RECENT ACTIVITIES IN FLAME RETARDANCY OF WOOD–PLASTIC COMPOSITES AT THE FOREST PRODUCTS LABORATORY

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ABSTRACT

For a variety of reasons, wood–plastic composite (WPC) products are widely available for some building applications. In applications such as outdoor decking, WPCs have gained a significant share of the market. As an option to improve the efficient use of wood fiber, the USDA Forest Service, Forest Products Laboratory (FPL), has an extensive research program on WPCs. Although often ignored in discussions of WPCs, the flammability of WPC's can be a significant factor in certain building applications. This paper reviews past, present, and planned cooperative FPL research projects on fire-retardant treatment of WPCs and related topics.

[1] Maintained at Madison, WI, in cooperation with the University of Wisconsin

INTRODUCTION

The continuing increase in wood–plastic composite (WPC) market share worldwide has led to an increase in decks built at the wildland–urban interface, which stresses the need for an understanding of WPC fire resistance. Expansion into other exterior construction applications (such as siding and roofing) and development of interior applications (such as door frames and millwork) also contributes to this critical need. A team of researchers based at the USDA Forest Products Laboratory (FPL) have focused research efforts to develop an understanding of WPC fire performance and investigate fire retardants for use in WPCs. Following a review of WPCs and their markets, this paper summarizes the results of cooperative fire performance studies performed at FPL.

Wood–Plastic Composites

The term wood–plastic composite (WPC) refers to a class of materials consisting of thermoplastics filled or reinforced with lignocellulosics. Because lignocellulosics thermally degrade at low temperatures, the thermoplastics used in WPCs are generally limited to those with melting temperatures below 200°C. Common thermoplastics used in WPCs include high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polyvinyl chloride (PVC). Various lignocellulosics, not strictly wood, are generally incorporated into the thermoplastic matrix at loadings of 40–65% by weight. Wood flour, the most common lignocellulosic used in WPCs, is a commercially available material sourced from industrial residues such as planer shavings, sawdust, and wood chips and ground to a consistent mesh size. Wood flour has a low aspect ratio (length-to-diameter ratio) compared with wood fiber, another raw material used in WPCs. Other lignocelluosics used in WPCs include agricultural fibers (such as flax, jute, kenaf, and hemp) and agricultural residues (such as corn stalks, rice hulls, and coconut coir). Recycled sources can include recycled paper and paper sludge. Additives are a minor component of WPCs, and the total additive loading may be up to 20% by weight. Lubricants may be added to improve some processing characteristics. Coupling agents are common to improve the compatibility of the hydrophobic thermoplastic and hydrophilic lignocellulosic. Additives to improve performance include impact modifiers, foaming agents, photostabilizers, biocides, fungicides, and fire retardants.

Common plastics processing techniques are used to manufacture WPCs. Processing WPCs can be thought of as a two-step process, compounding and forming. Compounding consists of melting the thermoplastic and incorporation of the lignocellulosic and additives into the melt, resulting in a homogeneous composite. Twin-screw extrusion is the most common compounding method used. Forming involves melting the compound and forming it into the end-product. Typical techniques include injection molding (forming a three-dimensional product by injecting the melt into a die), profile extrusion (pushing the melt through a two-dimensional die to obtain a product with constant cross-section), and compression molding (pressing a sheet between two hot plates to obtain the desired shape). In some cases, compounding and forming are done in a single step.

WPC Products and Markets

In the past two decades, lignocellulosics have become a legitimate filler and reinforcement for the thermoplastics, resulting in tremendous growth in the use of WPCs for many applications, including construction, automotive parts, furniture, and other consumer goods. Figure 1 shows recent growth in WPC production in North America and Europe as reported by Haider and Eder [2010]. Current growth rate of the WPC market is 22% for North America and 51% for Europe [Haider and Eder 2010]. Auto interiors and decking for outdoor applications represent the largest market for WPCs, both in North America and Europe, and in both regions growth is most rapid in the decking segment [Bowyer et al. 2010].

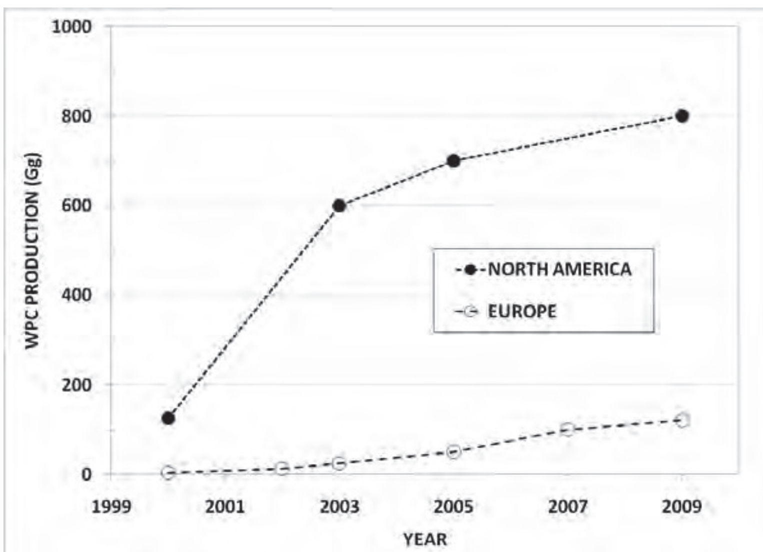

Figure 1. WPC production between 2000 and 2009 in Europe and North America [data from graph of Haider and Eder 2010].

The first major application for WPCs in the United States was in the automotive industry as interior panels, but it was the introduction and acceptance of WPC decking that is largely responsible for the growth of WPCs. WPC deckboard accounts for about 50% of WPC volume [Wood 2007]. Wood decking is still more popular than WPC decking. In 2009, 0.9 billion linear meters (3 billion linear feet) of wood decking was sold, compared with 106 million linear meters (349 million linear feet) of WPC decking [Anonymous 2011]. However, the market for wood decking is expected to grow 0.5% annually while the market for WPC decking is predicted to grow 12.9% annually through 2014 [Anonymous 2011]. This growth is largely due to consumer perception of WPCs as being low-maintenance and environmentally friendly (many of the components are derived from waste sources) compared with solid wood. In addition, WPCs are considered less likely to decay or splinter than solid wood. The number of WPC manufacturers in North America is dynamic, but there are currently more than 20 producers of WPC lumber. The positive growth in WPC decking has led manufacturers to introduce coordinating lines such as railing, fences, in-deck storage, and outdoor furniture. Other residential construction applications in North America include siding, roofing, windows, door frames, and millwork.

The markets and production of WPC from 2000 to 2009 in Europe were reviewed by Haider and Eder [2010]. In Europe, total WPC production amounts to 120 Gg (120,000 tonnes) (excluding product destined for the auto industry). Around 68 Gg of this production is currently destined for the decking sector. WPC market share in the European decking sector is estimated to be around 6% [Industry News & Markets 2010]. Most WPC is for decking material and other exterior building products, but furniture and automotive applications are more important in Europe than in North America. The decking and siding markets are 57% and 11%, respectively, of the total 2009 WPC market (excluding automotive) which leaves 32% for other applications [Haider and Eder 2010]. A survey of homepages on the web indicated that European applications of WPC in 2008 included interior and exterior furniture, window and door applications, roofing and siding, as well as railing, decking, and fencing [Haider and Eder 2010].

Today, WPC production in Europe is concentrated in Germany, Benelux, France, and Scandinavia, although companies from the eastern parts of Europe, such as Turkey and Latvia, are increasing manufacturing capabilities [Haider and Eder 2010]. A search of WPC companies in Europe yields 27 producers of WPC decking or siding. In Europe, 59 research and development (R&D) centers are dealing with WPCs. Germany dominates with 21 R&D institutions, followed by Austria with 6 [Haider and Eder 2010].

A relative newcomer to the WPC arena, China has been rapidly expanding its production of WPCs. Decking and other nonstructural lumber products are the most common product manufactured. Production of WPC products is currently about 150 million kg (330 million pounds) annually, of which about 70% is exported [Toloken 2010]. Most exports are bound for Europe, although there are opportunities to export to North America [Toloken 2010]. Manufacturers in China are aggressively developing WPC–metal composites for structural members and window frames.

FPL STUDIES

OSU Study

An early FPL study on the fire performance of WPCs was conducted with an Ohio State University (OSU) apparatus (ASTM E 906) [Stark et al. 1997]. Hot-pressed panels without any fire-retardant chemicals were made by two different initial processes: (1) melt-blended via high kinetic energy mixer and (2) air-laid via weaving a wood fiber and dry polymer together. The melt-blended composites included PP or HDPE at 50%, 60%, or 80% plastic (weight basis, wt %) and the remainder either recycled newspaper or pine wood flour (WF) as the wood component. The air-laid materials were PP or HDPE at 10, 30, or 50 wt % plastic and hemlock fiber as the wood component. Because the specimens melted and dripped, they were tested in the horizontal orientation. The effective heat flux was 18.3 kW/m^2. With the modified FPL OSU apparatus, the heat release rates (HRRs) were determined using an oxygen consumption method. The peak and average HRRs increased with increases in polymer content, and this was particularly true for the higher plastic content melt-blended composites. The addition of wood fiber to the plastic changed the HRR curve from one of increasing HRR to one with an early peak HRR followed by decreasing HRR.

Decking Study

As alternative decking products became more important, scientists at FPL studied the fire performance of many types of decking materials. As part of this study, four commercial WPC products were included in a series of cone calorimeter tests on wood-based decking materials that were presented at the 2007 BCC Flame Retardancy conference [White et al. 2007]. The limited available information on the commercial products was that their wood fiber contents were 50 wt % or higher. For these four commercial products, the peak heat release rate (PHRR), 300-s average heat release rate (AHRR-300), and average effective heat of combustion (AEHOC) in tests using a heat flux level of 50 kW/m^2 ranged from 374 to 518 kW/m^2, 204 to 329 kW/m^2, and 22.6 to 29.3 MJ/kg, respectively. Also included were two specimens made at FPL with 56 wt % pine WF and either HDPE or PP as the polymer content. For these two laboratory-produced WPC specimens, the PHRR, AHRR-300, and AEHOC were 465 and 519 kW/m^2, 282 and 311 kW/m^2, and 21.5 and 26.3 MJ/kg, respectively. In comparison, the PHRR, AHRR-300, and AEHOC for an untreated southern pine deck board were 172 kW/m^2, 107 kW/m^2, and 12.5 MJ/kg, respectively. In a test of a 14-mm-thick specimen of HDPE, the PHRR, AHRR-300, and AEHOC were 1790 kW/m^2, 601 kW/m^2, and 43.6 MJ/kg, respectively. The HRR values for the WPC samples manufactured at FPL were consistent with the commercial samples. However, it was not known if any of the commercial samples contained fire retardant.

University of Wisconsin Study

A limited number of studies evaluating the fire performance of WPCs at that time also investigated the effect of fire retardants. However, each of these studies used different fire-retardant classes and loadings, different plastics and wood content, and different fire tests, which made comparisons between studies difficult. To obtain baseline information on classes of fire retardants, the addition of fire-retardant (FR) treatments to extruded WPCs was investigated as a part of a FPL cooperative study with University of Wisconsin–Madison [Stark et al. 2010]. The five FR treatments that were compounded with HDPE included (1) decabromodiphenyl oxide and antimony trioxide, (2) magnesium hydroxide, (3) zinc borate, (4) melamine phosphate, and (5) ammonium polyphosphate. The FR-treated samples contained 50 wt % mixed pine WF, 10 wt % FR, 35 wt % HDPE, and 5% lubricant. There were also untreated specimens with 50 and 60 wt % WF contents and 100% HDPE samples.

Magnesium hydroxide resulted in the greatest reductions in the PHRR, whereas ammonium polyphosphate reduced the 300-s average HRR the most (Table I). The decabromodiphenyl oxide/antimony trioxide treatment resulted in the greatest reduction in average effective heat of combustion (Table I). The other FR treatments did not significantly change the AEHOC more than simply replacing 10% HDPE with WF. However, the decabromodiphenyl oxide/antimony trioxide treatment increased the average specific extinction area (ASEA) by 76 % over the value for the untreated 50 wt % WF samples. All five of the FR treatments reduced the HRR more than simply replacing 10 wt % HDPE with WF (Table I). The magnesium hydroxide increased the times for sustained ignition (TSI), whereas the ammonium polyphosphate treatment reduced the ignition times (Table I). Samples were also tested in an oxygen index (OI) apparatus, with OI results between 20 (untreated WPCs) and 26 (melamine phosphate). Flexural properties were also evaluated, with ammonium polyphosphate having the most negative impact on the flexural modulus of elasticity (MOE) values.

Istanbul University and Hamburg University Study

In a more recent FPL cooperative study with Istanbul University and Hamburg University, the effects of fire retardants on fire performance of flat-pressed WPCs were investigated [Ayrilmis et al. 2011a]. This study included WPC samples with three levels of softwood WF (40, 50, and 60 wt %) and various fire retardants at 10 wt % (Table II). The polymer was PP and a maleic anhydride-grafted PP (MAPP) was added (2 wt %). The four fire retardants were (1) decabromodiphenyl oxide, (2) magnesium hydroxide, (3) zinc borate, and (4) ammonium polyphosphate. The WF, fire retardant, PP, and MAPP were mixed in a blender, formed into a mat, and hot-pressed into the 10-mm-thick panels.

Table I. Cone calorimeter results for 13-mm-thick extruded WPCs made with HDPE and mixed pine WF. Samples tested as part of FPL–University of Wisconsin-Madison study [Stark et al. 2010]. Heat flux was 50 kW/m².

Treatment	Percentage change from results for reference sample[a]				
	PHRR	AHRR-300	AEHOC	ASEA	TSI
Decabromodiphenyl oxide and antimony trioxide (3:1)	–23	–43	–29	76	12
Magnesium hydroxide	–44	–51	–14	–52	26
Zinc borate	–35	–40	–14	–30	9
Melamine phosphate	–31	–48	–14	–1	–2
Ammonium polyphosphate	–37	–57	–15	–41	–11
Additional 10% WF	–13	–20	–14	–24	2
100% PE	254	85	46	31	236
Sawn lumber, pine	–59	–52	–54	–60	–9

[a] Reference sample had 50 wt % mixed pine WF, 45 wt % PE, and 5 wt % lubricant. WPC specimens listed had 10 wt % FR chemical(s) or additional 10 wt % WF (35 wt % PE). The PHRR, AHRR-300, AEHOC, ASEA, and TSI for the reference samples were 505 kW/m², 326 kW/m², 30 MJ/kg, 330 m²/kg, and 24.4 s, respectively.

Table II. Cone calorimeter results for 10-mm-thick flat-pressed WPCs made with PP and softwood WF. Samples tested as part of FPL-Istanbul University-Hamburg University study [Ayrilmis et al. 2011a]. Heat flux was 50 kW/m².

Treatment	Percentage change from results for reference sample[a]				
	PHRR	AHRR-300	AEHOC	ASEA	TSI
Decabromodiphenyl oxide	–20	–27	–32	85	4
Magnesium hydroxide	–18	–26	–11	–24	16
Zinc borate	–16	–24	–8	–35	5
Ammonium polyphosphate	–21	–39	–19	13	3
Additional 10 wt % WF	–10	–17	–13	–17	0
10 wt % less WF (58% PP)	26	36	10	19	–21

[a] Reference sample had 50 wt % softwood WF, 48 wt % PE, and 2 wt % MAPP. Other specimens had 10 wt % FR chemical(s) (38 wt % PP), additional 10% wt WF (38 wt % PP), or additional 10% wt PP (40% wt WF, 2%). The PHRR, AHRR-300, AEHOC, ASEA, and TSI for the reference samples were 401 kW/m², 266 kW/m², 29.7 MJ/kg, 458 m²/kg, and 23.8 s, respectively.

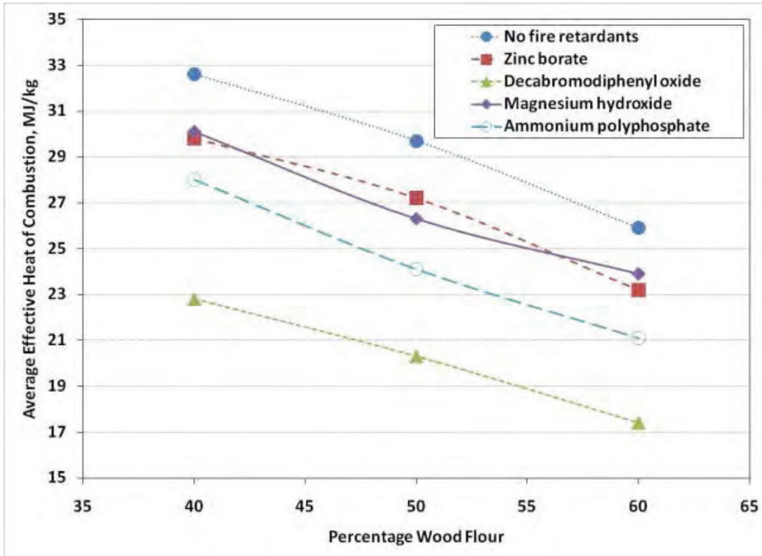

Figure 2. AEHOC for 10-mm-thick wood–plastic composites with 40 to 60 wt %t PP content. [Ayrilmis et al. 2011a]

The results largely reflected the type of FR treatment used and the relative amount of wood (or PP content) (Table II). In general, the results of this study (Table II) were consistent with the results of the earlier study (Table I). In addition to the data shown in Table II (50 wt % WF), the different fire retardants were evaluated with 40 and 60 wt % WF. For most of the parameters (AEHOC, AHRR-300, and ASEA), the results were somewhat consistent with linear extrapolations from the Table II results (Figure 2 for AEHOC). In the case of PHRR, differences between treatments were more pronounced with lower WF content (i.e., higher PP content). In the case of TSI, the differences between treatments were more pronounced for the 40 wt % WF with the exception of the magnesium hydroxide, which increased linearly with WF content (Figure 3). Also as part of the study, the magnesium hydroxide, zinc borate, and ammonium polyphosphate treatments were evaluated using 5 and 15 wt % FR treatment levels in addition to the 10% treatment level [Ayrilmis et al. 2011b]. The percentage WF was 50 wt % and the PP treatment level was adjusted to accommodate the higher FR treatment. A small number of limiting oxygen index (LOI) tests were also conducted on the untreated, 10 wt % FR-treated, and 15 wt % FR-treated samples that indicated a correlation between LOI and average HRR results from the cone calorimeter tests (Figure 4). The highest LOI result was for the 15 wt % ammonium-polyphosphate-treated sample.

Current Istanbul University Study

In a current FPL cooperative study with Prof. Nadir Ayrilmis and others of Istanbul University, the FR chemicals (1) borax:boric acid (1:1), (2) zinc borate, (3) monoammonium phosphate, and (4) diammonium phosphate were investigated as treatments for WPC composites made of wood fiber with the polymers PP or HDPE. The FR chemicals were added during the WPC extrusion process. The control samples were 40 wt % beech WF with 60% PP or HDPE. In Table III, the 40% wood/60% PP is used as the reference material to illustrate the effects of changes in compositions.

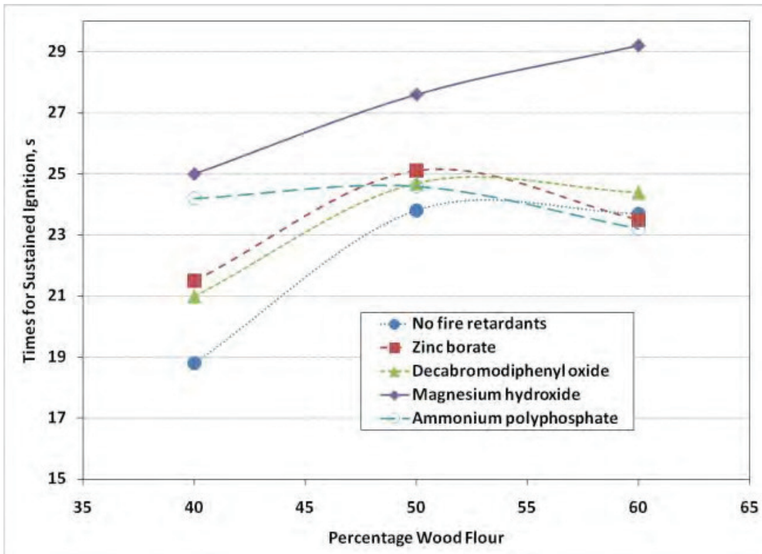

Figure 3. TSI of 10-mm-thick wood–plastic composites with 40 to 60 wt % PP content. [Ayrilmis et al. 2011a]

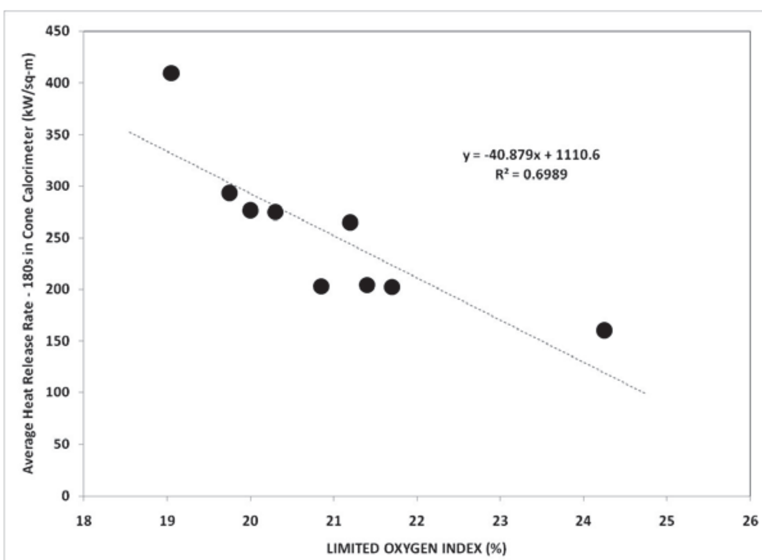

Figure 4. Correlation between the 180-s average heat release rate in the cone calorimeter with small number of LOI tests of the same material from FPL–Istanbul–Hamburg study.

Table III. Cone calorimeter results for 10-mm-thick extruded WPCs with 12 wt % FR chemicals. Samples tested as part of a FPL–Istanbul University study. Heat flux was 50 kW/m².

FR Treatment	Plastic	Percentage change from results for reference sample[a]				
		PHRR	AHRR-300	AEHOC	ASEA	TSI
Borax:boric acid (1:1)	PP	–1	–3	7	4	–11
Zinc borate	PP	–7	–10	7	14	–15
Monoammonium phosphate	PP	–15	–28	–1	36	–12
Diammonium phosphate	PP	–11	–19	1	42	–14
Untreated 60% HDPE/40% WF	HDPE	–4	5	6	10	–4
Borax:boric acid (1:1)	HDPE	–10	–4	12	7	12
Zinc borate	HDPE	–10	–8	7	–12	10
Monoammonium phosphate	HDPE	–2	–11	6	36	–12
Diammonium phosphate	HDPE	–13	–15	4	22	–6

[a] Reference sample had 40 wt % beech flour, 60 wt % PP. The FR-treated specimens had 12 wt % FR chemical, 54 wt % PE or PP, and 34 wt % beech flour. The PHRR, AHRR-300, AEHOC, ASEA, and TSI for the reference samples were 510 kW/m², 373 kW/m², 31.0 MJ/kg, 420 m²/kg, and 23.6 s, respectively.

The WF and plastic content were evenly adjusted to accommodate the 4%, 8%, and 12% addition of the FR chemical. Each FR treatment included samples with and without a coupling agent (MAPP for the PP samples and MAPE for the HDPE samples). For samples with the coupling agent, the loading level of the coupling agent was 50 wt % of the loading level of the FR chemical. The samples were tested in the cone calorimeter (50 kW/m², frame/no grid) and in an oxygen index apparatus. Selected results for the samples treated with 12% FR are listed in Table III. Results in Table III are for two replicates. The improvements for 12% zinc borate over the "reference material" were not as great as in the earlier studies (Table I for 10% zinc borate and Table II for 10% zinc borate). The reference material in Table III had a wood/plastic ratio of 40/60, compared with 50/45 for Table I and 50/48 for Table II. Also, in the studies of Tables I and II, the addition of FR chemical reduced the polymer content only, whereas in the study of Table III, the addition of FR chemical was accommodated by equal reductions in wood and polymer contents. Thus, the results in Tables I and II reflect the added reductions in the polymer content. In terms of ignition times, it is noted that 100% HDPE has a longer ignition time than sawn lumber (Table I).

Future Istanbul University Study

In 2012, FPL will be cooperating with Prof. S. Nami Kartal and Evren Terzi of Istanbul University on a study of WPCs made of 65% to 40% Scots pine flour, 40% HDPE, and 5% to 15% boron compounds. Treatments include various forms of boron and the FR chemicals aluminum hydroxide and magnesium hydroxide. The fire tests include thermal analysis, cone calorimeter, and LOI. Determinations of other properties of the WPC are also part of the study.

CONCLUDING REMARKS

This paper discusses studies conducted on the fire performance of WPCs. Studies on FR-treated WPCs have included tests on the effects of the FR treatments on other properties, particularly mechanical properties [Ayrilmis et al. 2011a,b; Stark et al. 2010] and moisture resistance [Ayrilymis et al. 2011a,b]. The addition of FR chemicals can have a detrimental effect on mechanical and moisture resistance (thickness swelling and water absorption) properties of the WPC.

This group of studies provides baseline knowledge of the fire performance of WPCs. It has been shown that fire retardants are effective in WPCs, and that this effectiveness can be related not only to fire-retardant content but also to plastic content. However, the studies performed to this date are laboratory-scale studies. Full-scale studies, including the E-84 tunnel test and studies performed on sample decks, are needed to fully understand how decks will perform in a fire. As WPCs are most commonly used in exterior environments, it becomes critical to understand how weathering affects the fire performance of WPCs. Accelerated weathering procedures for fire testing of exterior fire-retardant wood products were discussed in a 2009 BCC Flame Retardancy presentation [White 2009].

More research is also needed to develop alternative FR treatments. In the current group of studies, common additive-type fire retardants were used to protect the plastic matrix. Studies to protect the wood component as well as the plastic component are one avenue for future research. As coatings are developed for WPCs, there may be research opportunities to develop coatings with a fire-retardant component. Finally, alternative FR treatments for wood and wood composites are under development and should be tested in WPCs.

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SECTION IV

SESSION 9

PRESENTER

ROBERT WHITE

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