Effect of Wood Species on the Mechanical and Thermal Properties of Wood–Plastic Composites

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ABSTRACT: The effect of wood species on the mechanical and thermal properties of wood–plastic composites (WPCs) was explored. Various wood species, including cherry, sweet gum, hickory, yellow poplar, Osage orange, walnut, eastern red cedar, pine, maple, and red oak, were compounded with virgin isotactic polypropylene in a 50 : 50 weight ratio and injection-molded. The tensile strength of WPCs made with cedar and hickory was higher than that of WPCs made with maple, oak, and Osage orange. The tensile modulus of WPCs made with gum and walnut was higher than that of oak WPCs. The tan δ peak temperatures and peak values from dynamic mechanical analysis indicated that pine and hickory WPCs had higher amorphous or void contents than walnut and cherry WPCs. The induction time during isothermal crystallization suggested that red cedar, cherry, and gum WPCs had higher nucleation density than walnut, pine, and oak WPCs. Dynamic mechanical properties of the WPCs appeared to be related to the crystallization behavior of the wood flour, which depends on the surface roughness. Although there were statistically significant differences in mechanical properties among the species, the differences were small, implying that wood flours from many species can be used successfully as raw materials for WPCs. © 2009 Wiley Periodicals, Inc. J Appl Polym Sci 112: 1378–1385, 2009

Key words: biofibers; differential scanning calorimetry (DSC); mechanical properties; poly(propylene) (PP); viscoelastic properties

INTRODUCTION

Wood–plastic composites (WPC) are relatively new and high-value products comprising wood flours as fillers and reinforcements and thermoplastic polymers as matrices. Pine, maple, and oak are commonly used wood species, whereas polyethylene, polypropylene (PP), and poly(vinyl chloride) are usually used as the thermoplastics. The wood component in WPCs serves as a filler and typically makes up 40–65 wt % of the composite. The advantages of adding wood flour to a thermoplastic matrix are its low cost, low density, wide availability, high specific properties per weight, and the fact that it is less abrasive to processing equipment.[1–3]

In general, properties of WPCs depend on various factors, including the inherent properties of the constituent materials, interactions among these materials, and processing methods.[2] The amount, geometry, and surface characteristics of the wood component and the interfacial properties between the wood and plastic all influence the mechanical and physical properties of WPCs.[4–9] Because the interface between the hydrophilic wood and the hydrophobic plastic play a key role in determining the mechanical properties of the composite, coupling agents such as maleated PP have also received much attention in the literature.[10–16]

There is some evidence that wood species can affect the mechanical properties of WPCs. Rogers and Simonsen[17] suggested that the choice of wood species could influence the surface roughness, tendency to chip, and porosity and that these differences could affect the interfacial bonding of WPCs. Saputra et al.[18] indicated that the removal of extractives from pine and Douglas fir wood flour increased the flexural strength and modulus, and this implied that differences in surface chemistry could result in differences in the mechanical properties among WPCs made with different species. Gacitua and Wolcott[19] studied mechanical interlocking between wood and high-density polyethylene using a vacuum bagging process and scanning electron microscopy. They reported that the transverse flow of molten high-density polyethylene was affected by the presence, size, and distribution of simple pits on the cell wall as well as early wood and late wood in the wood sample. They further suggested that wood species that provide a high interface area with the polymer have the potential for better mechanical interlocking.

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Berger and Stark[20] identified the key variables when wood is used as a filler to be the moisture content, purity, particle size distribution, and species. They studied the effect of the wood species (ponderosa pine, loblolly pine, maple, and oak) and wood filler percentage on various mechanical properties of wood–PP composites and found that the wood species did affect the mechanical properties of WPCs. Wolcott[21] noted that mechanical properties such as the stress–strain behavior, modulus of elasticity, and modulus of rupture of WPCs made with loblolly pine were higher than those of WPCs made with Douglas fir, and this suggests that the species could have a significant influence on the properties of WPCs.[21] Differences in the mechanical properties of WPCs made with pine and fir were confirmed by Saputra et al.[18] Kim et al.[22] used ash trees infested by emerald ash borers as fillers in WPCs and found that the mechanical properties of WPCs made with wood from emerald ash borer infested ash trees compared favorably with those of WPCs made with pine and maple, which are commonly used in WPC manufacturing. Clemons and Stark[23] reported that the mechanical properties of WPCs decreased when pine flour was replaced with wood from salt cedar and Utah juniper.

The objectives of this research were to explore the effects of the wood species on the mechanical and dynamic mechanical properties and crystallization kinetics of WPCs. This information will provide baseline data on the suitability of various wood species for WPC manufacturing.

EXPERIMENTAL

Preparation of the wood flour

Yellow poplar (*Liriodendron tulipifera*), black cherry (*Prunus serotina*), sweet gum (*Liquidambar styraciflua*), eastern red cedar (*Juniperus virginana*), hickory (*Carya* spp.), and black walnut (*Juglans nigra*) wood were obtained from local sources. Fresh-cut Osage orange (*Maclura pomifera*) was harvested from a small tree (that contained heartwood), transported to the laboratory, and air-dried. Wood of each of the species was ground with a hammer mill and a Wiley mill; this was followed by sieving with 70 and 120 U.S. standard sieves (0.210 and 0.125 mm per side, square openings). The wood flours passing the 70 sieve but remaining on the 120 sieve were used as the test wood flours. Pine (*Pinus* spp.), maple (*Acer* spp.), and oak (*Quercus* spp.) wood flours were obtained from American Wood Fibers (Schofield, WI) and used in the research. These flours consisted of particles that passed a 60 U.S. standard sieve, but they were further sieved in the laboratory with the same mesh sizes described previously to get a simi-

lar wood particle size distribution. All wood flour was oven-dried at 105°C for 24 h before being compounded with PP. A virgin isotactic PP homopolymer with a melt flow index of 35 g/10 min (at 230°C and 2.16 kg) was used. The density at room temperature was 0.910 g/cm^3.

Compounding and sample preparation

Each wood species was compounded with PP (50% wood and 50% PP by weight) in a 27-mm corotating twin-screw extruder (Leistritz Micro 27, American Leistritz Extruder Corp., Somervile, NJ) with a length-to-diameter ratio of 40 : 1. The temperature profile ranged from 180 to 195°C, and the screw rotation rate was set at 30 rpm. The compounded material was immediately cooled in a water bath and pelletized. The obtained pellets were used to make injection-molded tensile test specimens in accordance with ASTM D 638 Type IV.[24] The barrel and mold temperatures of the pneumatic injection molder were 191 and 135°C, respectively.

Tensile testing

The tensile strength and modulus of the injection-molded specimens were measured with a universal testing machine (model 5567, Instron, Inc., Canton, MA) according to ASTM D 638.[24] Five replicates were made for each wood species.

Dynamic mechanical analysis (DMA)

DMA was used to determine the effect of wood species on the viscoelastic properties and fiber–matrix interaction with WPCs in ranges of temperatures and frequencies. DMA provides information concerning the viscoelastic behavior of polymers and polymer composites over wide ranges of frequencies and temperatures. During DMA measurements, a sinusoidal deformation at a controlled temperature and frequency is applied to the sample, and the responsive stress is measured. The response output is composed of the storage modulus (E'; i.e., the elastic response), loss modulus (E''; i.e., the viscous response), and tan δ (E''/E'). E' is related to stiffness, whereas E'' is related to damping and energy dissipation. DMA has been extensively used to characterize viscoelastic behavior and fiber–matrix interactions of composite materials, including WPCs.[14,25–31]

The injection-molded tensile specimens were cut and machined to specimen dimensions of 2.0 mm × 7.7 mm × 55.0 mm to fit a Diamond dynamic mechanical analyzer (PerkinElmer, Waltham, MA) operated in a dual-cantilever bending mode. DMA was conducted at a heating rate of 5°C/min from −50 to 150°C and with a wide range (1, 2, 4, 10, and 20 Hz)
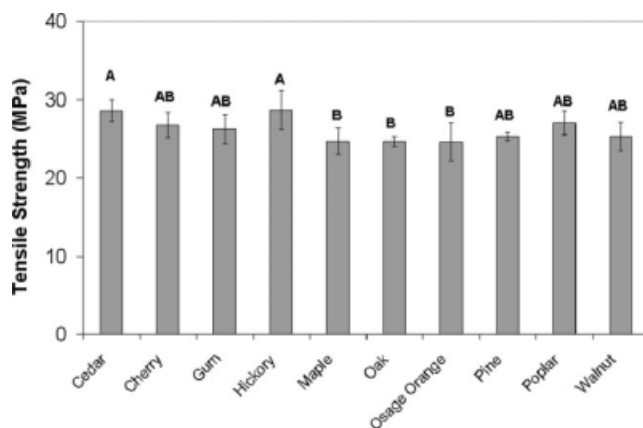
Figure 1 Tensile strength of WPCs made from different wood species. Averages of five samples are shown. The data were analyzed with one-way analysis of variance followed by Tukey's multiple comparison test ($P < 0.05$). Means with the same letter are not significantly different at the 95% confidence interval.

of frequency dynamic loadings under a nitrogen flow. Viscoelastic properties such as E', E'', and tan δ were measured as a function of temperature and frequency.

Differential scanning calorimetry

Isothermal crystallization kinetics of the WPCs and their subsequent melting behavior were studied with a Diamond differential scanning calorimeter (PerkinElmer). About 5–6 mg of compounded and pelletized materials was ramped from room temperature to 200°C at 50°C/min and held for 10 min to erase the thermal history. Then, the melts were cooled at 50°C/min to the various isothermal crystallization temperatures (128, 129, 130, 131, and 132°C) and held for up to 40 min. Upon the completion of crystallization, the specimens were quenched to room temperature. The samples were then heated again to 200°C at 50°C/min and then immediately cooled to room temperature at the same heating rate.

A semicrystalline polymer such as PP easily crystallizes into a spherulitic morphology when cooled from the melt. This crystallization generally involves random nucleation and growth processes. The introduction of foreign surfaces such as wood into a PP melt induces the nucleation of the polymer on its surface.[13] If the nucleation density is sufficiently high, the embryonic spherulites begin to impinge on one another and grow normal to the surfaces of the nucleating wood flour. The resulting crystalline layer on the surface of the nucleating material is termed the transcrystalline layer (TCL). Much research has been devoted to the effects of various synthetic fibers and fillers such as glass, carbon, nylon, and

polytetrafluoroethylene fibers on the crystallization kinetics and thus morphology of polymer matrices.[32–40] However, the research indicates that nucleation and crystal growth are very specific to the fiber type and the polymer matrix used. The effects of natural fibers on the crystallization kinetics have been explored.[13,41–49] Although nucleation and crystal growth are influenced by the fiber surface morphology, the chemical composition of the surface, and the surface energy, there is considerable debate on nucleation mechanisms and their effects on the mechanical properties of composites.[32,34,41,49] Borysiak and Doczekalska[48] reported that the nucleation ability of wood fibers measured as the crystallization half-time ($t_{1/2}$) of PP–pine composites was considerably higher than that of a PP–beech composite. In addition, when esterified wood fibers were used, $t_{1/2}$ was increased for beech WPCs but reduced for pine WPCs. Quillin et al.[43] found that a surface treatment with alkyl ketene dimer, alkenyl succinic anhydride, and stearic acid markedly reduced the recrystallization of the PP matrix.

RESULTS AND DISCUSSION

Tensile properties

Tensile strength (Fig. 1) and modulus (Fig. 2) values for the composites were within ranges of 24–28 MPa and 2.8–3.7 GPa, respectively, and compared favorably with those found in the literature when similar materials (50% wood flour and 50% PP) and processing conditions (compounding followed by injection molding) were used.[2,5,20] Small but statistically significant differences were found among the species for both the strength and modulus (one-way analysis of variance followed by Tukey's multiple
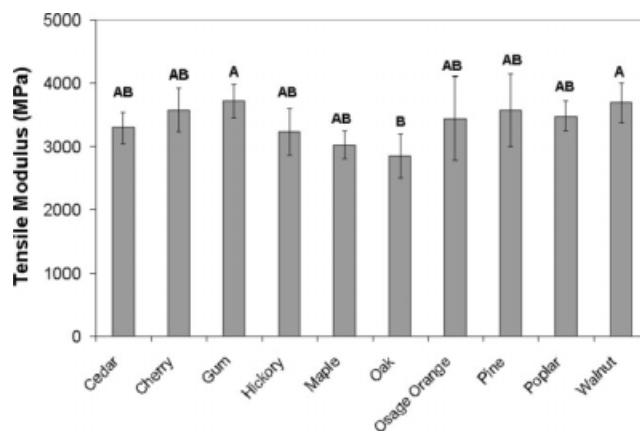

Figure 2 Tensile modulus of WPCs made from different wood species. Averages of five samples are shown. The data were analyzed with one-way analysis of variance followed by Tukey's multiple comparison test ($P < 0.05$). Means with the same letter are not significantly different at the 95% confidence interval.

TABLE I
E' and Tan δ Values of WPCs Measured at 20°C and 1 Hz

	E' (×10⁹ Pa)					Tan δ				
	1 Hz	2 Hz	4 Hz	10 Hz	20 Hz	1 Hz	2 Hz	4 Hz	10 Hz	20 Hz
Red cedar	4.16	4.25	4.34	4.45	4.52	0.0626	0.0650	0.0737	0.1077	0.1529
Cherry	4.19	4.27	4.35	4.47	4.53	0.0582	0.0623	0.0707	0.1049	0.1502
Gum	4.35	4.44	4.53	4.65	4.72	0.0599	0.0640	0.0723	0.1062	0.1511
Hickory	4.88	4.99	5.09	5.22	5.30	0.0619	0.0661	0.0745	0.1083	0.1535
Maple	4.90	5.01	5.11	5.25	5.34	0.0614	0.0658	0.0742	0.1082	0.1537
Oak	4.81	4.92	5.02	5.17	5.26	0.0612	0.0648	0.0742	0.1089	0.1539
Osage orange	4.66	4.76	4.86	4.99	5.07	0.0609	0.0650	0.0730	0.1071	0.1523
Pine	5.29	5.41	5.52	5.67	5.76	0.0618	0.0659	0.0738	0.1080	0.1526
Yellow poplar	4.94	5.06	5.16	5.30	5.38	0.0616	0.0658	0.0739	0.1080	0.1535
Walnut	5.41	5.52	5.62	5.77	5.85	0.0582	0.0622	0.0703	0.1040	0.1493

comparison tests at $P < 0.05$). The tensile strength of WPCs made with cedar and hickory was higher than that of WPCs made with maple, oak, and Osage orange. The tensile modulus of WPCs made with gum and walnut was higher than that of those made with oak.

These results show that, although many species can be successfully incorporated into WPCs, the choice of wood species can affect the mechanical properties of the composites. Differences in the mechanical properties could be caused by alterations to the interaction between the wood flour, in which species differences may affect the surface morphology and surface chemistry, and the plastic component.

Dynamic mechanical properties

The E' and tan δ values determined at 20°C and five different frequencies are listed in Table I. The E' values of pine and walnut WPCs were higher than those of red cedar, cherry, and gum WPCs at all frequency ranges. E' of WPCs is strongly affected by interfacial bonding between the wood and plastics. Harper et al.[14] reported that there was a positive correlation between E' and a nucleating advantage on wood surfaces with different PP blends. In the

absence of copolymers such as maleated PP, the nucleating ability of wood could be influenced by the morphology or surface roughness of the wood.

The tan δ peak values and temperatures measured at 1 Hz are listed in Table II. The tan δ peak values ranged from 0.0594 (walnut WPC) to 0.0628 (pine WPC). The tan δ peak values of pine and hickory WPCs measured at 1 Hz were higher than those of walnut and cherry WPCs, and this suggested that the pine and hickory WPCs had higher amorphous content (or more voids) than walnut and cherry WPCs. The tan δ peak temperature of pine WPCs was highest, whereas that of gum WPCs was the lowest. Generally, the tan δ curve of PP is characterized by three relaxations: the α transition around 100°C, the β transition around 10°C, and the γ transition around -80°C.[27,50] The α transition is related to the relaxation of amorphous PP chains in the crystalline phase, whereas the β transition is associated with the relaxation of unrestricted amorphous PP chains. The temperature and amplitude at the β-transition peak of WPCs can provide information about the interaction between the polymer and wood filler at the molecular level.[51] An increase in the peak amplitude indicates a decrease in the number of amorphous PP chains that can relax or increase in the void volume in the composites.[14,27]

TABLE II
Tan δ Peak Temperatures and Peak Values and Activation Energies of WPCs

	Tan δ peak value					Tan δ peak temperature (°C)					Activation energy (kJ/mol)	R^2
	1 Hz	2 Hz	4 Hz	10 Hz	20 Hz	1 Hz	2 Hz	4 Hz	10 Hz	20 Hz		
Red cedar	0.0613	0.0659	0.0745	0.1078	0.1534	7.24	7.66	8.32	9.53	10.56	246	0.96
Cherry	0.0601	0.0647	0.0733	0.1077	0.1521	8.60	8.57	9.04	10.03	11.33	255	0.96
Gum	0.0622	0.0668	0.0756	0.1091	0.1537	6.73	8.16	8.79	9.83	11.51	215	0.95
Hickory	0.0626	0.0672	0.0758	0.1095	0.1542	7.15	7.06	7.47	8.71	10.12	243	0.86
Maple	0.0620	0.0666	0.0751	0.1090	0.1540	7.30	7.45	8.13	9.59	10.78	223	0.94
Oak	0.0611	0.0661	0.0748	0.1090	0.1540	7.64	8.59	8.85	10.01	11.48	228	0.95
Osage orange	0.0607	0.0650	0.0734	0.1075	0.1526	8.44	10.24	11.23	11.50	13.12	242	0.89
Pine	0.0628	0.0668	0.0751	0.1092	0.1539	10.62	11.56	12.20	12.76	14.20	240	0.91
Yellow poplar	0.0623	0.0666	0.0747	0.1088	0.1541	9.07	9.36	10.23	10.84	12.77	214	0.93
Walnut	0.0594	0.0641	0.0724	0.1062	0.1511	8.00	7.76	8.11	9.42	10.81	219	0.93

There are several possible reasons for differences in the damping characteristics of WPCs made with different wood species, including the loading direction, low crystallinity, and inefficient packing density in the amorphous phase around fillers. In addition, the surface roughness and chemical composition of the surface influence the fiber–matrix interaction, leading to different viscoelastic properties of WPCs.

The relationship between the temperature at which the β transition is observed and the frequency of excitation can be described by the Arrhenius equation:

$$f = f_0 \exp(-E_a/RT) \qquad (1)$$

where f_0 is a constant, f is the frequency of the test, R is the gas constant, T is the temperature (K), and E_a is the activation energy for the β transition. According to the Arrhenius equation, the slope in a plot of $\log f$ versus $1000/T$ (K) should be proportional to the apparent activation energy for the relaxation process. In general, the higher the activation energy is, the stronger the interaction is between the wood and the polymer matrix because more energy is required to allow molecules to relax.[28] The activation energy and R^2 values of the fit are shown in Table II. The activation energy of WPCs varied from 214 (yellow poplar WPCs) to 255 kJ/mol (cherry WPCs). Statistical analysis of the average activation energy values indicated that there were no significant differences between the species used in the WPCs (one-way analysis of variance followed by Tukey's multiple comparison test at $P < 0.05$). Because activation energy data provide insight into the mechanics of interfacial interactions and relative volume of the interphase, there may be no difference in the interfacial interactions or relative volume of the interphase between WPCs made with different wood species. However, further study is necessary to elucidate the impact of species on the activation energy of WPCs.

Isothermal crystallization kinetics

The isothermal crystallization kinetics and subsequent melting behavior of WPCs were analyzed with Avrami kinetics, which describes the overall crystallization kinetics combining nucleation and growth. The development of crystallinity is associated with an exothermic peak during the isothermal crystallization of differential scanning calorimetry. The relative crystallinity at different crystallization times can be obtained with the following equation:

$$X(t) = \frac{Q_t}{Q_\infty} = \frac{\int_0^t \frac{dH(t)}{dt} dt}{\int_0^\infty \frac{dH(t)}{dt} dt} \qquad (2)$$

where Q_t and Q_∞ are the heat generated at time t and infinite time, respectively, and $dH(t)/dt$ is the heat

evolution rate. Isothermal crystallization kinetics can be analyzed with the Avrami equation:[52]

$$X(t) = 1 - \exp(-Kt^n) \qquad (3)$$

where $X(t)$ is the volume fraction of the transformed material, K is a temperature-dependent rate constant, n is an Avrami exponent, and t is the crystallization time. n is related to the types of nucleation and dimensionality of crystal growth.[52] Equation (3) can be transformed if we take a double logarithm:

$$\log\{-\ln[1 - X(t)]\} = n \log t + \log K \qquad (4)$$

From the plot of $\log\{-\ln[1 - X(t)]\}$ versus $\log t$, values of n (the slope of the linear portion) and K (the intersection with the y axis) can be calculated. In addition, $t_{1/2}$, at which the relative crystallinity equals 50%, can be obtained as follows:

$$t_{1/2} = \left(\frac{\ln 2}{K}\right)^{1/n} \qquad (5)$$

The time that elapses between the thermal equilibrium point and the onset of crystallization is called the induction time (t_{ind}). t_{ind} is known to be proportional to the time needed to produce a nucleus of sufficient size for growth and depends on both the filler and crystallization temperatures.[38] t_{ind} was calculated by the extrapolation of the slope of the relative crystallinity/time curves. The values of n, K, $t_{1/2}$, t_{ind}, and the subsequent melting temperature (T_m) are summarized in Table III.

n of all wood–PP composites ranged from 2.12 to 2.41, depending on the crystallization temperature and wood species used. As mentioned earlier, the introduction of synthetic or natural fibers or fillers such as wood flour leads to a change in the morphology of a semicrystalline polymer by forming a TCL at the surface of the fibers or fillers. The TCL is known to change exponent n in the Avrami analysis.[13,43] In the case of heterogeneous nucleation, the shape of crystallites rests between a diffusion-controlled sphere ($n = 3$) and a truncated sphere ($n = 1.5$).[13] The increased nucleation densities tend to push the crystallites more toward the truncated shape and affect the intensity of the TCL. Once the crystals nucleate, the growth rate of spherulites is not changed by the presence of fillers. Therefore, the differences in the n values of WPCs could result from differences in the nucleating ability of the wood species used.

t_{ind} is linearly related to heterogeneous nucleation through a constant and may be considered a parameter that represents the nucleation process.[53] As mentioned earlier, the wood surface acts as a nucleating site for PP crystal growth. Rougher surfaces with more surface area would induce nucleation and result in lower t_{ind} values for crystal growth.

TABLE III
n, K, $t_{1/2}$, t_{ind}, and T_m **Values of WPCs**

	Isothermal crystallization temperature (°C)	n	K (min^{-1})	$t_{1/2}$ (min)	t_{ind} (min)	T_m (°C)
Red cedar	128	2.171	2.256	0.581	0.177	171.6
	129	2.176	1.777	0.649	0.200	168.3
	130	2.197	1.439	0.717	0.225	171.6
	131	2.188	0.811	0.931	0.290	169.9
	132	2.247	0.368	1.326	0.437	170.8
Cherry	128	2.162	2.291	0.575	0.174	169.0
	129	2.134	1.542	0.688	0.203	170.0
	130	2.169	0.879	0.896	0.275	170.0
	131	2.130	0.666	1.019	0.301	168.3
	132	2.120	0.374	1.338	0.390	170.0
Gum	128	2.173	1.898	0.629	0.193	170.8
	129	2.186	1.031	0.834	0.260	167.5
	130	2.208	0.758	0.960	0.306	169.1
	131	2.170	0.535	1.126	0.346	172.5
	132	2.266	0.256	1.553	0.520	169.1
Hickory	128	2.226	0.490	1.169	0.375	168.3
	129	2.269	0.266	1.525	0.508	166.6
	130	2.261	0.186	1.791	0.594	168.3
	131	2.220	0.103	2.361	0.754	169.1
	132	2.153	0.051	3.346	1.005	168.3
Maple	128	2.389	0.152	1.888	0.689	170.8
	129	2.332	0.092	2.380	0.837	171.6
	130	2.280	0.057	2.989	0.951	175.0
	131	2.315	0.030	3.907	1.358	172.5
	132	2.282	0.018	4.948	1.674	175.0
Oak	128	2.401	0.148	1.905	0.700	170.0
	129	2.295	0.091	2.426	0.829	171.7
	130	2.293	0.052	3.084	1.051	174.1
	131	2.298	0.034	3.701	1.266	173.3
	132	2.300	0.018	4.922	1.687	172.5
Osage orange	128	2.129	0.129	2.204	0.640	169.9
	129	2.143	0.060	3.134	0.925	171.6
	130	2.150	0.043	3.644	1.083	169.1
	131	2.167	0.021	4.987	1.512	170.0
	132	2.160	0.016	5.757	1.737	171.7
Pine	128	2.280	0.098	2.355	0.797	170.8
	129	2.323	0.044	3.288	1.146	172.5
	130	2.283	0.031	3.891	1.317	170.0
	131	2.286	0.011	6.079	2.059	170.8
	132	2.271	0.008	7.208	2.409	172.5
Yellow poplar	128	2.225	0.489	1.170	0.375	173.3
	129	2.322	0.220	1.639	0.568	173.3
	130	2.332	0.138	1.995	0.698	172.5
	131	2.369	0.082	2.465	0.885	169.9
	132	2.334	0.057	2.923	1.022	171.6
Walnut	128	2.415	0.070	2.577	0.957	169.1
	129	2.363	0.041	3.324	1.191	169.1
	130	2.369	0.025	4.080	1.468	170.8
	131	2.294	0.019	4.790	1.637	169.9
	132	2.207	0.013	6.049	1.989	170.7

For all WPCs, t_{ind} was increased as the crystallization temperature increased. t_{ind} of cedar, cherry, and gum WPCs ranged from 0.17 min at 128°C to 5.2 min at 132°C, whereas that of maple, oak, Osage orange, and pine ranged from 0.64 min at 128°C to 2.4 min at 132°C. K and $t_{1/2}$ are closely related to the crystallization rate. $t_{1/2}$ increased with increasing crystallization temperature, whereas K decreased with increasing crystallization temperature. Interestingly, pine had the greater $t_{1/2}$ value, whereas cherry had the lowest values.

The differences in the isothermal crystallization behavior of WPCs could be due to the surface morphology of the wood flours.
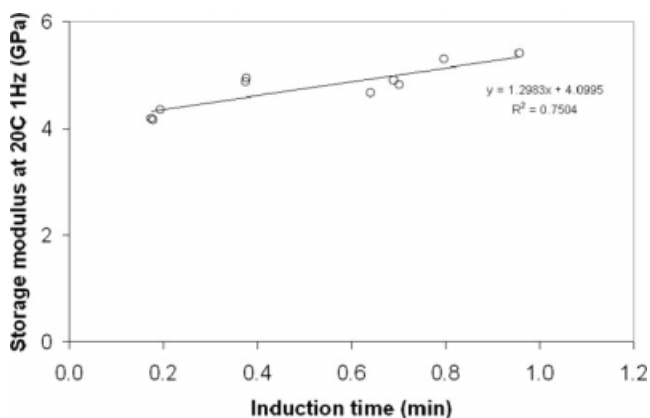
Figure 3 Relationship between E' (measured at 20°C and 1 Hz) and t_{ind}.

The species that had the lowest t_{ind} values were also the species that had the lowest E' values measured at 20°C and 1 Hz in the DMA study (Fig. 3). As t_{ind} increased, E' increased (Fig. 3). Such a positive relationship between E' and t_{ind} could be the result of the formation of a more perfect crystal with increased t_{ind}.

T_m was obtained from the endothermic peak during the reheating of the sample after the isothermal crystallization. Higher T_m values indicated more perfect crystals during isothermal crystallization. The T_m values of isothermally crystallized samples ranged from 168 to 173°C, depending on the species used, and tended to increase with an increasing crystallization temperature. It appears that there was little conclusive difference in crystal perfection, which could be related to any observable mechanical differences.

CONCLUSIONS

The effects of wood species on the mechanical, dynamic mechanical, and crystallization behavior of WPCs were explored. WPCs with good mechanical properties were produced with wood flour from all the wood species tested. Although there were statistically significant differences in the mechanical properties among species, the differences were small, and this implies that wood flours from most species can be used as raw materials for WPC manufacturing.

The relationship between E' and t_{ind} suggests that the mechanical properties of WPCs are related to the crystallization behavior of the wood flour, which depends on the surface roughness. DMA of the composites followed the general trend observed in the static mechanical tests, in which walnut and pine had high E' and modulus of elasticity values, but it failed to yield any conclusive difference between the composites that may suggest large differences in the viscoelastic performance of these materials. This

would suggest that there are similar molecular interactions between all of the wood species and the polymer matrix. However, the impact of the surface roughness on the mechanical and thermal properties merits further investigation.

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