Through-thickness ultrasonic characterization of wood and agricultural fiber composites

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Abstract

Direct contact ultrasonic transmission (UT) method was used to differentiate the effects of particle size on panel properties for oriented strandboard (OSB), redcedar particleboard (RCPB), and bagasse particleboard (BAPB). The measurements were done after conditioning samples at 50 and 70 percent relative humidity (RH) at 24°C. It was found that the equilibrium moisture content (EMC) was positively related to particulate size of the respective panel types. The UT variables attenuation and RMS voltage values varied significantly at the two EMC levels for the single-layer RCPB. Internal bond (IB) strength of a test panel type was affected by processing factors such as layering, resin content, and type of resin. The inclusion of bark in the RCPB panel had an adverse effect on IB. Ultrasonic velocity was found to be a good indicator of physical particle impediment to the propagation of stress waves in OSB and RCPB panels, but not in BAPB panels. The variable impedance was shown to be a reliable measure of tortuosity of velocity flux through the material. Minimum attenuation and maximum RMS points for RCPB, OSB, and BAPB were obtained at approximate density values 0.75, 0.9, and 1.1 g/cm^3, respectively, marking the respective minimum void scattering and absorption in each panel type. For the respective panel types, the greatest transmissivity of stress wave energy occurred at these density values (the zero void densities). Beyond these densities, absolute IB appeared to diminish with density. Hence, an appropriate ultrasonic system calibration of these material factors is essential for optimizing the desired properties of these reconstituted composites in the production line.

Desired product performance of wood composites for a particular application can be achieved through product design by combining appropriate processing and material variables in an industrial production system (Kelly 1997). With reconstituted wood materials, property characteristics are studied at the basic level (i.e., fiber, particle, flake, or veneer). The type and distribution of the different basic particle sizes determine the composite properties and end uses. Voids are inherently embedded in all bio-based reconstituted panels, affecting the internal structure of the panels. For example, the presence of voids in oriented strandboard (OSB) causes in-plane density variation that reduces mechanical strength (Wu 1999). Vun et al. (2003) successfully evaluated the density variation of OSB using a through transmission ultrasonic technique. This evaluation presents a potential quality control tool for the manufacturing processes of composite products. Since it is nondestructive, safe, inexpensive, and reliable, applicability of this technique to characterize other types of composites is highly desirable.

In the state of Louisiana, agriculture and forestry sectors generated 7.8 million tons of biomass waste annually in the form of bark, wood chips, sawdust, cotton gin trash, rice hulls, and sugar bagasse (Kleit et al. 1994, Youngquist et

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*Forest Products Society Member.

Forest Prod. J. 54(12):233-239.

al. 1994, DeHoop 1997). Converting biomass residue into particleboard is the *raison d'etre* to reduce the risk of environmental hazard and to reduce the exploitation of forestland for wood fiber. Although several agricultural composite panels are produced to standard (Odozi et al. 1986, Wu 2001), problems such as lack of dimensional stability and long-term durability, as well as susceptibility to termite attack (Grace 1996) must be overcome before these products can compete in the marketplace with other wood composites.

This study was aimed at using a direct contact ultrasonic methodology to differentiate properties among panels made of different particle sizes. Three different panel types were studied: aspen OSB, eastern redcedar particleboard, and bagasse particleboard. The specific objective was to characterize ultrasonic responses in relation to density and panel types among various products.

Panel manufacturing

Aspen OSB

Aspen (*Populus tremuloides*) lumber was processed using a disc-type flaker to obtain 0.635- by 13- by 76-mm flakes. The flakes were dried to about 3 percent moisture content (MC) before being blended with wax and resin. The single-layer aspen OSBs were made at four nominal densities (0.56, 0.72, 0.96, and 1.12 g/cm^3) and two resin content (RC) levels (4% and 6% based on the ovendry wood flake weight and abbreviated as OSB14 and OSB16, respectively) using liquid phenol-formaldehyde (PF) resin and 0.5 percent wax. Two boards were made for each nominal density (ND)-RC combination. Application of wax and resin was carried out in separate lines through air-atomizing nozzles inside a tumbling blender for about 10 minutes. The single layer mat was formed with a controlled alignment level. The 13- by 610- by 610-mm panels were prepressed to thickness prior to heating the mats for resin curing at 190°C for six minutes. After hot pressing, the panels were conditioned and edge-trimmed.

Eastern redcedar particleboard

Small-diameter eastern redcedar (*Juniperus virginiana*) trees were chipped in the field using a drum chipper. Two types of chips were prepared from the whole trees: one including bark and branches and the other only wood chips. The chips were hammermilled to pass through an 8-mm screen prior to panel manufacturing (Hiziroglu et al. 2002). For three-layer boards, larger particles were laid out as the core layer. Hand-screened fine particles were used for the two outer face layers. Separate blending was required for the outer face and core layers. A 30:70 percent wood weight ratio of face to core was used. Three-layer particleboard (RCPB3) was made at the four ND levels 0.40, 0.50, 0.65, and 0.75 g/cm^3. The single-layer boards were constructed using mixed particles. Single-layer redcedar particleboard (RCPB1) was constructed at two ND levels (0.50 and 0.65 g/cm^3). Particles were dried to 3.5 percent MC and then blended with commercial urea-formaldehyde (UF) and wax in a laboratory rotary drum-type blender. Both types of particleboard were bonded with 7 percent of UF resin and 1 percent wax. Two replicates at each ND were made for both the single- and three-layer boards. The mats were randomly formed and compressed to 13 by 508 by 610 mm under 190°C and 4.44 MPa in the hot press for 7 minutes. After hot pressing, the panels were conditioned and edge-trimmed.

Bagasse particleboard

One-year-old bagasse residuals in the form of fiber bundles of outer sheath and spongy pith were procured after sugarcane processing. The coarse bagasse was shredded and rotary dried to 10 to 12 percent MC. In the tub grinder, impurities were removed before the bagasse was hammermilled through a 6-mm screen. The particles were blended with diphenylmethane di-isocyanate (MDI) at two RC levels (5% and 8%) and at two ND levels (0.72 and 0.88 g/cm^3). Resination time was 4 minutes. The hot press cycle was 165 seconds at 185°C for the 13-mm boards. After hot press, the boards were cooled, stacked, and sanded (Donnell 2000). For each of the four RC-ND combinations, three 13- by 1,219- by 2,438-mm panels were selected for analysis (a total of 12 panels). From each panel, four 13- by 305- by 305-mm boards were cut randomly at the plant (a total of 48 boards).

Specimen preparation and conditioning

Eight 13- by 51- by 51-mm specimens were randomly selected and cut from the middle portion of each OSB and BAPB, whereas, 12 such specimens were obtained for each RCPB. Each specimen in the study was conditioned for three weeks at 24°C and 70 percent relative humidity (RH). To study the moisture effect, the RCPB specimens were conditioned for three weeks at 50 percent RH and 24°C prior to their three weeks conditioning at 70 percent RH and 24°C. Characteristics of the specimens processed are summarized in **Table 1**.

Table 1. — Basic parameters of the test panels.

Panel type	Usage	Layer	Particulate Type	Particulate Size	Resin	ND levels[a]	Replicate (specimens)	Total specimens
				(mm)	(% type)			
OSB (aspen)								
OSB14	Structure	Single	Slender	0.635 by 13 by 76	4% PF	0.56, 0.72, 0.96, 1.12	2 (8)	64
OSB16	Structure	Single	Flake	0.635 by 13 by 76	6% PF	0.56, 0.72, 0.96, 1.12	2 (8)	69
Particleboard (eastern redcedar)								
RCPB1	Termite	Single	Granule	6, core	7% UF	0.50, 0.65	2 (12)	50
RCPB3	Toxicity	Three	Granule	3, face	7% UF	0.40, 0.50, 0.65, 0.75	2 (12)	95
Bagasse particleboard (sugarcane)								
BAPB5	Residue	Single	Fiber	<1, bundle	5% MDI	0.72, 0.88	3 (4 by 2)	48
BAPB8	Product	Single	Bundle	<1, bundle	8% MDI	0.72, 0.88	3 (4 by 2)	48

[a] ND = target nominal density (g/cm^3).

Density and MC measurements

Average density (AD), equilibrium moisture content (EMC) which is defined as conditioned weight minus ovendried weight divided by ovendried weight), and density profile across thickness were measured for each specimen after each conditioning regimen. Density profile across thickness was obtained using a Quintek density profiler (QDP-01X) for each specimen.

Ultrasonic transmission measurements

Direct contact ultrasonic transmission (UT) measurements were taken on each specimen using a Panametric 5058 pulser/receiver after each conditioning regimen. One Panametric 100-kHz transducer transmitted a signal through the thickness; another transducer, on the opposite side, received the signal (**Fig. 1**). The transducers were coupled transversely with silicon gel onto the specimen under a constant pressure of 3-kg weight. The captured signal was amplified using the built-in preamplifier, acquired at a sampling rate of 5 MHz, and digitized into an 8-bit CS225 card of the Gage CompuScope2.18 system for post data processing.

For calibration purposes prior to performing this experiment, preliminary values for the UT variables were obtained for various settings of gain, damping, pulse height, pulse gain, and attenuation. As expected, changing these settings produced large variability in the UT measurements for the same specimen. Therefore, these settings were maintained at a constant level while the UT measurements were taken for specimens at all densities throughout the course of this experiment. As in a previous study (Vun et al. 2003), the ultrasonic variables velocity, impedance, attenuation, and root mean square (RMS) voltage were used in this study, as was the variable specific velocity (SV), defined as velocity divided by AD.

Destructive strength measurements

After AD and UT measurements were taken, the specimens were mounted on blocks and then conditioned at 24°C and 70 percent RH for about a week for moisture equilibration. Internal bond (IB) strength for each specimen was then evaluated at a constant strain rate of 1.0 mm/minute using an Instron 4260 universal machine according to the ASTM D-1037 standard. Only specimens without glueline failures in the IB tests were included in the analyses. EMC of each specimen was determined at the time of testing. IB strength was also adjusted for density differences among panel types as specific IB (SIB, in kN.m/kg), defined as IB divided by AD.

Results and discussion

EMC for 70 percent RH conditioning

Sample averages for all variables are tabulated in **Table 2** by ND and panel type. The highest EMC average (7.5%) was attained by OSB, which was followed by RCPB (6.3%), and BAPB8 (4.3%). The variation of the EMCs among various products may be attributed to differences in the sorption sites among the various particles (i.e., flakes versus particles), degree of particle processing, and types of resin used for various panels. The lower density panels (e.g., ND 0.72 BAPB8) attained higher EMC (i.e., 5.0%) than the ND 0.88 panels (3.7%), which is consistent with results from Wu (2001).

From the two-factor analysis of variance (ANOVA) model with F[3,52] tests for four ND and 56 total samples in **Table 2**, the EMC means between ND's in BAPB5 are not significantly different (neither are those of AD, Attenuation, RMS voltage, IB, etc.), indicating that these specimens originated only from higher ND panels; therefore, the BAPB5 data was excluded from all analyses. From the two-factor ANOVA model with F[7,110], there is significant ND × panel type (i.e., RC levels) interaction for EMC ($p = 0.015$), and the EMC main effects for the two OSB panel types are highly significantly different ($p = 0.005$). For the RCPB panels (using the ANOVA model with F[5,139]), there is no restricted panel type × ND (levels 0.50 and 0.65 g/cm^3 only) interaction for EMC ($p = 0.756$), and the two restricted EMC panel type main effects are highly significantly different ($p < 0.0001$).

IB strength

From **Table 2**, the highest SIB averages for the BAPB8, RCPB, and OSB specimens are 2.28, 1.15, and 1.09 kN.m/kg, respectively. This is consistent with the RC level for each specimen. The compaction ratio (C/R, defined as the ratio of the nominal panel density to material density) is inversely related to

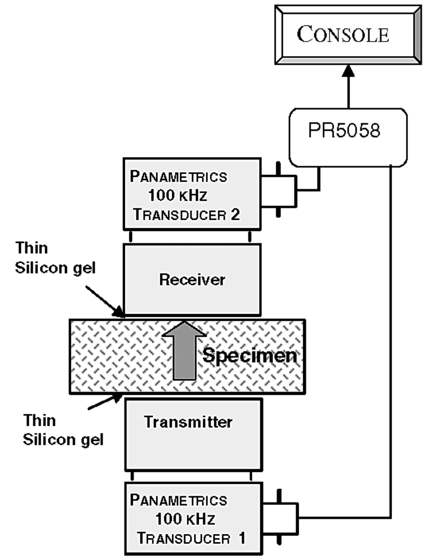

Figure 1. — Experimental setup for the contact ultrasonic system.

the maximum SIB average values and is directly related to specimen type particulate size. The C/R ratios for BAPB8, RCPB, and OSB are 1.3, 2.0, and 2.2, respectively. The OSB had to have higher C/R to achieve a strength value comparable to that of RCPB.

From the two-factor ANOVA models, there is no significant ND × OSB panel type (i.e., RC levels) interaction for IB ($p = 0.28$), while the restricted RCPB panel type × ND (levels 0.50 and 0.65 g/cm^3 only) interaction is highly significant ($p < 0.0001$). The OSB panel type main effects of IB (**Table 2**) are significantly different, as are the restricted RCPB panel type IB main effects ($p \leq 0.0001$). Within OSB panel type, the pairwise comparisons between ND levels are significant, the one exception being ND 0.72 and 0.96 g/cm^3 for OSB16 ($p = 0.487$). When IB is corrected for density (SIB), the SIB ND means for OSB14 are not significantly different beyond ND 0.72 g/cm^3 ($p \geq 0.18$). For OSB16, the maximum SIB average occurs at ND 0.72 g/cm^3.

Results of quadratic regressions of IB and SIB versus AD for the five panel types are summarized in **Table 3**. For all panel types, the least squares regression models for IB versus AD are highly significant ($r^2 \geq 0.67$); in fact, $r^2 \geq 0.86$ for RCPB3 and BAPB8. All quadratic regression IB curves increase with increasing density. For RCPB and BAPB specimens, the IB curves appear linear as compared to the quadratics of OSB shown in **Figure 2**. For the "linear"

Table 2. — Average values of properties and ultrasonic measurements by panel type.

Panel type	No.	ND levels	AD	C/R*	EMC %	IB	SIB	V	SV	Z	A	SA	RMS	SR
			- - - (g/cm^3) - - -		(75% RH)	(MPa)	(kN.m/kg)	(Km/s)	$m^4/(s.kg)$	$Gg/(s.m^2)$	–dB	$dB.cm^3/g$	v	$v.cm^3/g$
OSB (aspen)														
OSB14	17	0.56	0.574	1.5	pq7.1	0.45	n0.78	0.75	1.30	0.43	29	51.1	0.50	j0.88
	18	0.72	0.802	2.1	pr6.8	0.80	mo0.99	0.90	ef1.12	0.72	ac4.38	gh5.80	d1.13	1.40
	16	0.96	0.991	2.6	qrs7.3	0.93	ko0.93	1.17	e1.18	1.17	ab2.26	gi2.40	d1.10	1.12
	7	1.12	1.226	3.2	s7.8	1.07	kmn0.87	1.28	f1.05	1.57	bc1.01	hi0.82	0.96	j0.78
OSB16	58	avg.	D0.898	2.2	7.3	0.81	0.89	E1.02	1.16	F0.97	G9.20	H15.0	0.92	1.04
	18	0.56	0.587	1.5	8.2	0.70	de1.19	0.79	1.35	0.47	28.8	49.8	0.29	0.49
	16	0.72	0.776	2.0	fi7.6	x1.19	1.54	0.96	y1.25	0.75	u6.18	z8.65	0.85	b1.08
	17	0.96	0.977	2.6	fj7.7	x1.23	cd1.26	1.17	y1.20	1.15	v1.20	a1.27	w1.16	b1.19
	9	1.12	1.253	3.3	ij7.3	1.48	ce1.19	1.32	1.05	1.67	uv2.81	za2.19	w1.12	0.90
	60	Avg.	D0.898	2.2	7.7	1.15	1.30	E1.06	1.21	F1.01	G9.75	H15.5	0.86	0.92
Particleboard (eastern redcedar)														
RCPB1	25	0.50	0.585	1.8	t6.3	0.59	1.00	s1.03	1.77	0.60	7.17	12.7	0.53	0.89
	25	0.65	0.680	2.1	t7.0	0.72	1.06	s1.04	1.54	0.71	3.67	5.50	0.73	1.07
RCPB3	50	avg.	0.633	2.0	6.7	0.65	1.03	1.04	K1.65	0.66	5.42	9.08	0.63	0.98
	15	0.40	0.426	1.3	7.4	0.38	0.87	k0.99	2.36	0.42	9.93	23.6	0.34	0.78
	25	0.50	0.521	1.6	5.1	0.56	1.06	kj0.97	1.89	0.51	3.82	7.73	0.71	q1.34
	25	0.65	0.687	2.1	r5.9	0.97	1.41	j0.95	o1.38	0.65	m0.81	p1.20	n1.12	q1.63
	30	0.75	0.802	2.5	r6.2	1.21	1.50	1.08	o1.35	0.87	m0.63	p0.79	n1.13	1.41
	50	Avg.*	0.604	2.0	5.5	0.76	1.23	0.96	K1.64	0.58	2.32	4.47	0.91	1.48
Bagasse particleboard (sugar cane)														
BAPB5	12	0.72	a0.939	1.4	h4.3	d1.88	g2.00	1.33	1.41	1.24	b2.49	e2.67	c0.81	f0.87
	20	0.88	a0.933	1.4	h4.3	d1.82	g1.095	1.18	1.26	1.10	b2.47	e2.66	c 0.81	f0.86
BAPB8	32	avg.	0.936	1.4	C4.3	A1.85	1.98	1.25	B1.34	1.17	2.48	2.66	0.81	0.87
	16	0.72	0.802	1.2	5.0	1.54	1.91	1.09	i1.36	0.87	4.66	5.87	0.66	j0.82
	8	0.88	0.934	1.4	3.7	2.49	2.64	1.30	i1.39	1.22	2.93	3.22	0.76	j0.81
	24	Avg.	0.868	1.3	C4.3	A2.01	2.28	1.19	B1.37	1.05	3.80	4.55	0.71	0.81

ANOVA pairwise comparisons (p.c.) of ND's within panel type and also main effects (m.e.) between panel groups** (F[1,110] for OSB, F[1,139] for RCPB, and F[1,52] for BAPB): a,b,c, ... p.c.'s not significant with $p \geq 0.17$; A, B, C, ... m.e.'s not significant with $p \geq 0.11$; **For RCPB, m.e. defined for ND's 0.50 and 0.65 only. no. = number of specimens, * C/R = compact ratio (0.38 g/cm^3 aspen quaking, 0.32 g/cm^3 eastern redcedar, 0.65 g/cm^3 bagasse).

curves, BAPB8 has the steepest slope, followed by RCPB3, and RCPB1, respectively. The OSB16 quadratic curve rises to its apex and levels off and is uniformly higher than the OSB14 quadratic curve.

The least squares SIB quadratic curves for both OSB14 and OSB16 increase and then decrease over the range of observed data, unlike their IB counterparts. Maximum SIB occurs for OSB14 and OSB16 at the approximate AD values 1.0 and 0.9 g/cm^3, respectively. The SIB quadratic curves for RCPB3 and BAPB8 exhibit the pattern of increasing then leveling off at the largest AD data values, 1.1 g/cm^3 for BAPB8 and 0.85 g/cm^3 for RCPB3, while their IB counterparts appear linear and increase only. Both the IB and SIB least square quadratics for RCPB1 increase over the range of observed data.

The intersection of the IB (SIB) curves for BAPB8, RCPB3 and OSB16 occurs at the approximate AD value of 0.75 g/cm^3, indicating that a common IB (SIB) strength of about 1.1 (1.4) kN.m/kg could be attained for these panel types. For AD values ≥ 0.75 g/cm^3, the SIB curves for the five panel types follow the ordering BAPB8, RCPB3, OSB16, RCPB1, OSB14. The last two panel types contain bark impurities and have lower RCs than the first three types. This may account for the ordering of the SIB curves.

Velocity and impedance

For the UT variable velocity, the resin content main effects for the OSB type (**Table 2**) are not significantly different ($p = 0.129$), while the resin main effects for specific velocity (SV) are ($p = 0.032$). Conversely, for the RCPB specimens, the velocity single- and three-layer (restricted to ND 0.50 and 0.65 g/cm^3 only) main effects are significantly different ($p = 0.002$), whereas, those of SV are not ($p = 0.638$). The BAPB attained the highest average velocity value (1.19 km/s). For the variable impedance (Z), the OSB resin content main effects are not significantly different ($p = 0.308$).

In **Figure 3**, the least squares straight lines for the three UT variables velocity, SV, and Z versus AD are depicted. For OSB specimens, both velocity lines have positive slope, while the slopes of the SV lines are negative, suggesting that the tortuosity of the velocity flux through the material is negatively related to AD. Both RCPB velocity lines are basically level, and are, therefore, unaffected by density; however, both RCPB SV lines have negative slope. The

Table 3. — Regression models ($Y = A + B\rho + C\rho^2 + \varepsilon$) where Y is IB, SIB, Velocity, SV, Z, Attenuation, RMS, and ρ = AD (g/cm^3).

Variable	Panel type	A	B	C[a]	r^2
IB	BAPB8	–6.37	12.21	–2.91	0.86
	RCPB1	0.03	0.67	0.50	0.70
	RCPB3	–0.69	2.58	–0.27	0.94
	OSB14	–0.73	2.60	–0.90	0.77
	OSB16	–1.14	4.23	–1.73	0.67
SIB	BAPB8	–8.81	20.03	–8.28	0.69
	RCPB1	0.80	0.31	0.10	0.09
	RCPB3	–1.07	5.91	–3.36	0.82
	OSB14	–0.11	2.28	–1.20	0.16
	OSB16	–2.45	9.87	–6.16	0.28
Velocity	BAPB8	–0.03	1.40	/	0.81
	RCPB1	0.97	0.10	/	0.01
	RCPB3	0.84	0.25	/	0.17
	OSB14	0.19	0.93	/	0.76
	OSB16	0.30	0.86	/	0.77
SV	BAPB8	1.34	0.03	/	0.00
	RCPB1	3.29	–2.59	/	0.72
	RCPB3	3.31	–2.58	/	0.81
	OSB14	1.43	–0.30	/	0.21
	OSB16	1.59	–0.42	/	0.38
Z	BAPB8	–11.04	24.50	/	0.95
	RCPB1	–0.46	10.89	/	0.79
	RCPB3	–1.12	11.68	/	0.91
	OSB14	–6.39	17.72	/	0.91
	OSB16	–6.42	18.18	/	0.94
Attenuation	BAPB8	52.1	–94.6	44.3	0.56
	RCPB1	86.3	–217.0	139.7	0.78
	RCPB3	36.3	–90.8	57.3	0.68
	OSB14	137.8	–263.6	124.8	0.86
	OSB16	139.9	–263.4	122.0	0.83
RMS	BAPB8	–1.96	5.09	–2.29	0.47
	RCPB1	–3.16	9.77	–5.91	0.68
	RCPB3	–2.11	7.95	–4.83	0.82
	OSB14	–2.71	8.05	–4.16	0.79
	OSB16	–2.72	7.04	–3.18	0.74

[a] / based on simple linear regression (C=0).

BAPB velocity line increases with increasing density, but the BAPB SV line is level (i.e., specific velocity is unaffected by density). Since the SV line has zero slope only for BAPB specimens, and negative slope for the other two types, absolute velocity (defined to be SV) is impeded by AD for the larger particles of the other two types, but not by the fine fibrous particles of BAPB.

The impedance lines for all panel types have positive slopes (**Fig. 3**). The magnitudes of the slopes follow the particle sizes of the panels. The line for the fine particle of BAPB8 had the greatest slope followed by lines for OSB16, OSB14, RCPB3, and RCPB1 in that order. The slopes for the velocity lines follow this same ordering. Thus, impedance is also a measure of tortuosity of velocity flux through the material.

Attenuation and RMS

For all panel types, the least squares quadratic regression curves for attenuation against average density appear in **Figure 4**. The attenuation curves for OSB14 and OSB16 are parallel (p = 0.68). As previously mentioned, attenuation is a good measure of transmissivity of stress wave energy through the materials. Minimum attenuation for the RCPB and BAPB curves occurs at the approximate AD values 0.8 and 1.1 g/cm^3, respectively. The (negative) minimum value for the OSB least square curves occurs at the approximate AD value of 1.1 g/cm^3. Negative values for the OSB curve (from approximately 0.9 to 1.2 g/cm^3) correspond to attenuation values of zero.

Maximum RMS for the RCPB and BAPB curves occurred at the AD values for which the corresponding attenuation curves were minimized. The AD values at which the OSB14 and OSB16 curves were maximized (0.9 and 1.1 g/cm^3, respectively) constitute the AD interval over which both OSB attenuation curves were negative. The coincidence of these AD values may indicate the density for the greatest transmissivity of stress wave energy at these so-called “zero voids” densification levels for the respective panels. This densification phenomenon, also observed in Vun et al. (2003), is the transitional points of diminishing void structure, a function of particle size and density. Beyond these densities, SIB appeared to be diminishing with density. A similar finding of Smith (2001) indicated that the ultrasound dissipation by absorption or scattering are characterized by a careful balance of density, porosity, fineness of fibers, bulk elasticity, and thickness, all of which contribute to the mechanical behaviors and properties of a particular product.

Effect of EMC on UT parameters

The moisture effect for the RCPB3 ND 0.65 g/cm^3 (RCPB3-65), RCPB3 ND 0.75 g/cm^3 (RCPB3-75), and RCPB1 ND 0.65 g/cm^3 (RCPB1-65) specimens, EMC, IB, and the three primary UT measurements are studied and results are summarized in **Table 4** for the two 50 percent and 70 percent RH conditioning regimens. Using individual paired t-tests, average EMCs for 50 percent and 70 percent RH conditioning for the RCPB specimens were significantly different ($p \leq 0.021$). For RCPB1-65, attenuation and RMS voltage averages for the 50 percent and 70 percent RH conditions were significantly different ($p \leq 0.049$), while those for velocity are not ($p = 0.286$). This shows that both attenuation and RMS voltage are indicators of moisture change in the single-layer RCPB ND 0.65 g/cm^3 boards.

The 50 percent and 70 percent averages for the UT variables attenuation and RMS voltage are significantly dif-

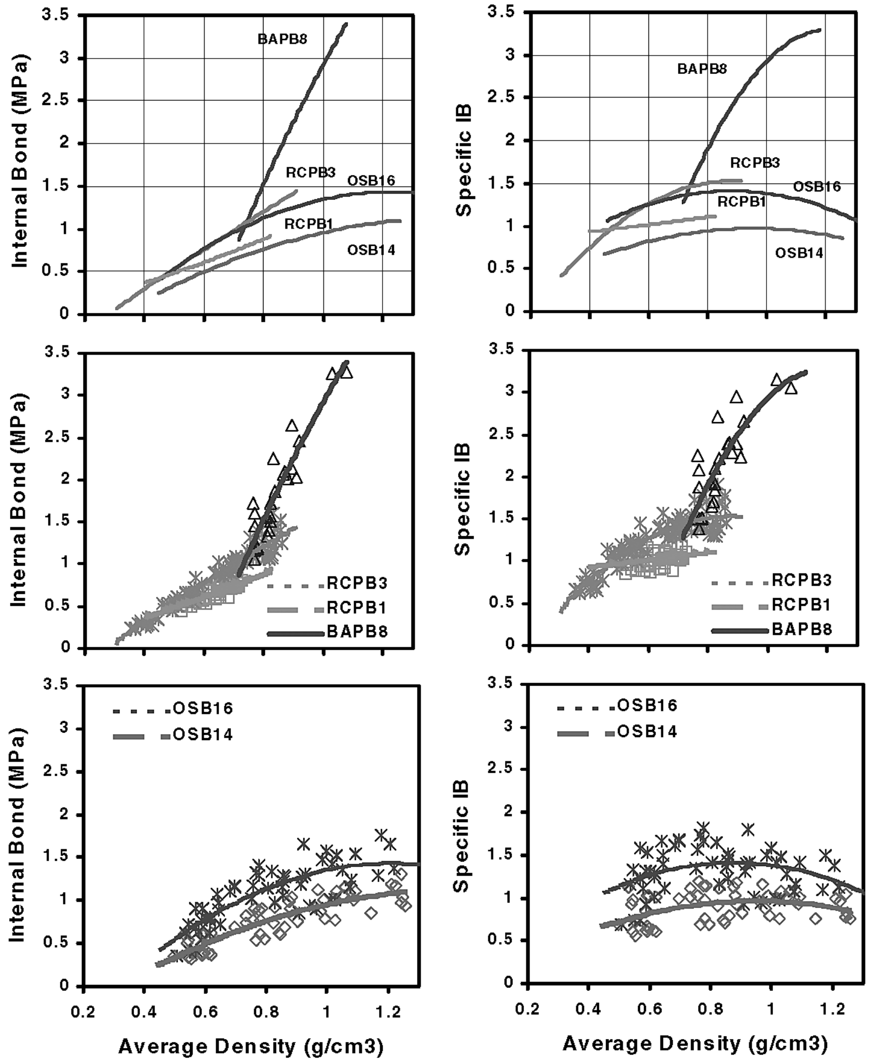

Figure 2. — Least squares quadratic curves of IB and SIB versus AD for the five panel types.

ferent ($p \leq 0.050$) for the RCPB3-65 specimens, but the velocity averages are not significantly different ($p = 0.160$). Hence, velocity is not affected by the change in MC. For higher density RCPB3-75 specimens, EMC averages for the two RH conditions are significantly different ($p = 0.002$), while the UT variables are not ($p \geq 0.173$). The increase in density for the RCPB3-75 specimens results in acoustic bulking that increases the molecular cohesion and reduces internal friction in particleboards, making velocity, attenuation and RMS voltage measurements invariant to the 50 percent and 70 percent RH conditioning regimens, consistent with the findings of Norimoto and Gril (1993). For all RCPB types, the IB averages for the two conditionings are not significantly different ($p \geq 0.122$).

Conclusions

For each panel type, IB strength varied with raw material and panel densities, impurities, fineness of particles, porosity, RC, and resin type. The net effect of velocity propagation was impeded by the large particle sizes of OSB and RCPB, but not by the fibrous constituents in BAPB. Therefore, velocity is a good indicator of physical impediments due to particle attributes in these types of panels. The impedance versus AD least squares lines generally followed their velocity counterparts for the five panels.

Minimum attenuation and maximum RMS voltage occurred at the density level of the greatest stress wave transmissivity of energy for each of the five panel types. Such densities were the transitional points

Table 4. — IB and UT variable values at 50 percent and 70 percent RH conditioning for the single-layer RCPB1-65 and three-layer RCPB3-65 and RCPB3-75.

	RCPB3-65		RCPB3-75		RCPB1-65	
	Total		Total		Total	
Specimens	Mean (COV)[a]	p-value[b]	Mean (COV)[a]	p-value[b]	Mean (COV)[a]	p-value[b]
EMC5 @50% RH (%)	5.16 (5.8)	0.021	5.13 (6.1)	0.002	6.14 (7.9)	0.000
EMC7 @70% RH (%)	5.88 (7.4)		6.20 (10)		7.02 (5.5)	
Velocity5 (km/s)	0.97 (5.0)	0.160	1.12 (6.4)	0.173	1.07 (10)	0.286
Velocity7 (km/s)	0.95 (5.3)		1.08 (11)		1.04 (6.7)	
Atten5 (-dB)	0.45 (32)	0.041	0.74 (40)	0.358	2.87 (86)	0.047
Atten (-dB)	0.81 (49)		0.63 (89)		3.67 (43)	
RMS5 (v)	1.09 (4.4)	0.050	1.10 (7.9)	0.623	0.85 (40)	0.049
RMS7 (v)	1.12 (17)		1.13 (26)		0.73 (33)	
IB5 (MPa)	0.97 (7.2)	0.846	1.28 (13)	0.122	0.81 (11)	0.246
IB7 (MPa)	0.97 (8.5)		1.21 (9.0)		0.72 (18)	

[a] COV = coefficient of variation (group standard deviation divided by the group average) in percent.
[b] Two-tailed p-values from paired t-tests: t(24) tests for both ND 0.50 and 0.65, and t(29) for ND 0.75. Gain set at (–8.40 dB).

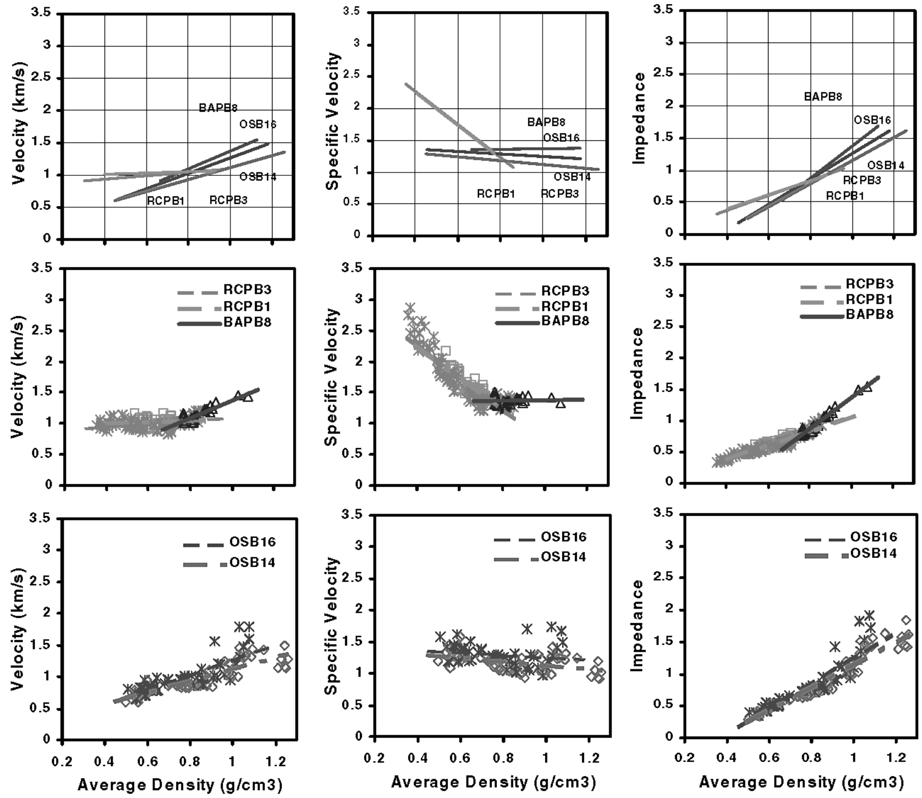

Figure 3. — Least squares straight lines of velocity, SV, and impedance versus AD for five panel types.

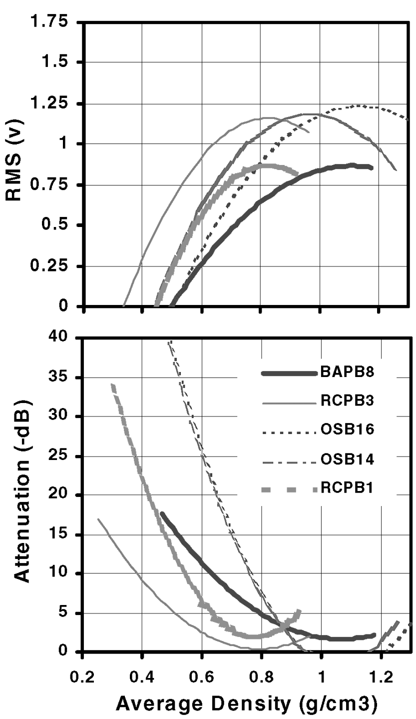

Figure 4. — Least squares quadratic curves of RMS voltage and attenuation versus average density for the five panel types.

of diminishing void structure, a function of particle size and density. In general, an appropriate ultrasonic system calibration of these material factors is essential for optimization of desired properties and a technological bridge for these reconstituted composites.

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