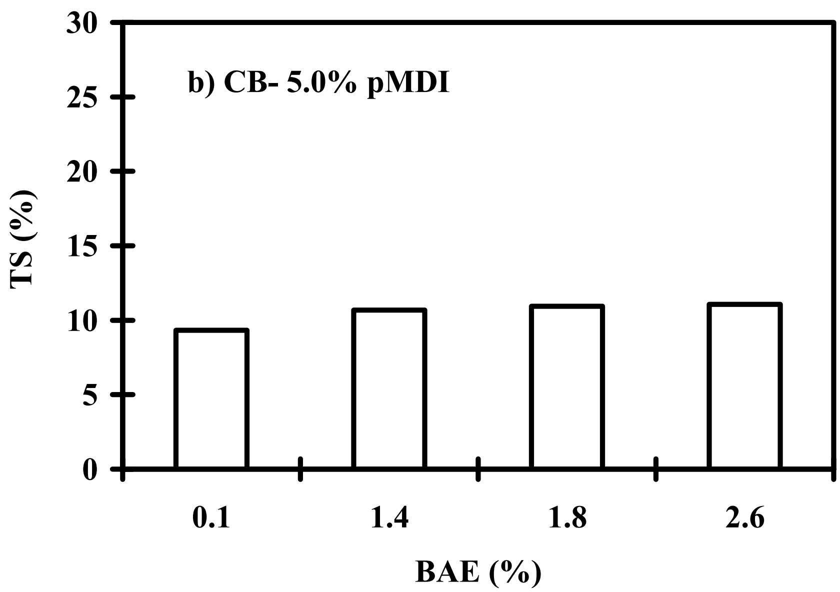


Figure 4.9 TS in relation with BAE for CB-treated strandboard. a) CB - 2.5% pMDI and b) CB - 5.0% pMDI.

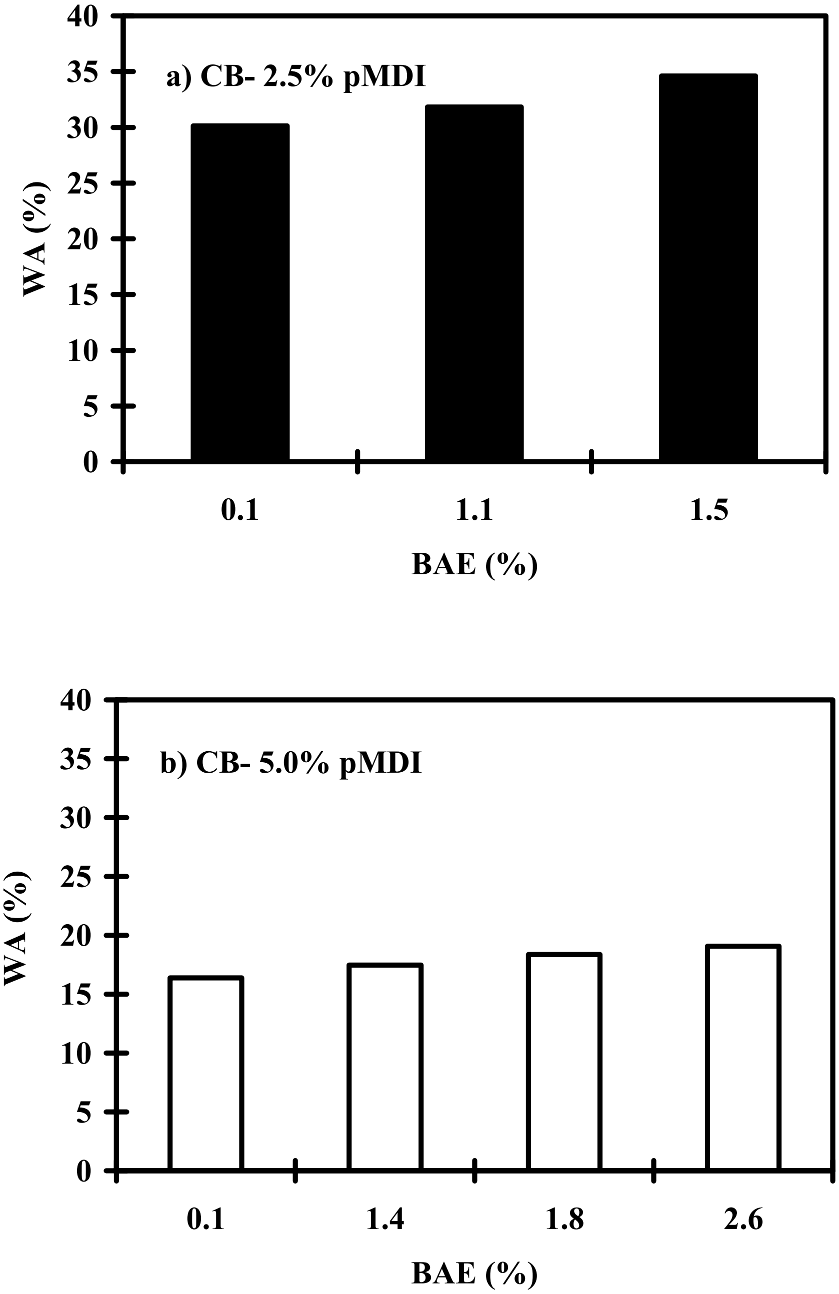


Figure 4.10 WA from TS tests in relation with BAE for CB-treated strandboard. a) CB - 2.5% pMDI and b) CB - 5.0% pMDI.

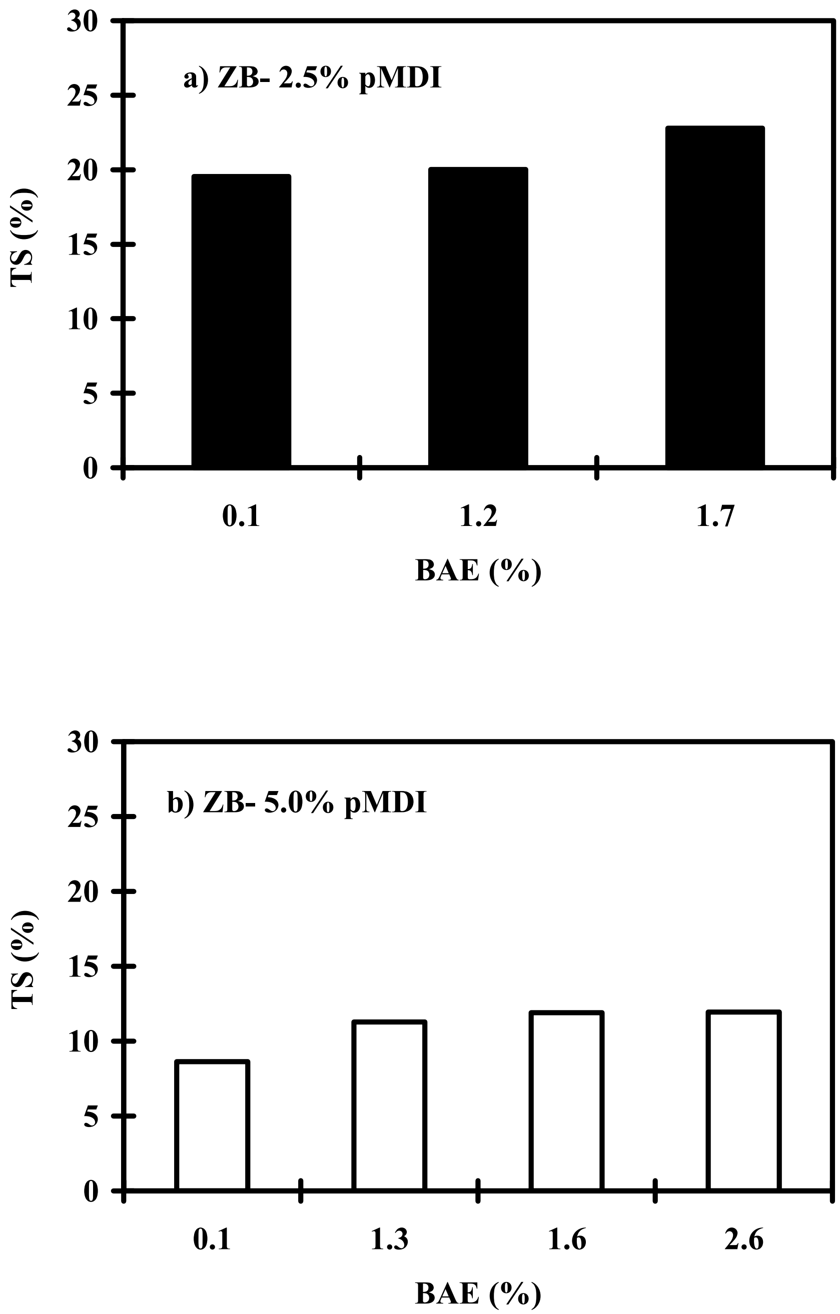


Figure 4.11 TS in relation with BAE for ZB-treated strandboard. a) ZB - 2.5% pMDI and b) ZB - 5.0% pMDI.

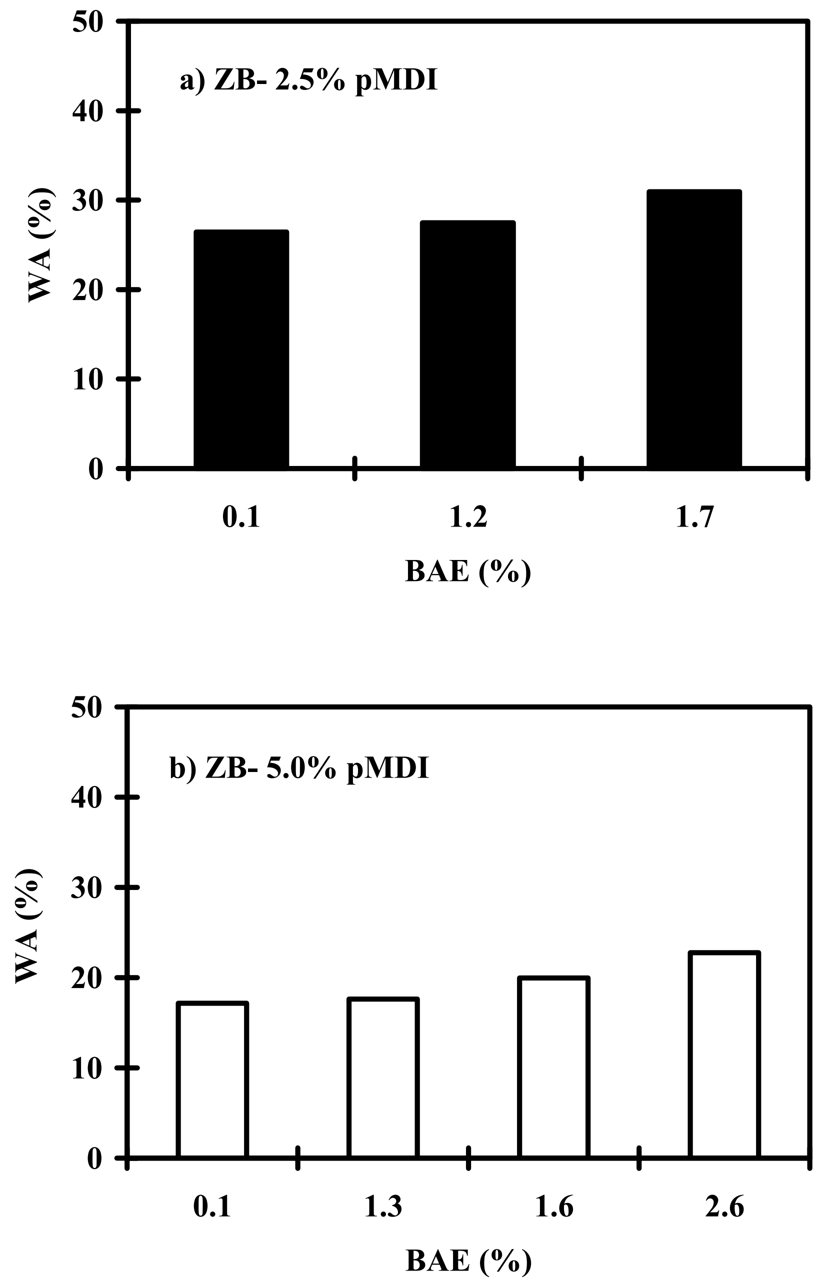


Figure 4.12 WA from TS samples in relation with BAE for ZB-treated strandboard. a) ZB - 2.5% pMDI and b) ZB - 5.0% pMDI.

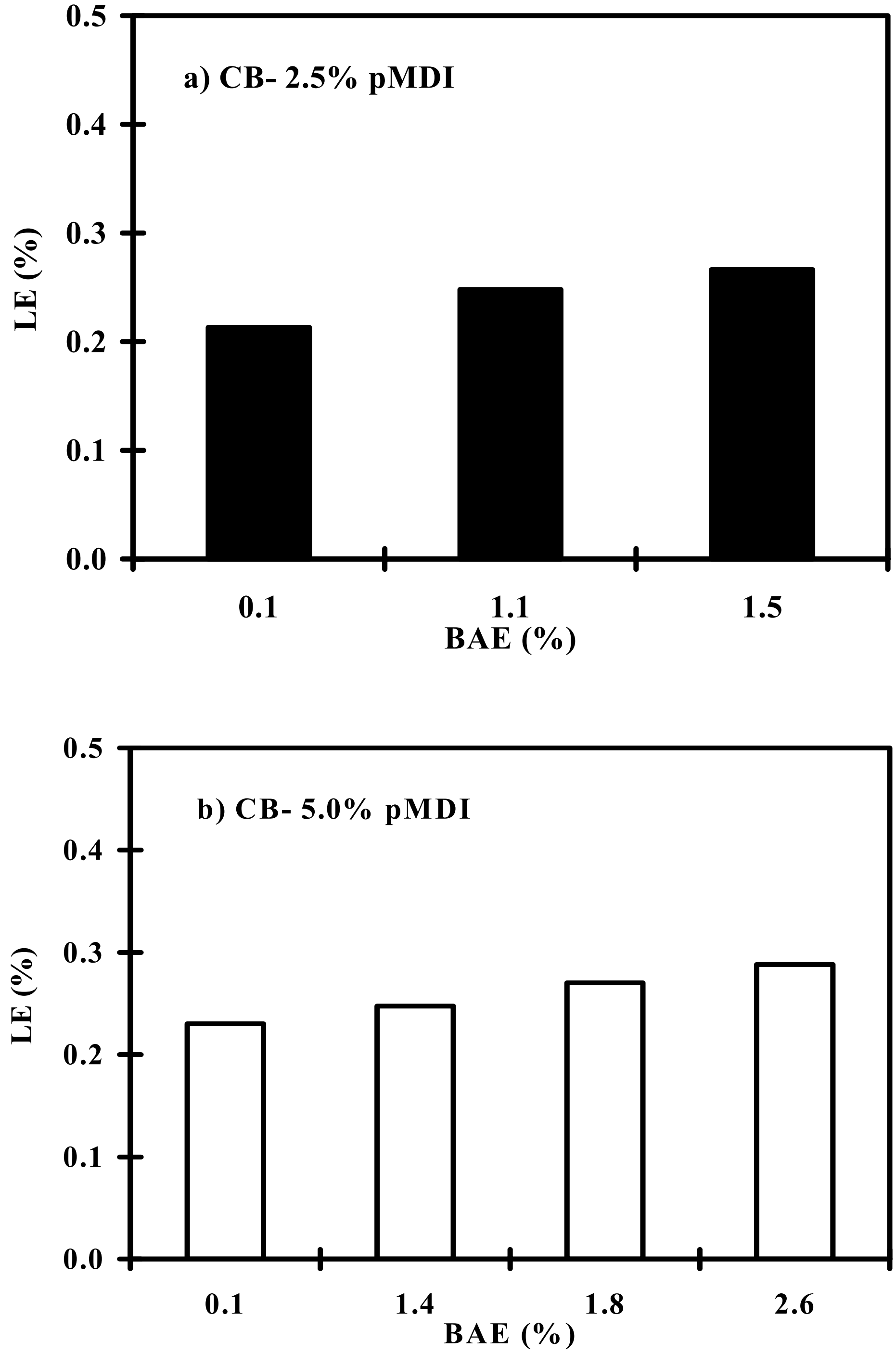


Figure 4.13 LE in relation with BAE for CB-treated strandboard. a) CB - 2.5% pMDI and b) CB - 5.0% pMDI.

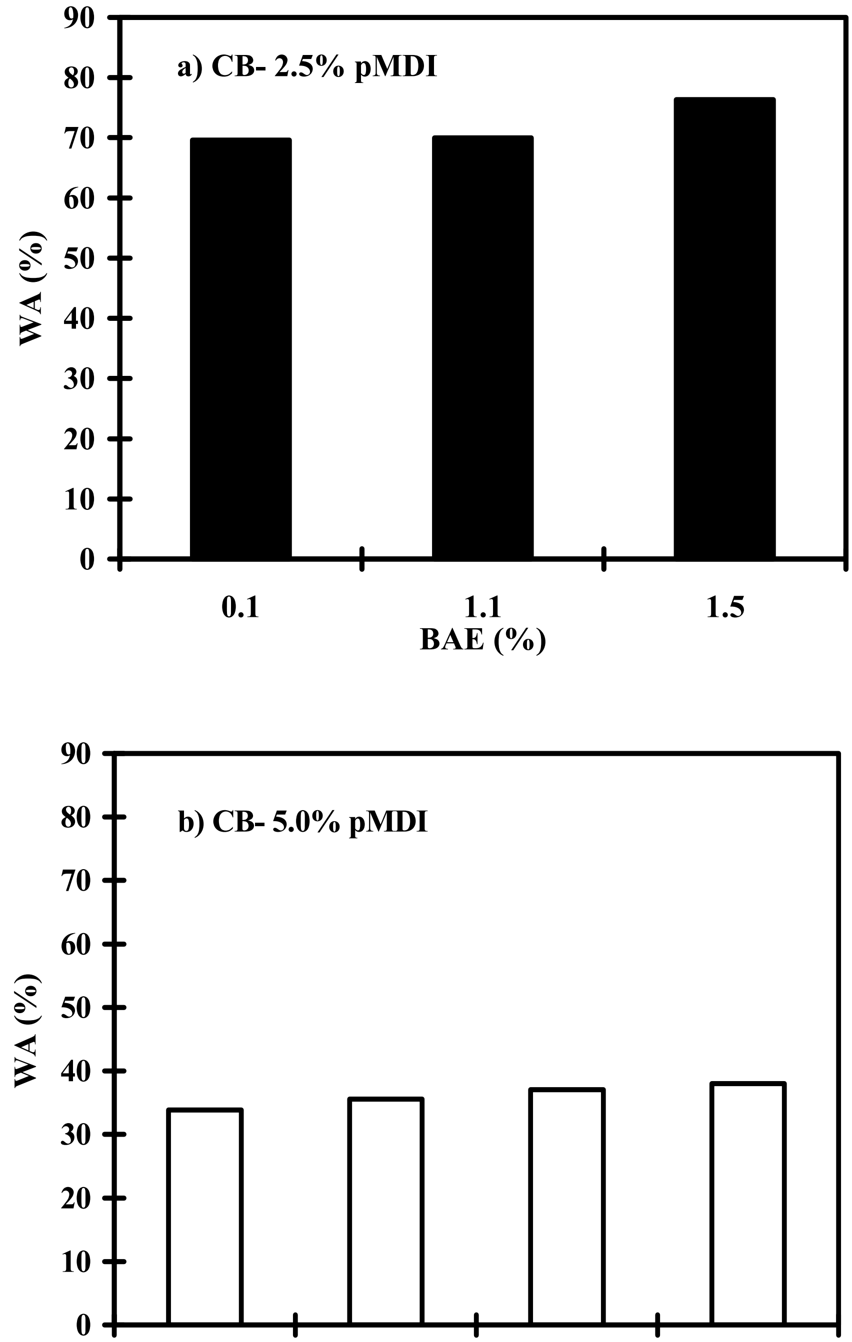


Figure 4.14 WA from the LE samples in relation with BAE for CB-treated strandboard. a) CB - 2.5% pMDI and b) CB - 5.0% pMDI.

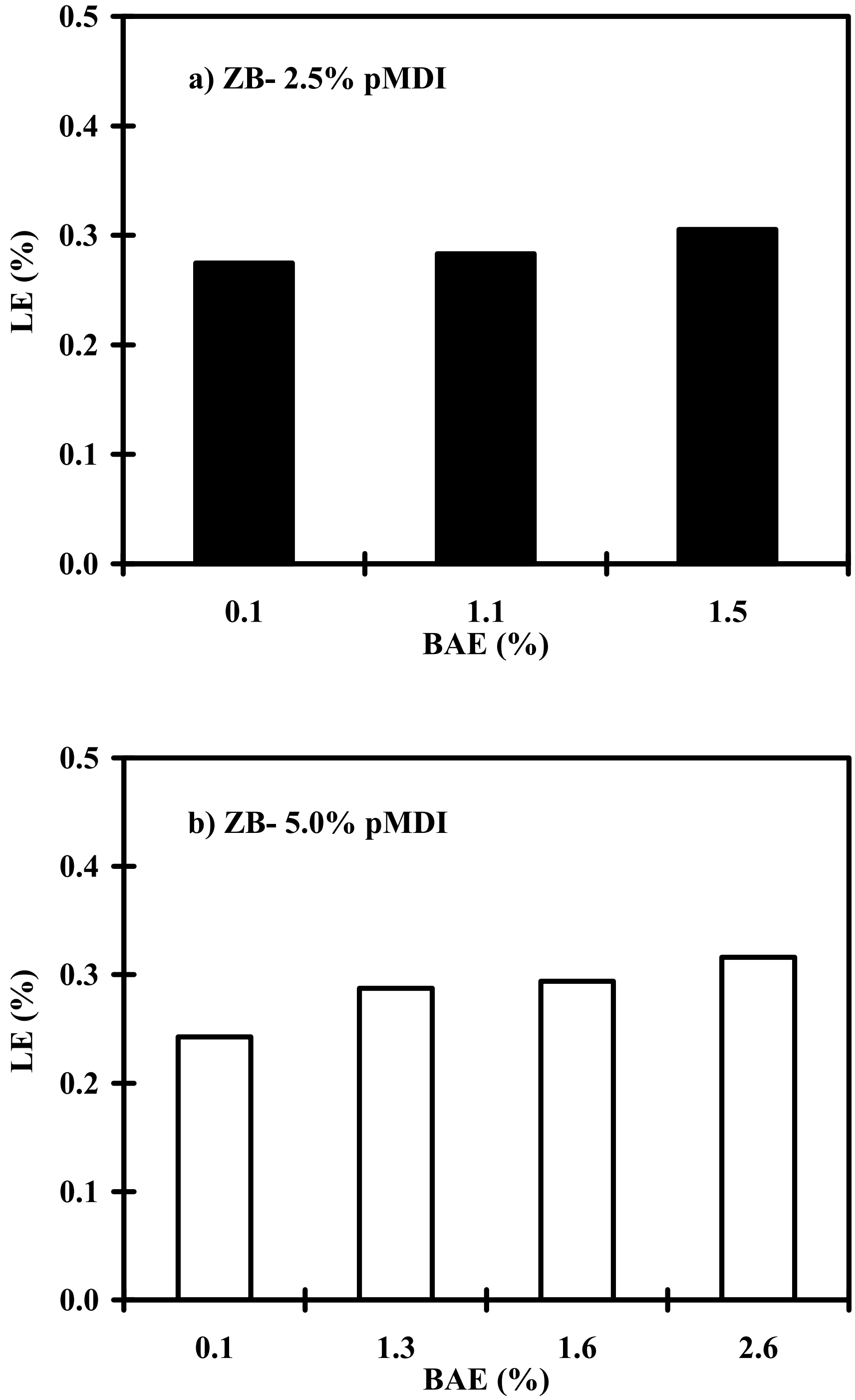


Figure 4.15 LE in relation with BAE for ZB-treated strandboard. a) ZB - 2.5% pMDI and b) ZB - 5.0% pMDI.

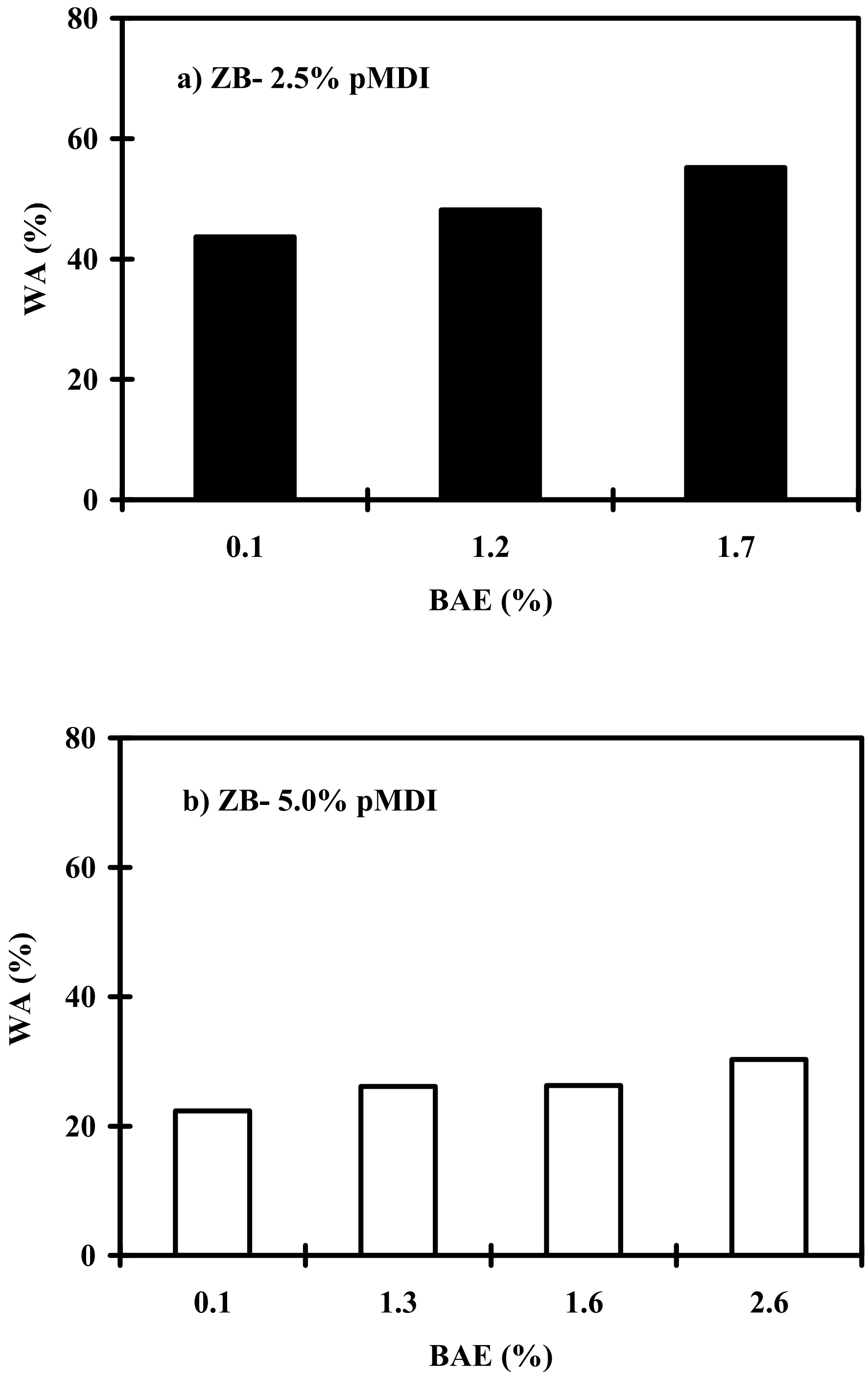


Figure 4.16 WA from the LE tests in relation with BAE for CB-treated strandboard. a) ZB - 2.5% pMDI and b) ZB - 5.0% pMDI.

4.3.1 Effect of Borate Content on Physical Properties

The graphs of TS and LE as a function of BAE are shown in Figures 4.10 to 4.16. TS, LE, and WA increased with the increase of BAE for both ZB and CB boards. This indicates that the addition of borate negatively influenced the physical properties of boards. The reason was that the addition of borate decreased the bond quality among the wood flakes. This result was consistent with the boards bonded with PF resin. TS generally increased with the increase of borate levels in the treated OSB bonded with PF resin (Lee 2003).

The results of statistical analysis proved the negative influence of borate on physical properties of the boards (Tables 4.10 to 4.12). At the 2.5% pMDI level, TS of the samples with 3% CB (or ZB) was significantly higher than that of the samples with 0% CB (or ZB). At the 2.5% pMDI level, TS of the samples with 1.5%, 3%, and 4.5% ZB were significantly higher than that of the samples with 0% ZB.

For linear expansion, at the 2.5% pMDI level, LE of the samples with 3% CB was significantly higher than that of the samples with 0% CB. At the 5% pMDI level, LE of the samples with 4.5% CB was significantly higher than that of the samples with 0% CB (Table 4.12). The influence of the borate addition on LE was lower than the influence of borate addition on TS.

For water absorption, at the 2.5% pMDI level, WA of the samples with 3% CB (or ZB) was significantly higher than that of the samples with 0% CB (or ZB). At the 5% pMDI level, WA of the samples with 4.5% ZB was significantly higher than that of the samples with 0% and 1.5% ZB (Table 4.11).

The water absorption increased with the increase of TS because the samples with higher TS had much larger voids among the flakes and can absorb more water. This point was reflected from the result mentioned above. From Figures 4.9 -- 4.16, both TS and WA of CB and ZB boards increased with the increase of BAE.

4.3.2 Effect of Borate Type on Physical Properties

The effect of borate type on physical properties of panel was investigated. Specimens with the same resin and borate loading level but different borate type were contrasted. There was no significant difference between the physical properties of ZB and CB panel, including TS, LE, and WA (Figures 4.9 to 4.16 and Table 4.13). The reason was that ZB and CB have similar chemical property as mentioned in section 4.2.2.

4.3.3 Effect of Resin Content on Physical Properties

Thickness swelling and water absorption of both ZB and CB boards with 2.5% pMDI resin was higher than these at the 5% pMDI resin level (Figures 4.9 -- 4.12 and Tables 4.8 and 4.9). There was no significant difference between LE of the boards bonded with 2.5% and 5% pMDI resin (Figures 4.13 -- 4.16, Tables 4.8, 4.9, and 4.14).

The result of TS was consistent with the result of WA. The increase of resin content significantly decreased the TS and water content. However, the resin content almost had no significant influence on LE. The reason was that TS reflects the expansion along the thickness direction of the panel, which was mainly controlled by the glue strength. However, LE reflected the expansion along the length or width direction of the panel, which was mainly controlled by the expansion property of the flake itself. Thus, the increase of resin content increased the glue strength between flakes, and decreased TS.

Table 4.10 TS contrast at different borate loading levels

Borate Type	pMDI (%)	Contrast Level	Mean Square	F Value	Pr > F
CB	2.5	0 VS. 1.5%	0.000625	3.12	0.1204
		0 VS. 3%	0.002025	10.12	0.0154
		1.5% VS. 3%	0.0004	2	0.2002
	5.0	0 VS. 1.5%	0.000025	0.12	0.7341
		0 VS. 3%	0.0001	0.5	0.5024
		0 VS. 4.5%	0.0004	2	0.2002
		1.5 VS. 3%	0.000025	0.12	0.7341
		1.5 VS. 4.5%	0.000225	1.12	0.3241
		3 VS. 4.5%	0.0001	0.5	0.5024
ZB	2.5	0 VS. 1.5%	0.000225	1.75	0.2275
		0 VS. 3%	0.0009	7	0.0331
		1.5% VS. 3%	0.000225	1.75	0.2275
	5.0	0 VS. 1.5%	0.001225	9.53	0.0176
		0 VS. 3%	0.0016	12.44	0.0096
		0 VS. 4.5%	0.0016	12.44	0.0096
		1.5 VS. 3%	0.000025	0.19	0.6725
		1.5 VS. 4.5%	0.000025	0.19	0.6725
		3 VS. 4.5%	0.00018	0.15	0.7623

Table 4.11 Contrast of WA from TS specimens at different borate loading levels

Borate compound	pMDI (%)	Contrast level	Mean Square	F Value	Pr > F
CB	2.5%	0 VS. 1.5%	2.89	1.44	0.2684
		0 VS. 3%	19.8916	9.95	0.0161
		1.5% VS. 3%	7.6176	3.81	0.0919
	5.0%	0 VS. 1.5%	1.21	0.6	0.4622
		0 VS. 3%	4	2	0.2002
		0 VS. 4.5%	7.3441	3.67	0.0969
		1.5 VS. 3%	0.81	0.4	0.5448
		1.5 VS. 4.5%	2.5921	1.3	0.2924
		3 VS. 4.5%	0.5041	0.25	0.631
ZB	2.5%	0 VS. 1.5%	1.0404	0.52	0.4941
		0 VS. 3%	20.25	10.13	0.0154
		1.5% VS. 3%	12.1104	6.06	0.0434
	5.0%	0 VS. 1.5%	0.2304	0.12	0.7443
		0 VS. 3%	8.0089	4	0.0855
		0 VS. 4.5%	31.5844	15.79	0.0054
		1.5 VS. 3%	5.5225	2.76	0.1405
		1.5 VS. 4.5%	26.4196	13.21	0.0083
		3 VS. 4.5%	7.7841	3.89	0.0891

Table 4.12 LE contrast at different borate loading levels

Borate compound	pMDI (%)	Contrast level	Mean Square	F Value	Pr > F
CB	2.5%	0 VS. 1.5%	0.003025	0.29	0.6084
		0 VS. 3%	0.086142	8.19	0.0243
		1.5% VS. 3%	0.056882	5.41	0.053
	5.0%	0 VS. 1.5%	0.000025	0.02	0.9625
		0 VS. 3%	0.017556	1.67	0.2374
		0 VS. 4.5%	0.01334	1.27	0.0462
		1.5 VS. 3%	0.018906	1.8	0.2219
		1.5 VS. 4.5%	0.01221	1.16	0.3171
		3 VS. 4.5%	0.061504	5.85	0.2973
ZB	2.5%	0 VS. 1.5%	0.005195	0.21	0.6626
		0 VS. 3%	7.34E-05	0	0.9583
		1.5% VS. 3%	0.006503	0.26	0.6261
	5.0%	0 VS. 1.5%	0.014858	0.59	0.4664
		0 VS. 3%	0.002646	0.11	0.7547
		0 VS. 4.5%	4.55E-05	0	0.9672
		1.5 VS. 3%	0.030046	1.2	0.3097
		1.5 VS. 4.5%	0.016549	0.66	0.4431
		3 VS. 4.5%	0.001998	0.08	0.7858

Table 4.13 Contrast of physical properties of ZB and CB boards under the same resin and borate loading level

Property	pMDI (%)	% Borate Compound	Mean Square	F Value	Pr> F
TS	2.5	1.5	0.0023	1.06	0.3616
		3	0.0004	1.88	0.2420
	5	1.5	0.0136	0.12	0.9379
		3	0.0093	2.73	0.0538
		4.5	0.0062	0.34	0.5261
WA [a]	2.5	1.5	19.0969	1.63	0.0866
		3	13.3225	6.66	0.0613
	5	1.5	3.2102	7.23	0.1210
		3	0.2356	0.16	0.5925
		4.5	0.0018	17.62	0.0612
LE	2.5	1.5	0.0161	0.59	0.4860
		3	0.0368	1.34	0.3212
	5	1.5	0.0723	1.63	0.2913
		3	0.0521	9.29	0.0867
		4.5	0.0162	0.06	0.6232
WA [b]	2.5	1.5	20.3121	0.15	0.3735
		3	10.6532	16.32	0.0684
	5	1.5	1.6543	0.03	0.9632
		3	23.1255	4.26	0.1546
		4.5	12.6913	1.68	0.4261

[a] Water absorption of TS specimens. [b] Water absorption of LE specimens

Table 4.14 Mechanical property contrast for boards with 2.5% and 5% pMDI resin levels

Property	Borate compound	Mean Square	F Value	Pr>F
TS	CB	0.0381006	59.99	<.0001
	ZB	0.02625	15.48	0.002
WA_{TS} [a]	CB	700.209	74.08	<.0001
	ZB	570.917	16.22	0.0017
LE	CB	0.02854821	1.48	0.2474
	ZB	0.00019286	0.01	0.9194
WA_{LE} [b]	CB	5212.96350	72.87	<.0001
	ZB	1900.994436	16.71	0.0035

[a] Water absorption of TS specimens; [b] Water absorption of LE specimens

Water absorption decreased with the decrease of TS. However, LE was almost not affected by the increase of resin content.

4.4 Leaching Properties

Test data of BAE, boron content of calcium and zinc, and ratio of B/ Ca and B/Zn at different leaching times are listed in Tables 4.15 and 4.16. The actual BAE and BAE ratios (current BAE/ initial BAE) under different borate loading levels as a function of leaching time are plotted in Figures 4.17, 4.18 and 4.19. There was an initial higher leaching rate (i.e., the line descended fast before 24-hour leaching time) and the rate decreased as the lapse of leaching time (i.e., the line was flat after 24-hour leaching time). Samples with higher initial BAE levels had a higher leaching rate. This result was consistent with the leaching result of the boards bonded with PF resin reported by Lee and Wu (2002).

The water leaching experiment with small samples (e.g., 5.04 cm by 5.04 cm) was a severe test for wood-based composite materials. This process led to a significant thickness swelling even with samples having their edge sealed. During the initial exposure to water, significant TS 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 24-hour water exposure, TS and washing effect were stabilized, leading to a reduced leaching rate. Thus, TS properties of the strandboard significantly affected the leaching rate. Since TS of wood composite varies from place to place within a composite panel, this variability might significantly affect the leaching results.

In Figure 4.20, BAE ratios between boards bonded with pMDI resin and PF resin (Lee 2003) with similar initial BAE are contrasted. For ZB boards, before 75 hours of leaching test, the BAE ratio of the boards bonded with pMDI resin and PF resin was similar. After 75 hours, the BAE ratio of pMDI boards decreased very little, while the BAE ratio of PF boards still decreased significantly. Over 175 hours, the BAE ratio of pMDI boards was higher than that of PF boards. For CB boards, the BAE ratio of the boards bonded with pMDI resin was much higher than that of the boards bonded with PF resin. Thus, the boards bonded with pMDI resin can hold borate much better and longer than PF bonded panels.

4.4.1 Contrast of Leaching Rate of ZB and CB on the Same Resin Level and Borate Content

In Figures 4.17, 4.18, and 4.19, the BAE line of ZB and CB as a function of leaching time were similar except the condition of 5% pMDI and 3% borate loading level. This indicates that the leaching rate of zinc borate and calcium borate are essentially the same. This point was also proved by the statistic analysis (Table 4.17). There was no significant difference between ZB and CB leaching rates.

4.4.2 Contrast of Leaching Rate under Different Borate Loading Levels

The leaching rate of the boards with high initial BAE was significantly higher than that with low borate loading level (Figure 4.17, 4.18, and 4.19). This shows that the boron in the strandboard with higher initial BAE level leached out faster than boron with lower BAE level. This point was also proved by the statistic analysis (Table 4.18). All the P values are lower than 0.05.

Table 4.15 Summery of assayed BAE and B/Ca ratio at various leaching times for CB-treated OSB panels

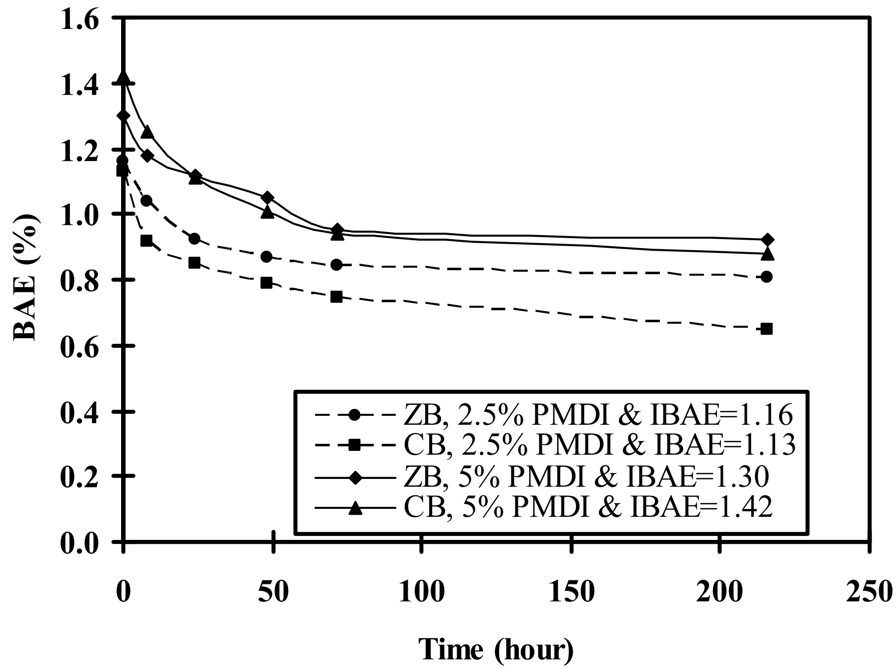
Time (h)	Variable	Resin Content (%)						
		2.5			5			
		Borate Content (%)						
		0 [a]	1.5	3	0 [a]	1.5	3	4.5
0	BAE (%)	0.05	1.13	1.52	0.07	1.42	1.83	2.56
	B (%)	0.01	0.12	0.16	0.01	0.15	0.19	0.33
	Ca (%)	0.17	0.12	0.17	0.13	0.15	0.20	0.36
	B/Ca	0.06	0.98	0.93	0.08	0.97	0.96	0.91
8	BAE (%)	0.04	0.57	0.81	0.05	0.72	0.96	2.03
	B (%)	0.01	0.10	0.15	0.01	0.13	0.18	0.37
	Ca (%)	0.20	0.12	0.17	0.17	0.15	0.22	0.43
	B/Ca	0.05	0.85	0.86	0.06	0.87	0.83	0.87
24	BAE (%)	0.04	0.53	0.76	0.05	0.63	0.90	1.70
	B (%)	0.01	0.10	0.14	0.01	0.12	0.17	0.31
	Ca (%)	0.20	0.13	0.19	0.17	0.16	0.24	0.42
	B/Ca	0.05	0.78	0.74	0.06	0.76	0.72	0.74
48	BAE (%)	0.04	0.50	0.53	0.05	0.57	0.87	1.75
	B (%)	0.01	0.09	0.10	0.01	0.10	0.16	0.32
	Ca (%)	0.20	0.14	0.15	0.17	0.16	0.24	0.51
	B/Ca	0.05	0.65	0.67	0.06	0.64	0.66	0.63
72	BAE (%)	0.04	0.46	0.54	0.05	0.52	0.82	1.64
	B (%)	0.01	0.09	0.10	0.01	0.09	0.15	0.30
	Ca (%)	0.20	0.15	0.17	0.17	0.15	0.25	0.52
	B/Ca	0.05	0.62	0.60	0.06	0.60	0.61	0.58
216	BAE (%)	0.04	0.40	0.49	0.05	0.47	0.78	1.56
	B (%)	0.01	0.07	0.09	0.01	0.09	0.14	0.29
	Ca (%)	0.20	0.13	0.17	0.17	0.16	0.25	0.55
	B/Ca	0.05	0.56	0.52	0.06	0.55	0.57	0.53

[a] Boron, zinc, and calcium from wood flakes only.

Table 4.16 Summery of assayed BAE and B/Zn ratio at various leaching times for ZB-treated OSB panels

Time (h)	Variable	Resin content (%)						
		2.5			5			
		Borate content (%)						
		0[a]	1.5	3	0[a]	1.5	3	4.5
0	BAE (%)	0.08	1.16	1.67	0.1	1.3	1.64	2.59
	B (%)	0.01	0.2	0.29	0.02	0.23	0.29	0.45
	Zn (%)	0.25	0.21	0.30	0.29	0.24	0.30	0.49
	B/Zn	0.04	0.95	0.96	0.07	0.97	0.96	0.92
8	BAE (%)	0.06	1.04	1.44	0.08	1.18	1.60	2.47
	B (%)	0.01	0.18	0.25	0.01	0.21	0.28	0.43
	Zn (%)	0.17	0.21	0.29	0.17	0.23	0.31	0.49
	B/Zn	0.06	0.86	0.87	0.06	0.90	0.89	0.88
24	BAE (%)	0.06	0.92	1.33	0.08	1.12	1.47	2.38
	B (%)	0.01	0.16	0.23	0.01	0.20	0.26	0.42
	Zn (%)	0.00	0.20	0.28	0.13	0.24	0.31	0.53
	B/Zn	0.05	0.82	0.83	0.08	0.85	0.83	0.80
48	BAE (%)	0.06	0.87	1.24	0.08	1.05	1.40	2.29
	B (%)	0.01	0.15	0.22	0.01	0.18	0.24	0.40
	Zn (%)	0.00	0.21	0.34	0.17	0.23	0.32	0.56
	B/Zn	0.04	0.70	0.65	0.06	0.78	0.76	0.72
72	BAE (%)	0.06	0.84	1.21	0.08	0.95	1.29	2.19
	B (%)	0.01	0.15	0.21	0.01	0.17	0.23	0.38
	Zn (%)	0.00	0.24	0.37	0.01	0.23	0.32	0.54
	B/Zn	0.05	0.62	0.57	1.88	0.73	0.72	0.70
216	BAE (%)	0.06	0.81	1.10	0.08	0.92	1.25	1.93
	B (%)	0.01	0.14	0.19	0.01	0.16	0.22	0.34
	Zn (%)	0.00	0.26	0.38	0.17	0.27	0.39	0.55
	B/Zn	0.04	0.54	0.50	0.06	0.60	0.57	0.62

[a] Boron, zinc, and calcium from wood flakes only.



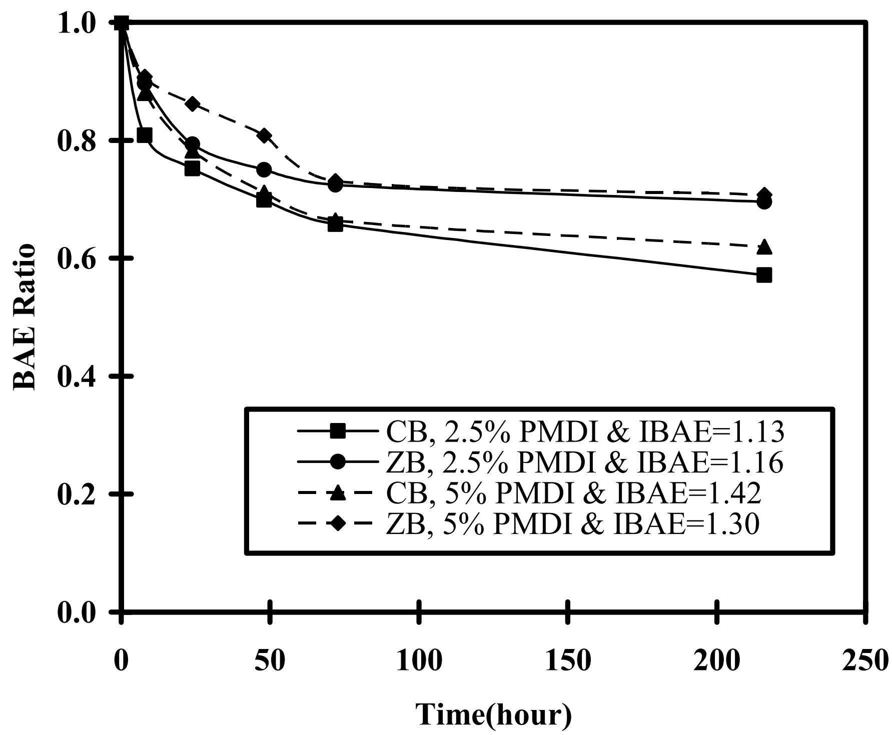


Figure 4.17 Typical leaching BAE (top) and BAE ratio (bottom) curves between ZB and CB panels (1.5% Target borate level)

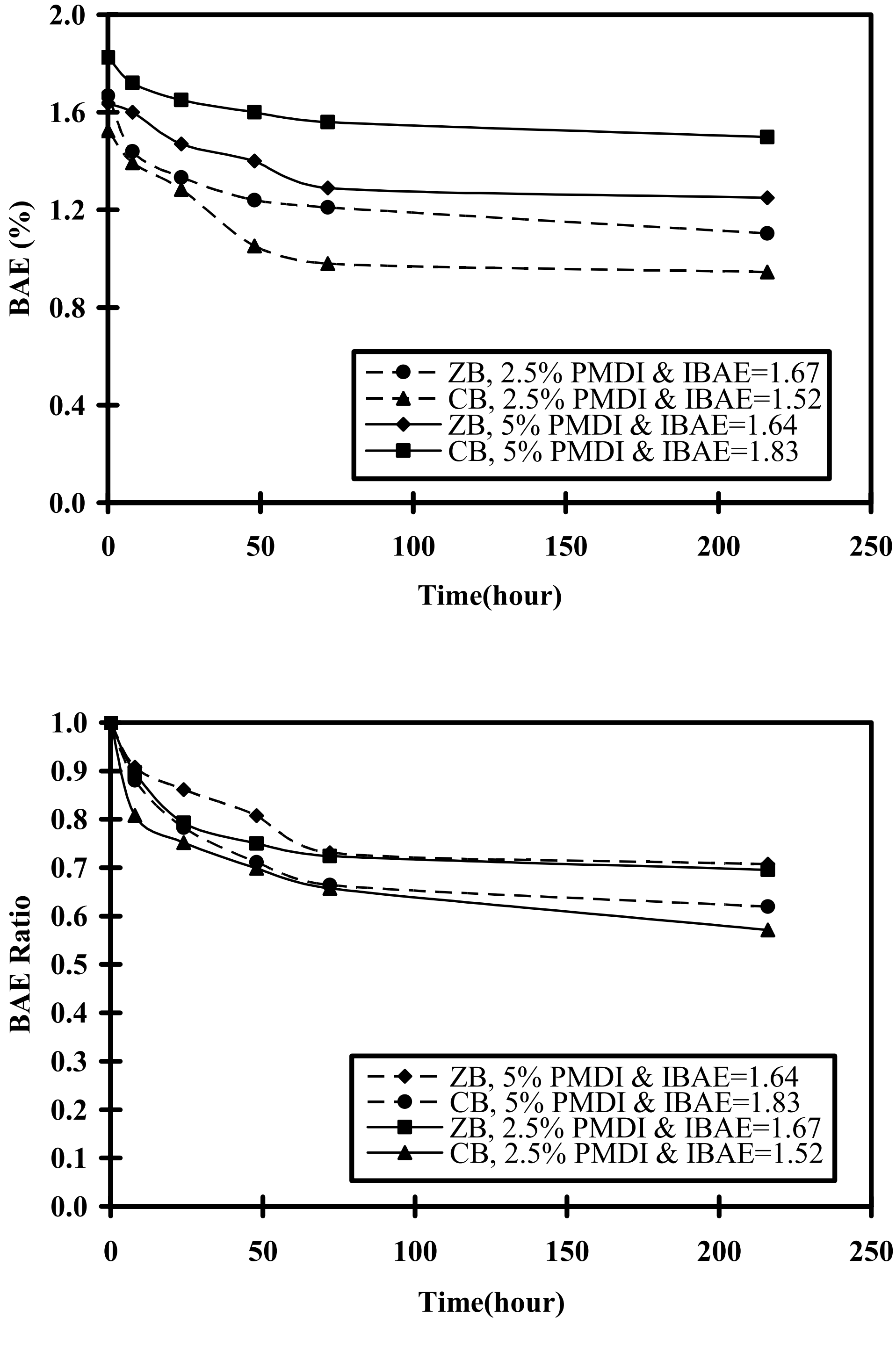


Figure 4.18 Typical leaching BAE (top) and BAE ratio (bottom) curves between ZB and CB panels (3% Target borate level)

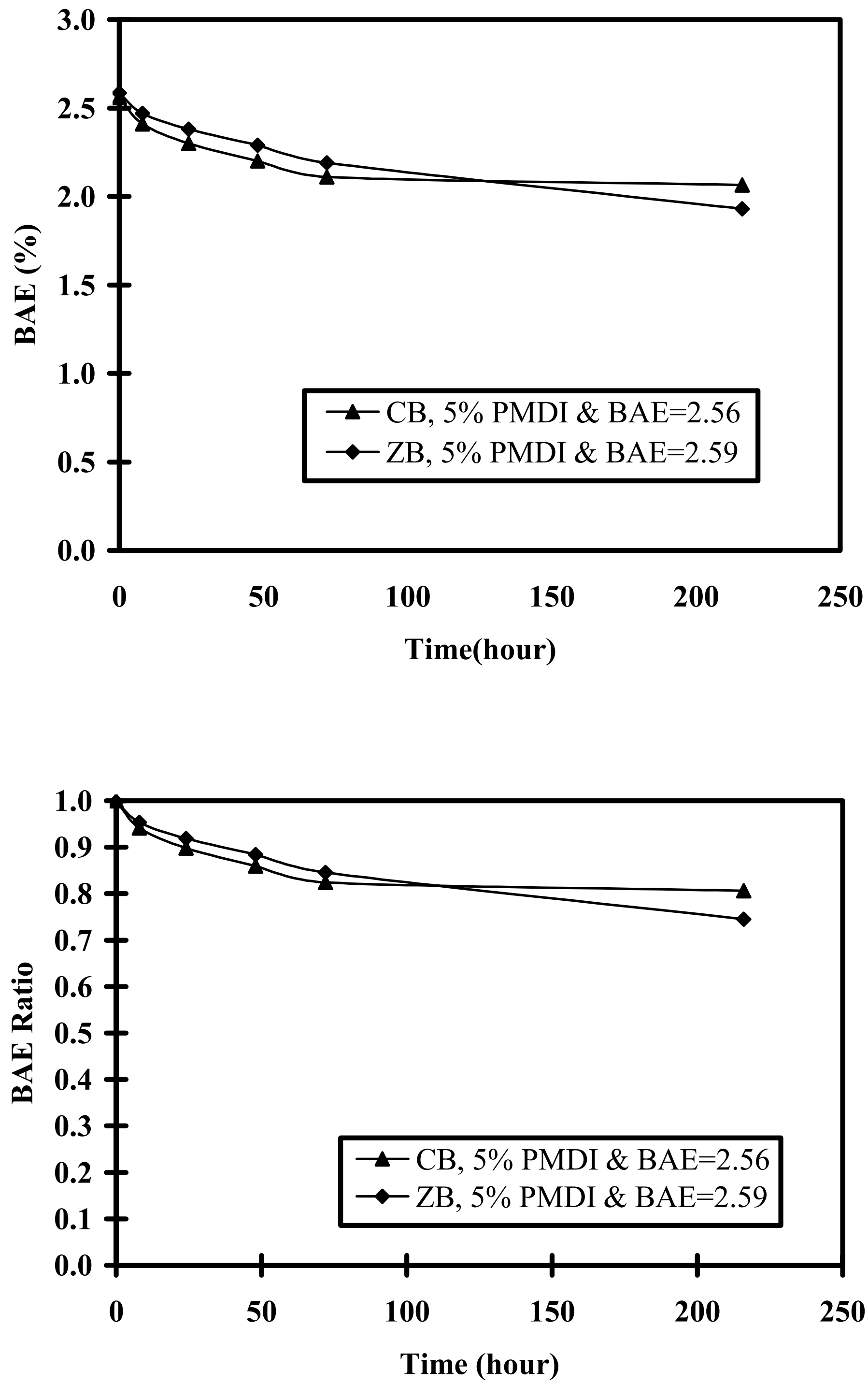


Figure 4.19 Typical leaching BAE (top) and BAE ratio (bottom) curves between ZB and CB panels (4.5% Target borate level)

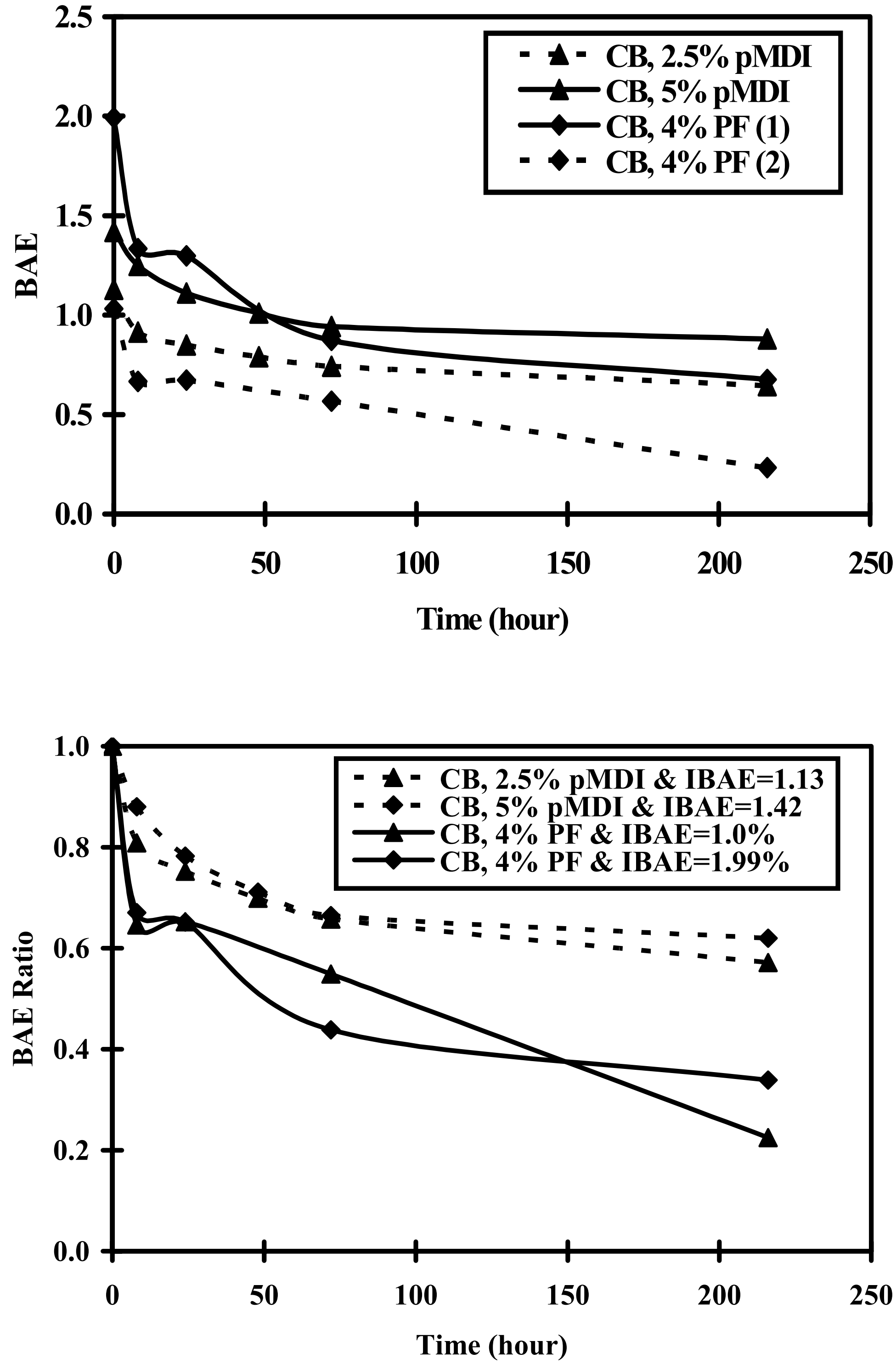


Figure 4.20 Comparison of BAE ratios from panels made with pMDI and PF resin. Data for PF-bonded boards are from Lee (2003).

4.4.3 Contrast of Leaching Rate between 2.5 and 5% Resin

The leaching rates of CB and ZB boards with 2.5 % pMDI resin were significantly higher than that with 5% pMDI resin (Figures 4.17 -- 4.19 and Table 4.19). This result was consistent with the TS result. The increase of resin content can decrease the borate leaching rate by decreasing TS.

4.4.4 Boric/ Zinc Ratio

The measured B/Ca and B/Zn ratio of the modified OSB are shown in Tables 4.16 and 4.17, and are plotted in Figure 4.21. The initial ratio from the unleached control groups was close to unity for boards. As the leaching time increased, however, the ratio decreased significantly, which indicated that boron element leached out at a higher rate compared to calcium and zinc. This result shows a possible CB and ZB decomposition during manufacturing under heat and pressure and/or under water exposure, leading to the subsequent formation of zinc hydroxide, $Zn(OH)_2$, $Ca(OH)_2$, and boric acid, H_3BO_3. Zinc hydroxide is less water soluble than boric acid. As a result, boron element leached out faster than calcium and zinc, resulting in a decrease of B/Zn and B/Ca ratios. This result was similar as the result of strandboard bonded with PF resin. The measured B/Zn ratio of the zinc borate treated strandboard decreased with the increase of leaching time (Lee and Wu, 2002).

4.5. Swelling and Strength Retention Properties under Cyclic Humidity Exposure

4.5.1 Thickness Swelling

Measured TS and MC data at the selected relative humidity (RH) levels were summarized in Table 4.20. Sample weight and thickness measured at an initial dry condition (70°C until constant weight) was used as a reference in calculating TS and MC

changes. Figure 4.23 shows typical curves of TS as a function of MC change for various panels. As shown in Figure 4.23, TS curves started at zero percent MC change (i.e., initial dry condition). The last data point (i.e., oven-dry condition) showed a negative MC, indicating an MC decrease from the initial dry condition. The effects of moisture cycling on TS were clearly seen from the graphs. TS increased with the increase of MC and decreased with the decrease of MC. At a given level, TS values on the moisture increasing line were lower than those on the moisture decreasing line. This was caused by TS hysteresis or residual TS. This result clearly indicated the damaging effect of the cyclic humidity exposure on boards' quality. The permanent residual TS caused the bond failure in the panel. This behavior is similar to the sorption hysteresis demonstrated in a previous study (Wu and Ren 2000).

Figures 4.24 and 4.25 show the plot of the maximum TS and residual TS under two resin content levels (i.e., 2.5% and 5%). Statistical analysis of the data is presented in the following sections. The maximum TS and residual TS increased with the increase of BAE indicating a negative impact of boron on the long term swelling properties of the treated strandboards.

4.5.1.1 Effect of Borate Content, Borate Type, and Resin Content on Maximum TS

For the effect of borate content, the maximum TS increased with the increase of BAE for both ZB and CB boards (Figures 4.24 and 4.25). This result indicates that the addition of borate negatively influenced the maximum TS. The results of statistical analysis proved this point (Table 4.21). At the 2.5% pMDI level, the maximum TS of the boards with 3% CB was significantly higher than that of the boards with 0% CB. At the 5% pMDI level, the maximum TS of the boards with 4.5% CB was significantly higher than

Table 4.17 Leaching rate contrast among ZB and CB boards

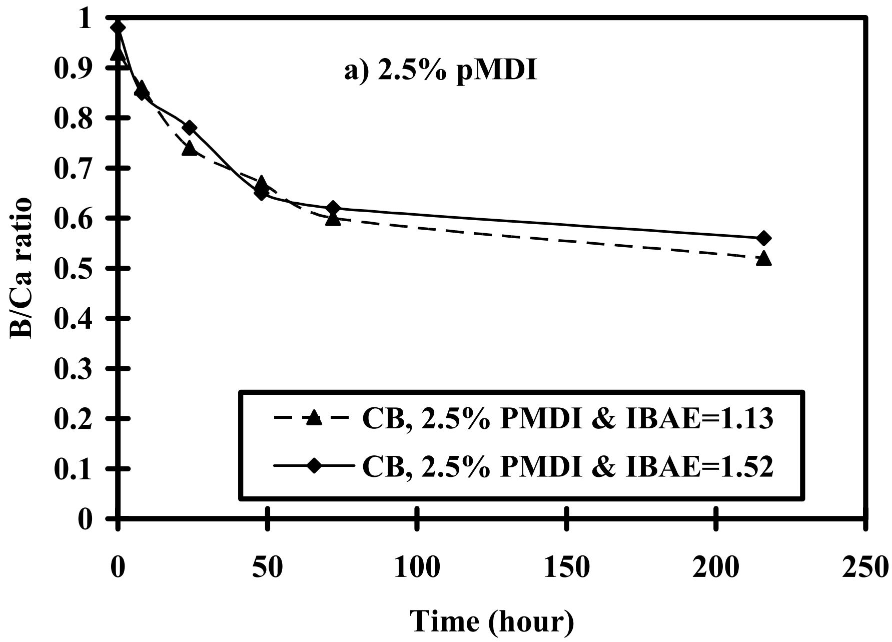
%pMDI	Borate content (%)	Mean Square	F Value	P>F
2.5%	1.5%	0.027075	1.19	0.3015
	3.0%	0.056033	1.16	0.3059
5.0%	1.5%	0.000675	0.02	0.8857
	3.0%	0.122008	6.2	0.052
	4.5%	0.003675	0.08	0.7802

Table 4.18 Leaching rate contrast among different borate loading levels

Borate compound	pMDI (%)	Contrast level	Mean Square	F Value	Pr > F
CB	2.5	1.5% VS. 3%	0.2268750	6.32	0.0307
	5	1.5 VS. 3%	0.876771	28.91	<.0001
		1.5 VS. 4.5%	4.118408	135.8	<.0001
		3 VS. 4.5%	1.194705	39.39	<.0001
ZB	2.5	1.5% VS. 3%	0.45240833	14.94	0.0031
	5	1.5 VS. 3%	0.313633	7.72	0.014
		1.5 VS. 4.5%	4.2483	104.63	<.0001
		3 VS. 4.5%	2.253333	55.5	<.0001

Table 4.19 Leaching rate contrast between the boards with 2.5% and 5% resin

Borate compound	Borate content (%)	Mean Square	F Value	Pr>F
CB	1.5%	0.197633	5.73	0.0377
	3.0%	0.603008	17.31	0.0019
ZB	1.5%	0.064533	3.33	0.018
	3.0%	0.0363	1.1	0.0167



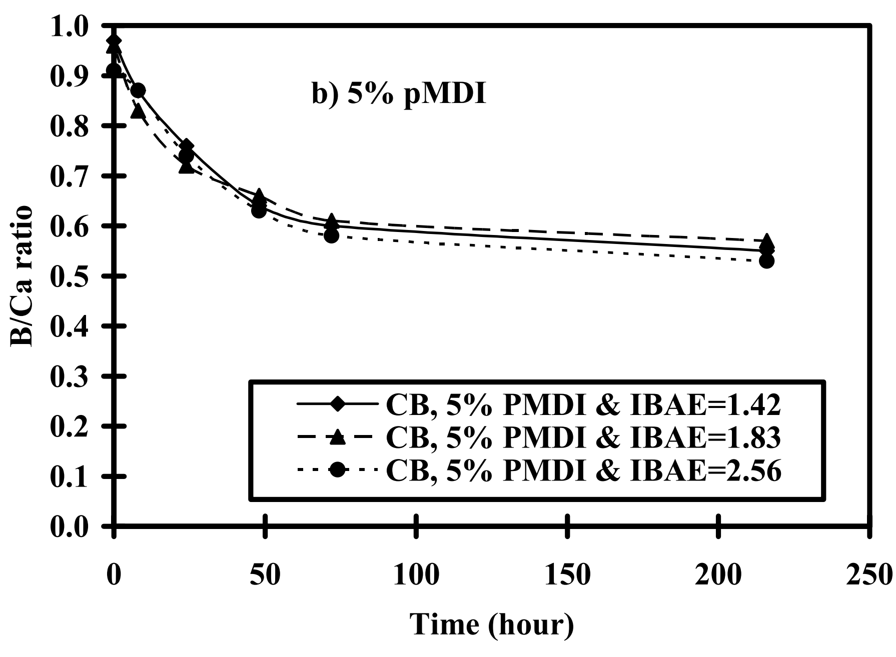
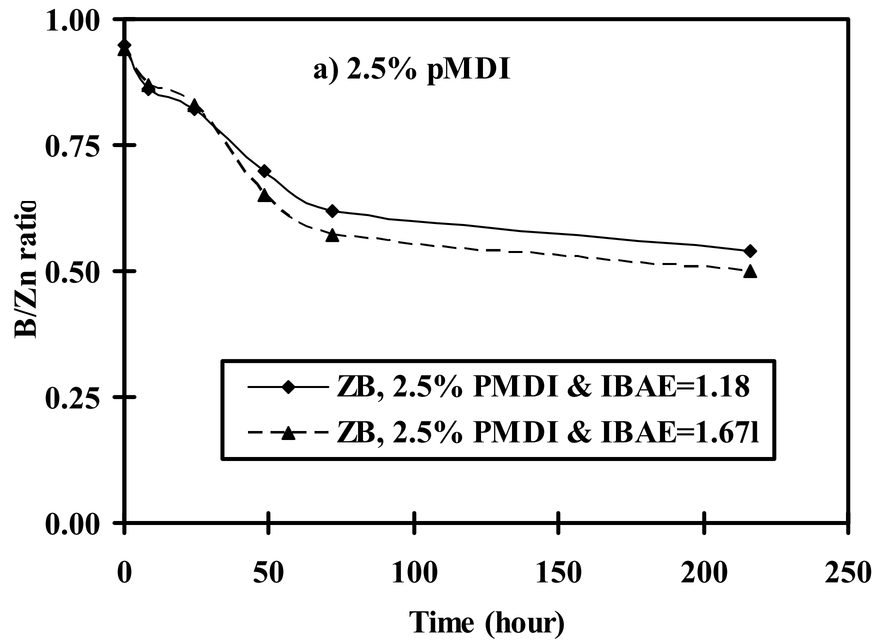


Figure 4.21 Relationship between assayed boron/calcium ratio and leaching time. a) 2.5% pMDI and b) 5% pMDI



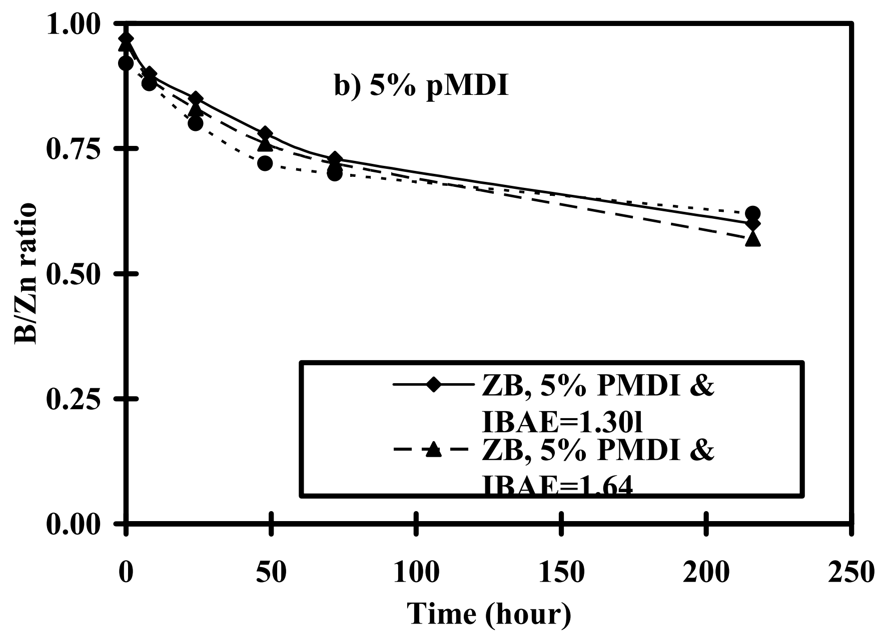


Figure 4.22 Relationship between assayed boron/zinc ratio and leaching time a) 2.5% pMDI and b) 5% pMDI

that of the boards with 0% and 1.5% CB. The maximum TS of the boards with 4.5% ZB was significantly higher than that of the boards with 0% ZB.

For the effect of borate type, the maximum TS of ZB boards were close to that of CB boards under the same resin loading level and similar BAE (Figures 4.24 and 4.25). according to the statistical analysis, there was no significant difference between the maximum TS of ZB and CB samples (Table 4.22). This indicates that ZB and CB had a similar effect on the maximum TS.

For the effect of resin content, the maximum TS of the boards bonded with 2.5% pMDI resin was slightly higher than the maximum TS of the boards bonded with 5% pMDI (Figure 4.24 and 4.25). From the result of statistical analysis, the maximum TS of the samples with 2.5% pMDI was not significantly different from the values of the samples with 5% pMDI (Table 4.23). This result indicates that the increase of resin content had small influence on the maximum TS.

4.5.1.2 Effect of Borate Content, Borate Type, and Resin Content on Residual TS

For the effect of borate content, the residual TS increased with the increase of BAE for both ZB and CB boards (Figure 4.24 and 4.25). However, statistical analysis shows that there was no significant difference between residual TS of the samples with different borate loading levels (Table 4.24). This result indicates that the addition of calcium borate and zinc borate did not significantly influence the residual TS.

For the effect of borate type, the residual TS of ZB boards was close to that of CB boards under the same resin loading level and similar BAE (Figures 4.24 and 4.25). Statistical analysis indicated that there was no significant difference between the residual TS of ZB and CB samples (Table 4.22).

Table 4.20 Thickness swelling and moisture content of boards bonded with pMDI resin under cyclic humidity exposure condition

Borate	%pMDI	BAE	Room Condition		RH=75		RH=93		RH=75		OD	
			TS	Δ MC	TS	Δ MC	TS	Δ MC	TS	Δ MC	TS	Δ MC
Type	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
CB	2.5	0.05	3.82	4.88	10.28	12.55	19.98	18.17	15.47	12.87	13.20	-1.61
	2.5	1.13	4.40	4.70	12.90	12.67	23.24	17.55	17.74	12.71	15.15	-1.41
	2.5	1.52	4.01	4.91	14.25	12.28	23.70	17.32	18.21	12.59	16.26	-1.51
	5.0	0.07	4.19	4.84	9.61	12.72	18.82	17.68	16.12	12.77	8.51	-1.55
	5.0	1.42	4.46	4.86	10.17	12.26	18.91	17.11	16.71	12.70	9.50	-1.34
	5.0	1.83	4.74	4.70	12.71	12.54	20.83	16.29	15.86	12.12	9.92	-1.44
	5.0	2.56	4.29	4.86	13.83	12.07	23.43	17.39	17.27	12.61	10.73	-1.35
ZB	2.5	0.07	4.17	5.00	9.64	12.86	19.20	17.99	17.11	12.89	12.30	-1.48
	2.5	1.18	4.97	5.15	11.43	12.30	21.37	17.84	17.41	12.84	13.95	-1.50
	2.5	1.67	3.49	4.87	13.11	12.63	22.82	17.72	17.72	12.62	14.63	-1.60
	5.0	0.10	5.21	5.08	8.10	12.18	18.17	18.67	15.73	12.69	7.61	-1.58
	5.0	1.49	4.19	4.93	9.95	11.84	19.48	17.51	16.26	12.57	8.48	-1.55
	5.0	1.64	4.64	4.95	11.61	12.58	20.07	17.40	16.96	12.58	9.03	-1.56
	5.0	2.59	4.09	4.93	13.95	12.49	21.22	17.45	18.66	12.62	9.44	-1.42

[a]. Values in parenthesis are standard deviations based on four points.

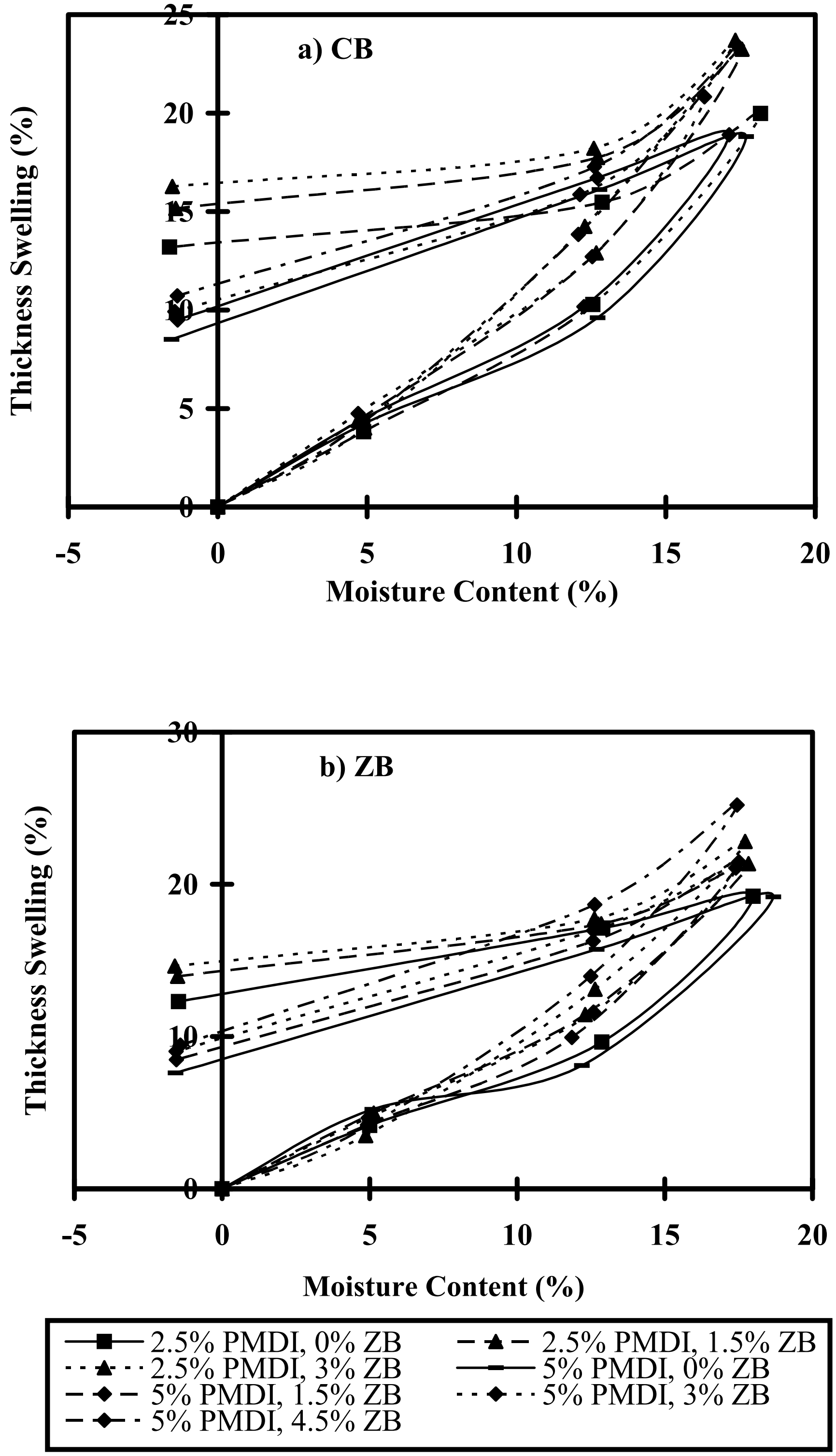


Figure 4.23 Thickness swelling and moisture content relationship. a) CB and b) ZB

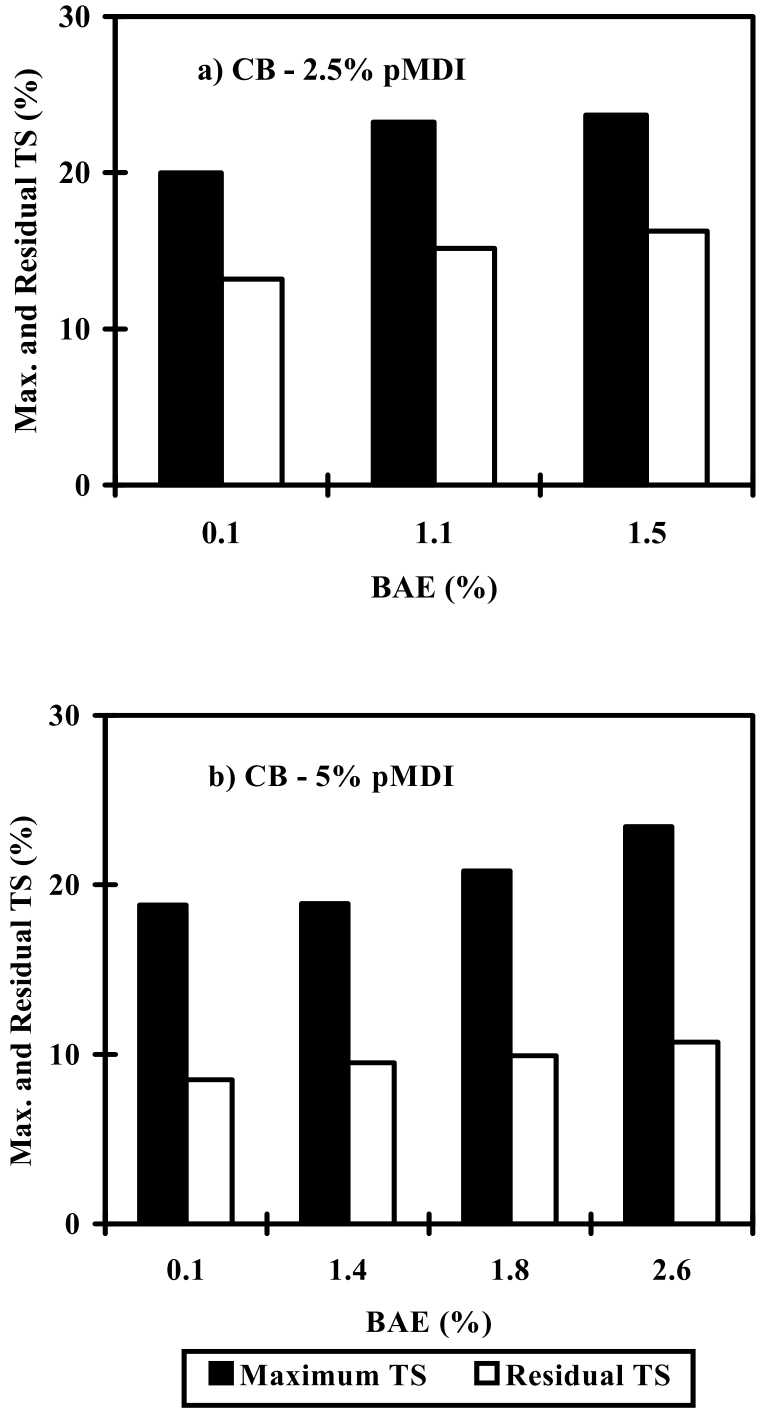


Figure 4.24 Maximum and residual TS in relation with BAE for CB-treated strandboard. a) CB - 2.5% pMDI and b) CB - 5% pMDI

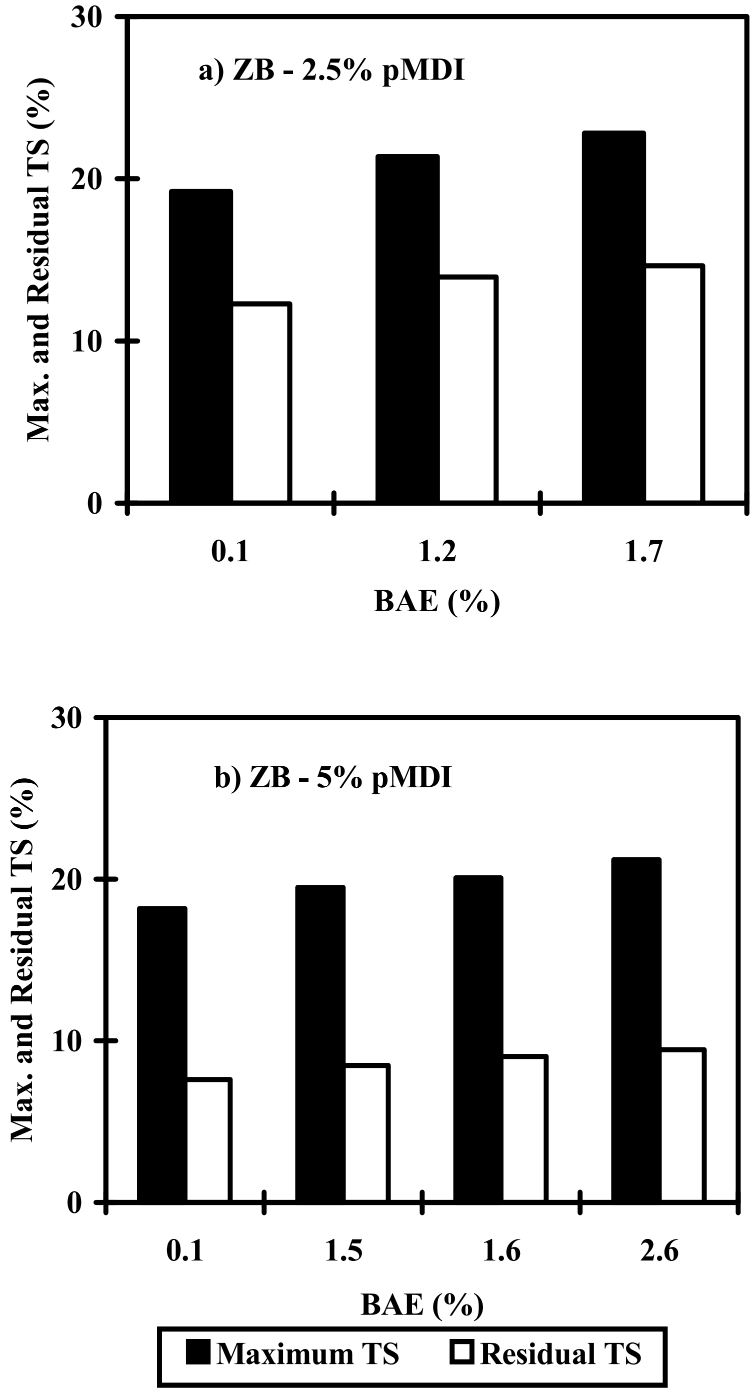


Figure 4.25 Maximum and residual TS in relation with BAE for ZB-treated strandboard. . a) ZB - 2.5% pMDI and b) ZB - 5% pMDI

Table 4.21 Maximum TS contrast at different borate loading levels

Borate Type	pMDI (%)	Contrast Level	Mean Square	F Value	Pr > F
CB	2.5	0 VS. 1.5%	21.28781	3.45	0.0775
		0 VS. 3%	27.63961	4.47	0.0465
		1.5% VS. 3%	0.41405	0.07	0.7982
	5.0	0 VS. 1.5%	0.02	0.023	0.9552
		0 VS. 3%	8.1608	1.32	0.2633
		0 VS. 4.5%	42.64261	6.9	0.0157
		1.5 VS. 3%	7.3728	1.19	0.287
		1.5 VS. 4.5%	40.81561	6.61	0.0178
		3 VS. 4.5%	13.49401	2.18	0.1542
ZB	2.5	0 VS. 1.5%	9.352813	1.03	0.3222
		0 VS. 3%	26.24501	2.88	0.1042
		1.5% VS. 3%	4.2632	0.47	0.5011
	5.0	0 VS. 1.5%	10.64911	1.17	0.2916
		0 VS. 3%	7.25805	0.8	0.3819
		0 VS. 4.5%	73.08405	8.03	0.0099
		1.5 VS. 3%	0.324013	0.04	0.8521
		1.5 VS. 4.5%	27.93781	3.07	0.0943
		3 VS. 4.5%	34.2792	3.77	0.0658

Table 4.22 Contrast of maximum TS, residual TS, and mechanical properties of ZB and CB boards under the same resin and borate compound level

Variable	pMDI (%)	Borate (%)	Mean Square	F Value	Pr> F
Maximum TS	2.5	1.5	7.050	1.33	0.2712
		3	1.522	0.29	0.6018
	5	1.5	13.158	1.15	0.2981
		3	0.117	0.01	0.9204
		4.5	6.372	0.56	0.4655
Residual TS	2.5	1.5	2.892	0.69	0.4315
		3	5.330	0.33	0.5823
	5	1.5	2.101	0.45	0.8632
		3	1.62	0.12	0.4205
		4.5	3.341	0.13	0.8604
MOE	2.5	1.5	0.01	0.04	0.8631
		3	1.65	4.3	0.1716
	5	1.5	0.07	0.1	0.7826
		3	0.22	0.51	0.5565
		4.5	0.01	0.02	0.9112
MOR	2.5	1.5	33.12	0.86	0.4532
		3	116.75	6.38	0.1325
	5	1.5	129.95	0.53	0.5421
		3	13.38	0.21	0.6932
		4.5	73.55	2.46	0.2613

Table 4.23 Contrast of maximum TS, residual TS, and mechanical property under 2.5% and 5% pMDI resin

Property	Borate Type	Mean Square	F Value	Pr>F
Maximum TS	CB	22.45951458	2.67	0.1144
	ZB	2.49780030	0.22	0.6425
Residual TS	CB	162.9097631	12.22	0.0016
	ZB	170.6865190	18.03	0.0002
MOE	CB	0.20563355	0.96	0.3475
	ZB	0.09370793	0.26	0.6175
MOR	CB	58.58704821	1.76	0.2094
	ZB	2.58267202	0.10	0.7532

Table 4.24 Contrast of residual TS at different borate loading levels

Borate Type	pMDI (%)	Contrast Level	Mean Square	F Value	Pr > F
CB	2.5	0 VS. 1.5%	7.663613	0.99	0.3467
		0 VS. 3%	18.81911	2.42	0.1542
		1.5% VS. 3%	2.4642	0.32	0.5872
	5.0	0 VS. 1.5%	1.9602	0.11	0.7487
		0 VS. 3%	3.990313	0.22	0.6484
		0 VS. 4.5%	9.834613	0.54	0.4769
		1.5 VS. 3%	0.357013	0.02	0.8911
		1.5 VS. 4.5%	3.013513	0.17	0.6916
		3 VS. 4.5%	1.29605	0.07	0.7943
ZB	2.5	0 VS. 1.5%	5.445	0.39	0.5466
		0 VS. 3%	10.8578	0.78	0.3994
		1.5% VS. 3%	0.9248	0.07	0.8021
	5.0	0 VS. 1.5%	1.505113	0.18	0.6817
		0 VS. 3%	4.00445	0.47	0.5061
		0 VS. 4.5%	6.679513	0.78	0.3934
		1.5 VS. 3%	0.599513	0.07	0.7953
		1.5 VS. 4.5%	1.8432	0.22	0.6502
		3 VS. 4.5%	0.340313	0.04	0.845

For the effect of resin content, the residual TS of the boards bonded with 2.5% pMDI resin was higher than the residual TS of the boards bonded with 5% pMDI (Figures 4.24 and 4.25). Statistical analysis shows that the effect of resin content on the residual TS was significant (Table 4.23). Thus, resin content is one of main factors that control the long term swelling properties of OSB.

4.5.2 Mechanical Properties

Measured MOE and MOR of cyclic humidity treated and control boards are summarized in Table 4.25. Figures 4.26 -- 4.29 show the plot of MOE and MOR in relation to measured BAE under two resin content levels (i.e., 2.5% and 5%). The mechanical properties (e.g., MOE and MOR) decreased with the increase of BAE (Figures 4.26 to 4.29). This result indicates that the addition of borate negatively

influenced the mechanical properties of the boards under cyclic humidity exposure. Statistical analysis of the data is presented in the following sections.

4.5.2.1 Effect of Borate Content, Borate Type, and Resin Content on Mechanical Properties

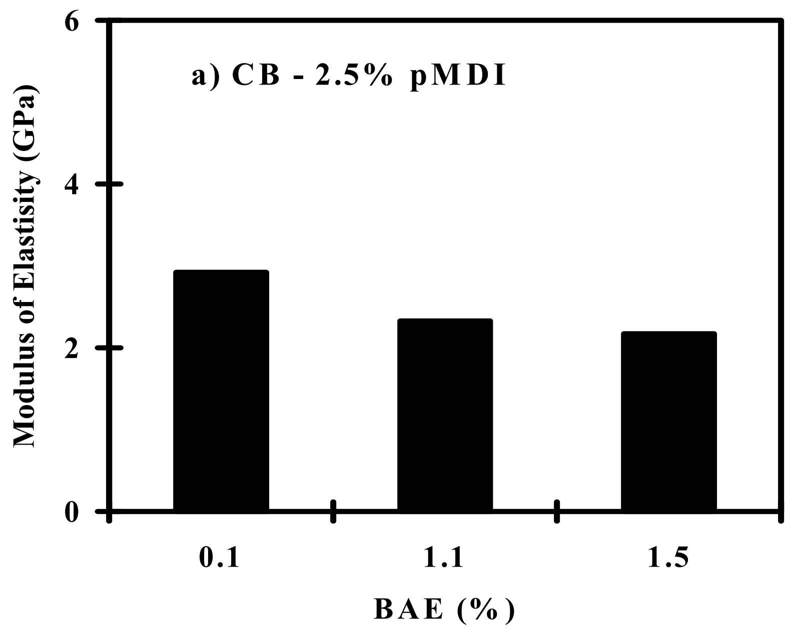
For the effect of borate content, bending MOE and MOR decreased with the increase of BAE (Figures 4.26 -- 4.29). At the 2.5% pMDI level, MOE and MOR of the samples with 0% ZB were significantly higher than those of the samples with 3% ZB. At the 5% pMDI level, MOE of the samples with 0% CB was significantly higher than those of the samples with 4.5% CB. MOE and MOR of the samples with 3% ZB was significantly higher than those of the samples with 4.5% ZB (Table 4.26 and 4.27). This result indicates that the higher borate loading level had a significantly negative influence on MOE and MOR of the boards under cyclic humidity exposure.

For the effect of borate type, bending MOE and MOR of ZB samples were close to those of CB samples under the same resin loading level and similar BAE (Figures 4.26 -- 4.29). Statistical analysis indicated that there was no significant difference between the mechanical properties of ZB and CB samples (Table 4.22). Thus, the influence of borate type on residual bending properties was minimum.

For the effect of resin content, both MOE and MOR of the samples bonded with 2.5% pMDI resin were similar to the values of the samples bonded with 5% pMDI resin (Figures 4.26 -- 4.29). Statistical analysis also showed that there was no significant effect of the resin content level on the residual bending properties (Table 4.23).

Table 4.25 Mechanical properties of cyclic humidity treated and control boards

			MOE			MOR		
Borate Type	pMDI (%)	BAE (%)	Treated (Gpa)	Control (Gpa)	Treated/ Control Ratio	Treated (Mpa)	Control (Mpa)	Treated/ Control Ratio
CB	2.5	0.05	2.92	4.92	0.59	22.93	33.34	0.69
	2.5	1.13	2.33	4.45	0.52	20.13	30.30	0.67
	2.5	1.52	2.17	3.81	0.57	16.12	26.92	0.68
	5.0	0.07	3.29	6.14	0.54	29.92	52.44	0.57
	5.0	1.42	2.77	5.25	0.53	24.62	49.23	0.50
	5.0	1.83	2.55	4.82	0.53	22.72	40.06	0.58
	5.0	2.56	2.26	4.34	0.52	18.18	34.30	0.53
ZB	2.5	0.08	3.22	5.40	0.60	30.62	41.75	0.74
	2.5	1.16	2.66	4.62	0.58	26.39	36.65	0.73
	2.5	1.67	2.05	3.71	0.55	20.36	29.17	0.70
	5.0	0.10	3.47	6.38	0.54	32.58	53.99	0.61
	5.0	1.30	3.02	5.79	0.52	26.48	49.64	0.53
	5.0	1.64	2.60	4.85	0.53	25.99	43.44	0.60
	5.0	2.59	2.15	4.28	0.50	22.11	40.40	0.55



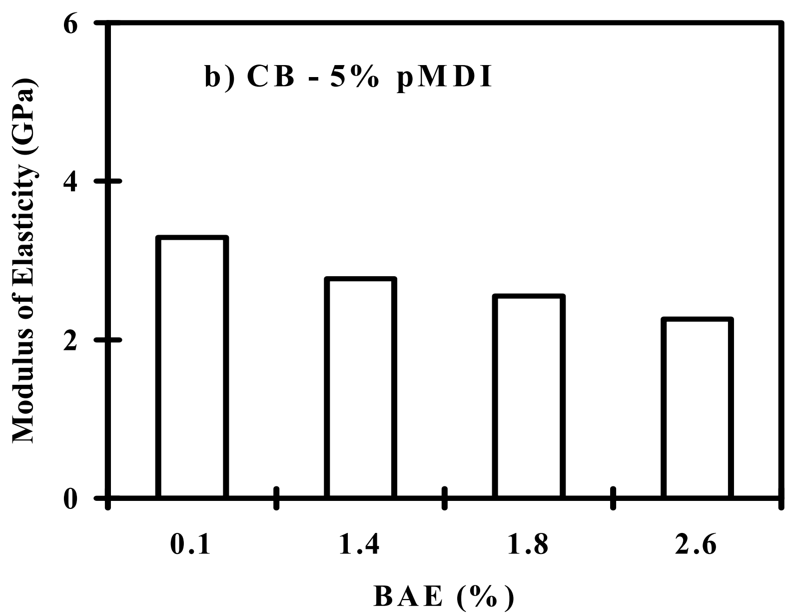


Figure 4.26 MOE of cyclic humidity treated CB-board in relation with BAE. a) CB – 2.5% pMDI and b) CB – 5% pMDI

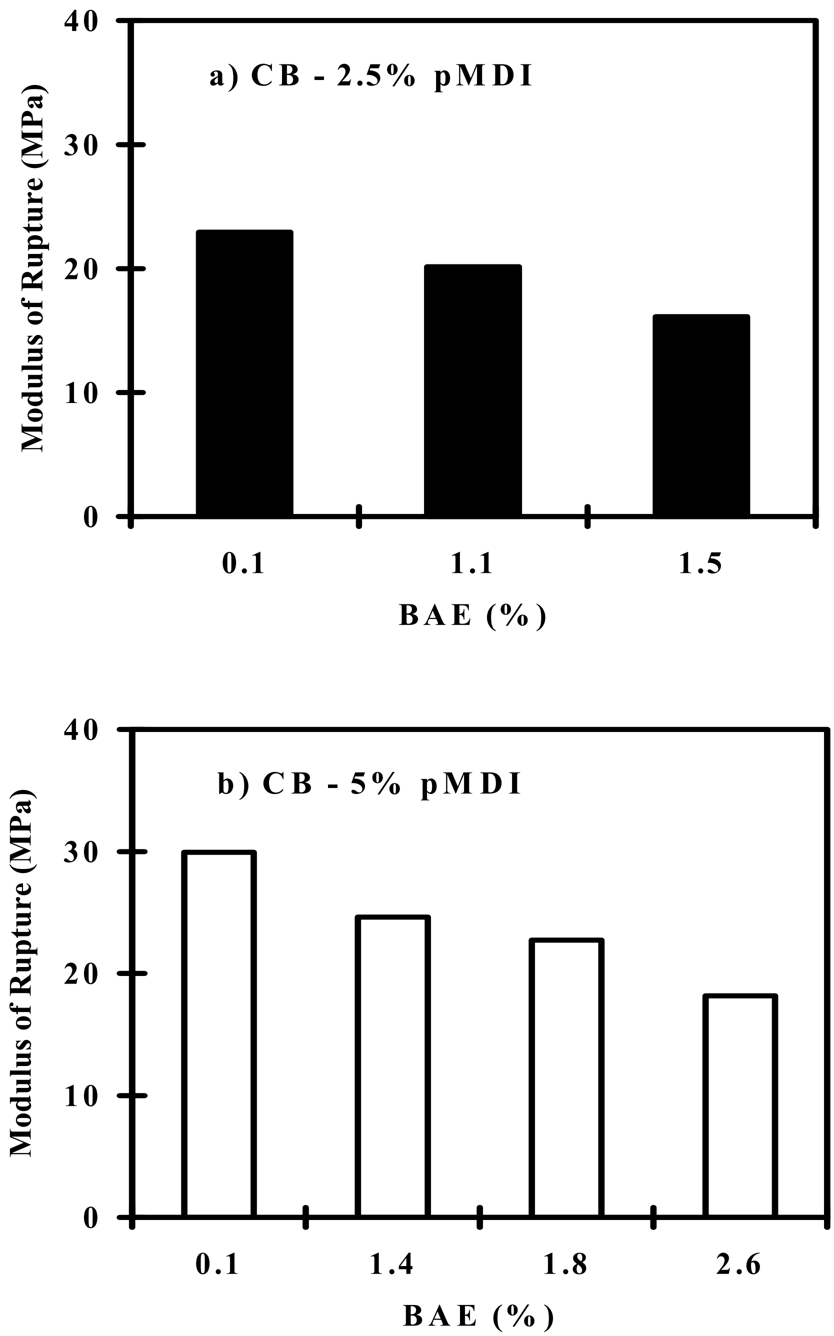


Figure 4.27 MOR of cyclic humidity treated CB-board in relation with BAE a) CB – 2.5% pMDI and b) CB – 5% pMDI

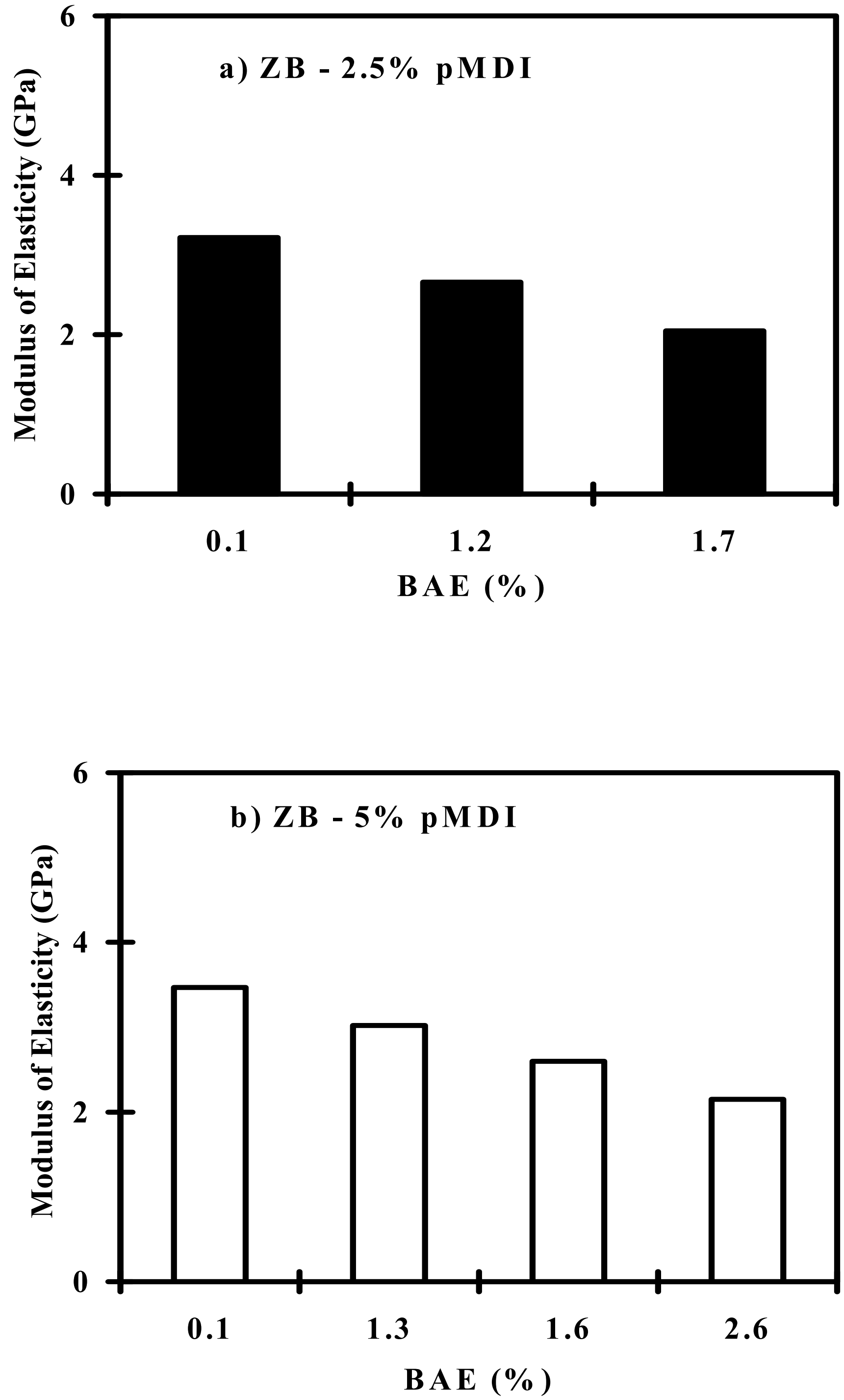
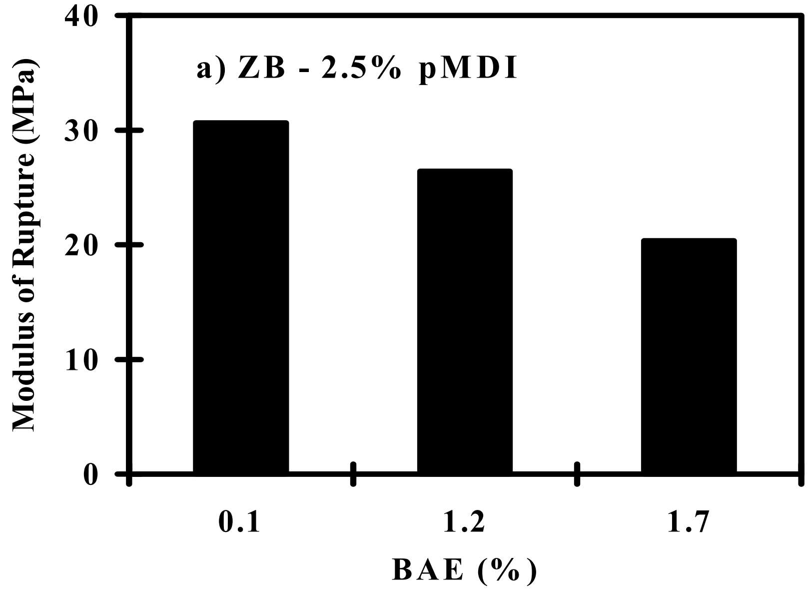


Figure 4.28 MOE of cyclic humidity treated ZB-board in relation with BAE a) ZB – 2.5% pMDI and b) ZB – 5% pMDI



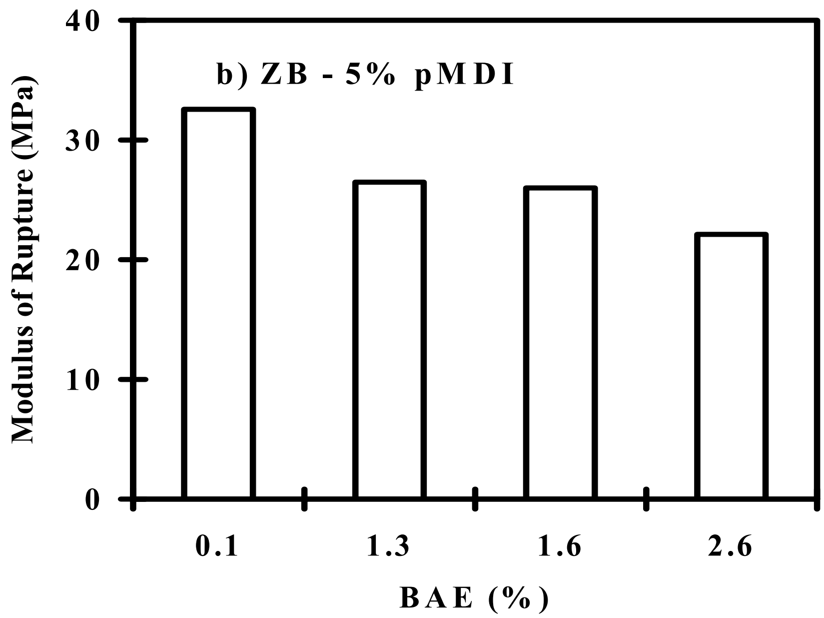


Figure 4.29 MOR of cyclic humidity treated ZB-board in relation with BAE a) ZB – 2.5% pMDI and b) ZB – 5% pMDI

Table 4.26 MOE contrast at different borate loading levels

Borate Type	pMDI (%)	Contrast Level	Mean Square	F Value	Pr > F
CB	2.5	0 VS. 1.5%	0.3449	2.98	0.1278
		0 VS. 3%	0.556883	4.82	0.0643
		1.5% VS. 3%	0.02527	0.22	0.6544
	5	0 VS. 1.5%	0.278147	2.41	0.1649
		0 VS. 3%	0.558012	4.83	0.0641
		0 VS. 4.5%	1.077717	9.32	0.0185
		1.5 VS. 3%	0.048227	0.42	0.539
		1.5 VS. 4.5%	0.26085	2.26	0.1768
		3 VS. 4.5%	0.084756	0.73	0.4203
ZB	2.5	0 VS. 1.5%	0.309609	2.15	0.1864
		0 VS. 3%	1.358782	9.42	0.0181
		1.5% VS. 3%	0.371177	2.57	0.1528
	5	0 VS. 1.5%	0.197425	1.37	0.2804
		0 VS. 3%	0.759278	5.26	0.0555
		0 VS. 4.5%	1.727683	11.97	0.0105
		1.5 VS. 3%	0.182363	1.26	0.298
		1.5 VS. 4.5%	0.757054	5.25	0.0558
		3 VS. 4.5%	0.196292	1.36	0.2817

Table 4.27 MOR contrast at different borate loading levels

Borate Type	pMDI (%)	Contrast Level	Mean Square	F Value	Pr > F
CB	2.5	0 VS. 1.5%	7.7841	0.26	0.6268
		0 VS. 3%	46.3761	1.54	0.2545
		1.5% VS. 3%	16.1604	0.54	0.4876
	5.0	0 VS. 1.5%	28.1961	0.94	0.3654
		0 VS. 3%	51.91203	1.72	0.2306
		0 VS. 4.5%	138.0625	4.59	0.0695
		1.5 VS. 3%	3.591025	0.12	0.74
		1.5 VS. 4.5%	41.4736	1.38	0.2789
		3 VS. 4.5%	20.65703	0.69	0.4348
ZB	2.5	0 VS. 1.5%	18.02003	1.58	0.2493
		0 VS. 3%	106.2961	9.31	0.0185
		1.5% VS. 3%	36.78423	3.22	0.1157
	5.0	0 VS. 1.5%	37.14903	3.25	0.1142
		0 VS. 3%	43.2964	3.79	0.0925
		0 VS. 4.5%	109.4116	9.58	0.0174
		1.5 VS. 3%	0.235225	0.02	0.8899
		1.5 VS. 4.5%	19.05323	1.67	0.2374
		3 VS. 4.5%	15.0544	1.32	0.2885

Table 4.28 MOE and MOR contrast among treated and control boards

	Borate type	%pMDI	Contrast SS	F Value	Pr>F
MOE	CB	2.5	5.5296	12.32	0.0022
		5.0	11.7128	26.09	<.0001
	ZB	2.5	5.60666667	12.49	0.0021
		5.0	12.65045	28.18	<.0001
MOR	CB	2.5	164.1174	5.26	0.0329
		5.0	811.8435125	26	<.0001
	ZB	2.5	152.0066667	4.87	0.0392
		5.0	806.2120125	25.82	<.0001

4.5.2.2 Contrast of Mechanical Properties between Cyclic Humidity Treated Boards and Controls

Bending MOE and MOR from the cyclic humidity treated and control samples decreased with the increase of BAE (Figures 4.30 and 4.31). It is clearly shown that there are two groups of curves (each group has two curves for ZB and CB) in Figure 4.30 and Figure 4.31. The upper group curves indicate the control samples and the lower group curves show the cyclic humidity treated samples. At a given BAE level, MOE and MOR of the control samples were significantly higher than those of cyclic humidity treated samples. This was caused by the permanent residual TS and the bond failure developed in the panels during cyclic humidity treatments. As shown in Table 4.28, all P values of the contrast between cyclic humidity treated boards and control samples were lower than 0.05. This indicates that MOE and MOR of treated samples were significantly lower than that of control samples. During bending test, some of treated samples broke along the surface of the flakes. This indicates significant de-bonding between wood flakes during the cyclic humidity treatment.

Figures 4.32 and 4.33 show MOE ratio (i.e., MOE of cyclic humidity treated samples divided by MOE of the control samples) and MOR ratio (i.e., MOR of cyclic humidity treated samples divided by MOR of the control samples) as a function of BAE, respectively. Although the general retention rate trend decreased with the increase of BAE, the effect was generally not significant. Thus, the addition of borate did not have a significant influence on the strength retention of the boards under long term cyclic humidity exposure condition. The effect of BAE on the strength retention properties was largely masked the effect of TS developed during the humidity treatments.

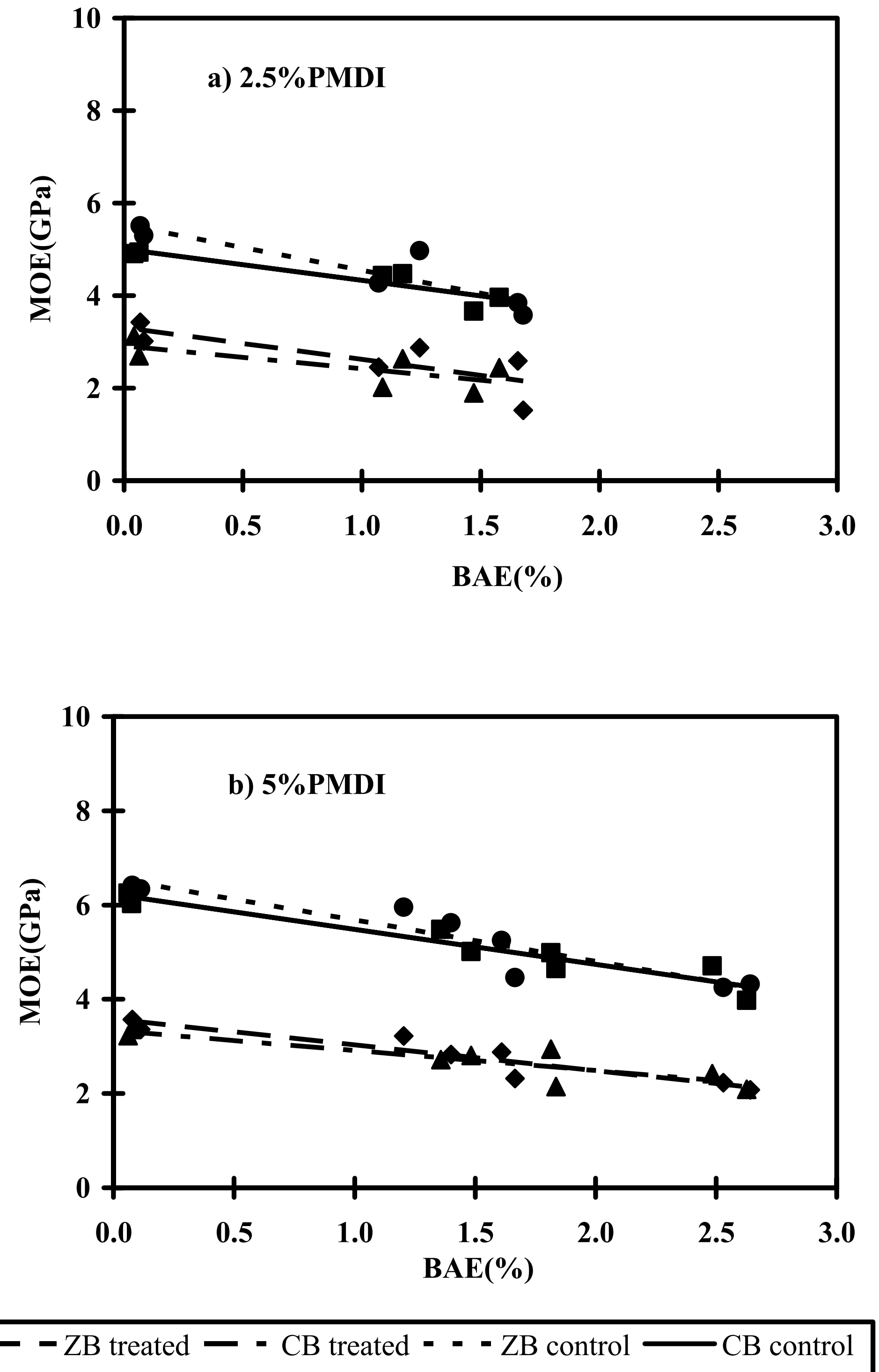


Figure 4.30 MOE contrast among treated and control boards a) 2.5% pMDI and b) 5% pMDI

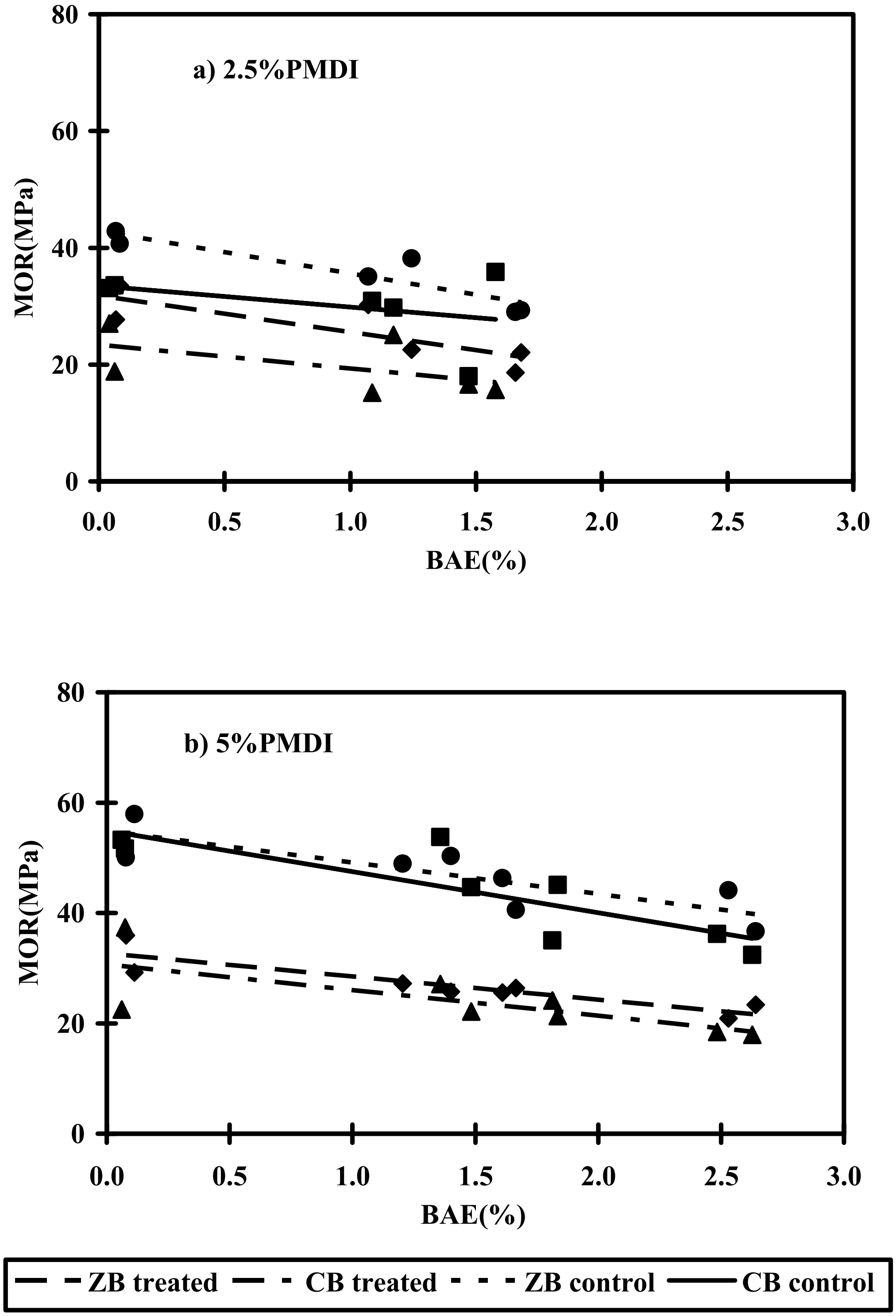


Figure 4.31 MOR contrast among treated and control boards a) 2.5% pMDI and b) 5% pMDI

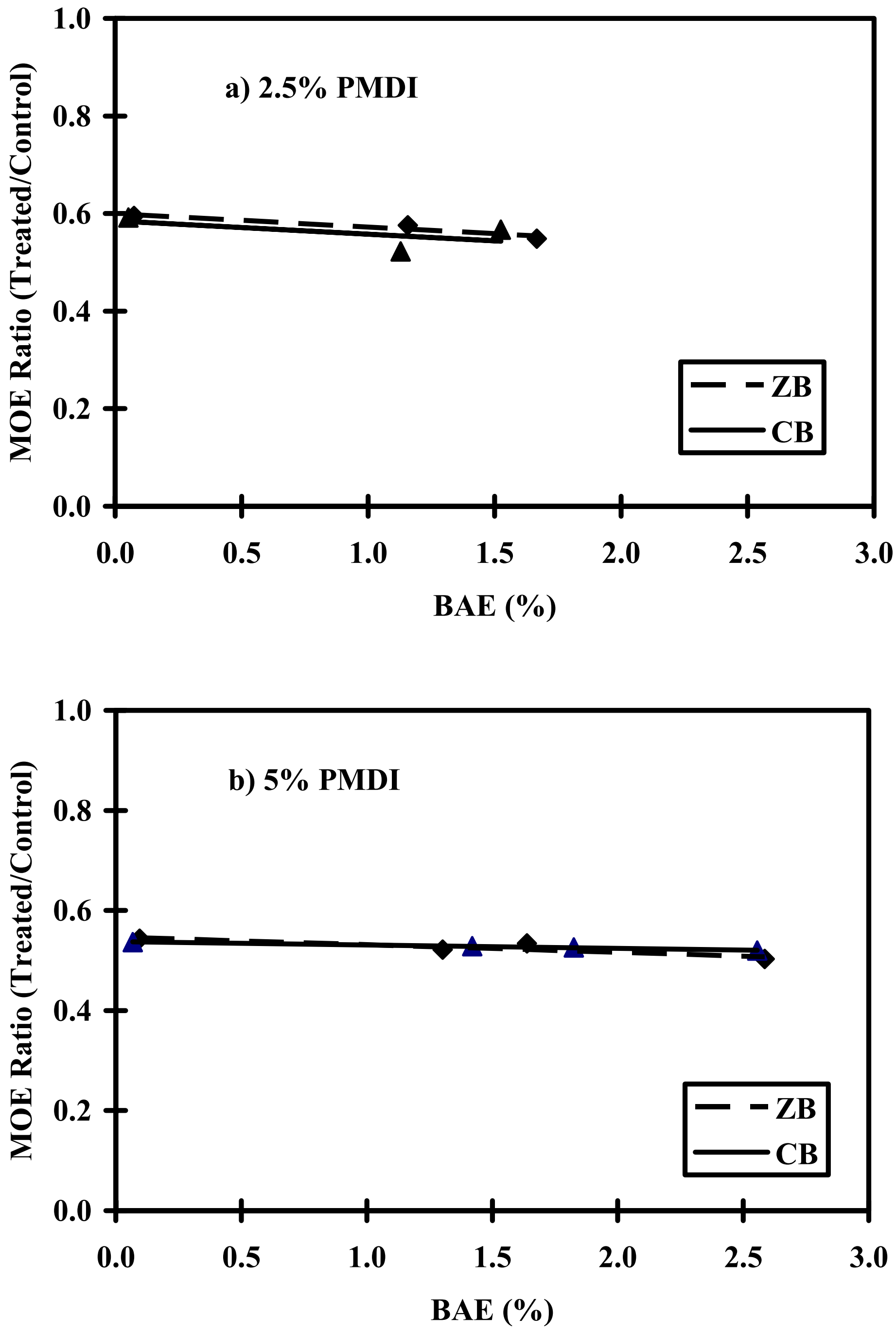


Figure 4.32 MOE retention rates as a function of BAE a) 2.5% pMDI and b) 5% pMDI

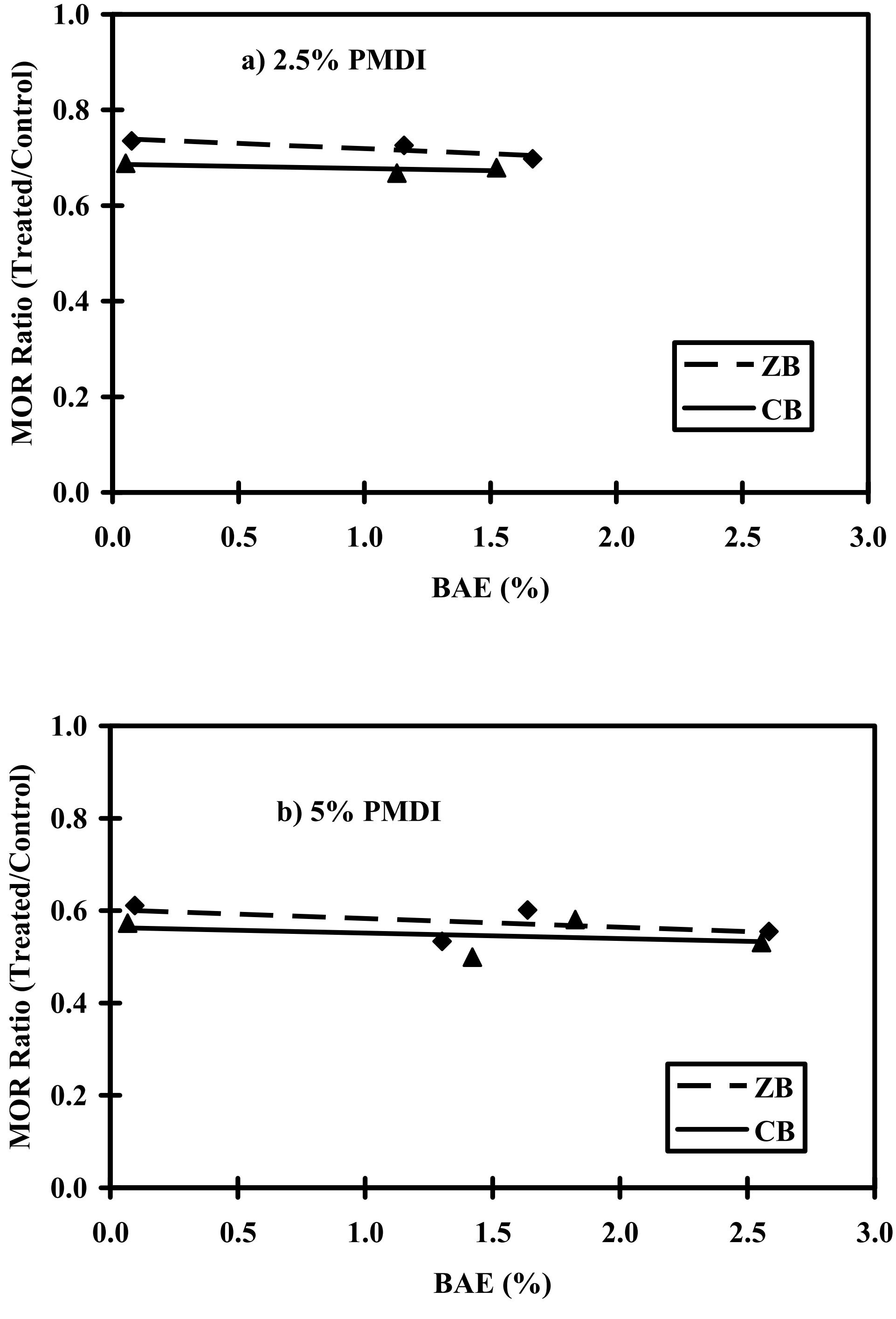


Figure 4.33 MOR retention rates as a function of BAE a) 2.5% pMDI and b) 5% pMDI

CHAPTER 5

CONCLUSIONS

This study was done to examine the properties of borate-modified strandboard bonded with pMDI resin. The properties investigated include mechanical, physical properties, leaching, and long term thickness swelling and strength retention properties under cyclic humidity exposure condition. Based on the results from the study, the following conclusions can be made.

1. The addition of borate (both CB and ZB) negatively influenced the mechanical properties (i.e., MOE, MOR, and IB) of the panels. The mechanical properties decreased with the increase of BAE. Some of CB and ZB existed in a powder state on the flake surface, thereby reducing the bonding efficiency of the adhesive and contributing to the lower property values. The influence of ZB and CB on the mechanical properties was similar. The increase of resin content can significantly improve the mechanical properties of the boards.
2. The addition of borates (both CB and ZB) negatively influenced the physical properties (i.e., TS, LE, and WA) of the panels. The physical properties decreased with the increase of BAE. The influence of ZB and CB on the physical properties was similar. There was no significant difference between the physical properties of ZB and CB panels, including TS, LE, and WA. The increase of resin content increased the physical properties of the boards, especially for TS value. Borate and resin contents had much more influence on TS than LE. The reason is that the addition of borate and resin mainly influence the bond efficient among the flakes

and TS is mainly influenced by this bond quality. In contrast, LE is mainly influenced by the property of the wood flakes.

3. A portion of boron in the treated OSB leached out under a water-soaked condition. Boron leaching from ZB and CB treated OSB occurred upon the initial water exposure. There was a higher initial leaching rate and the rate decreased with the lapse of leaching time. Panels with higher initial BAE level had higher leaching rate. The leaching rates of ZB and CB were similar. The higher resin content helped reduce borate leaching rate. The ratio between boron and zinc (or calcium) decreased with the lapse of leaching time. This indicates that boron element leached out at a higher speed compared to calcium or zinc. In contrast, the boards bonded with pMDI resin can hold borate much better and longer than the boards bonded with PF resin.
4. Under cyclic humidity exposure condition, TS hysteresis developed in all panels. The addition of borate negatively influenced the maximum TS, residual TS, and mechanical properties. The effects of ZB and CB on the maximum TS, residual TS, and mechanical properties were similar. The increase of resin content significantly reduced residual TS. However, the increase of resin content had no significant influence on the maximum TS and bending MOE and MOR.
5. Strength retention properties measured with MOE and MOR ratios varied little with the increase of samples` BAE. The effect of borate treatment was largely masked by the large effect of TS on the strength properties.

6. Overall, the use of pMDI resin as a binder for borate-treated strandboard helped reduce the influence of borate type, content level, and boron leaching compared with PF resin, leading to more stable panels for possible exterior application.

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