FEASIBILITY OF USING MOUNTAIN PINE BEETLE-ATTACKED WOOD TO PRODUCE WOOD–PLASTIC COMPOSITES: PRELIMINARY WORK

Feng-Cheng Chang†
PhD Student

*Frank Lam**†
Professor
Department of Wood Science
University of British Columbia
2424 Main Mall
Vancouver, BC V6T1Z4, Canada

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Abstract. This study investigates the feasibility of using mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins)-killed lodgepole pine (*Pinus contorta* var. latifolia Engelm) to manufacture wood–plastic composites (WPCs). Preliminary formulations of various flour sizes (20, 40, 60, and 80 mesh), wood contents (40, 50, and 60%), and corresponding contents of high-density polyethylene (HDPE) without additives were used to make strip-like specimens. Extrusion and injection molding were performed to fabricate specimens for investigation of mechanical properties. A simple tensile experiment was conducted to select an appropriate formulation. The injection-molded MPB–wood–HDPE composites resulted in properties that were comparable with a commercial product and other similar studies. MPB wood showed great potential to be a raw material of WPC products.

Keywords: Mountain pine beetle, MPB, wood–plastic composites, WPCs, lodgepole pine, high-density polyethylene, HDPE, injection-molding.

INTRODUCTION

In western Canada, infestations of the mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) have been documented for over 85 yr (Taylor et al 2006). The MPB inoculates the tree with blue-staining fungi, primarily *Ceratocystis* spp. and several *Europhium* spp. (Woo et al 2005), which weakens the tree's defense mechanisms, interrupts water translocation, lowering MC, and eventually leading to death (Byrne et al 2006).

In addition, blue stain that occurs in the sapwood of the attacked trees appears in products made from stained logs, affecting which products can be made and sold profitably (Byrne et al 2006; Watson 2006). Moreover, processing dry MPB trees can generate more fine material and residues compared with healthy, green logs. Thus, there is a need to investigate alternative value-added wood-based products that can make use of these processing residues. In previous studies, the feasibility of using MPB wood for wood-cement was investigated (Chang and Lam 2008, 2009). Another potential option may be MPB wood–plastic composites (WPCs).

With market expansion, the WPC industry has experienced rapid growth in North America. These can range from decking products, lawn furniture, and playground equipment to industrial applications such as railings in marinas and bumpers for shipyards. WPCs are successful in the marketplace, primarily because they deliver consistent structural performance at a reasonable cost (Smith and Wolcott 2006).

WPCs are typically made using 30 – 60% wood filler. Wood flour can be used as a filler to reduce raw material costs and improve stiff-

* Corresponding author: franklam@interchange.ubc.ca
† SWST member

ness and dimensional stability over a range of temperatures with minimal weight increase (English et al 1997). When appropriate additives are added to increase fiber-matrix compatibility and adhesion, properties can be improved (English et al 1996; Lu et al 2000). Currently, most WPCs are made with low- or high-density polyethylene (LDPE and HDPE, respectively), both recycled and virgin. Based on the study of Selke and Wichman (2004), the performance of products made from recycled HDPE is at least as good as that from virgin. Other thermoplastics have also been used as matrices, including polypropylene, polyvinyl chloride, polystyrene, and acryloni-trile-butadiene-styrene (Clemons 2002), depending on the purposes of the products.

Wood flour is made by grinding postindustrial material such as planer shavings, chips, and sawdust into a fine, flour-like consistency. Typical sizes are 10 – 80 mesh (Stark and Berger 1997; Clemons 2002), and the geometry may affect the properties of products (Stark and Rowlands 2003).

Wood is available from both virgin and recycled sources (English et al 1996; Hwang 1997; Clemons 2002). Wood from small-diameter trees and underused species can also be used. Various wood species have been applied to the manufacture of WPCs, commonly pine (*Pinus* spp.), maple (*Acer* spp.), and oak (*Quercus* spp.) (Stark and Berger 1997; Clemons 2002). In general, hardwoods have slightly better tensile and flexural properties than softwoods (Stark and Berger 1997). In addition to wood, many particle and fiber types such as wheat, kenaf, cornstalk, and jute have been investigated (Rowell 1996; Caulfield et al 1998; Chow et al 1999). Based on other successful experiences, WPCs could be a potential value-added application for MPB wood.

Three common forming methods for WPCs are extrusion (forcing molten composite through a die), injection molding (forcing molten composite into a cold mold), and compression molding (pressing molten composite between mold halves). Extrusion is by far the most common method (Clemons 2002).

Different processing methods may affect the properties of products. Stark et al (2004) found that the strength of a product made by injection is greater than that made by extrusion. Because of its higher processing pressure, the density of injection-molded products is higher than that of extrusion products. Furthermore, Clemons and Ibach (2004) indicated that processing methods also affect the moisture adsorption and fungal resistance.

The properties of WPCs have been intensively investigated and compared with solid wood and conventional wood-based products (Falk et al 1999). The results have shown that WPCs are inferior to solid wood products in strength properties, including bending, compression, shear, and hardness, with the exception of withdrawal strength; however, WPCs performed well in thickness swelling, moisture absorption, and durability.

The development of such products and exploration of new methodologies for producing new materials need to be accompanied by a full understanding of the structural properties of WPCs. The suitability of MPB wood in the manufacture of WPC products requires careful evaluation. In this study, preliminary work was done with different wood/plastic ratios and flour sizes to examine the natural compatibility between MPB lodgepole pine and HDPE. Finally, the prototype specimens were fabricated with the injection molding process, and mechanical properties were evaluated.

MATERIALS AND METHODS

MPB-killed lodgepole pine (*Pinus contorta* var. latifolia Engelm) chips were obtained from logs from the Vanderhoof area of British Columbia. The wood flours were prepared by grinding chips to pass ASTM 20, 40, 60, and 80 mesh screens. The wood flours were dried at $103 \pm 2°C$ to reduce the MC to less than 3% before manufacture. One advantage of using MPB pine is that the MC of the wood is significantly lower than the wood in healthy trees, thereby reducing drying cost.

The commonly used plastic material in commercial WPC products—virgin HDPE, density 950 kg/m^3—was selected as the matrix. The specimens were produced with various formulations of wood content (40, 50, and 60%) and the balance of HDPE. To study the natural compatibility between the MPB wood and HDPE, no additives were used in this study.

The constituents were mixed dry by hand and passed through a single-screw extruder (C.W. Brabender Instruments Inc, PL2000 and FE2000). The mixture of MPB pine and HDPE was fed into the hopper of the extruder at 180°C in the three sections of the barrel and 185°C in the die. A screw rotation speed of 60 rpm was used to move the extrudate through an annular die. It was cut and pelletized for further specimen formation and mechanical tests. The extrusion process of the MPB–wood–plastics prototypes was undertaken at CST Innovations Ltd. in New Westminster, BC.

Preliminary Tests

The experimental plan included three parts. Part 1 was a preliminary test to narrow the focus to appropriate formulations. The WPC strip-like extrudate, with length and diameter approximately 50 and 2.7 mm, respectively, was subjected to a simple tensile test (Fig 1a). Thirty replicates were tested using a Thwing-Albert electronic tensile tester. Distance between grips was 20 mm and the loading rate was 2 mm/min. Values of the maximum load were recorded to calculate the approximate tensile strength, and the results were analyzed using analysis of variance (ANOVA) and Tukey's studentized range test for multiple comparisons of various formulations.

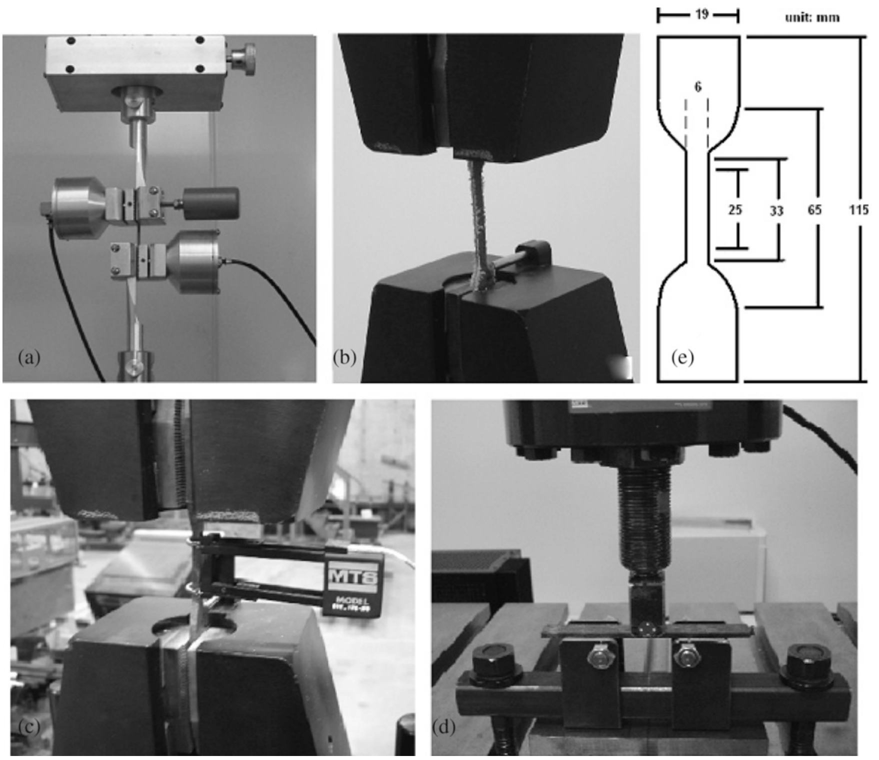

Figure 1. The assembly for various tests of this study. (a) Simple tensile test for the wood-plastic strip; (b) tensile test for the extruded sheet; (c) tensile test for the injection-molded specimen; (d) flexural test for injection-molded specimen; (e) ASTM D638 type IV tensile specimen.

Table 1. *Injection molding conditions.*

Condition	Unit	Zones			
		Rear	Middle	Front	nozzle
Injection pressure	MPa	52	52	52	39
Temperature profile	°C	190	185	185	180
Injection speed	(L/s)	0.042	0.042	0.042	0.021
Screw rotation speed	rpm	180			
Screw diameter	mm	25			
Cooling time	s	20			
Mould temperature	°C	50			

Extruded-Sheet Specimens

Next was a test for the chosen formulations. The MPB pine–WPC mixture was molded by the extruder with a die to form approximate 2.9-mm-thick sheets and cut as a type-IV specimen for a tensile test in accordance with ASTM D638 (Fig 1b). The MTS Sintech 30/D test machine was used to conduct the test on 15 specimens, from which one formulation was selected for the prototype process.

Injection-Molded Specimens

In part 3, selected formulation of MPB pine–WPC pellets, which were made by the extrusion process, were processed using injection molding to make test specimens. The specimens were fabricated at the Plastic Industry Development Center, Taichung, Taiwan, using a 50-ton Chen-Hsong Super Master 90TS. Processing conditions are given in Table 1.

The density of the specimen was measured by the water immersion method to obtain the volume of irregular specimens. The type-IV tensile test was done according to ASTM D638 (Fig 1c) and the flexural test to ASTM D790 (ASTM 2007b) with five replicates per test. Specimens of 127 × 12.7 × 3.2 mm with 51-mm span and 1.35-mm/min crosshead motion (Fig 1d) were tested using MTS Sintech 30/D and MTS 810 systems. The commercial product was tested as a reference. Finally, the cross-section from the fracture surface of tensile specimen was observed with an optical microscope and a scanning electron microscope (SEM).

The theoretical density of composites, in terms of mass fractions, is as follows:

$$\frac{1}{\rho_c} = \frac{W_f}{\rho_f} + \frac{W_m}{\rho_m} \tag{1}$$

where ρ_c, ρ_f, and ρ_m are the densities of the composite, fiber, and matrix, respectively; and W_f and W_m refer to the mass fractions of the fiber and matrix, respectively. Moreover, during manufacture, voids were introduced into the composites, causing the theoretical density of the composite to be higher than the actual density (Kaw 1997). Therefore, the volume fraction of the void of this product was calculated by the following equation:

$$V_v = \frac{\rho_{ct} - \rho_{ca}}{\rho_{ct}} \tag{2}$$

where ρ_{ct} and ρ_{ca} are the theoretical and actual densities of the composite, respectively.

RESULTS AND DISCUSSION

Preliminary Tests

Preliminary tests were conducted to narrow the selection of several appropriate formulations for further analysis. Figure 2 shows the MPB–wood–HDPE extrudate strips. It was observed with a high-resolution scanner that the smaller wood flour size (higher screen number) and the higher wood content resulted in a smoother surface.

The results of the tensile test (Table 2) showed that 60 mesh wood flour and 40% wood content resulted in the highest strength. According to the results of ANOVA (Table 3), both variables of wood flour size and wood content influenced the final property. Generally, a lower wood content resulted in higher strength. This trend has also observed in other studies (Raj et al 1990; Hwang 1997; Stark and Berger 1997). Furthermore, the geometry of wood flour also affects results: smaller flour resulted in better strength, which was found in another study (Takatani et al 2000).

Not only the size of the wood flour, but also its aspect ratio affects strength and stiffness (Stark and Rowlands 2003). However, based on the

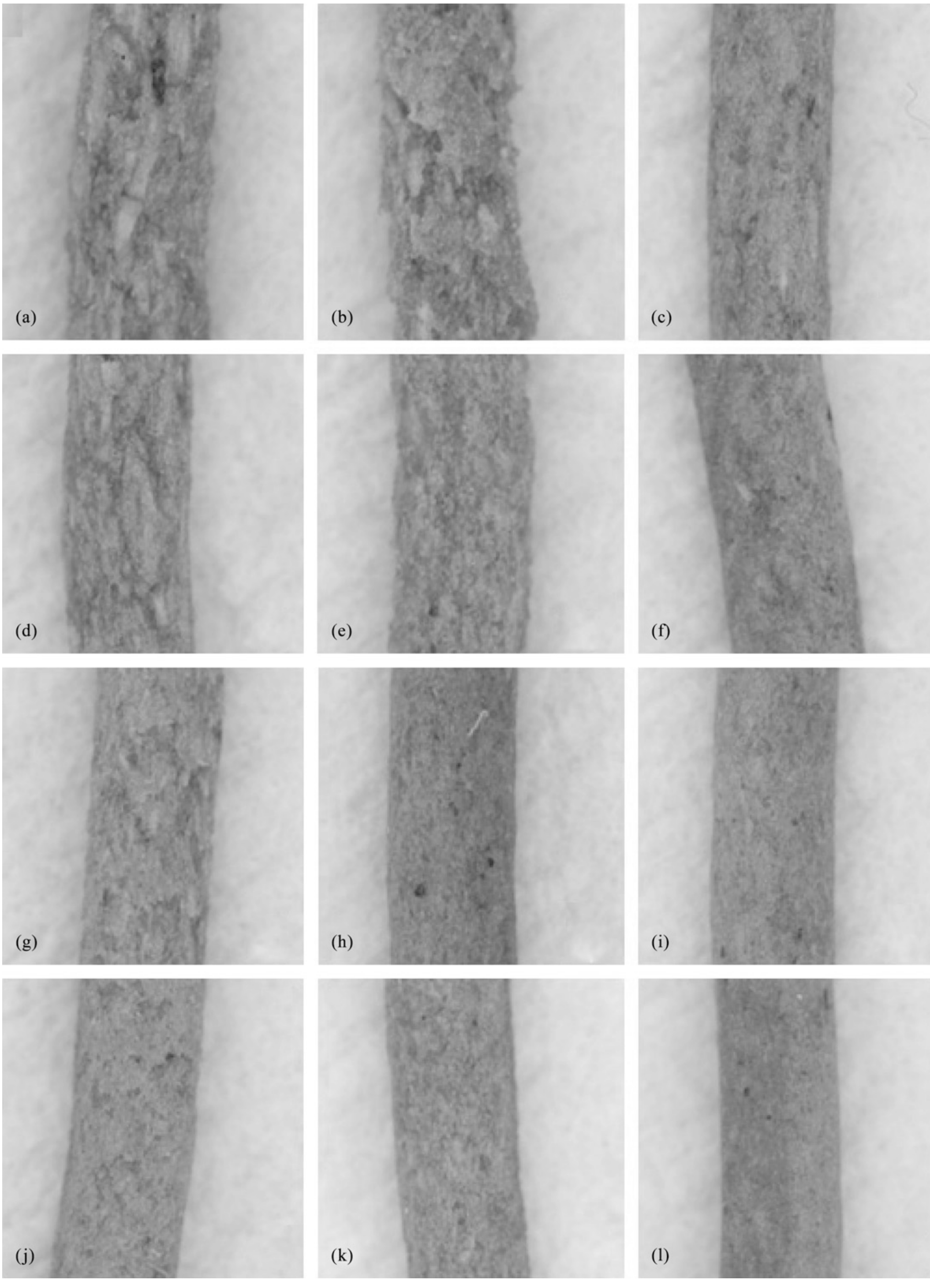

Figure 2. MPB–WPC strip specimens (no. of screens–wood content [%]). (a) 20 mesh–40%; (b) 20 mesh–50%; (c) 20 mesh–60%; (d) 40 mesh–40%; (e) 40 mesh–50%; (f) 40 mesh–60%; (g) 60 mesh–40%; (h) 60 mesh–50%; (i) 60 mesh–60%; (j) 80 mesh–40%; (k) 80 mesh–50%; (l) 80 mesh–60%.

results of multiple comparisons (Table 2), there was no statistically significant difference among the 40 mesh–40% wood content, 60 mesh–40% wood content, and 80 mesh–40% wood content WPCs, whereas the 20 mesh–40% wood content was not as strong. This may imply that the flour size should be smaller than 20 mesh to obtain better quality; nevertheless, considering processing efficiency, the flour size should not be much smaller. Berger and Stark (1997) also mentioned that the finer the wood flour, the more the processing and therefore the higher the cost.

Stark and Berger (1997) indicated that using smaller wood particles decreased the melt flow index, because the unfilled region within the polymer decreased and this may cause difficulty in processing. Moreover, in the report of Gacitua et al (2005), it was also found that the size of wood flour does not have an important influence on the mechanical properties of the compound.

Table 2. *Results of multiple comparison for preliminary tensile strength by Tukey's studentized range test.*

Formulation[a]	Mean (SD) (MPa)	Tukey grouping[b]				
60 mesh–40%	4.56 (0.98)	A				
80 mesh–40%	4.17 (0.94)	A	B			
60 mesh–50%	4.07 (0.61)	A	B			
60 mesh–60%	4.01 (0.40)	A	B			
40 mesh–40%	4.12 (1.16)	A	B	C		
40 mesh–60%	3.74 (0.34)		B	C	D	
80 mesh–60%	3.68 (0.65)		B	C	D	
40 mesh–50%	3.55 (0.64)		B	C	D	
80 mesh–50%	3.48 (0.71)			C	D	
20 mesh–60%	3.42 (0.40)			C	D	
20 mesh–40%	3.35 (0.94)				D	E
20 mesh–50%	2.91 (0.36)					E

[a] Formulation means wood flour size (mesh)–wood content (%).
[b] Means with the same letter are not significantly different.

The interfacial bonding between wood and HDPE is not strong because of the inherent hydrophobic nature of HDPE and hydrophilic nature of wood. The function of wood is as a filler rather than reinforcement; therefore, a higher content of wood may not improve the strength. However, improvement in the modulus with increasing wood content was observed in other studies (Stark and Berger 1997; Selke and Wichman 2004; Lee et al 2008).

Also, a high wood content may cause some processing difficulties owing to the uneven dispersion of the wood flour, poor wettability, and the low-flow mobility of the composite (Jam and Behravesh 2007, 2009)

Tensile Test for Extruded-Sheet Specimens

Based on the data in Table 2, the formulations of 60 mesh–40% wood content, 80 mesh–40% wood content, and 40 mesh–40% wood content were selected for this step. The selected formulations were used to fabricate sheet-like extrudates, which were then machined as ASTM D638 type IV tensile specimens (ASTM 2007a). Because no processing-aid additive was used, the surface of the specimen was very rough; therefore, lubricants should be considered for manufacture. The results of the tensile tests were analyzed with the t-test ($\alpha = 0.05$) and ANOVA (Table 4) and showed that there was no significant difference among three groups of specimens, reflecting the same outcome as the preliminary test. Therefore, this also indicates that the simple tensile test is adoptable for pre-evaluation. Finally, the formulation of 60 mesh–40% wood content was selected for further tests.

Table 3. *Result of two-way analysis of variance for preliminary test.*

Source of variation	SS	df	MS	F	p value[a]	$F_{critical}$
Wood content	1.84E+13	2	9.22E+12	17.35814	6.52E-08	3.021669
Wood flour size	4.45E+13	3	1.48E+13	27.90972	3.39E-16	2.630567
Interaction	4.33E+12	6	7.22E+11	1.360271	0.2299	2.124654
Within	1.85E+14	348	5.31E+11			
Total	2.52E+14	359				

[a] p value less than $\alpha = 0.05$ means significant effect.

Injection-Molded Specimens

The prototype specimens were made with the selected formulation (60 mesh–40% wood content) using the injection molding process. The pelletized MPB–wood–HDPE materials were fabricated as per ASTM standard specimens. The overall density of the products was 1080 kg/m^3 (coefficient of variation [CV] = 0.41%). Based on Eq 1, the wood density was calculated as 1360 kg/m^3.

Because wood cells could be compressed or filled during processing, the high pressure of the injection molding process on the composite caused the high density of wood flour (Stark et al 2004) to approach the wood cell wall density of approximately 1500 kg/m^3 (Haygreen and Bowyer 1996). Furthermore, the theoretical density of the composite product should be approximately 1110 kg/m^3. Based on Eq 2, the void fraction of the product was 2.7%, which may result from the cell lumens of wood that were not compressed or filled during processing as well as free space of the polymeric matrix.

The results of the tensile and bending tests are summarized in Table 5. The injection-molded MPB–WPC with no additive showed higher tensile strength than the extruded commercial

Table 4. *Result of tensile test for extruded-sheet specimens and analysis of variance (ANOVA).*

Groups	Mean (MPa)	SD				
40 mesh	5.23	0.30				
60 mesh	5.09	0.33				
80 mesh	5.07	0.54				
ANOVA						
Source of variation	SS	df	MS	F	p value[a]	$F_{critical}$
Between groups	0.235965	2	0.117982	0.725994	0.49305	3.354131
Within groups	4.387811	27	0.162512			
Total	4.623775	29				

[a] p value greater than $\alpha = 0.05$ means no significant effect.

Table 5. *Results of tensile and flexural tests for injection-moulded specimens and comparison with a commercial product and similar products that also used HDPE and 40% fillers from other studies.*

	Tensile MOE (GPa)	Tensile MOR (MPa)	Flexural MOR (MPa)	Processing method	Wood species	Additive
MPB–WPC	2.29 (20.01)	19.99 (6.89)	23.02 (6.22)	Injection	MPB lodgepole pine	Not applicable
Commercial product	1.69 (11.73)	9.66 (4.13)	17.36 (4.24)	Extrusion	Reclaimed hardwood sawdust	Not available
Raj and Kokta 1995	1.27	Roughly 15.00	Not available	Compression	40% Aspen	Not applicable
Balatinecz et al 1999	2.57 (2.7)	34.20 (0.58)	63.70 (0.31)	Injection	40% Hardwood Grade 600	5% Malleated processing aid
	1.68 (3.57)	25.10 (0.80)	49.50 (1.21)		40% Coal ash	
Stokke et al 2001	1.05	20.5	59.83	Extrusion	40% Pine	Not applicable
	0.94	16.34	27.25		40% Fescue	
	1.114	20.82	32.67		40% Switchgrass	
Adhikary et al 2008	1.64 (5.49)	11.8 (9.32)	17.9 (5.02)	Compression	40% Radiata pine	Not applicable
Migneault et al 2008	2.83 (1.41)	23.4 (0.85)	37.8 (1.3)	Extrusion	40% White birch chemithermomechanical pulps	Not applicable
Zhang et al 2008	1.25	14.46	Not available	Compression	40% Black spruce with steam treatment	Not applicable

Numbers in parentheses are the coefficient of variation (%).

product and had comparable properties with other similar studies (Table 5). Furthermore, based on the low CV, WPC products showed relatively consistent qualities in the tests. This implies that the application of MPB wood in WPCs is acceptable, because in this case, the mechanical properties of products are governed by the matrix. However, it should be noted that the results may be influenced by the formulations, processing methods, sample sizes, and properties of the plastic.

During the bending test, a large deflection occurred without failure of the sample. It was assumed that a low wood content may not be able to significantly improve stiffness. In addition, the lack of coupling agent and compatibilizer caused the product to be very ductile, and the interaction and adhesion between the fibers and matrix has a significant effect in determining the mechanical and physical behavior of composites (Caulfield et al 1998; Oksman and Clemons 1998; Stark 1999).

The key factor in the reinforcement for properties of thermoplastic with fiber is the building of strong bonding to efficiently transfer stress from matrix to fiber. Some malleated copolymers (eg maleated polypropylene, maleated polyethylene) and silane have been studied and proven as useful compatibilizers or coupling agents for WPC manufacture (Lu et al 2000; Selke and Wichman 2004; Chowdhury and Wolcott 2007; Lee et al 2008; Zhang et al 2008). In addition, the effects of different lubricants on WPCs have also been studied (Harper and Wolcott 2004). Selection of additives should be carefully considered for future manufacture to improve the quality of the product.

Figure 3 shows the microscopic images of an injection-molded WPC specimen cut after the tensile test. Ideally, wood flours are completely encapsulated in the matrix to form the product; however, it is clearly observed that the bonding between wood and HDPE is not strong evidenced by wood being pulled out during the test. Furthermore, wood flour did not greatly contribute to the strength with HDPE tensile

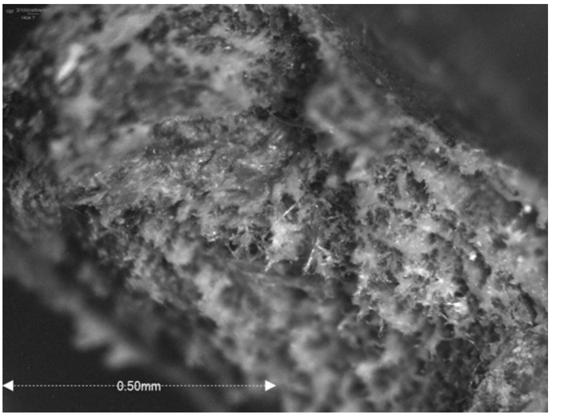

Figure 3. Microscopic images (3×) of fracture surface.

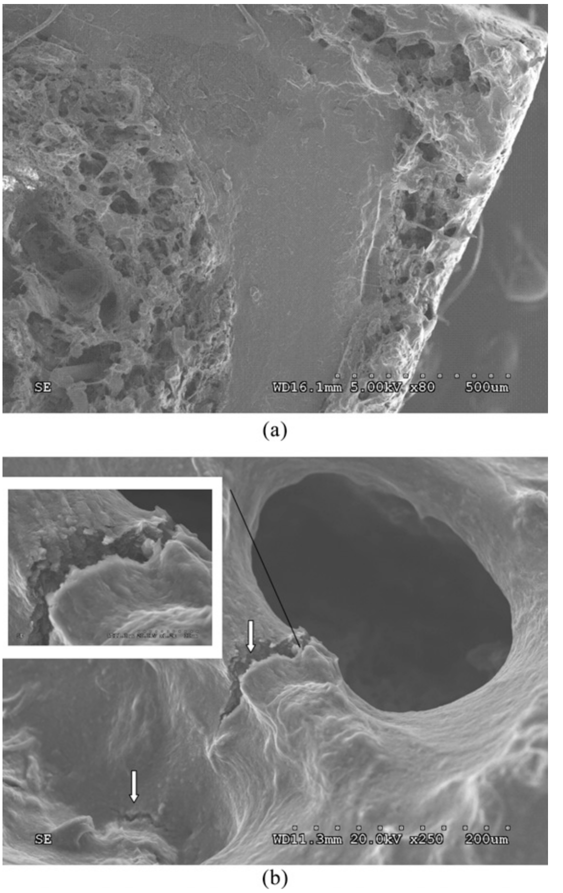

Figure 4. Scanning electron microscopic images. (a) Inner morphology of the product; (b) crack because of tension failure.

failure observed on the fracture surface. The SEM image (Fig 4a) shows the morphology of the inner structure of the product. The voids may be attributed to the lack of holding pressure. The fracture generated from tension failure was also observed (Fig 4b).

CONCLUSIONS

This research is the first stage in developing prototype WPCs using MPB wood. In view of the experiments undertaken in this study, the injection-molded MPB–wood–HDPE composite product showed comparable properties with a commercial product and other similar studies. In addition, a simple tensile test for strip-like extrudate may be acceptable for preliminary selection of formulations.

To test the natural compatibility between MPB wood and HDPE, no additive was used. Further study on the improvement of bonding at the interface between filler and matrix is necessary to obtain better quality products.

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