

THE INTERNATIONAL RESEARCH GROUP ON WOOD PROTECTION

Section 4

Processes & Properties

Biocide Treatments for Wood Composites—A Review

by

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**Paper prepared for the 37th Annual Meeting
Tromsø, Norway**

18-22 June 2006

**IRG Secretariat
S-100 44 Stockholm
SWEDEN**

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Abstract

This paper reviews the biocidal treatment of wood composites. Included are in-process and post-process treatments. Various biocides are covered as are methods of application. Novel treatments and technologies are also presented.

Keywords: Biocide, OSB, MDF, LVL, WPC, glue-lam, plywood, composites, treatment

Introduction

Wood-based composite products are commonly substituted for solid wood in today's building structures. Structural and non-structural engineered wood composites based on oriented strandboard (OSB), plywood, medium density fiberboard (MDF), laminated veneer lumber (LVL), thermoplastic/wood fiber blends, etc. are now used in both interior and exterior applications (Laks 2002). Their use, however, is often limited due to high sensitivity to moisture and decay (Baileys *et al.* 2003).

The production of wood composites has increased dramatically over the past three decades due to a number of factors. The changing wood supply, the development of new composite technologies, and the widespread acceptance by architects and builders have each contributed to increased wood composite production (Gardner *et al.* 2003). With these changing uses has come increased exposure to wetting and consequently to decay fungi and insects (Barnes & Amburgey 1993). The emergence of new technologies to produce an increasing array of new wood composite products has forced the industry to follow-up with varied protection processes and/or treatments to protect these new wood-based products from biodeterioration.

Wood-based composite products offer complexities and opportunities not found in the solid wood preserving industry. Because there are many types of wood composite products and manufacturing processes, there are a number of ways to apply preservative treatments to these materials (Gardner *et al.* 2003). Biocidal protection may be incorporated into solid wood by pressure/vacuum treatment processes with liquid-based systems, by surface coatings

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(dip, spray, or brush), or by direct placement in the product (such as borate rods). These strategies are all post-manufacture treatments (PMT), and the main concern with each of these treatments is chemical gradients within the product. The advantage of wood-based composites is that they offer in-process treatment (IPT) options (incorporation during manufacture), as well as PMT (Manning 2002). Several common systems for preservation of composites include: 1) use of pretreated wood; 2) in-process preservative treatments favored for composites made from flakes, particles, and fibers where the preservative treatment is incorporated during the manufacturing process; 3) post-process preservative treatments (PMT); and 4) use of recycled treated wood elements in manufacturing or the use of wood species with a high natural resistance against biodegradation (Gardner *et al.* 2003).

The inherent nature of wood-based composites allows them to be treated with IPT, which offers several distinct advantages not found with solid wood products (Manning 2002). Laks (1999) noted several advantages to preservative incorporation during the manufacturing process:

- Homogeneous distribution of the preservative is possible with an efficient blending system. If desired, selective loading can also be achieved—for example, the preservative may be incorporated throughout the thickness of an OSB panel or alternatively, only loaded into the surface layers;
- Overall manufacturing costs should be less expensive compared to conventional pressure treatment with the elimination of a second processing step;
- Composite manufacturers maintain quality control of the final product—the material does not have to be sent off-site to a treating plant. Engineered Wood Product (EWP) producers can easily monitor the physical properties of the treated material;
- Ability to add the preservative along with the adhesive and water repellent during the blending step with minor modifications (typically) to the EWP manufacturing process; and
- Ability to machine and remanufacture the end-product without any loss of decay resistance (Laks & Manning 1995).

Challenges and disadvantages stem from complex relationships between component interactions. Gardner and others (2003) noted several disadvantages to IPT including:

- Chemical interaction and inhibition with adhesive and adhesion;
- Effects on physical or mechanical properties of composite;
- Emissions and high treatment chemical losses during hot pressing of treated furnish; and
- Treated wood must be machined and associated concerns with treated waste shavings/sawdust must be addressed.

Most current technology centers on treatments using IPT technologies.

The methods of preservative incorporation into flake- and wafer- type wood composites during the manufacturing process were noted by Laks and Palardy (1993). These methods also apply to fiber and particle composites. The methods are:

- Treatment of the wood furnishes (flake, fiber, or particle) before or after drying using an additional sprayhead or blender system in the production process;
- Mixing the preservative chemical with the adhesive or wax which is subsequently applied to the wood furnish in the blender;
- Spraying the wood furnish with a preservative solution or emulsion, or mixing the powdered chemical with the furnish in the blender; and
- Metering a powdered preservative onto the dried wood furnish immediately before the blender. The powder and furnish is then mixed together in the blender.

With the exception of glu-lam and plywood, the conventional pressure treatment of waterborne preservatives into solid wood cannot be used on wood composite products without detrimental effects (Manning 2002). Moderate to severe thickness swell and other dimensional stability properties impair composite products treated by waterborne preservatives. Some research has been performed using solvent-borne preservatives in composites, but these technologies are not economically feasible for commercial use or widely available (Manning 2002). According to Laks (1999) and Manning (2002), preservative systems for IPTs of wood composites should possess the following qualities: heat stability during manufacture, especially during pressing; no negative interaction with adhesive bond formation; very limited leachability; no adverse affects on strength properties; paintability; low relative cost as a component of the manufacturing process; minimal environmental impact; and low volatility.

Chemical Preservation

Many types of chemical compounds have been applied successfully to wood composites. Currently, the most common preservative used on wood composites in North America is zinc borate, applied either as a powder or an emulsion (Laks 1999). Nieh *et al.* (2004) reported on a commercial OSB treated with a copper-based system. Some common wood composites and their standard preservatives can be seen in Table 1.

These types of chemical preservation systems eliminate a source of nourishment for biological attack (Richardson 1993). Major problems with preservative chemicals used to treat composite products include leachability and toxicity. Sodium borate-treated composite products may be more susceptible to leaching and are not usually rated for ground exposure. Borates used as a preservative for wood composite panels bonded with phenol-formaldehyde

(PF) resin often reduce resin gel time, not allowing the resin to flow and cure sufficiently. This problem is related to the functional methlylol groups on resin molecules and their interaction with borate ions (Sean *et al.* 1999). This interaction is detrimental to bond performance and ultimately reduces physical properties of the panel. Additionally, water repellency and dimensional stability cannot be overlooked. Many studies choose to focus on these aspects. In any case, a preservative-treated wood composite product must provide adequate protection without sacrificing mechanical or physical properties.

Table 1. Wood Composites and Preservative Treatments (Gardner, *et al.* 2003, and Smith and Wu 2005)

<i>Composite Type</i>	<i>Treatment Chemical</i>
Glu-lam Timbers	Ammoniacal Copper Quat (ACQ), Chromated Copper Arsenate (CCA), Creosote, Pentachlorophenol (PCP), 3-iodo-2-propynyl butyl carbamate (IPBC) & chlorpyrifos (CPF), Copper azole (CA-B), copper naphthenate (CuN), copper-8 quinolinolate (Cu8), IPBC-CPF
Plywood	Ammoniacal Copper Arsenate (ACA), Ammoniacal Copper Zinc Arsenate (ACZA), ACQ, CCA, CA-B, propiconazole (PPZ), tebuconazole (TEB), permethrin, deltamethrin, bifenthrin, imidacloprid, arsenic trioxide, glycol borates, DOT
Laminated Veneer Lumber (LVL)	CCA, PPZ, TEB, permethrin, deltamethrin, bifenthrin, imidacloprid, arsenic trioxide, glycol borates, penta, copper-8
Parallel Strand Lumber	CCA, creosote, penta, copper naphthenate, copper-8, copper azole, ACQ, PPZ, TEB, permethrin, deltamethrin, bifenthrin, imidacloprid
Oriented Strandboard (OSB)	Zinc borate, copper complex, copper, cypermethrin or permethrin, IPBC plus chlorpyrifos or permethrin
Laminated Strand Lumber	Zinc borate, IPBC plus chlorpyrifos or permethrin
Particleboard	Fire retardant, permethrin
Fiberboard (Medium density fiberboard)	Fire retardant, zinc borate, boric acid
Hardboard	Fire retardant
I-Joists	IPBC-CPF in light organic solvent
Wood plastic composites	Zinc borate

Treatment by Composite Type

Waferboard/OSB/strandboard

The inception of waferboard (strandboard) can be traced back to the 1950's (Clark 1955), but did not evolve into OSB until several decades later (Gilbert 2003). OSB was first

produced commercially in the U.S. in the late 1970's, and saw a dramatic increase in production and acceptability as waferboard was phased out. The trend continues today, and OSB production now exceeds that of plywood. OSB, like many other wood composite products, cannot successfully be treated with waterborne preservative systems because of thickness swelling problems, but other non-waterborne treatments have been successfully used (Shupe & Dunn 2000).

Hall *et al.* (1982) attempted to use CCA, pentachlorophenol, and creosote in some of the earliest studies done on waferboard. Other early preservative tests were presented at the 1982 Workshop on the Durability of Structural Panels (Hall *et al.* 1984). ACA, CCA, chloronaphthalene and tributyltin oxide, fluorine and copper compounds, 2-(thiocyanomethylthio) benzothiazole (TCMTB), {CIS-N-[(1,1,2,2-tetrachloroethyl) thio]-4-cyclohexene-1, 2-dicarboximide}, sequential treatment with formaldehyde and sulfur dioxide gases, copper-8-quinolinolate (Cu8), and IPBC treatments were examined on aspen waferboard models. In other early research, ACA outperformed CCA in a study examining the influence of waterborne preservatives on aspen waferboard properties (Boggio & Gertjejansen 1982). Later, Gertjejansen and co-workers studied aspen waferboard treated with ACA, copper-fluorine wax, IPBC, or Cu8. After five years exposure, white-rot fungi were considered major decay agents (Gertjejansen *et al.* 1989).

After an intense period of research during the early 1980's, much work was done on the incorporation of borate into OSB and waferboard furnish during blending (Gardner *et al.* 2003). Over the last two decades, several different formulations have been used in an attempt to incorporate borates into OSB/waferboard, including: zinc borate (ZB), boric acid, boric salts, calcium borate, silicone borate, disodium octaborate tetrahydrate (DOT) and trimethyl borate.

The effect of the addition of anhydrous borax, ZB, or DOT to PF bonded wood waferboard was examined by Knudson & Gnatowski (1989) in a patent filed in 1988. Borates were applied before consolidation in the amount of 0.2%-0.25% based on the weight of the wafers. The DOT-treated panels showed insufficient strength properties and the addition of a dispersing agent, Claytone, in ZB and anhydrous borax-treated panels showed unsatisfactory internal bond (IB) results. IBs of anhydrous borax-treated panels, however, were significantly higher than IB tests of untreated controls. Mill trials produced the same result.

Myles (1994) investigated the efficacy of DOT in aspen waferboard against the eastern subterranean termite, *Reticulitermes flavipes*. Resole and novolac phenolic resins were used and the biocide was added as a dry powder to resin. The termites preferred to feed

on untreated samples and total mortality of termites was reached within one month. However, the study made no mention of physical or mechanical properties of the produced boards.

Sean and co-workers (1999) produced PF bonded OSB panels treated with ZB. The panels contained polyethylene glycol (PEG) to improve resin flow during hot-pressing. The biocide and PEG were added during the blending process. After two years exposure, panels treated with 1% ZB were in good condition while untreated panels were heavily attacked and field tests in Hawaii showed good protection against Formosan termites (Sean *et al.* 1999). Sean noted enhanced fluidity with added PEG, but also noticed curing problems with excessive amounts of PEG. Of particular importance, Sean noted that “the adverse effects of borate compounds on the mechanical properties of the treated panels can be reduced by simply adding an organic flowing agent containing hydroxyl groups into the panel composition.”

Laks and Manning (1995) studied two borates for use on aspen waferboard. DOT and ZB were added before addition of polymeric diphenylmethane diisocyanate (pMDI) adhesive and wax. Panels made with water-soluble borates were successfully made with pMDI resin. The ZB was found to have better efficacy and leach resistance. ZB fungus cellar stakes performed much better than the DOT stakes. Performance of ZB to Formosan termites was superior to the DOT samples at the same boric acid equivalent (BAE) levels.

The addition of calcium borate to southern yellow pine flakeboard was investigated by Jones (2002). Calcium borate (CB) provided some protection against decay fungi and termites, but higher levels than those tested were needed to provide adequate protection. Physical and mechanical properties were negatively impacted with the addition of calcium borate, and higher loadings resulted in lower property values (Jones 2002). This study found calcium borate unacceptable for use as a preservative in flakeboard. Lee (2003) also found properties to be negatively affected with CB addition and attributed this to the larger particle size of the CB powder.

Mobility issues relating to borates are well known and have limited their use in some environments. Laks and Manning (1997) studied the mobility of two borates in aspen waferboards. ZB and DOT-containing samples were tested for depletion. The zinc component was depleted at a lower rate than the boron, while depletion for DOT-treated samples was faster. The investigators noted that the greater the leaching hazard, more boron was depleted, and boron from low depletion rate areas (center) may diffuse into higher diffusion rate areas (edges). In another study, powdered tebuconazole out-performed powdered

chlorothalonil, probably because of chlorothalonil's extremely low solubility (Laks & Palardy 1992).

The compatibility of adhesives when bonding borate-containing OSB/flakeboard has been investigated by several researchers (Hsu & Pfaff 1993, Laks *et al.* 1988). Hsu and Pfaff (1993) made panels with either two-stage novolac type PF resins or one-stage resole-type resins in a conventional hot press. The curing time and flow were reduced for both resins with the addition of boric acid or DOT. The one-stage resole-type PF resin panels displayed a drastic reduction in properties while the two-stage novolac-type resin panels were satisfactory. Interestingly, panels made with a self-sealing steam-injection press showed good internal bonds with either type of resin (Hsu & Pfaff 1993). Lee *et al.* (2004) has shown borate-modified strandboard to provide protection against *Coptotermes*.

Panels, either treated with CCA or produced from furnish incorporating recycled CCA-treated wood wastes, have been manufactured by several researchers (Li *et al.* 2004a, 2004b, Zyskowski and Kamdem 1999, Lebow and Gjovik 2000, Vick *et al.* 1996, Jeihooni 1994, and Boggio and Gertjensan 1982). At least three of these studies used CCA treated lumber in recycling methods to produce treated panels (Vick *et al.* 1996, Zyskowski and Kamdem 1999, Li *et al.* 2004a, 2004b). CCA has long been known to interfere with many cold and hot setting adhesives and numerous reports have addressed possible causes and solutions. Vick and co-workers (1996) found that an addition of a resorcinol type liquid primer just before resin addition and blending improved mechanical and physical properties. Boggio and Gertjensan (1982) obtained acceptable bending properties with CCA treated flakeboard, but failed to attain minimum internal bond requirements. Li and co-workers found the optimum ratio of treated flakes to untreated flakes was 50:50. These panels had enough CCA treated wood component to prevent substantial weight losses in decay tests, while not severely reducing mechanical or physical properties (Li *et al.* 2004b).

Researchers at the University of Wales have investigated treatments for a more dimensionally stable, and decay resistant OSB (Goroyias and Hale 2000, 2002, 2004). A water-based formulation containing copper carbonate hydroxide, boric acid, tebuconazole, and an amine derivative was used throughout the study. Five treatment methods were used: diffusion treatment of green strands, vacuum pressure treatment of strands, spray treatment of strands during blending, heat and cold quench post treatments, and vacuum treatment of manufactured boards. Physical and mechanical properties were evaluated as well as decay resistance and the effect of different heat treatments. The point of preservative addition significantly effected mechanical and physical properties. Dimensional stability (and decay

resistance to a lesser degree) was improved with increasing length and temperature of heat treatments. Heat and cold quench treatments designed to simulate dipping in preservative solution after hot-pressing generally gave inferior properties compared to controls. The authors concluded that vacuum treatment of dried strands was the best method for preservative addition of Tanalith.

Several researchers have investigated various azoles in strand based panels (Clausen & Yang 2004, Baileys *et al.* 2003, Berg 1995, and Laks & Palardy 1992). Baileys and others (2003) evaluated several water repellent preservative systems as furnish treatments on single layer aspen strandboard. The best application method tested was a rotary drum/spray apparatus. Three preservative systems were tested: two IPBC treatments and a third IPBC treatment with the addition of tebuconazole and propiconazole. The authors concluded that water repellent preservative formulations can be used as integral furnish treatments to improve water and fungal resistance without negatively impacting their static bending properties.

Kirkpatrick (2005) has presented preliminary data on treatment of strandboard with polymeric betaine (didecyl-bis(2-hydroxyethyl ammonium borate, didecylpolyoxethyl-ammonium borate). The results were encouraging with boards incorporating betaine showing no significant reduction in mechanical properties when compared with untreated controls. A similar result was found for the dimensional properties.

In a preliminary study of copper naphthenate (CuN) to preserve aspen composites, Schmidt (1991) found good compatibility between CuN and a resole type PF resin. Previous research had shown a detrimental effect when CuN was added to hardwood composites (Boggio & Gertjansen 1982, Hall *et al.* 1982, Short & Lyon 1982). Schmidt (1991) added that more research should be conducted to further investigate the compatibility of CuN in PF bonded waferboard. Preliminary research using both CuN solution and powder yielded acceptable results (Kirkpatrick & Barnes 2005). In general, values for mechanical properties followed the trend untreated controls > waterborne CuN = powdered CuN > ZnB. Water absorption and dimensional properties followed a similar trend. This preliminary study suggests that CuN is a viable alternative treatment for engineered wood composites. The authors (Barnes & Kirkpatrick 2005) also found excellent properties for two copper betaine formulations.

Recent research has centered on the use of silica-based borates to provide efficacy against decay fungi and termites. In a study by Maldas and co-workers (1999), wood flakes were treated with siloxane to provide water resistance. The authors saw detrimental effects on

physical properties of the waferboards (Maldas *et al.* 1999). Silicone-based water repellent systems were incorporated into flakeboard by Larkin and co-workers (1999). Initial indications showed that lower loadings were needed to achieve acceptable properties. Furuno (1996) has completed a number of studies regarding relationships of silicate/water glass. Considerable proprietary research encompassing the incorporation of silanes, silicones, and siloxane into wood-based composites has been conducted recently and the data are not in the public domain.

Glu-lam Timbers

Glu-lam beams are made of lumber elements and have been treated with CCA, PCP in light or heavy solvents, creosote, IPBC-CPF, and ACQ in both pre- and post-manufacture (AWPA 2005). These types of composites have substantial differences in terms of preservation compared to other wood-based composites due to the large size of wood components. Manbeck and co-workers (1995) post-treated resorcinol-formaldehyde (RF) bonded glu-lam beams of various woods with creosote. Red oak, red maple, and yellow-poplar samples treated with creosote saw no adverse effects on bond quality or mechanical properties (Manbeck *et al.* 1995). Vinden (1986) investigated the penetration of CuN in light organic solvent in radiata pine glue-lam beams. Borate diffusion has been studied by Dirol (1988) on several different species. Because of the exposed environments they are sometimes subjected to, further research on glue-lam treatments is needed..

Plywood

Pressure treatment of plywood has been employed for a number of decades and comprises fungicides, insecticides, water repellents, and fire retardants (Bender *et al.* 2002). Several studies examining adhesive compatibility with preservative systems and adhesive were carried out in the 1940s as systems were sought to provide durability to glu-lam products. Newer studies examining adhesive compatibility with preservatives include those performed at the USDA Forest Products Lab (Vick 1990, Vick *et al.* 1990), and elsewhere (Schmidt & Gertjansen 1988, Prasad *et al.* 1994). Vick and others (1990) investigated preservative compatibility with PF resin for thirteen non-acidic waterborne preservatives using pretreated aspen veneers. Results indicated that the borate containing preservatives tested caused poor bonds, as did an emulsion of copper naphthenate. The authors found promising results for several didecyldimethyl ammonium chloride (DDAC) formulations, sodium fluoride, and ammonium hydrogen fluoride. Another study (Vick 1990) found that

ACA and CuN performed better than chlorothalonil and zinc naphthenate. ACA and copper naphthenate had higher percent wood failures for longer pressing times at each of the retentions examined (Vick 1990). Prasad and others (1994) evaluated bond strength development of CCA- or ACZA-pretreated lap shear specimens bonded with PF resin. The authors concluded that neither CCA nor ACZA pretreatment produced negative effects on tensile strengths tested. Variations in preservative treatability have been studied by Mitchoff and Morrell (1991) and Van Acker and Stevens (1993a). Besides pressure treatment after manufacture, other treatment methods place the preservative in the glue-line. Kamdem *et al.* (2002) showed good results with fipronil (5-amino-1-(2, 6-dichloro- α , α , α -trifluoro-*p*-tolyl)-4-trifluoromethylsulfinylpyrazole-3-carbonitrile) added to the glue-line. Additional work with OSB also showed reasonable results (Kamdem *et al.* 2000). Richardson (1993) notes that lindane, dieldrin, heptachlor, chlordane, and boric acid are suitable for this type of use. In Japan and India, insect resistant plywood is commercially produced incorporating chlorpyrifos in the glue-line (Laks 1999). Beal (1975) had success in adding insecticides to plywood to prevent termite attack.

Van Acker and Stevens (1993b) produced various hardwood and softwood plywood panels (most of which were bonded with PF adhesive) impregnated with waterborne or oilborne preservatives. The waterborne salt preservatives used were CCA, copper chromate fluorine (CCF), and copper chromate borate (CCB), while the waterborne and solvent-borne preservatives used were azaconazole plus insecticides, and alkyl ammonium compounds (AAC). Some important conclusions drawn by the authors were: 1) more durable species require less uptake than do the less durable species, 2) the refractory character of some species leads to heterogeneous distribution, and 3) differences in impregnability lead to a range of uptake levels and hence, a variation in durability (Van Acker & Stevens 1993b).

Laminated Veneer Lumber (LVL)

Kimmel and co-workers (1995) treated hardwood and softwood LVL with creosote. Specimens showed very uniform distribution of creosote compared to solid wood. Flatwise and edgewise flexural modulus of elasticity and shear strength were not reduced by creosote treatments. Tsunoda and Kawai (1993) tested phenolic dip-treated Japanese cedar veneers for biological resistance. Threshold loadings for efficacy against decay fungi and termites were not achieved (Tsunoda & Kawai 1993). Several preservatives were examined for use on LVL in a large study conducted by Roos *et al.* (1993). DOT, CuN, ACZA, CCA, and copper ammonium carbonate were evaluated for use with four adhesives on a number of different

species. The authors noted that the appropriate preservative and adhesive must be used together to successfully make LVL. Also, pretreatment with an appropriate preservative does not adversely affect strength, stiffness, or durability, unlike post-treatment methods. Additionally, sodium borate or CuN-treated veneers should not be used in ground contact LVL applications.

Wood Thermoplastic Composites (WPC)

Wood thermoplastic composites were primarily studied in the 1980's although some studies were decades before. These products became widespread during the 1990's. They were initially thought to be resistant to biodegradation due to the presence of a plastic component and encapsulation of wood particles (Verhey & Laks 2002). Recent studies however, show wood thermoplastic composites are susceptible to decay (Gardner *et al.* 2003). After a four-year exposure in Florida, Morris and Cooper (1998) found that a wood-plastic composite was colonized by both brown and white-rot fungi attack. Verhey *et al.* (2001) studied the decay resistance of polypropylene/pine composites made with 30, 40, 50, 60, and 70% wood. In that study, zinc borate (ZB) samples provided protection against brown rot fungi at loadings of 1, 3, and 5%. Verhey and Laks (2002) later reported ZB to be effective under laboratory conditions, but excessive leaching was present in field studies in Hawaii. Nevertheless, they concluded that ZB was a promising preservative for wood thermoplastic products because of its thermal stability and prior use as a flame retardant for plastics (Laks 1999; Laks & Manning 1997). A copper-chitosan complex has shown promise for protecting WPCs (Duan *et al.* 2004).

Particleboard/MDF/Hardboard

Particleboard was first produced after World War II and quickly became a premier composite product during the 1950's. The first preservative that found widespread use for protection of particleboard was pentachlorophenol (Huber 1958; Becker 1959; Brown & Alden 1960; and others). Huber (1958) found the preferred method of adding sodium pentachlorophenol to UF or PF bonded particleboard was by adding the biocide to resin prior to spraying the chips. Studies investigating efficacy against mold, decay fungi, and termites have been conducted for non-preservative-containing particleboard/MDF/hardboard as well as preservative-containing products (Merrill & French 1963; Becker 1972; Toole & Barnes 1974). However, focus shifted away from preservation of particleboard with the rise of waferboard. Today, protection of these wood composites centers on fire retardancy and water

repellency. Accordingly, wax and fire retardants are the principle additives (Gardner *et al.* 2003). Recently, some research has been conducted to investigate properties of particleboards made of CCA-treated furnish (Clausen *et al.* 2001, Munson & Kamdem 1998). These efforts were aimed at creating disposal options for treated wood at the end of its service life for incorporation into engineered wood composite products.

Novel Treatments and Technologies

Gaseous Boron/Vapor Phase Treatments

Gaseous boron treatments of OSB/waferboard/strandboard products have been performed by a number of researchers (Bergervoet *et al.* 1992, Hashim *et al.* 1992, Jones *et al.* 2001, Nuñez *et al.* 1995, Turner *et al.* 1990, and others). Scheurch (1968) suggested that treatment using the vapor phase could negate problems associated with liquid treatment. Preservative and flame retardant treatments of wood composites using a vapor boron treatment (VBT) process have been thoroughly evaluated (Murphy 1994, Murphy *et al.* 2002). This method is achieved through a partial vacuum at elevated temperatures to vaporize methyl borate liquid which is impregnated into dry wood panels. Diffusion is rapid and complete (Barnes & Amburgey 1993). Gaseous boron ether then reacts within the wood substrate to form unfixed borate acid and methanol (Murphy 1994). The main advantages of this type of process are the speed and cleanliness of treatment. Drying, conditioning, and treating can be accomplished in a single vessel (Barnes & Amburgey 1993). A wide range of composites have been treated using VBT including OSB, LVL, plywood, and MDF (Barnes & Murphy 2006).

Supercritical Fluid (SCF) Treatment

Even more fascinating is the potential for treating wood using supercritical CO₂ (ScCO₂) as a carrier (Junsophonsri, 1994; Morrell *et al.* 1993, 1994). Supercritical fluid (SCF) treatment of wood composites uses modified fluids to improve impregnation and is a relatively new concept with little research done to date. SCFs can be defined as fluids which are above their critical temperature and pressure and having properties similar to liquids or gases (Morrell & Levien 1995). In this case, there are no problems with the high surface tension associated with liquid treatment since no phase boundary exists between liquids and gases in the supercritical region (Barnes & Amburgey 1993). These materials move through porous media almost instantly, providing fast equilibration between the wood substrate, yet also have solvating powers similar to that of liquids (Morrell & Levien 1995). Carbon

dioxide and copper naphthenate (CuN) are two promising compounds for supercritical fluid treatment (Morrell & Levien 1995). Evans (2003) reports that a plant for ScCO₂ treatment has been commissioned in Denmark.

The use of ScCO₂ in composites is particularly appealing (Oberdorfer *et al.* 2000). Successful treatment of composites with IPBC and an IPBC + silafluofen mixture has been achieved (Tsunoda & Muin 2003a, b). ScCO₂ treatment on a wide range of composites showed minimal loss in mechanical properties for most composites (Muin *et al.* 2001). The notable exception was a large loss of bending strength in OSB. Previously, Kim *et al.* (1997) had shown some loss in bending strength when treating southern pine with TCMTB using ScCO₂ treatment. For above-ground exposure in Hilo, Hawaii, Morrell *et al.* (2005) showed excellent performance of plywood, MDF, particleboard, and OSB treated with tebuconazole using ScCO₂ treatment so long as retention was high enough.

Chemical Modification

Another approach investigated by researchers for many years is wood modification. Chemical modification of wood has advantages such as reduced environmental impact compared to conventional treatments. Common problems associated with modification include unacceptable weight gain and reduced properties. Isocyanates are promising and react with wood agents to form crosslinks (Barnes and Amburgey 1993). Novel treatments and technologies will see increasing use in the future as standards and regulations become more stringent. Studies involving chemical modification include those by Rowell *et al.* (1988), Vick *et al.* (1991). Silicone compounds and their derivatives have shown promise as water repellent agents (Rowell and Banks 1985; Hager 1995) and some derivatives, such as silafluofen, have shown promise as termiticides (Adams *et al.* 1995; Tsunoda & Muin 2003). Acetylation and furfurylation (Balfas & Evans 1994) continue to be studied and commercialized in Europe and Japan. Dizman *et al.* (2005) have reported good results with the modification of alder and spruce particleboards using acetic, maleic, succinic, and phthalic anhydrides.

Conclusions

The production and end-uses of preservative treated wood composite products are relatively new segments with little documented research to date. Laks (1999) notes three important factors to the development of these products: 1) reduced availability of high quality

solid wood commodities for exterior applications; 2) poor performance of untreated composite siding; and 3) composite manufacturer's value-added products for both domestic and export markets. It is clear that wood-based composites are here to stay. Careful attention to design and maintenance of structures using wood-based composite products is needed. No amount of biocide will prevent moisture ingress into a building structure. Industry and academia must continue to make these products increasingly durable for years to come in order to maintain and expand markets (Morrell 2001).

Acknowledgements

The authors gratefully acknowledge the partial funding support of the USDA CSREES Special Research Grant Program No. 2004-34158-14682 and the Wood-Based Composites Center headquartered at Virginia Tech University.

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