DOI:10.4067/S0718-221X2024005XXXXXX

USING ACOUSTIC TESTING TO ESTIMATE STRENGTH AND STIFFNESS OF WOOD-POLYMER COMPOSITES

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Received: November 09, 2021
Accepted: August 19, 2023
Posted online: August 20, 2023

ABSTRACT

This study used non-destructive testing with ultrasonic and stress wave propagation to evaluate bending strength and stiffness of wood-polymer composites. Twelve composite plate products were produced with different formulations of polymer matrix (high- and low-density polyethylene and polypropylene) and type and proportion of flour (coconut shell and wood). Mechanical and acoustic properties were influenced primarily by the type of matrix used in the composite. The greater the proportion of wood and coconut shell flour the higher the wave propagation velocity, stiffness, and strength. We found a correlation between mechanical properties (strength and stiffness) and wave velocity and stiffness coefficient. We also present linear regression equations of the stiffness and strength of the specimen as a function of wave velocity and stiffness coefficient obtained through non-destructive testing. For polypropylene and high-density polyethylene matrix composites, the stiffness coefficient provided a better estimate of stiffness, while for low-density polyethylene the wave velocity provided better results.

Keywords: *Cocos nucifera*, *Pinus taeda*, stress wave, ultrasound wave, wood-plastic materials.

INTRODUCTION

Previous studies have demonstrated that it is possible to estimate the elastic properties of timber and its derivatives (plywood, Medium Density Particleboard (MDP), Oriented Strand Board (OSB), etc.) by non-destructive testing. Using these methods, sample extraction is not necessary as the evaluation is done on the piece or structure itself (Han *et al.* 2006, Wang *et al.* 2012, Baar *et al.* 2015, Taghiyari *et al.* 2017). The use of non-destructive testing (NDT) and evaluation (NDE) has been growing in Europe and North America since the 20th century. Currently, such technologies are being used to successfully evaluate wood and wood-based materials (Dündar and Divos 2014).

According to Legg and Bradley (2016), technologies such as x-ray diffraction, near infrared (NIR) spectroscopy, and x-ray tomography, have been used to evaluate timber in a non-destructive manner. However, acoustic techniques are more common because they are relatively inexpensive, fast, robust, and easy to use in the field.

Ultrasonic waves have frequencies of 20 kHz or higher which are commonly produced by piezoelectric transducers that convert voltage to mechanical motion. The transducers must maintain contact with the analyzed material, which can be achieved with the use of coupling agents that do not affect the conditions of the specimen (Senalik *et al.* 2014). Due to an increasing number of advanced materials that can be contaminated by these coupling agents, air-coupled ultrasonic (ACU) methods have become increasingly popular in testing (Fang *et al*. 2017).

The stress wave evaluation method is performed by striking a piece of timber, panel, or composite in the transverse or longitudinal direction with a hammer. The impact can be on the piece or the transducer, depending on the type of equipment used to detect the start and stop wave propagation times. The hardness and weight of the material used as the hammer can also affect the wave frequency that is produced (Kasal *et al.* 2010).

A methodology for estimating the mechanical properties of thin wood panels (less than 6,4 mm) through the velocity of ultrasonic waves was developed by Tucker *et al.* (2003). However, variations in the static modulus of elasticity (MOE) and stiffness coefficient (C) for composites with the same composition may occur due to imperfections in the instruments or data collection procedures. In addition, variations in temperature, material porosity, and heterogeneity can also produce differences in these properties (Nesvijski 2000).

In a bar whose width and thickness are much smaller than the wavelength the sound propagates only as a strain wave or quasi-longitudinal wave, therefore, the dynamic modulus of elasticity is calculated from the velocity of wave propagation and the density of material ($E = V^2 \cdot \rho$). In wood ultrasound tests, was verified that velocity was affected by the frequency, increasing up to 500 kHz and remaining almost constant for higher frequencies (Bucur 2006).

For wood, based on the modulus of elasticity values measured, the ultrasonic wave velocity is found to be suitable for determining the dynamic modulus of elasticity, however, non-diagonal terms of the stiffness matrix must be considered. "While the ultrasonic technique is found to be reliable to measure the elastic moduli, based on the measured values, its eligibility to measure the Poisson's ratios remains uncertain" (Ozyhar *et al.* 2013). For wood-based composites (particleboard) the anisotropy is smaller and this assumption oversimplifies the structure of particleboard, which is considered a plane isotropic material. However, the accuracy of ultrasound for determining the Poisson's ratios of particleboard layers was considered questionable (Güntekin *et al.* 2018).

Recently, papers showed consistent relationships between dynamic and static modulus of elasticity for wood-based composites (Haseli *et al.* 2020). Based on the relationship between strength and stiffness, works also present the relationship between MOR and MOEd, however, with less accuracy (Chung and Wang 2019, Maulana *et al.* 2019, Ahmed *et al.* 2020). These works have in common the use of ultrasonic waves considered as a strain or quasi-longitudinal wave, with frequencies below 150 Khz.

Bachtiar *et al.* (2017) also verified that the ultrasound wave velocity can be used to estimate the modulus of elasticity of wood. The authors used a frequency of 2,27 MHz for longitudinal waves, which allows the use of small specimens, but which lead to the wavelengths (λ) of 5,0 mm – 2,5 mm. The authors considered that the chosen data evaluation method influenced the calculated Young's moduli and that before applying the ultrasound method to a new wood species, a validation study with respect to mechanical tests should be performed to quantify uncertainties and derive the optimum correction factors.

Bucur (2006) indicates that up to 1 MHz, velocity variation is associated with geometric questions related to wavelength, while above 1 MHz this variation is a result of the combination of material structural dimensions and wavelength. On the other hand, if the wavelength is no greater than both dimensions of specimen cross-section, velocity is influenced by frequency and decreases with falling frequency (Hillig *et al.* 2018). The authors demonstrated that for WPCs and using frequencies of 22 Khz and 45 Khz (λ ranging from 28,9 mm to 140,3 mm), polymer type significantly affects velocity, overcoming variations due to specimen dimensions.

Nzokou *et al.* (2006) used the transverse vibration technique and a Metriguard Model 340 system to assess the stiffness coefficient (C) of wood-polymer composites (WPC). The authors evaluated the relationship between C and static MOE using specimens with different dimensions and did not find a statistically significant correlation between them for each dimension.

Najafi *et al.* (2008) concluded that the length of the piece, wood flour content, use of maleic anhydride grafted polypropylene (MAPP) as a coupling agent, and the incorporation of glass fiber influenced a 16 kHz wave velocity in polypropylene wood composites. Bobadilla *et al.* (2011) concluded that it is possible to estimate the state of deterioration of an OSB panel and its properties through the loss of ultrasonic or stress wave velocity. Meanwhile, determining the C of particleboard by stress wave time was studied by Mendes *et al.* (2012), who observed that the type of material exerts the greatest influence on C.

For an orthotropic bagasse fiber polypropylene composite, six diagonal stiffness tensor components were quantified based on ultrasonic longitudinal and shear wave velocity measurements. This data, combined with quasi-static test data, enabled the determination of Poisson's ratio of orthotropic material (Bader *et al.* 2016).

Considering these previous analyses, the aim of the present study was to evaluate the possibility of using non-destructive tests, including ultrasonic (22 KHz and 45 KHz) and stress wave propagation, to estimate the strength and stiffness of wood-polymer composites (WPC) produced with different types of plastic and cellulose flour.

MATERIAL AND METHODS

Raw material

Coconut shell flour (*Cocos nucifera* L.) and two different grain sizes (thick and thin) Loblolly pine (*Pinus taeda* L.) wood flour were used. The thick-grain wood flour was obtained from forest industry waste, while the thin-grain flour and thin coconut shell flour were provided by a company that produces the material. The particle diameter for each type of flour, whose volume is equal to the average volume of all particles, was 0,0143 mm, 0,0196 mm, and 0,2599 mm for coconut shell, thin-, and thick-grain pine, respectively.

Three kinds of polymers were used in the matrix phase composites: high-density polyethylene (HDPE); a 50/50 mix of virgin and recycled, low-density polyethylene, (LDPE), and polypropylene (PP). Also were used a coupling agent MA-HDPE, that a HDPE graphitized maleic anhydride. Their properties are shown in Table 1.

Table 1: Properties of the polymers used.

Property	**Standard ASTM***	**LDPE**	**HDPE**	**PP**	**MA-HDPE**
Density (g·cm^{-3})	D 1505	0,918	0,954	0,900	0,950
Melt flow rate 190 ºC / 2,16 kg (g/10min)	D 1238	8,3	4,5	20	5,0
VICAT softening temperature	D 1525	86	124	130-160	127
Tensile Stress (MPa)	D 638	9	27	22	--
Static Bending Modulus (MPa)	D 790	200	1150	900	--
Maleic anhydride content (%)	--	--	--	--	1

Source: Braskem (2016); Chemtura (2006). *For LDPE (low-density polyethylene), HDPE (high-density polyethylene) and PP (polypropylene). MA-HDPE: HDPE graphitized maleic anhydride.

Production of composites and molds

The production of the composites was performed using an MH-COR-20-32 co-rotating twin-screw extruder with a 20 mm diameter screw, length/diameter ratio (L/D) of 32, and degassing. The extrusion was conducted with varying temperatures in the different heating zones according to the following profile: 160 ºC, 160 ºC, 180 ºC, 180 ºC, 185 ºC, and 190 ºC; and melt temperature at 220 ºC. The speed was set to 0,23 m·s^{-1}.

The preparation of plates was performed using a steel mold with dimensions of 250 mm x 300 mm x 10 mm. The molds were male and female snap oriented with guide pins. After the distribution of granulated composite in the mold, it was pressed at 7,85 MPa and a temperature of 180 °C, then braked. After pressing, the mold was cooled in water and the plate removed manually. Specimens of 50 mm x 220 mm were then cut for the acoustic and mechanical tests.

Experimental design and statistical analysis

In order to evaluate the acoustic properties of specimens made from different materials, composites were produced that varied in terms of polymer type, flour ratio, and particle type and size (Table 2).

Table 2: Types of composites produced.

Composite	Polymer[1]	Flour ratio[2] (%)	Flour type[3]
1	HDPE	20	*Pinus taeda* thin
2	HDPE	40	*Pinus taeda* thin
3	HDPE	10 + 10	*Pinus taeda* thin + Coconut shell
4	HDPE	20 + 20	*Pinus taeda* thin + Coconut shell
5	PP	20	*Pinus taeda* thin
6	PP	40	*Pinus taeda* thin
7	PP	10 + 10	*Pinus taeda* thin + Coconut shell
8	PP	20 + 20	*Pinus taeda* thin + Coconut shell
9	LDPE	40	*Pinus taeda* thin
10	LDPE	20 + 20	*Pinus taeda* thin + Coconut shell
11	LDPE	40	*Pinus taeda* thick
12	LDPE	20 + 20	*Pinus taeda* thick + Coconut shell

[1] HDPE = high-density polyethylene; PP = polypropylene; LDPE = 50 % virgin low-density polyethylene + 50 % recycled low-density polyethylene; [2]By weight; [3]Mean particle diameter of 0,0143 mm, 0,0196 mm, and 0,2599 mm for coconut shell, thin-grain pine, and thick-grain pine, respectively.

Five specimens of each composite type were used in the statistical analysis, for a total of 60 samples. The mean and standard deviation values of the properties evaluated by composite type were calculated. Correlation and regression analysis were performed for all specimens and for each polymer matrix group.

Acoustic and physical-mechanical tests

Acoustic tests

To conduct the acoustic tests, three commercial devices were used: USLab, Sylvatest-Duo, and Fakopp Microsecond Timer, manufactured by Agricef, CBS-CBT, and Fakopp Enterprise, respectively (Figure 1). The first two measure the velocity of ultrasonic wave propagation in the evaluated specimens. USLab operates at a frequency of 45 kHz and the Sylvatest-Duo at 22 kHz. The third device measures the stress wave velocity generated by a hammer strike on the start sensor, which is received at the end sensor. The pulse used is at a lower frequency than with ultrasound and is generally lower than 20 kHz (Dackermann *et al.* 2014). For the ultrasonic and stress wave tests the specimens were placed on wooden supports and held by a horizontal clamp.

The wave propagation time between the two transducers was recorded to calculate the propagation velocity, according to equation 1. During the test, the transducers were positioned at opposite sides of the specimens (direct test) to read the compression wave propagation time (t) across a 220 mm span (s) for ultrasound or 216 mm span (s) for stress wave, due to the penetration of stress wave sensors by 2 mm on each side of the specimen (Figure 1.A and 1.B).

$$V = \frac{s}{t} \tag{1}$$

where, V = velocity ($m \cdot s^{-1}$); s = distance between transducers or sensors (m); t = time (s).

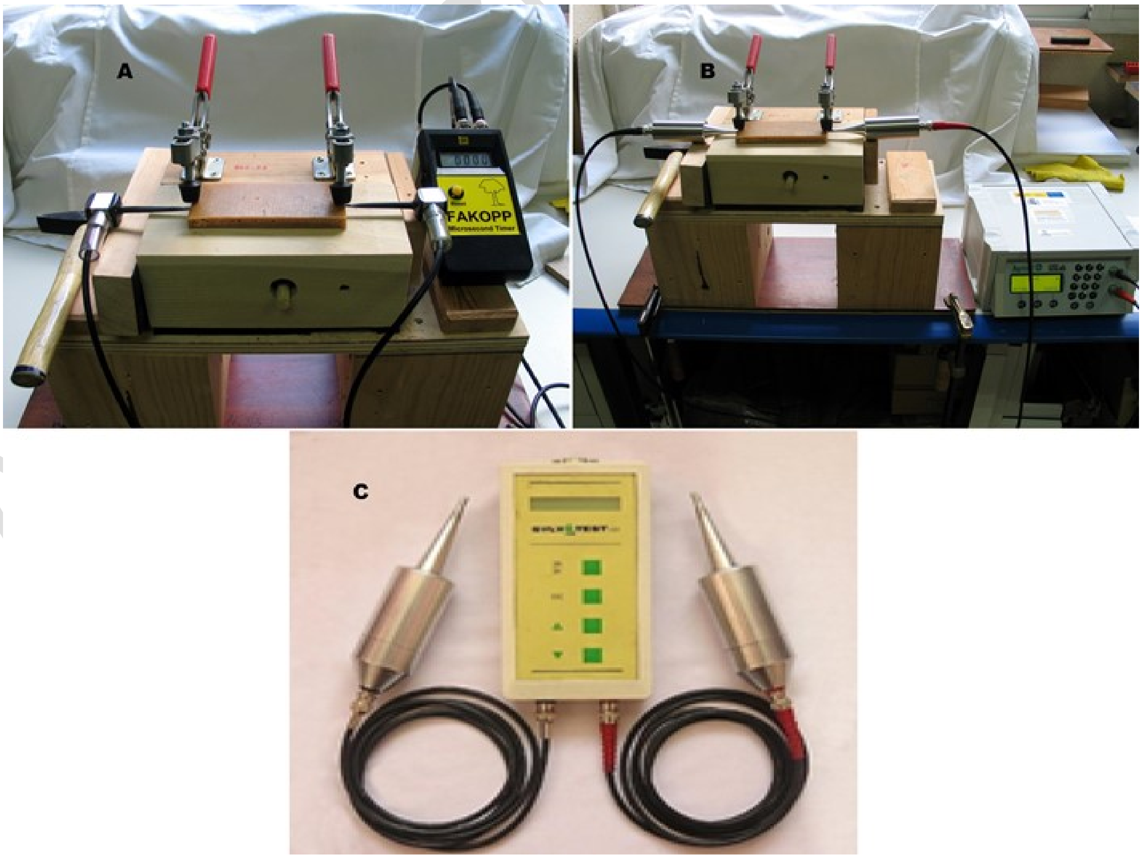

Figure 1: A: Stress wave test. B: Ultrasound test USLab, C: Ultrasound Sylvatest.

The stiffness coefficient (C) was calculated according to Equation 2 from density and velocity. This coefficient avoids the interference of density in the main analysis.

$$C = \rho \times V^2 \qquad (2)$$

where, ρ = apparent density ($g\cdot cm^{-3}$); V = velocity ($m\cdot s^{-1}$).

Physical-mechanical tests

The apparent density was calculated by the apparent mass to volume ratio determined by the stereometric method. The assessment of bending strength (modulus of rupture - MOR) and stiffness (modulus of elasticity - MOE) was performed according to EN 310-93 (UNE, 1994). The test specimens, with dimensions of 220 mm x 50 mm x 10 mm, were conditioned at 20 ºC and 65 % relative humidity, and submitted to a three-point bending test.

RESULTS AND DISCUSSION

Physical-mechanical and acoustic properties of the specimens

Table 3 shows the mean values of the specimen properties by composite type. Properties varied among composites, mainly due to the type of matrix (polymer) used. In addition, the inclusion of voids in the molding process interfered with the density of some specimens. Specimens made with HDPE presented the greatest number of voids, except for formulation 4 which reached a density of 0,98 $g\cdot cm^{-3}$.

Specimens made from PP showed the highest mean values for all properties except for bending strength (MOR), with HDPE showing intermediate values and LDPE lower values. Although the melting temperature of PP is 175 °C, the temperature of 180 °C used in the press plates was insufficient to evenly melt the polymer. As such, the plates showed regions where the granules did not melt. This explains the higher stiffness and lower strength values of these composites compared to those made with HDPE matrix.

Table 3: Mean values and standard deviation of the specimen properties by composite material type.

Cp	Matrix	Dens ($g\cdot cm^{-3}$)	MOR (MPa)	MOE (MPa)	vel22 ($m\cdot s^{-1}$)	C22 (MPa)	vel45 ($m\cdot s^{-1}$)	C45 (MPa)	velSW ($m\cdot s^{-1}$)	CSW (MPa)
1	HDPE	0,89	31,56	1347	1914	3114	2209	4157	1603	2191
		(0,06)	(4,38)	(97)	(50)	(579)	(62)	(763)	(93)	(493)
2		0,71	27,39	1213	1812	2328	2062	3014	1471	1532
		(0,04)	(1,22)	(101)	(43)	(210)	(39)	(240)	(15)	(81)
3		0,92	34,35	1413	1858	3167	2201	4447	1490	2035
		(0,03)	(6,77)	(58)	(59)	(279)	(75)	(412)	(27)	(106)
4		0,98	36,49	1627	2043	4082	2384	5565	1633	2612
		(0,04)	(3,56)	(114)	(17)	(226)	(63)	(461)	(60)	(213)
5	PP	0,96	21,47	2566	2303	4791	2670	6456	1880	3227
		(0,01)	(3,71)	(246)	(73)	(740)	(71)	(914)	(46)	(394)
6		0,98	35,82	3014	2449	5894	2830	7869	1985	3873
		(0,01)	(5,26)	(157)	(55)	(290)	(62)	(385)	(39)	(177)
7		0,93	28,96	2491	2296	4626	2674	6291	1909	3250
		(0,02)	(4,26)	(215)	(58)	(737)	(78)	(981)	(25)	(372)
8		0,99	27,50	2834	2272	5123	2605	6733	1856	3417
		(0,01)	(5,66)	(171)	(41)	(164)	(42)	(223)	(27)	(84)
9	LDPE	0,79	15,19	493	1436	1642	1619	2084	1193	1133
		(0,03)	(1,09)	(24)	(37)	(157)	(30)	(170)	(36)	(120)
10		0,87	16,45	496	1480	1906	1656	2386	1230	1317
		(0,01)	(0,31)	(13)	(10)	(37)	(9)	(46)	(25)	(50)
11		0,83	17,25	520	1458	1762	1636	2216	1226	1246
		(0,01)	(0,62)	(27)	(17)	(62)	(20)	(66)	(22)	(51)
12		0,82	14,04	395	1394	1585	1575	2024	1184	1145
		(0,01)	(1,33)	(35)	(8)	(38)	(15)	(61)	(8)	(29)

Cp= composite; Dens= density; MOR= modulus of rupture; MOE= modulus of elasticity; Vel22, Vel45, VelSW= wave velocity at 22 kHz, 45 kHz, stress wave; C22, C45, CSW= stiffness coefficient at 22kHz, 45kHz, stress wave; Values in brackets refer to the standard deviation.

An increase in the proportion of flour is expected to increase the bending strength and stiffness of the plates; however, when comparing the results between composites 1 and 2 (HDPE) and composites 7 and 8 (PP), such a result was not obtained. For the HDPE matrix, the lack of increase in bending strength can be attributed to the occurrence of voids which caused a difference in density between composites 1 and 2. For the PP matrix, the lower strength and stiffness of composite specimen 7 compared to 8 can be attributed to the difficulty of melting the polymer at the temperature used in the press plates, as mentioned above. The occurrence of regions where the granules did not melt affected the strength of the PP matrix plates, since it did not provide a good plate conformation.

The wave propagation velocity and stiffness coefficient varied between methods as a result of the type of matrix and type and proportion of flour used in the composite. As expected, the mean value of both properties was lowest for the stress wave, followed by the 22 kHz ultrasonic wave, and highest for the 45 kHz ultrasonic wave for all evaluated composites. This difference can be explained by the influence of frequency on wave velocity, because according to Bucur (2006), wave velocity was affected by the frequency increasing up to 500 kHz and remaining almost constant for higher frequencies.

The density had some influence on wave velocity, as can be seen in the velocity values obtained for composite 2 which are inferior to those obtained for the other HDPE composites. However, for wood and wood byproducts, differences in wave velocity are related to changes in the ratio between density and modulus of elasticity. With a higher wood density, the wave propagation velocity should decrease, but this usually results in an increase in wood stiffness, which counterbalances the effect (Baar *et al.* 2012).

The acoustic properties of a medium are determined by its physical-mechanical properties, such as density, modulus of elasticity, and structure. In general, for solid media that have similar levels of rigidity, an increase in density results in a decrease in wave velocity because it requires a greater amount of kinetic energy to make larger molecules vibrate (Nazarchuk *et al.* 2017). However, for wood panels (fiberboard, particleboard, and OSB), the velocity increases almost linearly with increasing density between 350 $kg \cdot m^{-3}$ and 900 kg/m^3 due to an increase in MOE (Hilbers *et al.* 2012).

Najafi *et al.* (2008) found propagation velocity values varying from 2285 m/s to 2784 $m \cdot s^{-1}$ using 16 kHz ultrasonic waves with wood-polypropylene composites at ratios of 50 %, 60 %, and 70 %. These values are similar to those found herein with 22 kHz waves that ranged from 2272 $m \cdot s^{-1}$ to 2449 $m \cdot s^{-1}$.

If we compare the wave velocity reported for other composites or wood panels, we can see that the mean values found in this study are lower but similar to those reported for particleboard and fiberboard. Table 4 provides a comparison with the values reported in other studies on wood panels, where it is verified that MDF and MDP panels had lower wave velocity, followed by OSB. Plywood was the panel that wave velocity was considerably higher.

Table 4: Values of wave propagation velocity (ultrasonic and stress waves) reported in research on wood panels.

Source	**Panel type**	**Wave type**	**Velocity (m/s)**
Bekhta *et al*. (2000)	MDP, MDF, OSB	US 50 kHz, 100 kHz, 200 kHz	2118 - 3294
Silva and Gonçalves (2007)	MDF	US 45 kHz	2162 - 2720
Morales *et al*. (2007)	OSB	US 45 kHz	2575 - 3216
Del Menezzi *et al*. (2007)	OSB	Stress wave	2600 - 2850
Bobadilla *et al*. (2011)	Plywood	US 22 kHz	3231 - 3770
Bobadilla *et al*. (2012)	MDF and MDP	Stress wave	1828 - 2031[1]

[1]For panels that have not undergone accelerated aging.

Correlation and Regression

Table 5 shows the Pearson correlation coefficient between the analyzed properties of the composite specimens. There was a significant correlation between all evaluated properties, with a strong correlation among the three types of waves evaluated and between wave type and MOE. Furthermore, a strong correlation was observed between the wave velocity or stiffness coefficient and MOE.

Table 5: Pearson correlation coefficient between properties.

	Dens	**Vel22**	**C22**	**Vel45**	**C45**	**VelSW**	**CSW**	**MOR**	**MOE**
Dens	1								
Vel22	0,724*	1							
C22	0,815*	0,984*	1						
Vel45	0,731*	0,997*	0,979*	1					
C45	0,819*	0,983*	0,997*	0,984*	1				
VelSW	0,716*	0,988*	0,973*	0,987*	0,974*	1			
CSW	0,808*	0,975*	0,991*	0,972*	0,990*	0,984*	1		
MOR	0,483*	0,652*	0,615*	0,670*	0,632*	0,607*	0,579*	1	
MOE	0,720*	0,979*	0,976*	0,973*	0,972*	0,976*	0,974*	0,566*	1

*Significant correlation at 1 % probability of error; Dens= density; Vel22, Vel45, VelSW= wave velocity at 22 kHz, 45 kHz, stress wave; C22, C45, CSW= stiffness coefficient at 22 kHz, 45 kHz, stress wave; MOR= modulus of rupture; MOE= modulus of elasticity.

The MOE showed some variation among composites of the same matrix, which is consistent with the variations in density (Figure 2). The stiffness coefficient (C22, C45, CSW) followed a trend that was more similar to the MOE than wave velocity, except for LDPE composites because the variation in density and MOE are limited. For MOR, other sources of variation occurred mainly in composites 1 to 5.

Furthermore, the normalized density and MOR followed a trend in variation similar to the MOE, which confirms the correlation between these properties (Table 4). The density of the composite was affected by voids and the problems discussed above in relation to the melting temperature of the PP polymer. This resulted in differences in density among the composites that mainly affected their strength. On the other hand, the stiffness was more heavily influenced by the characteristics of each fiber/matrix combination.

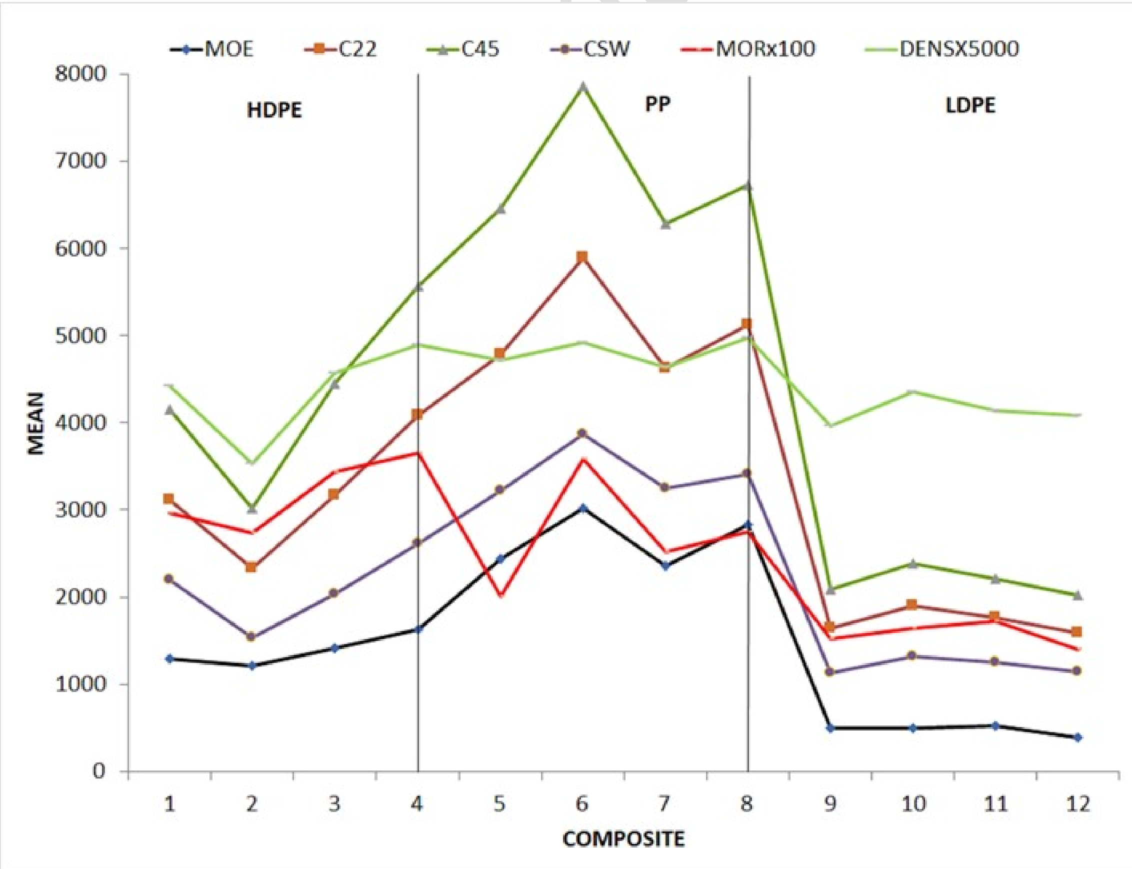

Figure 2: Trend line graph for density, MOE, MOR, and stiffness coefficient of the different composites.

MOE and stiffness coefficient formed three distinct groups which correspond to the matrix used in the composite. In addition, we found that the assumptions of linear regression for independence, normality, and homogeneity of error variances were not obtained when considering all composites. However, these assumptions were met when analyzing the data separately for each matrix.

Thus, in Figure 3, the MOE plot is presented as a function of the wave velocity and stiffness coefficient separated by the type of matrix used in the composite. We can see that the MOE varied as a function of the wave velocity, which is similar to the variation found as a function of the stiffness coefficient. Thus, this shows that the influence of the composite density on their dynamic stiffness properties verified in Table 5 occurs in the same way for all three types of polymers used.

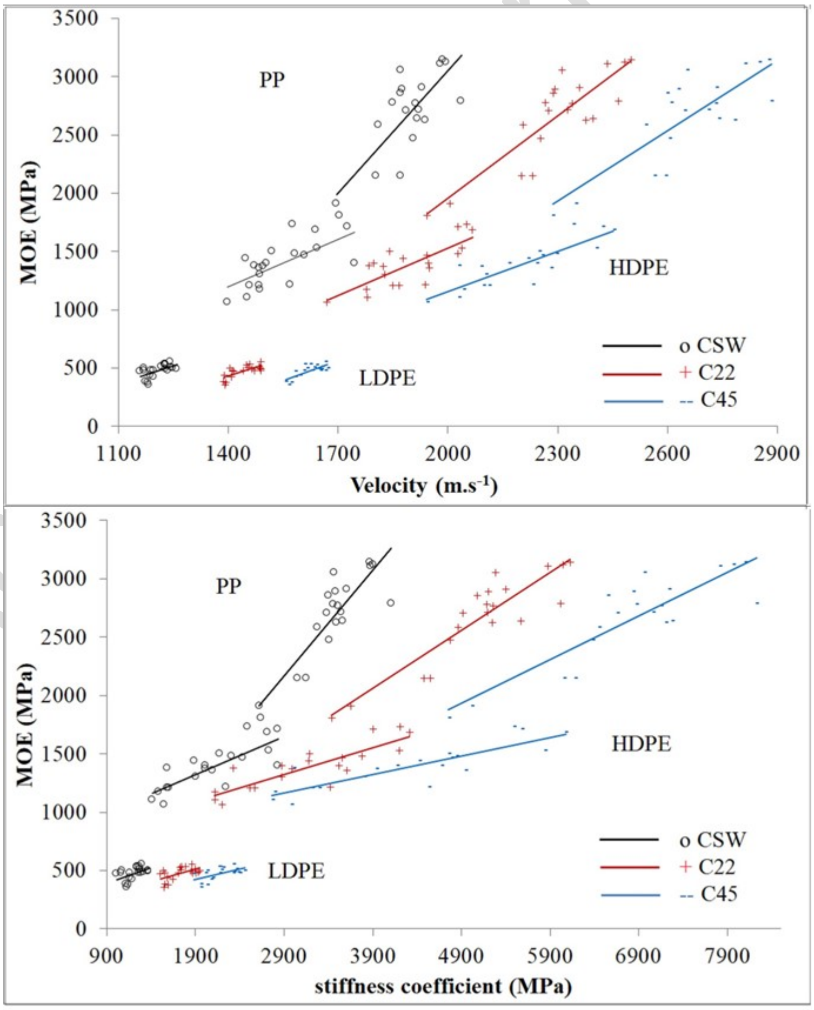

Figure 3: MOE as a function of the wave velocity and stiffness coefficient with the regression line for each composite group with the same matrix.

Table 6 presents the linear regression equations of MOE as a function of the wave velocity and stiffness coefficient for each composite group of the same matrix. The results show an estimated standard error of less than 11 %, which is low and indicates the applicability of acoustic techniques to estimate MOE.

Table 6: Linear regression equations of Modulus of Elasticity (MOE) as a function of the variables obtained in non-destructive tests for composites of each matrix.

Matrix	Model	R^2_{aj}	S_{yx}	S_{yx} (%)	F	p-value
HDPE	MOE = -1196,8 + 1,363*V22	0,625	120,6	8,7	30,0	<0,001
	MOE = 662,9 + 0,228*C22	0,709	103,4	7,5	47,3	<0,001
	MOE = -1150,2 + 1,152*V45	0,728	99,9	7,2	51,9	<0,001
	MOE = 698,3 + 0,160*C45	0,741	97,7	7,1	55,2	<0,001
	MOE = -716,9 + 1,366*VSW	0,421	145,9	10,5	14,8	0,001
	MOE = 698,6 + 0,328*CSW	0,631	116,5	8,4	33,5	<0,001
PP	MOE = -2743,3 + 2,351*V22	0,744	201,6	7,6	52,2	<0,001
	MOE = 120,97 + 0,497*C22	0,818	165,4	6,2	86,3	<0,001
	MOE = -2683,2 + 2,009*V45	0,638	233,6	8,8	34,6	<0,001
	MOE = 94,97 + 0,375*C45	0,755	191,9	7,2	59,5	<0,001
	MOE = -3942,3 + 3,496*VSW	0,601	244,9	9,2	29,6	<0,001
	MOE = -455,8 + 0,905*CSW	0,755	191,8	7,2	59,6	<0,001
LDPE	MOE = -1027,9 + 1,043*V22	0,533	38,3	8,0	20,6	<0,001
	MOE = 124,52 + 0,204*C22	0,276	46,4	9,7	8,2	0,010
	MOE = -1410,4 + 1,164*V45	0,563	36,1	7,6	25,4	<0,001
	MOE = 78,43 + 0,183*C45	0,282	46,2	9,7	8,5	0,009
	MOE = -787,5 + 1,046*VSW	0,309	45,4	9,5	9,5	0,006
	MOE = 161,72 + 0,260CSW	0,190	49,1	10,3	5,5	0,031

R^2aj: Adjusted regression coefficient (coefficient of determination); S_{yx}: Standard error of estimate; F: F value of the variance analysis; p-value: level of statistical significance; MOE= modulus of elasticity; V22, V45, VSW= wave velocity at 22 kHz, 45 kHz, stress wave; C= stiffness coefficient at 22 kHz, 45 kHz, stress wave.

For HDPE and PP, the coefficient of determination was greater and the estimated standard error was lower when the stiffness coefficient was used instead of wave velocity. However, the reverse was true for LDPE. Regarding the types of waves used, for HDPE and LDPE the best results were obtained with the 45 kHz ultrasonic waves, while for PP it was with the 22 kHz ultrasonic wave.

This can be explained by the plate characteristics produced with each type of matrix. For the plates produced with PP, which had problems obtaining a good polymer melting, a lower frequency was less affected by the discontinuous points of the plates. On the other hand, for HDPE and LDPE, a higher frequency was less affected by the relationship between cross-sectional dimensions and specimen length. (Bachtiar *et al.* 2017).

The stress wave velocity presented the lowest coefficient of determination and the highest estimated standard error for the three matrices. Han *et al.* (2006) presented MOE estimates as a function of stress wave velocity obtained using a Metriguard 239A system for wood panels in different conditions of humidity, obtaining coefficients of determination ranging from 0,35 (plywood panels) to 0,80 (OSB panels). Furthermore, Nzokou *et al.* (2006) concluded that the stress wave technique was ineffective in determining the MOE for PVC composites made with oak wood flour. However, the authors performed regression analyses to estimate the MOE as a function of wave velocity in specimens that were all made with the same type of composite. They suggest that further studies are needed on composites produced with a range of different materials. In this study, for ultrasound waves of 22 kHz and 45 kHz and for stress waves, we found significant correlations between different composites of the same matrix.

Najafi *et al.* (2008) reported that composite characteristics influenced the propagation velocity of ultrasound waves. This fact was confirmed herein for the composites produced with different matrices and with different types and proportions of wood flour. These characteristics also affected the strength and stiffness of the specimens, with a significant correlation found between these properties and the velocity of the three types of waves studied.

Figure 4 shows graphs of MOR as a function of density, MOE, wave velocities, and stiffness coefficients with the regression line for each group of composites of the same matrix. The regression coefficients are smaller than those obtained for the estimates of MOE but demonstrate that part of the variation of MOR can also be explained by the variation in these properties.

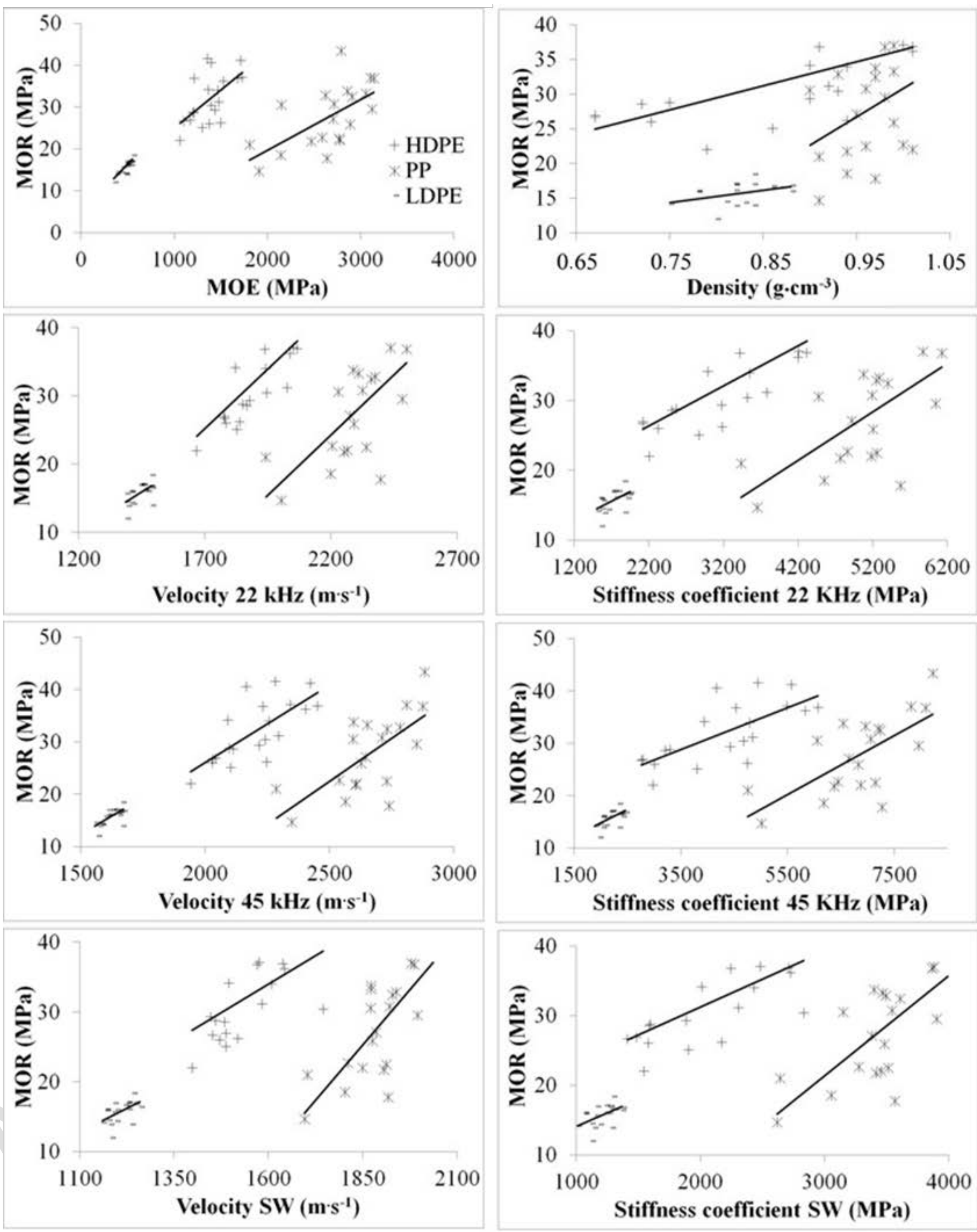

Figure 4: MOR of the specimens as a function of MOE, density, wave velocity, stiffness coefficient, with regression lines for each group of composites of the same matrix (- LDPE; +HDPE; ⁎PP).

Figure 4 shows that for each matrix there is a relationship between MOR and MOE and this relationship is more significant than MOR as a function of density. The greatest variation in density among composites of the same matrix occurred for those produced with HDPE (Table 3), due to the existence of voids, as discussed above. These voids affected the specimen strength; therefore, for this matrix the relationship between density and MOR was higher.

For the PP matrix composites, we found less variation in density; however, there was variation in MOR due to the problems with polymer melting during pressing. For the LDPE matrix composites, we found little variation in MOR. Therefore, for these two matrices the relationship between MOR and density was low.

Several studies have demonstrated the relationship between the bending properties of wood panels and wave velocity, obtained using ultrasound, transverse vibration, or stress waves (Silva and Gonçalves 2007, Morales *et al.* 2007, Del Menezzi *et al.* 2007, Bobadilla *et al.* 2011). For the composites evaluated herein, we found that there is a relationship between the studied properties and wave velocity. However, for MOR there was a lower coefficient of determination (Table 7).

Considering the results obtained in this study and the results obtained for wood panels by others, estimates of composite stiffness (MOE), as obtained through velocity or the stiffness coefficient (C), presented the best conditions for analysis as a function of ultrasonic or stress wave velocity.

We can infer that wave velocity is a promising technique for estimating the modulus of elasticity and, to a lesser extent, the strength of WPC specimens. Nevertheless, evaluated specimens must be significantly different, for example, when they are produced with different materials or when subjected to weathering and environmental factors. In addition, the dimensions of the specimens must be considered in comparison with the frequency of waves used.

Table 7: Linear regression equations of Modulus of Rupture (MOR) as a function of the variables obtained in the non-destructive tests for the composites of each matrix.

Matrix	Model	R^2_{aj}	S_{yx}	S_{yx} (%)	F	p-value
HDPE	MOR = -34,76 + 0,035*V22	0,416	4,48	14,0	14,6	0,001
	MOR = 13,78 + 0,006*C22	0,463	4,30	13,4	17,4	0,001
	MOR = -32,91 + 0,029*V45	0,494	4,17	13,0	19,5	<0,001
	MOR = 14,76 + 0,004*C45	0,478	4,23	13,2	18,4	<0,001
	MOR = -18,41 + 0,033*VSW	0,237	5,12	16,0	6,91	0,017
	MOR = 15,26 + 0,008*CSW	0,379	4,62	14,5	12,6	0,002
	MOR = 6,83 + 0,018*MOE	0,317	4,84	15,1	9,8	0,006
PP	MOR = -76,18 + 0,045*V22	0,566	5,48	20,2	25,8	<0,001
	MOR = -17,70 + 0,009*C22	0,535	5,68	20,9	22,9	<0,001
	MOR = -82,78 + 0,041*V45	0,581	5,39	19,8	27,3	<0,001
	MOR = -20,99 + 0,007*C45	0,563	5,51	20,3	25,5	<0,001
	MOR = -117,66 + 0,077*VSW	0,628	5,08	18,7	33,1	<0,001
	MOR = -33,16 + 0,018*CSW	0,603	5,25	19,3	29,8	<0,001
	MOR = -13,46 + 0,015*MOE	0,478	6,02	22,2	18,4	<0,001
LDPE	MOR = -18,87 + 0,024*V22	0,329	1,24	7,9	10,3	0,005
	MOR = 6,17 + 0,006*C22	0,262	1,30	8,3	7,7	0,012
	MOR = -30,86 + 0,029*V45	0,431	1,15	7,3	15,4	0,001
	MOR = 4,23 + 0,005*C45	0,310	1,26	8,0	9,5	0,006
	MOR = -16,91 + 0,027*VSW	0,259	1,31	8,3	7,6	0,013
	MOR = 6,31 + 0,008*CSW	0,229	1,33	8,5	6,7	0,019
	MOR = 4,42 + 0,024*MOE	0,714	0,88	5,6	48,5	<0,001

R^2aj: Adjusted regression coefficient (coefficient of determination); S_{yx}: Standard error of estimate; F: F value of the variance analysis; p-value: level of statistical significance; MOE= modulus of elasticity; V22, V45, VSW= wave velocity at 22 kHz, 45 kHz, stress wave; C= stiffness coefficient at 22 kHz, 45 kHz, stress wave.

CONCLUSIONS

The specimens presented mechanical and acoustic properties that were mainly determined by the type of matrix used in the composite. The composites produced with polypropylene presented greater stiffness and higher values of wave velocity, followed by those made with high-density polyethylene and low-density polyethylene.

Increasing the proportion of wood flour and coconut shell flour increased the wave propagation velocity and the stiffness and strength of the specimens.

There was a significant correlation between bending strength and dynamic modulus of elasticity based on analyses with the three types of waves. We found that wave velocity is a promising technique to estimate mechanical properties (bending strength and modulus of elasticity) of WPC specimens, however, the wave frequency and its relationship to the cross-sectional dimensions of the specimen must be considered.

The best regression coefficients and lower standard errors for estimates of the modulus of elasticity were obtained as a function of the stiffness coefficient for polypropylene and high-density polyethylene matrix composites. For low-density polyethylene the wave velocity provided better results.

It is recommended that future studies test the use of higher frequencies to estimate the strength and stiffness of polymer-wood composites.

AUTHORSHIP CONTRIBUTIONS

É. H.: Conceptualization, Funding acquisition, Methodology, Investigation, Data Curation, Formal Analysis, Writing – original draft. **I. B.:** Conceptualization, Funding acquisition, Methodology, Data Curation, Formal Analysis, Supervision, Writing – review & editing. **F. A.:** Funding acquisition, Validation, Formal Analysis, Supervision, Writing – review & editing. **G. Í-G.:** Funding acquisition, Validation, Formal Analysis, Supervision, Writing – review & editing.

ACKNOWLEDGMENTS

The present study was carried out with the support of CNPq, National Council of Scientific and Technological Development - Brazil; UNICENTRO, Midwestern State University; UPM, Universidad Politécnica de Madrid; and UCS, Caxias do Sul University. Partial financial support (2020) was provided by the Timber Construction Research Group, Universidad Politécnica de Madrid, Spain.

DECLARATION OF CONFLICTING INTERESTS

The Authors declares that there is no conflict of interest.

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