Physical and Mechanical Properties of Wood Polymer Composites

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ABSTRACT

Filling wood cell cavities or modifying walls with polymer improves mechanical properties and reduces influences of moisture and biodeterioration agents. Properties of untreated wood and wood polymer composites are presented in the paper.

Keywords: *Wood polymer composites, WPC, modified wood, mechanical properties, physical properties*

INTRODUCTION

Wood has been used as an engineering material for centuries. Impregnating wood with a polymerizable monomer formulation and then polymerizing it in place produces a wood polymer composite (WPC). WPC could be more useful for more products, and have a longer life, because it is less susceptible to moisture-induced swelling and shrinking and biodeterioration, and has a harder surface.

Monomers used to make WPC can fill cell lumens but be largely independent of the cell walls (cell lumen type), enter and swell cell walls (cell wall type) or a combination. Cell lumen WPC is made using vinyl-type polymers (such as styrene and methyl methacrylate) which partially or fully fill cell cavities but do not enter cell walls. In untreated wood, the cavities make each cell, and therefore the wood, susceptible to crushing in side loading and buckling in longitudinal compressive loading. The polymer in the cavities should reinforce the wood and improve its mechanical properties. In untreated wood, cell cavities are the most rapid pathway for moisture movement. Blocking them with polymer reduces moisture diffusion and rates of dimensional change. Wood stain and decay fungi invade wood most rapidly along cell cavities. Filling the cavities with polymer mechanically blocks invasion and therefore reduces susceptibility to stain and decay.

Cell wall WPC is made using a treating solution which enters cell walls, changing the basic nature of the wood substance. Since the polymer in cell wall WPC also partly fills cell lumens, this type of WPC has some characteristics of cell lumen WPC. Cell walls modified this way accept less moisture than untreated cell walls and wood-destroying organisms are not be able to degrade it. Since polymers used in making cell wall WPC are brittle, the WPC made from them is also brittle.

Combination WPC is made using a treating solution designed to both enter the cell wall to some extent and also to fill or partially fill cell lumens. It has some of the better properties of both cell lumen and cell wall WPC with less brittleness than cell wall WPC. In moisture effects, toughness and decay resistance it is intermediate in properties.

The wood samples used to obtain the data in this publication were chosen for their perfection and were uniformly impregnated. They therefore represent defect-free, well-impregnated zones of larger pieces of WPC. If larger pieces have defects like knots or sloped grain or if they have zones which do not accept monomer well, these larger pieces will have lower overall properties than their best zones.

Polymer loading is the weight percent polymer based on the original wood weight. Moisture content (MC) is based on mass at ovendry. The monomer used for making cell wall WPC was furfuryl alcohol. MMA cell lumen WPC was made using methyl methacrylate monomer. The other cell lumen WPC was made using proprietary vinyl monomer formulations with physical properties similar to MMA. The species of wood used in the studies and their Latin names are given in Table 1.

Table 1. Wood species used to make WPC.

Name used in tables	Latin name
Red (soft) maple	*Acer rubrum*
Hard maple	*Acer saccharum*
(Eastern) White pine	*Pinus strobus*
Scots pine	*Pinus sylvestris*
European birch	*Betula pendula.*
Yellow birch	*Betula alleghaniensis*

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This review of measured WPC properties collected could be helpful to those considering WPC for products and structures.

DATA

The data are given in Tables 2 to 5.

Table 2. Mechanical properties (tensile, compressive, bending, impact bending, hardness).

Mechanical properties in bending

				Study 1	*Study 2*
Material	*Property*	*% polymer load*	*% MC*	MPa	
Hard maple and hard maple cell lumen WPC	Elastic modulus	0	0	14664	14798
		0	12	11183	13071
		50	0	15838	17157
		50	12	14398	15689
	Rupture modulus	0	0	171	200
		0	12	95	133
		50	0	199	221
		50	12	150	171
	Stress at proportional limit	0	0	95	109
		0	12	43	81
		50	0	105	130
		50	12	66	83
	Reference, Study 1	Brebner, Schneider & Jones 1988			
	Reference, Study 2	Schneider, Phillips. Tingley & Brebner 1990			
White pine and white pine cell lumen WPC	Elastic modulus	0	0	10340	
		0	12	8930	
		60	0	14100	
		60	12	8900	
	Rupture modulus	0	0	91	
		0	12	45	
		60	0	161	
		60	12	108	
	Stress at proportional limit	0	0	51	
		0	12	24	
		60	0	97	
		60	12	47	
	Refence	Brebner, Schneider & St-Pierre 1985			

Table 3. Swelling and decay properties.

Swelling from treatment

		50% p.l.	80% p.l.
Species	*Material*	*% tangential swelling*	
Hard maple	Cell lumen WPC	0	
	Cell wall WPC		11
	Combination WPC	1	
Notes	Percent tangential swelling after impregnation, 24 hr in monomer and then cured and baked for 38 h. P.l. is polymer load.		
Reference	Schneider 1995		

Water swelling: antiswell efficiency

		50% p.l.	80% p.l.
Species	*Material*	*% antiswell efficiency*	
Hard maple	Cell lumen WPC	0	
	Cell wall WPC		73
	Combination WPC	26	
Notes	Tangential direction, swollen to maximum in 95°C water.		
Reference	Schneider 1995		

Swelling in liquid water

		20°C	80°C
Species	*Material*	*% swelling*	
Hard maple	Cell lumen WPC	4	14
	Cell wall WPC	1	2
Notes	% tangential swelling of about 60% polymer loaded samples after 24 hr in water (maximum swelling was reached at 80°C, slightly less than maximum at 20°C)		
Reference	Schneider, Brebner & Hartley 1991		

Decay resistance

		0% p.l.	70% p.l.
Species	*Material*	*% weight loss*	
Red maple	Untreated wood	93	
(sapwood)	Cell lumen WPC		13
	Cell wall WPC		0
Notes	Percent weight loss after 34 weeks of soil block exposure to *Trementes versicolor* L. ex Fr. Samples 25mmx25mmx9mm (9mm in grain direction). P.l. is polymer load.		
Reference	Schneider 1996		

Table 4. Movement of heat, electricity and water vapour.

Thermal conductivity

		Direction		
Species	Material	Transverse	Longitudinal	Polymer
Red maple		kW/mK		
	Untreated wood	0.155	0.358	
	Cell lumen PS WPC	0.191	0.389	0.111
	Cell lumen MMA WPC	0.206	0.405	0.193
	Cell wall WPC	0.173	0.370	0.119
Notes	At 0% MC for wood, WPC and polymer and 60% polymer loading for WPC. PS is poly (styrene) and MMA is poly (methyl methacrylate).			
Reference	Couturier & Schneider 1996			

Electrical resistivity

		0% p.l.	25% p.l.	50% p.l.
Species	% MC	Log (resistivity X 10^6 Mohm cm)		
Hard maple	0	13.8	13.5	13.5
	6	11.8	11.5	9.8
	12	9	8.5	7.6
	16	8.2	7.5	na
Notes	Transverse DC electrical resistivity of yellow birch cell lumen WPC at 21°C. P.l. is polymer load.			
Reference	Hartley & Schneider 1989			

Water vapor diffusion coefficient

		Transverse	*Longitudinal*
Species	*Material*	$10^{-12}\ m^2\ s^{-1}$	
Hard maple	Untreated wood	6.9	25
	Cell lumen WPC	5	5.2
	Cell wall WPC	0.5	2.1
Notes	66% polymer load for both types of WPC		
Reference	Hartley & Schneider 1993		

Table 5. Working properties.

Machinability

Material	*Curved saw crosscut*	*Saw crosscut*	*Boring*
Untreated wood	Excellent	Slight chipping	Slight chipping
Cell lumen WPC	Excellent	Excellent	Excellent
Cell wall WPC	Good	Slight chipping	Moderate chipping
Combination WPC	Good	Slight chipping	Moderate chipping
Notes	Bandsaw and forstner bits were used for cutting.		
Reference	Schneider 1993		

Gluability

% polymer	*When glued*	*Tested*	*Adhesive*	*mPa*	*% Wood failure*
0	Solid material	Dry	None	16	100
0	Solid material	Dry	None	28.9	100
0		Dry	PRF	21	100
0		Dry	EPI 320	20.7	56
0		Dry	Epoxy	20.2	100
0		Dry	PVA	21.2	51
0		Wet	PRF	7.7	100
0		Wet	EPI 320	7.1	0
50	After treatment	Dry	PRF	20.7	74
50		Dry	EPI 312	19.9	50
50		Dry	Epoxy	21	48
50		Dry	PVA	18.9	50
50	After treatment	Wet	PRF	9.9	100
50	Before treatment	Dry	PRF	23.9	92
50		Dry	EPI 320	26.3	54
50		Dry	EPI 312	28.5	93
50	Before treatment	Wet	PRF	10.8	100
50		Wet	EPI 320	10.2	0
Notes	Hard maple shear blocks tested to failure at 8% MC, two solid wood and the rest glued. PRF is phenol resorcinol formaldehyde, EPI is emulsion polymer isocyanate, PVA is polyvinyl acetate emulsion, epoxy is 2-component type.				
Reference	Schneider & Phillips 1995				

DISCUSSION

Cell lumen WPC

Wood cells have hollow cavities. The cavities make each cell, and therefore the wood, susceptible to crushing in side loading and buckling in longitudinal compressive loading. In cell lumen WPC, the cavities are filled or nearly filled with polymer. This dramatically increases hardness and compressive strength and stiffness perpendicular to the grain. Since buckling of cells is the first failure mode in bending, the reinforcing effect of cell lumen WPC is noticeable as increased stiffness and higher ultimate loads in bending. Toughness is increased because the polymer is additional material which must be fractured, and the polymer may have some effect on crack initiation and termination processes.

The blocking of cell cavities by polymer in cell lumen WPC retards moisture movement greatly, especially along the grain. This causes longitudinal and transverse movement to be low and about equal. The presence of polymer should block wood boring insects and marine organisms. The slowing of water movement manifests itself in lowered swelling rates in water, lowered effects of weathering and lowered water vapor diffusion coefficient values. Polymer in cell cavities slows the attack of decay fungi since their major path of attack is along cell cavities.

Cell wall WPC

The modified cell walls in cell wall WPC change the basic nature of the wood substance. Since the polymer in cell wall WPC also partly fills cell lumens, this type of WPC has some characteristics of cell lumen WPC. Modified cell walls accept less moisture than untreated cell walls and wood-destroying organisms do not appear to degrade it. The most noticeably changed properties of cell wall WPC in the tabulated values are those which depend on moisture movement and uptake (swelling, water vapor diffusion coefficient, weathering and decay resistance). Its modified cell walls are more brittle than untreated wood cell wall which can be seen in the toughness values.

Combination WPC

Combination WPC has some of the better properties of both cell lumen and cell wall WPC with less brittleness than cell wall WPC. In moisture effects, toughness and decay resistance it is intermediate in properties.

Effects of moisture on WPC mechanical properties

Most WPC mechanical properties reported in the literature, including our own work, were measured at the ovendry condition. This is because it is easier to measure monomer and polymer uptake when the wood is dry and WPC is very slow to equilibrate to a new MC because of its low diffusion coefficient, requiring long experiments at anything above ovendry. However, WPC will eventually reach the equilibrium MC of its surroundings when in service, so having an idea of the effect of moisture on mechanical properties is important.

Wood cell wall material is hygroscopic and its mechanical properties are strongly influenced by MC in the hygroscopic range (up to about 30%MC). Polymers filling cell lumens have little affinity for water, and should not be noticeably affected by its presence. Since the wood cell framework in the WPC is expected to take the main structural loading, however, there should be a noticeable decrease in mechanical properties with increased MC because of the influence of moisture on the wood. Those values which had been measured at ovendry and 12% MC in Table 1 show decreased mechanical properties at 12% except for impact bending where the value remains about the same or increases slightly.

Compression perpendicular to the grain

Values for compression loading perpendicular to the grain (side loading) can not be found in the literature, but are important for uses such as floors and bridge decks. The values obtained in our laboratory and reported in Table 1 show substantial increases in stiffness, yield stress (elastic limit) and ultimate load for all types of WPC compared to untreated wood. Cell wall WPC has lower values than cell lumen types because the cell lumens are not filled with polymer as fully as they are in cell lumen WPC.

CONCLUSIONS

WPC improves many of wood's mechanical properties and its resistance to moisture and biodeterioration. The measured values reported in this review provide specific instances of that improvement, and allow designers to familiarize themselves with properties of the material and consider its possibilities for use in engineering applications.

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