FEASIBILITY OF USING MOUNTAIN PINE BEETLE ATTACKED WOOD TO PRODUCE WOOD–PLASTIC COMPOSITES

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Abstract. Previous work showed that mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) attacked wood has the potential as raw material for producing wood–plastic composites (WPCs). In the present study, MPB-WPC products were fabricated by extrusion, and the properties of density, flexural, compression, hardness, and nail and screw withdrawal were evaluated. Statistical analyses, including the analysis of variance, multiple comparisons, multiple regression, and the analysis of probability distribution, were conducted to understand the properties of products and the effect of formulations. Results of regression analysis showed significant relationships between the properties and the formulations. Mechanical properties of coupled products were significantly better than those of uncoupled products. The formulation also influenced the behavior and surface condition of the products. In general, greater wood content resulted in a slightly higher density but showed relatively less ductile behavior and failure at smaller deformations. The products with a higher content of high-density polyethylene showed better strength in all aspects, however, a relatively lower stiffness and larger deformation at failure also appeared. Because of the uniform quality of WPCs, the mean value of the properties can be used as a characteristic value for application.

Keywords: Mountain pine beetle (MPB), wood–plastic composites (WPCs), lodgepole pine, high-density polyethylene (HDPE), extrusion.

INTRODUCTION

The mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) epidemic has been a serious issue for western Canada for years. MPB is an inoculator of blue-stain fungi in trees, which weakens the defense mechanisms, interrupts water translocation, lowers wood moisture content, and eventually leads to death (Byrne et al 2006). The British Columbia Ministry of Forests and Range estimated that MPB has now killed a total of 675 Mm^3 of timber since the current infestation began, and the cumulative area affected is estimated at 16.3 MHa (BCMFR 2010).

Outbreaks have been observed in all pine species, however, they have occurred principally in lodgepole pine (*Pinus contorta* var. latifolia). In British Columbia, lodgepole pine stands constitute a major commercial resource, comprising 50% of the province's interior annual harvest (Woo et al 2005). Lodgepole pine timber, because of MPB, is affected by blue stain that occurs in the sapwood of the attacked trees and

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appears in products made from stained logs, which limits the products that can be made from the wood and profitably sold (Byrne et al 2006).

According to a recent report (Hamilton 2009), the government of British Columbia has declared that the MPB epidemic is largely over, however, it is not because the beetles have been defeated, but because they have run out of trees. This, in itself, turns out to be another problem of wood supply, because the vast majority of pine stands has been killed. Therefore, two important tasks need to be carefully considered: finding replacements for solid wood and developing value-added products for the low-grade wood of interest.

Wood–plastic composites (WPCs) are being used to create products such as landscape timbers, railing, decking, fencing, window and door elements, panels, molding, roofing, siding, and even flooring, louvers, indoor furniture, railings in marinas, and bumpers for shipyards. Past research has shown that WPCs have experienced rapid growth and become a major player in the North American decking market (Clemons 2002; Winandy et al 2004; Smith and Wolcott 2006). This success is primarily attributed to appropriate structural performance at a reasonable cost (Smith and Wolcott 2006). Schneider and Witt (2004) indicated that the advantages of WPCs can result in increased demands for value-added WPC products and that the market will increase dramatically in the near future and continue to grow in the long term.

Many factors may influence the properties of WPCs. The formulation, including the contents of wood, plastic, and additives (Stark and Berger 1997; Caulfield et al 1998; Lu et al 2000; Stark and Rowlands 2003; Wolcott 2003; Chowdhury and Wolcott 2007), and wood particle size and geometry (Stark and Berger 1997; Takatani et al 2000; Stark and Rowlands 2003) significantly affect WPC properties. Extrusion is currently the most common method for processing WPCs. Extrusion is a continuous process in which many operating parameters such as screw speed, temperature profile in extruder barrel and die, and cooling rate can influence product qualities (Tucker and Bender 2003).

Various wood species have been used in the manufacture of WPCs; pine (*Pinus* spp.), maple (*Acer* spp.), and oak (*Quercus* spp.) are commonly used (Stark and Berger 1997; Clemons 2002). 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). Our previous work showed that the MPB-killed wood has great potential to be a raw material for WPC products (Chang and Lam 2010).

Comparisons between WPCs and conventional wood composites indicate that wood fiber–plastic composite panels are inferior to conventional wood-based panels in bending modulus of elasticity (MOE) and bending modulus of rupture (MOR). However, the composite panels performed well in thickness swell and moisture sorption (Falk et al 1999). In other research, the quality of WPCs in dimension stability, weather resistance, moisture absorption, and fungi resistance has also been studied (Morris and Cooper 1998; Chow et al 1999; Falk et al 2000a, 2000b; Verhey et al 2001; Clemons and Ibach 2002; Pendleton et al 2002; Verhey and Laks 2002; Verhey et al 2003; Wang and Morrell 2004; Lopez et al 2005; Wang and Morrell 2005).

The processing of the dry MPB-killed logs may lead to the generation of more fines and residues (Byrne et al 2006; Watson 2006) compared with healthy, green logs. Finding a value-added use for the fines and residues from the processing of MPB logs is an important task. In this work, MPB-WPC decking products were fabricated by extrusion, and various properties were evaluated based on formulations and mechanical behavior. The statistical analyses, including the analysis of variance, multiple comparisons, multiple regression analysis, and analysis of probability distribution, were also conducted to understand the properties of products and the effect of formulations. The results of this work provide information on how the MPB-WPC products perform in various mechanical tests and what factors influence these properties.

MATERIALS AND METHODS

MPB-killed lodgepole pine lumber was obtained from logs from the Vanderhoof area of British Columbia. The lumber was chipped and refined into flour with a hammermill. A hammermill screen was selected to provide a particle size distribution similar to that of commercial wood flour (Fig 1). Sixty-mesh pine flours (*Pinus* spp.), supplied by American Wood Fibers (AWF), were also obtained as a reference. The wood flours were dried with a steam tube dryer to approximately 2% MC before extrusion.

Specimens were produced with various formulations of wood content and the corresponding amount of plastic by weight. Virgin high-density polyethylene (HDPE) (Equistar Petrothene® LB0100-00, density 950 kg/m^3, and melt index 0.5 g/10 min) was selected as the matrix. Additives, meleated polypropylene (MAPP, Honeywell A-C® 950P) and a lubricant (Honeywell OptiPak™ 100) were included in the formulations to improve the processability and quality of the products. Details of the formulations are shown in Table 1.

The constituents were dry-mixed using a ribbon blender for 10 min and fed directly through a counterrotating twin screw extruder (Cincinnati-Milacron TC86) at a screw speed of 5 rpm with the temperature profile as shown in Table 2. MPB-WPC solid deck boards were produced through a 25 × 140-mm solid profile die and cooled by a water spray system. The extrusion was done at the Composite Materials and Engineering Center at Washington State University, Pullman, WA.

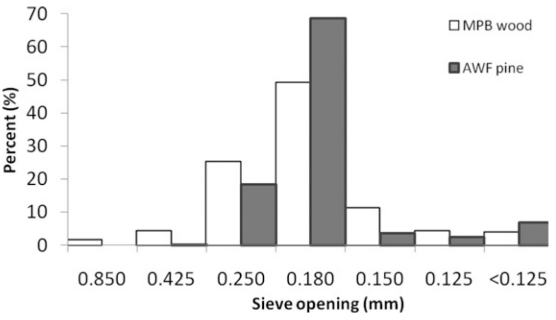

Figure 1. Particle size distribution of mountain pine beetle wood and American Wood Fibers pine flours.

Tests for the product properties were conducted according to D7031 (ASTM 2009d), particularly for the evaluation of mechanical and physical properties of the WPC products and reference to the corresponding standards (Table 3). Before the tests were conducted, the products were conditioned for at least 4 wk in a constant climate room at 20 ± 1°C and 65 ± 5% RH.

The density of the specimens was determined by ratio of the weight to the volume of the specimen. The volume of the specimen was measured by the water immersion method according to the D2395 standard method B mode II (ASTM 2009b). MTS Sintech 30/D and MTS 810 systems were used to conduct tests at ambient conditions. Comparisons of the different formulations were examined with analysis of variance (ANOVA, $\alpha = 0.05$) for significant effects, and the Tukey test (confidence level 95%) was also

Table 1. Formulations of products.

	Formulations (% by weight)				
Material	F1	F2	F3	F4	F5
MPB wood flour	50.0	58.9	66.7	60.0	—
60-mesh AWF pine	—	—	—	—	58.9
HDPE	46.7	37.8	30.0	39.0	37.8
MAPP	2.3	2.3	2.3	0.0	2.3
Lubricant	1.0	1.0	1.0	1.0	1.0
Total	100.0	100.0	100.0	100.0	100.0

MPB, mountain pine beetle; AWF, American Wood Fibers; HDPE, high-density polyethylene; MAPP, meleated polypropylene.

Table 2. Temperature profile for the extrusion process.

	Temperature (°C)
Barrel zone 1	171
2	171
3	171
4	171
Screw	171
Die zone 1	177
2	177
3	177
4	193

Table 3. Experimental conditions.

Property	ASTM	Sample size Length (mm)	Width (mm)	Thickness (mm)	Load speed (mm/min)	Replicates
Density	D 2395[a]	50	50	22	—	10
Flexure	D 4761[b]	406	50	22	10	10
Compression	D 4761	102	22	22	0.61	5
Hardness	D 1037	150	75	22	6	10
Nail withdrawal	D 1037	150	75	22	1.5	5
Screw withdrawal	D 1037	100	75	22	15	5

[a] D 2395 was used only to measure the volume of specimen. Density was determined by weight/volume of the specimen.
[b] ASTM (2009c)

conducted for significant differences between groups.

Regression analyses for various properties were conducted to determine the effect of formulations on properties of the products. Three main explanatory variables, wood content (WC), HDPE content (PC), and coupling agent (CA), were examined. CA was deemed a qualitative variable, because there were only two options in this study—with or without the coupling agent. The interactions between the variables were also investigated and removed if no significant effect existed.

Because the true function is unknown, this study adopted a polynomial response surface method, which is usually approximated by a second-order regression model, which was set up with three variables:

$$\begin{aligned} Y = {} & \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 \\ & + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{12} x_1 x_2 \\ & + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \varepsilon_i \end{aligned} \tag{1}$$

where,

$$Y = \text{the property of interest}$$
$$x_1 = \text{WC}$$
$$x_2 = \text{PC}$$
$$x_3 = \text{CA} = \begin{cases} 1 \text{ with coupling agent} \\ 0 \text{ without coupling agent} \end{cases}$$

β_0 = interception; β_1, β_2, β_3 = coefficient for WC, PC and CA, respectively; β_{12}, β_{13}, and β_{23} = the interaction effect coefficients for interaction between pairs of variables; and ε_i = error.

RESULTS AND DISCUSSION

Properties of Products

The appearance of MPB-WPC products were affected by their formulation. Jam and Behravesh (2007, 2009) mentioned that a high content of wood may cause some processing difficulties from an uneven dispersion of wood flour and low flow mobility of the composites. In addition, slip resistance between wood flours may increase within the melt, thus, when there is an increase in the wood filler fraction, the shear viscosity of the melt rises as well (Chastagner and Wolcott 2005). Kumari et al (2007) also mentioned that the incorporation of rigid material to polymeric matrices limits the free mobility and increases the apparent viscosity.

However, products with lower wood content (formulations F1 and F2, Table 1) and MAPP had edge tearing and matte surfaces (sharkskin, as shown in Fig 2a, caused by the stick-slip phenomenon), whereas a higher wood content formulation with MAPP (F3) and without MAPP (F4) (Fig 2b) resulted in a glossy surface. In addition, the wood flours may deposit on the wall and die surfaces to allow continuous slip for the molten WPC mixture. Thus, the sharkskin was decreased in F3. Li and Wolcott (2004) also mentioned that the addition of wood flours increases the contribution of wall slip. Solutions to improve the surface quality can include

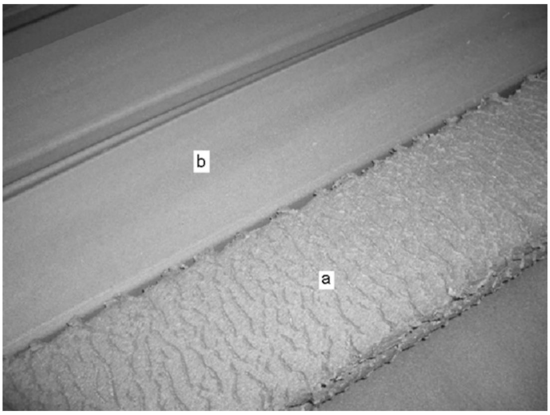

Figure 2. Mountain pine beetle wood–plastic composite products.

addition of a lubricant, an additive, or a processing aid (such as talc); adjustment of the temperature profile of the die lips; and modification of the die exit (Vlachopoulos and Strutt 2003).

The density of the product is summarized in Table 4. If the effect of the lubricant is neglected, a higher wood content resulted in a slightly higher density. The density of MAPP is 930 kg/m^3, similar to HDPE (950 kg/m^3), therefore, it has approximately the same product density contribution as HDPE. With an increase in wood flour content, voids may develop, because they are created principally from cell lumens of wood and voids between wood flour that were not compressed or filled during processing as well as free space in the polymeric matrix. However, the density of cell wall substance is approximately 1500 kg/m^3, which is higher than HDPE, and assuming that the wood structure was completely compressed or if the polymer filled the lumen and voids in the wood flours during processing, it is reasonable that the density of the products became higher with increasing wood content.

Table 4 also shows the results of the mechanical tests. In comparison with the commonly used pine flours, except for hardness, there was no significant difference between the MPB-WPC products (F2) and the AWF-WPC products (F5) on the basis of the same formulation. This implies that even beetle-infected wood can be good raw material for WPCs. In addition, the low coefficients of variation imply that the properties of WPCs are consistent.

Table 4. Properties of MPB-WPC decking products.

	Formulations				
Properties	F1	F2	F3	F4	F5
Density (kg/m^3)	1110	1153	1184	1163	1167
	(0.6)[a]	(0.4)	(0.6)	(0.8)	(0.5)
MOE (GPa)	3.9	4.3	5.1	3.4	4.5
	(3.1)	(6.6)	(7.4)	(15.3)	(4.0)
MOR (MPa)	38.3	34.3	30.5	21.9	33.9
	(4.4)	(3.1)	(8.8)	(6.3)	(1.3)
Compression (MPa)	30.8	28.6	27.4	19.4	28.8
	(3.8)	(2.4)	(5.5)	(1.1)	(3.3)
Hardness (kN)	12.6	12.0	10.2	9.6	10.9
	(1.0)	(1.8)	(3.8)	(2.7)	(3.7)
Nail withdrawal (N)	542.1	548.7	485.1	376.3	486.0
	(14.2)	(9.7)	(7.8)	(7.1)	(9.2)
Screw withdrawal (N)	3656	3474	3271	2413	3443
	(4.0)	(4.3)	(3.8)	(3.8)	(6.8)

[a] Numbers in parentheses are the coefficients of variation (%).

MPB, mountain pine beetle; WPC, wood–plastic composite; MOE, modulus of elasticity; MOR, modulus of rupture.

Figure 3 shows the characteristic load-deformation curves of products from the mechanical tests. Because WPCs are polymer-based materials, all products showed a nonlinear load-displacement response and a more or less plastic deformation during the tests, and they sustained large elongation before fracture. The mechanical properties of the uncoupled product (F4) were apparently inferior to the other three coupled products (F1-F3), resulting in a lower yielding strength and lower stiffness but better nail withdrawal. It is assumed that poor interfacial adhesion between wood and HDPE could provide a weak area for crack propagation, thus producing properties with less strength. The coupling agent could build interfacial adhesion to improve the properties. Furthermore, a greater wood content showed relatively less ductile behavior and failure at a smaller deformation. The products with a higher HDPE content showed better strength in all aspects but with relatively lower stiffness and larger deformation. Consequently, depending on specific formulations, WPCs can show very different responses. An important task when formulating WPCs should be consideration of the behavior of the end product.

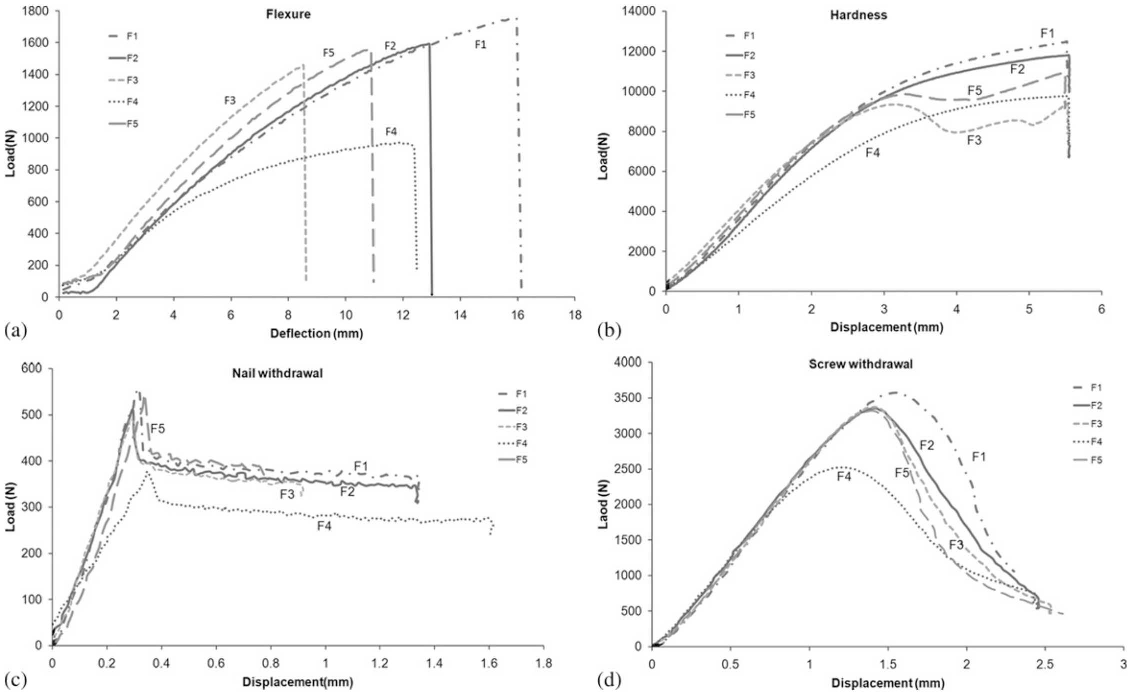

Figure 3. Characteristic load-deflection/displacement curves from various mechanical tests: (a) flexure; (b) hardness; (c) nail withdrawal; (d) screw withdrawal.

Statistical Analysis

According to the ANOVA (Table 5), the formulation of the WPCs significantly influenced the product properties. The results of the mechanical tests had a general trend that higher wood content has lower strength but higher stiffness. The same improvement in the stiffness with increasing wood content has been observed (Stark and Berger 1997; Selke and Wichman 2004; Lee et al 2008). In addition, nail withdrawal was relatively unaffected by the different formulations. The critical factor that affected the fastener properties was the coupling agent. Falk et al (2001) also found a similar result and pointed out that the screw-withdrawal capacity of WPCs panels was equal to or greater than that of conventional wood panel products. Therefore, in summary, the determinative component is the coupling agent, which can significantly improve WPC product properties.

The results of the response function analysis are summarized in Table 6. The interaction and quadratic effects were eliminated when they were found to be highly correlated with the explanatory variables (ie WC, PC, and CA). Low P values provided evidence regression relationships between properties and formulations. Generally, there was a strong relationship between the formulation and each property, except nail withdrawal. This observation agrees with Falk

Table 5. Results of ANOVA for the effect of formulations on product properties.

	ANOVA		Tukey test				
Properties	F-value	*p*-value	F1	F2	F3	F4	F5
Density	195.52	<0.01*	a[a]	b	c	d	d
MOE	39.81	<0.01*	a	a	b	c	a
MOR	149.82	<0.01*	a	b	c	d	b
Compression	118.99	<0.01*	a	b	a	c	b
Hardness	291.07	<0.01*	a	b	c	d	e
Nail withdrawal	11.69	<0.01*	a	a	a	b	a
Screw withdrawal	88.30	<0.01*	a	a	b	c	a

* Significant effect.

[a] For each property, the same letter means no significant difference between groups.

ANOVA, analysis of variance; MOE, modulus of elasticity; MOR, modulus of rupture.

Table 6. Results of regression analysis.

Properties	Regression equation	SE_E[a]	R^2	R^2-adj	p	Parameter estimate	p-parameter estimate
MOE (MPa)	$= 53504 - 782\, x_1 - 422\, x_2 + 3.69\, x_1^2$	354.67	0.768	0.749	<0.01	β_1	<0.01
						β_2	<0.01
						β_{11}	0.071
MOR (MPa)	$= 553 - 5.40\, x_1 - 5.15\, x_2 - 0.0019\, x_1^2$	1.80	0.926	0.920	<0.01	β_1	<0.01
						β_2	<0.01
						β_{11}	0.853
Compression (MPa)	$= 406 - 3.90\, x_1 - 3.59\, x_2 - 0.00541\, x_1 x_2$	1.02	0.957	0.949	<0.01	β_1	<0.01
						β_2	<0.01
						β_{12}	0.511
Hardness (N)	$= 79839 + 63\, x_1 - 969\, x_2 - 10.1\, x_1^2$	264.16	0.960	0.957	<0.01	β_1	0.675
						β_2	<0.01
						β_{11}	<0.01
Nail withdrawal (N)	$= 9066 - 97.5\, x_1 - 105\, x_2 + 0.533\, x_1 x_2$	52.21	0.687	0.628	<0.01	β_1	<0.01
						β_2	<0.01
						β_{12}	0.214
Screw withdrawal (N)	$= 49116 - 486\, x_1 - 470\, x_2 + 0.33\, x_1 x_2$	131.07	0.943	0.932	<0.01	β_1	<0.01
						β_2	<0.01
						β_{12}	0.754

[a] Standard error of the estimate; in same units as each property.
MOE, modulus of elasticity; MOR, modulus of rupture.

et al (2001) that nail withdrawal was relatively unaffected by formulation.

From the data in Table 6, the regression equations explain the properties very well. For flexural MOE, MOR, and hardness, the equations showed curvilinear responses and the quadratic effect of WC may have influenced the final properties. The interaction effect between the WC and the HDPE content (PC) influenced compression and nail and screw withdrawal. It is noted that the estimate of the coefficient for some variables was not significant ($P > \alpha = 0.05$) in the presence of the other variables in the equation. That is, the interaction between WC and PC and the quadratic effect of WC may appear, although it is insignificant in the presence of the other two variables.

In the study of Zhang et al (2008), the response surface strategy was adopted to investigate the effect of the coupling agent content (0-3%), wood fiber content (0-40%), and wood types on tensile strength, MOE, and strain at break. In the current study, more wood content was used, and the matrix content was also taken into consideration. Additionally, the effect of the coupling agent from various fractions was not studied (ie with or without 2.3% MAPP). Thus, different trends were found, but both studies indicate the effect of formulation on WPC product properties.

After estimating the ultimate strength of a group of test specimens, the flexural strengths of products were fitted with normal, log-normal, and 2-parameter Weibull distribution models, and the corresponding parameters and values of the fifth percentile strength are summarized in Table 7. In general, this strength value was close to the mean within a difference of approximately 5-15%. Moreover, the normal distribution model fit well for F1 and F2, whereas the 2-p Weibull model fit better for F3 and F4. It is uncertain if the formulation influenced the distribution of properties, because the sample size was small and more tests are required for verification. Nevertheless, this probability fitting implied that, in general, the properties of WPCs are uniform and easy to control when developing and using products.

CONCLUSIONS

MPB-WPC products were manufactured with various formulations, and their mechanical

Table 7. Statistical model parameters for flexural MOR of MPB-WPCs.

	Distribution	Mean (MPa)	Standard deviation (MPa)	Weibull scale	Weibull shape	Error	5th percentile value (MPa)
F1	Normal	38.26	1.81	—	—	0.0004	35.34
	Log-normal	38.27	1.81	—	—	0.0004	35.41
	2-p Weibull	38.19	1.83	39.00	26.06	0.0008	34.76
F2	Normal	34.25	1.13	—	—	0.0003	32.40
	Log-normal	34.25	1.13	—	—	0.0003	32.49
	2-p Weibull	34.20	1.16	34.71	37.23	0.0004	32.08
F3	Normal	30.39	2.63	—	—	0.0161	26.12
	Log-normal	30.42	2.62	—	—	0.0168	26.35
	2-p Weibull	30.32	2.67	31.47	13.90	0.0156	25.50
F4	Normal	21.87	1.43	—	—	0.0052	19.55
	Log-normal	21.87	1.41	—	—	0.0057	19.67
	2-p Weibull	21.82	1.48	22.47	18.23	0.0038	19.14
F5	Normal	33.91	0.43	—	—	0.0001	33.20
	Log-normal	33.91	0.43	—	—	0.0001	33.20
	2-p Weibull	33.89	0.24	34.11	87.95	0.0002	32.96

MOR, modulus of rupture; MPB, mountain pine beetle; WPCs, wood–plastic composites.

properties were evaluated and analyzed. The MPB-WPC products showed no significant difference from products that were made with pine. This indicates that WPCs are an option for value-added products of MPB-killed wood, because the fine residues from processing logs can be utilized and drying costs would be less because of the lower moisture content of MPB wood.

The test results showed that formulation affected the MPB-WPC product properties. A higher wood content resulted in a slightly higher density and lower strength but higher stiffness. The quadratic effect of the wood content influenced the flexural MOE, MOR, and hardness, while the interaction between the wood and the HDPE impacted compression and nail and screw withdrawal. The capacity of the uncoupled product was significantly inferior to the coupled products, therefore, properties can be significantly improved when a coupling agent is added. The surface condition of the product was also influenced by the formulation.

Depending on the formulation, WPCs can show very different behavior and appearance. Considering the formulation based on the use of products is an important task. Moreover, because of uniform quality, the fifth percentile strength values of WPCs were close to the mean with differences of approximately 5-15%; therefore, the mean value may be used as a characteristic value for application.

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