Coating WPCs Using Co-Extrusion to Improve Durability

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Abstract

Wood-plastic composites (WPCs) have been gaining market share in the residential construction industry as lumber for decking, roof tiles, and siding. The durability of these materials in exterior environments is just beginning to be understood. Current research suggests that controlling moisture absorption by the composite is key to improving durability. Methods to improve moisture resistance of WPCs have met with limited success. Co-extrusion involves the simultaneous extrusion of two dissimilar materials as a single profile. In this study, co-extrusion was used to improve the moisture resistance, and in this manner, the durability of WPCs. We manufactured a material with a WPC base coated with a clear plastic cap layer of either high-density polyethylene or polypropylene. The co-extruded composites and corresponding WPCs without a plastic coating were tested for moisture absorption and weathering performance. The cap layer co-extruded over a WPC provided improved moisture resistance compared with the control WPC. Co-extrusion of WPCs with a clear plastic cap layer did not provide protection against changes in mechanical performance. However, composites capped with high-density polyethylene exhibited some resistance to color change.

In Proceedings: Coating Wood and Wood Composites: Designing for Durability, July 23-25, 2007, Seattle, WA.

Introduction

Biobased thermoplastic composites have been gaining market share in the residential construction industry as lumber for decking and roof tiles. Advanced biobased composites such as wood-plastic composites (WPCs) represent an emerging class of materials that combines the favorable performance and cost attributes of both wood and plastics [1]. WPCs have been identified as a potential outlet for biomass and a way to increase the utilization of waste wood and wood of low commercial value [2]. Currently, commercially available wood flour is the most commonly used filler material in WPCs. Although decking is the main application for WPCs currently, another residential application, siding, has tremendous potential. To enter the siding market, the durability of WPCs needs to be improved.

The outdoor durability of these materials is just beginning to be understood. There has been work examining the weathering of WPCs and the degradation due to decay. The results demonstrate that degradation in exterior environments occurs in the form of color change, mechanical property loss, and loss in weight. Some of the current research demonstrates that controlling moisture absorption by the composite is key to controlling the degradation that occurs during weathering and fungal attack [3]. Therefore it is critical to improve the moisture resistance of WPCs in order to increase WPC durability and expand into new markets.

Current methods to improve the moisture resistance of WPCs have included changing the morphology of the composite, treating the wood component with acetic anhydride, and incorporating a maleated polyolefin into the composite. Changing the manufacturing technique and/or variables alters the composition of the composite surface, changing the way the WPC degrades [4]. This has been shown to improve the composite durability in the short term only. Given enough exposure time this method does not prevent the wood from absorbing moisture. Treating the wood fiber with acetic anhydride results in tremendous improvements in moisture resistance, but requires an extra step to pre-treat the wood fiber, and requires exotic catalysts [5]. This has proven to be too expensive for commercial use. Using a coupling agent to improve moisture resistance is cost-effective; it is added directly during the extrusion process. However it has not been very successful to this date [6].

Another technique that can be used to improve the moisture resistance of WPCs, thereby improving durability, involves coating the WPC surface using co-extrusion. This is the method that we investigated. Co-extrusion involves extruding two dissimilar materials into a single profile. Of the more than 30 commercial manufacturers of WPCs, co-extrusion is currently used by at least two; however the cap layer is typically a solid color and hides the wood composite underneath. This leads to a product that has the appearance of solid plastic, and does not convey a "high-end" feeling. In this project, we used co-extrusion to add a clear cap layer to WPCs. This allowed the beauty of the natural wood color to show through, resulting in a higher-valued, durable product.

Experimental Methods

Materials and Manufacturing

Materials used for the base WPC include 40 mesh maple wood flour supplied by American Wood Fibers (AWF 4010, Schofield, WI), high-density polyethylene (HDPE) supplied by BP Solvay Polymers (Houston, TX) and a lubricant (TPW 104) supplied by Struktol Company (Stow, OH). The base WPC formulation was 50% wood flour, 44% HDPE, and 6% lubricant. Two polymers were used to coat the composite: HDPE and PP. The properties of the polymers used are shown in Table 1.

Table 1. Specifications of polymer materials used for the base WPC and for the cap layers.

Polymer Materials	Suppliers	Grades	MFI* (g/10 min)	Flexural MOE* (MPa)	Tensile Strength* (MPa)
HDPE (base)	BP Solvay Polymers	Fortiflex B53-35-FLK	0.49	1497	27.6
HDPE (cap)	ExxonMobil Chemical	HD 6605.70	5.0	710	23.3
PP (cap)	Basell Polyolefins	Pro-fax 6523	4.0	1380	33.8

*Properties reported by the respective manufacturers

Compounding the base WPC was accomplished using a 10 liter high intensity mixer (Papenmeier, Type TGAHK20). The coating materials, HDPE and PP were used as received. The control material was extruded without a cap layer. Composites with and HDPE or PP cap layer were co-extruded, i.e., two extruders fed into a single die to produce a single profile. A 32 mm conical counter-rotating twin-screw extruder (C.W. Brabender Instruments Inc.) with a length to diameter ratio of 13:1 supplied the base WPC while a 19.1 mm single screw extruder with a L/D ratio of 30:l (C.W. Brabender Instruments, Inc.) fed the cap material. Both materials were co-extruded through a die (2.54 cm wide by 0.95 cm thick), cooled in a water bath, and cut to 203 mm (8 in.) length. The processing conditions are shown in Table 2.

Table 2. Co-extrusion conditions for the base WPC, the base WPC with an HDPE cap, and the base WPC with a PP cap.

Sample	Extruder	Temperature (ºC), hopper to die				Screw Speed (rpm)	Weight % of total
		Zone 1	Zone 2	Zone 3	Zone 4		
Control	Twin	145	145	140	135	40	100
	Single	Not used					
HDPE Cap	Twin	145	145	140	160	40	96
	Single	170	170	170		4	4
PP Cap	Twin	145	145	140	160	40	96
	Single	170	170	170		3	4

Testing and Analysis

Water Soak

Five WPC samples from each of the three formulations were cut to a length of approximately 25 mm (1”). The samples were dried in an oven for 24 hours at 105 °C. The original extruded surface remained on 4 sides of the blocks, and the two cut sides were sealed by applying a latex paint material (Edge-Seal provided by Louisiana Pacific, Hayward, WI), and the composites were further dried in an oven for 6 hours at 105 °C. Samples were placed in a room temperature water bath. Every 24 hours, samples were removed, blotted dry, and the thickness and weight was recorded. The increase in weight was determined using:

$$\Delta W = \left(W_f - W_p\right) - W_i$$

where W_f was the final weight of the sample with the painted ends, W_p was the weight of the paint (weight of samples after painting-weight of samples before painting) and W_i was the initial weight of the samples before painting.

Weathering

All composite samples were placed in a xenon-arc type light exposure apparatus operated according to ASTM D2565 [7] with borosilicate filters (Weather-Ometer 65-WT, Atlas Materials Testing Technology, Chicago, IL) During exposure, the samples were mounted on a drum that rotated around the xenon arc bulb at 1 rpm. All composite formulations were exposed to both xenon-arc radiation and water spray. The exposure was a 2-h cycle consisting of 108 min of xenon-arc radiation followed by 12 min of simultaneous water spray and UV radiation. An irradiance sensor was used to measure light intensity for wavelengths from 300 to 400 nm (XenoCal, Atlas Materials Testing Technology, Linsengericht, Germany). The irradiance was monitored and voltage to the bulb was changed periodically in order to maintain a constant irradiance. The samples were weathered for 1000 hours, corresponding with a radiant exposure of 151 MJ/m^2.

Flexural Properties

The extruded samples were tested for flexural modulus of elasticity (MOE) and modulus of rupture (MOR) according to ASTM D6109 [9]. The samples were tested as extruded and were 203 mm (8 in.) long. The samples were tested in the flat position with 4-point bending and a support span of 152 mm (6 in.) with an outer fiber strain rate of 0.01. The supports on the under side of the board were on pivots that moved with the board as it flexed. The average of five replicates is reported.

Color Analysis

A Minolta CR-400 Chroma Meter (Minolta Corporation, Ramsey, NJ) was used to measure color using the CIELAB color system. CIELAB is a three-dimensional color space measuring the lightness of the sample (L*) and color coordinates (a* and b*). L* ranges between 0 and 100 (black and white, respectively). An increase in L* means the sample is lightening. The color coordinates a* and b* range from –150 to +150. They are defined as the red/green coordinate, a* (+Δa* signifies a color shift toward red, −Δa* toward green) and the yellow/blue coordinate, b* (+Δb* toward yellow, and −Δb* toward blue). Color was measured for five replicate samples, at two locations on each sample. Color change (ΔE_{ab}) was determined using the procedure outlined in ASTM D2244 [9]:

$$\Delta E_{ab} = \left(\Delta L^2 + \Delta a^2 + \Delta b^2\right)^{1/2}$$

where ΔL, Δa, and Δb represent the difference between initial and final values of L*, a*, and b*, respectively.

Results and Discussion

The change in sample weight and thickness during the water soak is shown in Figures 1 and 2, respectively. The weight and thickness of all of the composites increased during the water soak. However, after 10 days the increase in weight and thickness was much higher for the control samples than for those coated with a co-extruded HDPE or PP layer.

This supports the conclusions made by Clemons and Ibach [10]. They examined WPCs with the same formulation but manufactured via extrusion, injection molding, or compression molding. After a two-week water soak, extruded composites absorbed more water than compression molded and injection molded composites, respectively. The conclusion was that the plastic-rich film that formed on the surface of the injection molded composites due to higher processing temperatures and pressures provided some moisture resistance. Our results clearly show that the addition of a plastic coating to WPCs results in more moisture resistance.

Figure 1. Change in weight versus time during room temperature water soaks of a control WPC and WPC co-extruded with a HDPE or PP cap layer.

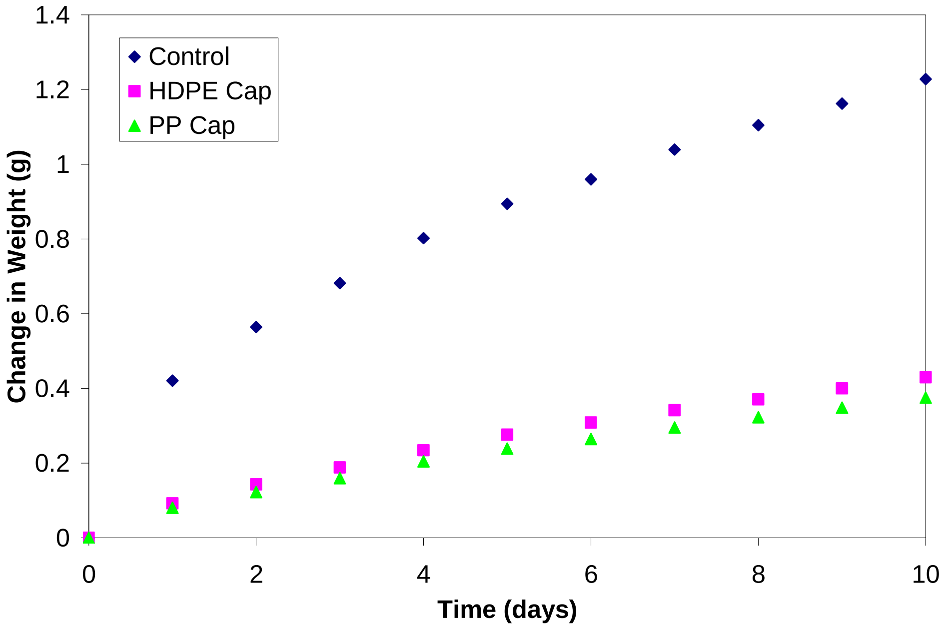
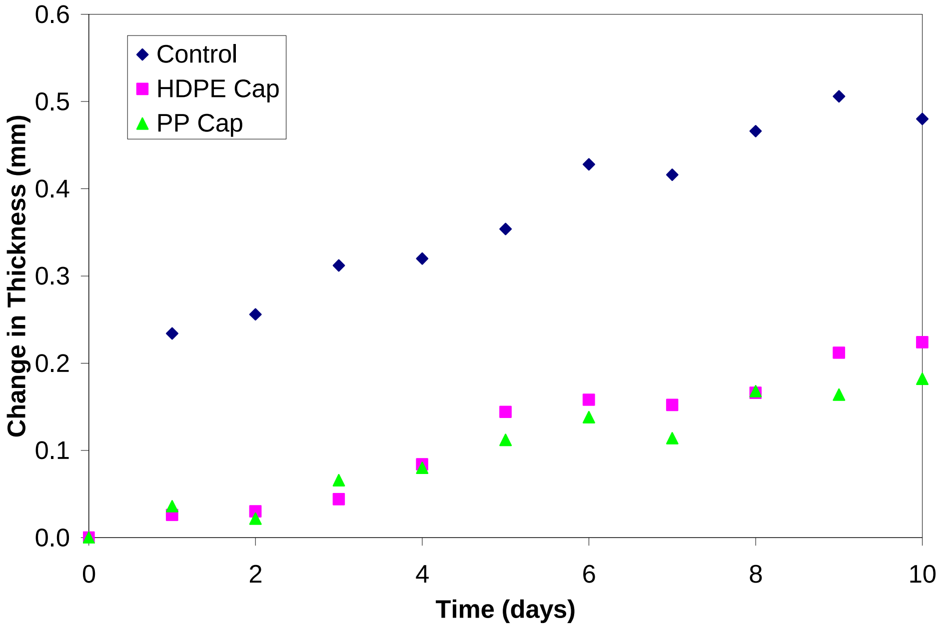


Figure 2. Change in thickness versus time during room temperature water soaks of a control WPC and WPC co-extruded with a HDPE or PP cap layer.



The effect of the increased moisture resistance on the weathering performance was determined by evaluating the change in composite color and mechanical properties. The composite surfaces can be seen in Figure 3. Color values are reported in Table 3.

Figure 3. Composite surfaces before and after weathering.

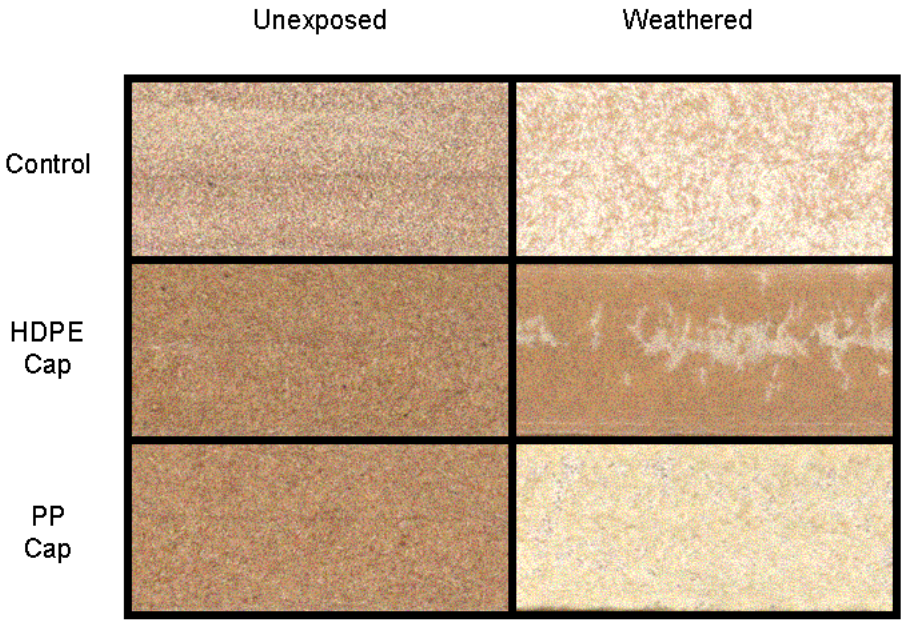


Table 3. Average values of color coordinates for control composites, and those with an HDPE or PP cap layer before and after weathering.

		L*	a*	b*	$\Delta E_{(\text{Weath – Unex})}$
Control	Unexposed	56.9 (1.2)	7.7 (0.2)	18.0 (0.3)	23
	Weathered	78.3 (0.8)	4.0 (0.2)	10.6 (0.6)	
HDPE	Unexposed	54.7 (0.3)	7.8 (0.2)	18.0 (0.3)	15
	Weathered	68.8 (5.3)	6.4 (1.8)	14.4 (3.5)	
PP	Unexposed	52.6 (0.5)	7.9 (0.1)	18.2 (0.2)	32
	Weathered	81.5 (0.7)	2.3 (0.1)	6.8 (0.2)	

Values in parentheses represent one standard deviation.

Figure 3 shows that the co-extruded composites were a bit darker than the control composites before weathering. This is confirmed by the color coordinates, the L* for unexposed samples with an HDPE of PP cap layer is slightly lower than for the control samples. Before weathering, the color coordinates a* and b* are similar for all three formulations. After weathering, the same trend occurred for all three formulations; L* increased while a* and b* decreased. This suggested a simultaneous lightening and loss of color. The composites with the best color retention were those with the HDPE cap layer, followed by the control sample, and the PP cap layer. The increase in L* was 26%, 38%, and 55% for the HDPE-capped WPCs, control WPCs, and PP-capped WPCs, respectively.

During weathering the composites are degraded by both water spray and UV light. Exposure to only UV light results in smaller increases in L* than exposure to both UV light and water spray [3]. Therefore, it was suggested that improving the moisture resistance of WPCs would improve color retention during weathering. Degradation of HDPE and PP by UV light includes surface oxidation. Comparing HDPE and PP, the degree of molecular branching determines the oxidation rate; more branching results in more oxidation [11]. Therefore PP oxidizes more readily than HDPE. One result of photodegradation can be surface cracking.

In our composites, both cap layers experienced surface cracking. However, the PP cap layer cracking was more extreme than the HDPE cap layer. Surface cracking of the PP appeared over the entire composite surface. The action of the water spray washed away the loose surface layer of the PP-capped composites, and there was no longer a continuous cap layer present. Surface cracking of the HDPE appeared as a crack down the middle of the composite with some cracks propagating to the edge, but the layer was mostly intact after weathering. For both capped materials, as the barrier that provided moisture resistance cracked, the action of both UV light and water contributed to composite lightening.

The mechanical properties are reported in Table 4. Before weathering, the MOE and MOR of the composites with the PP cap layer were higher than the control composites or the HDPE-capped composites. This was likely due to the higher MOE and strength reported for PP than for HDPE (Table 1).

Table 4. Average values of MOE and MOR for control composites, and those with an HDPE or PP cap layer before and after weathering.

		MOE (GPa)	MOR (MPa)
Control	Unexposed	2.09 (0.06)	14.7 (0.5)
	Weathered	1.83 (0.09)	25.1 (1.4)
HDPE	Unexposed	2.04 (0.05)	16.6 (0.7)
	Weathered	1.85 (0.06)	19.8 (1.0)
PP	Unexposed	2.21 (0.14)	18.7 (1.2)
	Weathered	1.65 (0.04)	20.4 (0.7)

Values in parentheses represent one standard deviation.

After weathering, all composites experienced a decrease in MOE and an increase in MOR. This appeared to conflict with past reports. After 1000 hours of accelerated weathering, flexural MOE and strength of injection molded 50% wood flour filled HDPE composites decreased [3]. The WPCs in this case were 3.2 mm (0.125 in.) thick. The decrease in mechanical performance was concluded to be a result of the degradative mechanism of water in the WPC. Crosslinking has been shown to occur during HDPE photodegradation [11]. Increases in MOE can be found when the matrix polymer crosslinks. HDPE was crosslinked during the manufacture of 40% wood flour filled HDPE. When compared with un-crosslinked composites, crosslinking HDPE resulted in composites with a much higher flexural strength and little, if any, improvement in MOE [12].

It may be that there are two competing mechanisms for mechanical property changes: losses in MOE and MOR due to the action of water with UV light, and increase in MOR with little or no change in MOE due to crosslinking HDPE matrix. The composites in this study were approximately 9.5 mm (0.375 in.). Perhaps in thicker composites the changes due to moisture are not as dominant, and crosslinking occurs through the thickness of the composite by means of free radical propagation. Further study is needed to completely elucidate the mechanism.

Summary and Conclusions

It has been shown that controlling moisture is key to improving weathering performance. Therefore, the effect of coating WPCs using co-extrusion on moisture uptake and weathering performance was evaluated. Co-extruded composites were manufactured using a base material of 50% wood flour, 44% HDPE and 6% lubricant. The composites investigated included a control WPC, and WPC capped with HDPE, and a WPC capped with PP.

Co-extrusion was found to greatly reduce moisture absorption of the WPCs. It was thought that this would improve the weathering performance. However, the cap layer of both the HDPE-capped composites and PP-capped composites cracked during photodegradation. This provided a pathway for moisture absorption by the WPC. Cracking of the PP cap layer was more extensive than cracking of the HDPE cap layer. As a result, color change was more extensive for the PP-capped WPC than for the HDPE-capped WPC. Color change was also higher for PP-capped WPC than the control WPC, likely due to increased susceptibility of oxidation of PP compared with HDPE.

Weathering changed the mechanical properties; the MOE decreased while the MOR increased. It is possible this was due to the dominant mechanism of HDPE crosslinking in the base composite over the degradative action of absorbed water. The mechanism needs further study.

Coating WPCs with a clear, co-extruded cap layer results in improvements in moisture resistance. Although co-extrusion did not provide real benefits for the protection of changes in mechanical properties, some promise was shown regarding improvements in color stability when WPCs were capped with HDPE.

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