Acoustic and Strength Characterization of Particleboard and Micronized Rubber Powder Composites

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Abstract

Waste rubber is abundant worldwide and threatens to be an environmental hazard for decades to come. This has led to an interest in the use of recycled rubber materials in value-added products. One such possible use is in the wood products industry. The research analyzed the strength and acoustic properties of composite pine particleboard that contained 10, 20, 30, and 40 percent micronized rubber powder, a dry powdered elastomeric crumb rubber, by weight. Methylene diphenyl diisocyanate was used as the bonding adhesive to produce five particleboard samples, including a control board. Test samples were cut from the five parent boards for use in strength and acoustic testing. Measured displacement values for a simply loaded and simply supported load scenario were used to calculate the modulus of rupture and apparent modulus of elasticity for each composite particleboard. Acoustic measurement by impedance tube provided comparisons of the sound absorption coefficient for frequencies ranging from 60 to 6,300 Hz. Results revealed that the addition of micronized rubber powder led to a decrease in modulus of elasticity and no significant difference in modulus of rupture values as compared with the control. Statistical analysis indicated a decrease in sound absorption in particleboard that contained micronized rubber powder when compared with the control.

Concern related to the environmental impact of waste tire rubber has grown as landfills run out of space and the landscape of cities and rural areas alike are dotted with heaps of worn-out tires. Other cast-off rubber products can be found at abandoned job sites, in factory scrap yards, and lining roadways worldwide. The research reported upon in this paper worked to characterize the basic strength and acoustic properties of composite particleboard that contained increasing proportions of micronized rubber powder. Micronized rubber powder (MRP) is categorized as a dry powdered elastomeric crumb rubber in which the majority of the particles are <100 μm (Ayyer et al. 2012).

Exploring means by which to use rubber particles, ranging in size from powder form to large chunks, in wood products has been a topic of research for many years. As landfills continue to fill with unusable tires, interest in finding strategies to use such large quantities of nonbiodegradable waste has increased. New technology provides a pathway for further refinement, to consistent particles sizes <100 μm, of waste rubber. These small sizes, much smaller than shredded tire rubber pieces, have led to expanded opportunities for incorporation into new products. Recycled rubber particles, of any size, may be used in a variety of ways. These include application into new rubber products, carpet underlayment, mulch, insulation, and other construction materials including sound insulation (Forrest 2014). The mechanism of the sound absorption of materials is explained by Zhu et al. (2014). There is a viscous effect between the numerous air cavities and solid framework that attenuates the sound energy and converts it to heat. The heat transfer occurs between different areas (caused by friction) and the vibration of the air in the bulk materials will lead the vibration of the material, which causes the soundwave to dissipate.

Forrest (2014) specifically mentions a study dealing with wood and rubber composite materials, which was completed by Zhao et al. in 2010. That research compared the sound transmission loss coefficient of four samples, two of which contained rubber particle diameters of 5 mm. Data were

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collected for commercial particleboard, commercial floorboard, a sample containing a 50:50 mix of wood particles to rubber particles, and a sample with a 60:40 wood to rubber ratio. The research pointed to better sound insulation as rubber concentration grew. In addition, transmission loss, which is an indicator of acoustic insulation properties of a material, was improved as the rubber particle size increased. Transmission loss of sound is a measurement of the reduction in the decibel level of a sound source as it passes through an acoustic barrier, and rubber veneer has been shown to have a greater transmission loss than medium-density fiberboard when comparing materials at the same thickness (Liu et al. 2019).

Scrap-tire rubber particles have also been used to form adhesive mortar–rubber composites with high sound-absorption coefficients (Corredor-Bedoya et al. 2017). The adhesive mortar–rubber composites with an inclusion rate of 25 percent rubber particles showed a high sound-absorption coefficient when compared with the pure mortar sample in the frequency range of 600 Hz to 2,400 Hz. Similarly, Yang et al. (2004) reported research that studied a bio-composite composed of rice straw combined with wood particles. Rice straw concentration and length were modified, measured for their mechanical and acoustic properties, and samples with lower specific gravities were noted to have higher sound-absorption coefficients. A voluminous amount of research has been conducted that focused on characterizing the strength, physical, and acoustic properties of rubberized composite boards. Most studies agree that strength properties are decreased as rubber content is increased, while rubber incorporation produced improved acoustic qualities in wood composites as well.

Objectives

The primary objective was to provide a characterization of the acoustic properties of bio-composite particleboards, composed of various concentrations of micronized rubber powder (MRP) and pine, by calculation of the sound-absorption coefficient values. Additionally, examination of the effect of MRP on the strength properties, specifically modulus of rupture and apparent modulus of elasticity, of the particleboard was to be measured. The overall hypothesis of this study involved using micronized rubber particles to fill in any small voids that may be present in pine–rubber composites, which would allow a better ability for the boards to absorb soundwaves. However, the data showed that the rubber increased soundwave reflectivity at certain frequencies.

Materials and Methods

Five particleboards were fabricated. Each were composed primarily of southern yellow pine (*Pinus* spp.) with increasing proportions of MRP by weight. Southern yellow pine particles were obtained from Southeastern Timber Products in Ackerman, Mississippi. In order to obtain consistent pine particle size for board fabrication, the sawmill shavings were milled down using a refiner mill (Bauer Model 248, size - 18'', RPM - 1700, Graz, Austria). Table 1 details the particle size distribution for the pine (which had 7.96% moisture content) that was used for fabricating the particleboard samples.

The micronized rubber powder (MRP) was obtained from Lehigh Technologies of Tucker, Georgia, USA. The product part number used in this study is denoted by the company as MicroDyne™ MD-188-TR. MicroDyne MD-188-TR is a free-flowing powder that disperses easily into a multitude of liquid systems and applications (Lehigh Technologies 2018). The powder has a narrow, controlled particle size distribution that is possible because of Lehigh's exclusive cryogenic turbo-mill technology, which transforms crumb rubber material into micron-scale rubber. Table 2 details the particle size distribution for the MRP that was used for fabricating the particleboard samples.

Table 1.—Particle size distribution for pine.

Particle size (mm)	Proportion by weight (%)
≥2.80	0.4
2.00 < 2.80	19.4
1.40 < 2.00	30.7
1.00 < 1.40	16.6
0.50 < 1.00	22.0
0.25 < 0.50	7.0
<0.25	4.0

Methylene diphenyl diisocyanate (MDI), Rubinate™ 1840 (supplied by Huntsman, The Woodlands, Texas, USA) was used as the bonding adhesive for the fabrication of the composite particleboards.

Sample preparation

Five pine and MRP composite particleboards were fabricated via conventional particleboard production methods. One board was a control board, which contained no MRP. Four particleboards composed of 10, 20, 30, and 40 percent MRP by weight were fabricated. Finished board dimensions were 711.2 by 711.2 by 12.7 mm. Small samples were cut from the five parent particleboards for use in acoustic properties, moisture content, and density determinations.

A finished board density of 0.785 g/cm^3, considered a medium-density board (Karlinasari et al. 2012), was targeted for the determination of material proportions by weight. The targeted equilibrium moisture content for each finished board was 10 percent. Table 3 details the material proportions for each composite particleboard sample created.

A Dieffenbacher (Dieffenbacher North America, Inc.) 915-mm by 915-mm hot press system located at the Sustainable Bioproducts Laboratory at Mississippi State University was utilized to fabricate the particleboards. All of the particleboards were produced on the same day. The hot press was preheated to a temperature of 175°C for a period of 2 hours. The platens, which are steel sheets and are placed on the top and bottom of the particleboard during pressing, were also preheated to the same temperature. The mixing process began by placing the pine particles into a drum mixer. The MDI adhesive was sprayed into the center

Table 2.—Particle size distribution for micronized rubber powder.

Particle size (mm)	Proportion by weight (%)
≥0.250	0.00%
0.178–0.250 (80 mesh)	39.71%
0.150–0.178	20.57%
0.104–0.150	23.22%
0.074–0.104	14.05%
<0.074	2.44%

Table 3.—Material amounts for pine micronized rubber powder (MRP) composite particleboards. MDI is methylene diphenyl diisocyanate.

Board sample	Pine (kg)	MRP (kg)	MDI (kg)
Control	4.95	0.00	0.21
10% MRP	4.37	0.53	0.21
20% MRP	3.79	1.06	0.21
30% MRP	3.28	1.59	0.21
40% MRP	2.75	2.12	0.21

of the mixer via a pneumatic, gravity-feed sprayer while the mixer was spinning. The drum mixer was halted after the full amount of MDI was dispensed. Next, the proportioned amount of MRP was then added to the mixer, which was subsequently mixed for approximately 10 minutes.

The preheated platens were removed from the press and coated on one side with a silicone release agent. A wooden frame, measuring 711.2 by 711.2 mm in size internally, was placed on one of the platens. Next, the contents of the drum mixer were emptied into the frame to form the initial mat of particles for the press operation. The material was spread to a consistent mat thickness inside of the frame. A board was pressed down onto the mat, inside the frame, in order to manually compress the mixture to a thickness of approximately 2.54 cm. The wooden frame was removed, and the second platen was placed on top of the mat. Finally, both platens, with the material mat between them, were positioned into the hot press. The press cycle of 420 seconds was initiated with the targeted board thickness of 12.7 mm. Maximum pressures ranged from 1.2 to 4.1 MPa during the pressing of the various particle boards. After pressing, the boards were allowed to cool for safe handling, labeled, and then stored in a conditioned space at 60 percent relative humidity at 21°C ± 3°C until testing.

Prior to testing, three representative samples measuring 76 by 355.6 mm were cut from each of the five parent particleboards. This allowed for 15 samples to be used in mechanical property testing. Additionally, three 30-mm-diameter and three 100-mm-diameter samples were cut from each of the five parent particleboards. These samples were to be used for acoustic properties testing.

Moisture content and density testing

Moisture content and density were measured and calculated in accordance with ASTM D 1037-12 Part A (American Society for Testing and Materials 2012). Based upon ASTM D 1037-12, ASTM D 2395-17 Method A (American Society for Testing and Materials 2017) was referenced for the determination of density for each sample. In addition, ASTM D 4442-16 (American Society for Testing and Materials 2016) Method B was referenced for calculation of moisture content of each specimen.

Mechanical properties testing

ASTM D 1037-12 Part A (American Society for Testing and Materials 2012) was referenced for processes regarding conducting static bending tests to evaluate flexural strength properties, specifically modulus of rupture and apparent modulus of elasticity. Loading and testing were accomplished via a computer-controlled Instron 5566 (Instron, Norwood, Massachusetts) universal testing machine located at the Sustainable Bioproducts Laboratory at Mississippi State University.

As depicted in Figure 1, the load scenario was a simply supported and simply (center) loaded setup. The distance between the spans, based on the sample size and according to the standard, was determined to be 304.8 mm. The speed of testing (load actuation speed) was calculated and applied per the specification at a rate of 6 mm per minute. Displacement (extension of load application point) and applied load data were logged in real-time. Maximum load and extension at failure were recorded. Calculations were completed, per ASTM D 1037-12 (American Society for Testing and Materials 2012), for modulus of rigidity and stiffness (apparent modulus of elasticity).

Acoustic properties testing

Acoustic tests were conducted in order to characterize the acoustic properties of the five particleboards. The tests resulted in the calculation of the sound absorption coefficient (α).

Sound absorption coefficient.—The impedance tube method, per ASTM E 1050-08 (American Society for Testing and Materials 2008), was used to determine the sound absorption coefficient (α) for each of the particleboard samples. A BSWA SW series, two-microphone impedance tube measurement system, represented in Figure 2, with computer control and data logging were utilized to test the particleboard samples (BSWA model SW422+SW477, BSWA Technology Co., Ltd., Beijing, China). The particleboard test sample is represented by the gray block on the right side of the tube. In order to use the system, a specific set of samples was required. These consisted of three 30-mm-diameter and three 100-mm-diameter samples that were cut from each of the five parent particleboards. The 30-mm-diameter samples were used in the 63 to 1,800-Hz frequency testing. The 100-mm-diameter samples were required for the 800 to 6,300-Hz frequencies.

Sound absorption coefficient procedure.—Each 30-mm sample was tested three times using the 30-mm inner diameter tube. Each 100-mm sample was tested a total of six

Figure 1.—Static bending test configuration.

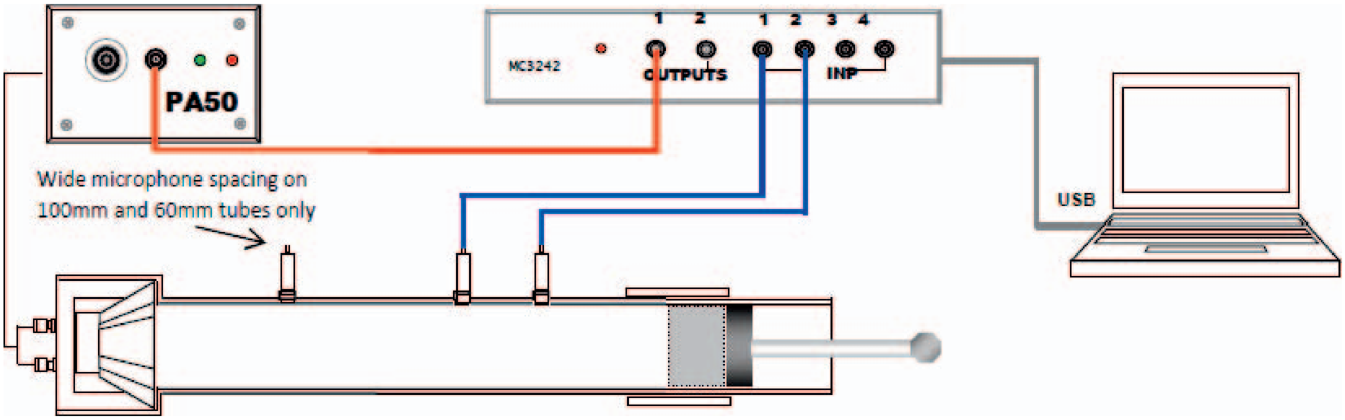

Figure 2.—BSWA SW422+SW477 impedance tube system for measurement of the sound absorption coefficient.

times, consisting of three replications that utilized normal microphone spacing position and three replications that utilized the wide microphone spacing configuration. The duration of each test was 30 seconds. After each individual sample was tested in each of the three impedance tube configurations, the three sets of data were combined for each sample. The result was a complete set of sound absorption coefficients over the entire 60 to 6,300-Hz frequency range. The result was 15 data sets, which consisted of three replications for each of the five parent particleboards.

Results and Discussion

Moisture content and density

Three samples from each particleboard treatment group were stored in a conditioned space at 60 percent relative humidity at 21°C ± 3°C for 3 months and then tested to determine their moisture content. Average values were calculated for each of the five treatment groups sets and the data were determined to be normally distributed for both moisture content and density (using the Shipiro-Wilk test). Statistical analysis was completed via Levene's test, which indicated that the assumption of homogeneity of variance was not violated when comparing the data from the MOE values. Therefore, Tukey's post hoc test was used to compare the data between treatments and the post hoc statistical results for both the moisture content and oven-dry density. Figure 3 details the measured moisture content and Figure 4 shows the oven-dry density of each particleboard sample. The moisture contents obtained for the five particleboards were not equal and were less than the target of 10 percent. This is due to the increasing amounts of MRP and fewer pine particles, which was responsible for the majority of the moisture contained in the particleboard. The resulting oven-dry finished board densities were very close to the target of 0.785 g/cm^3. The particleboards fell within the medium-density particle classification according to ranges cited by Karlinasari et al. (2012).

Mechanical properties

Fifteen samples, consisting of three replications cut from each of the five parent particleboards, were tested for mechanical properties. For each of the 15 samples, apparent modulus of elasticity (MOE) and bending modulus of rupture (MOR) were calculated.

Average values for MOE were calculated for each of the five sample sets and the data were determined to be normally

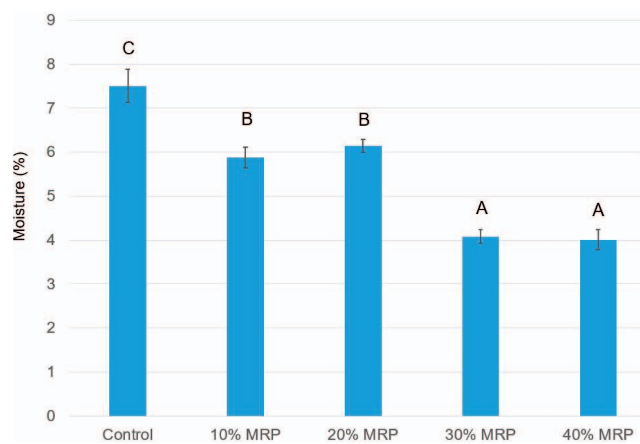

Figure 3.—Plot of moisture mean results after samples remained in a conditioned space at 60 percent humidity at 21°C ± 3° C for 3 months. Data did not violate the assumption of equality of error variances from Levene's test. Different letters denote statistical significance at an alpha value of 0.05 using the Tukey post hoc test.

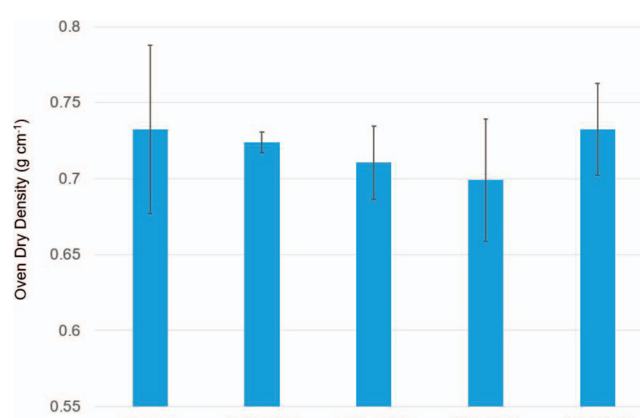

Figure 4.—Plot of oven-dry density mean results that did not violate the assumption of equality of error variances from Levene's test. Different letters denote statistical significance at an alpha value of 0.05 using the Tukey post hoc test.

distributed (using the Shipiro-Wilk test). Statistical analysis was completed via Levene's test, which indicated that the assumption of homogeneity of variance was not violated when comparing the data from the MOE values. Therefore, Tukey's post hoc test was used to compare the data between treatments and the post hoc statistical results are presented for MOE (Fig. 5). Figure 5 shows that the 10 percent MRP had a significantly greater average MOE than the 30 percent MRP and 40 percent MRP treatments. The control group MOE mean value had a significantly greater average MOE than the 20 percent MRP, 30 percent MRP, and 40 percent MRP treatments. The control group and the 10 percent MRP did not have significantly different average MOE values.

The average MOR values were calculated for each of the five sample sets, along with standard deviation, coefficient of variation, and the data were determined to be normally distributed (using the Shipiro-Wilk test). The data were found to be normally distributed and the statistical results are presented for the MOR in Figure 6. Levene's test indicated that the assumption of homogeneity of variance had been violated when comparing the MOR values. Therefore, Games-Howell post hoc tests were performed with 95 percent bias-corrected confidence intervals on the mean differences. This revealed that the 10 percent MRP had a significantly greater average MOR than the 20 percent MRP and 30 percent MRP. However, the control group MOR mean values did not differ significantly from the other treatment groups containing MRP (Figure 6).

Acoustic properties

Sound absorption coefficient.—The sound absorption coefficient data were plotted for the five averaged data sets as shown in Figure 7. Measurement of the sound absorption coefficient was completed in order to typify the feasibility of the use of MRP composite particleboard as a possible sound absorption material. A value of 1 would indicate the total absorption of the sound wave with no reflection. A value of 0 would indicate the total reflection of the sound wave with no absorption by the composite. The sound transmission loss as a function of frequency is shown in Figure 8.

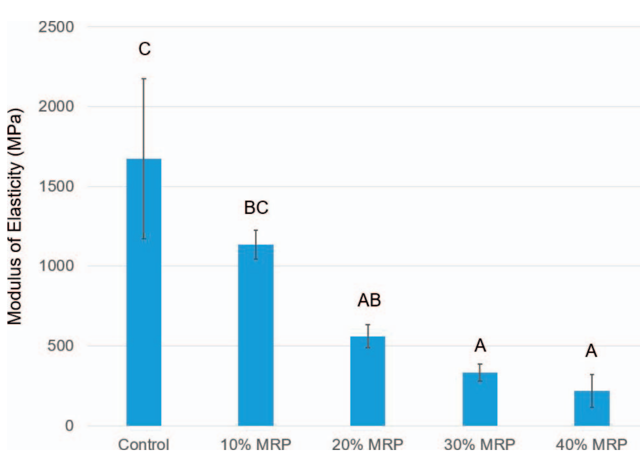

Figure 5.—Plot of means of modulus of elasticity for each sample set that did not violate the assumption of equality of error variances from Levene's test. Different letters denote statistical significance at an alpha value of 0.05 using the Tukey post-hoc test.

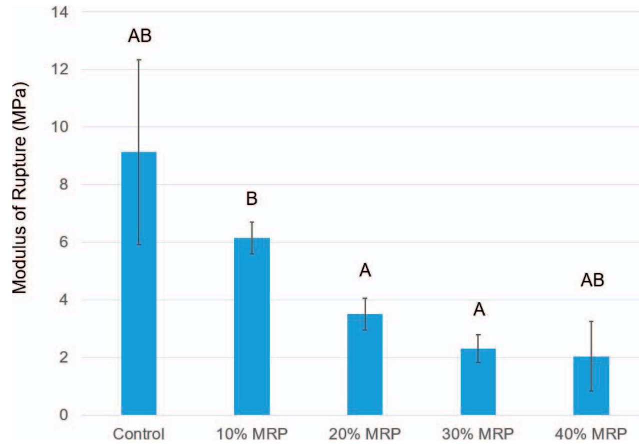

Figure 6.—Plot of means of modulus of rupture for each sample set. The data set violated the assumption of equality of error variances from Levene's test. Different letters denote statistical significance at an alpha value of 0.05 using the Games–Howell post hoc test.

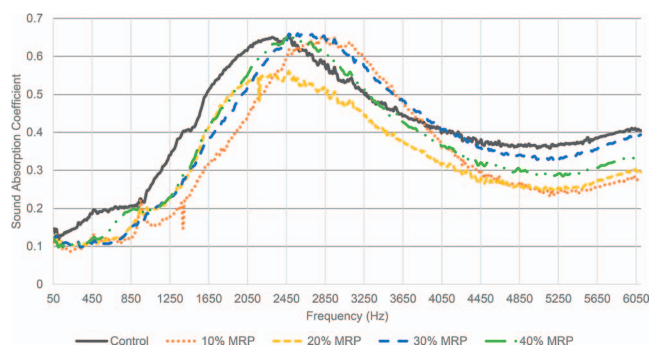

Figure 7.—Sound absorption coefficient as a function of frequency.

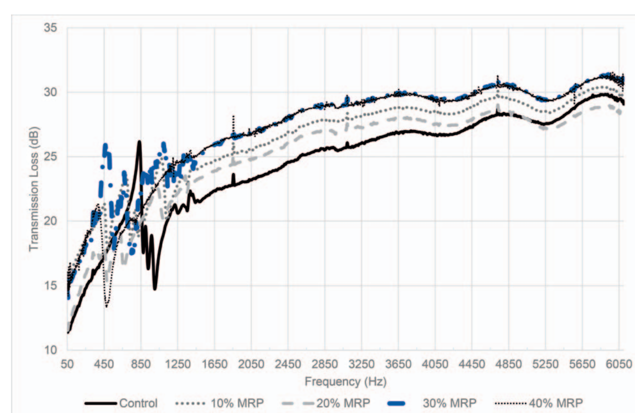

Figure 8.—Sound transmission loss as a function of frequency.

The sound absorption coefficient data were analyzed at each one-third octave band at frequencies of 160 Hz, 200 Hz, 250 Hz, 315 Hz, 400 Hz, 500 Hz, 630 Hz, 800 Hz, 1,000 Hz, 1,250 Hz, 1,600 Hz, 2,000 Hz, 2,500 Hz, 3,150 Hz, 4,000 Hz, and 5,000 Hz (Table 4) and data were found to be normally distributed. These data were analyzed with the

Table 4.—Post hoc test results for each one-third octave band comparing the sound absorption coefficient. Different letters denote statistical significance at an alpha value of 0.05. Tukey's test was used except where ᶲ denotes that data in those columns violated the assumption of equality of error variances from Levene's test statistic, and therefore a Games-Howell post hoc test was used to differentiate between these samples. M10, M20, M30, and M40 denote the particleboards that contain 10 percent, 20 percent, 30 percent, and 40 percent micronized rubber powder (MRP), respectively.

	160 Hz	Φ 200 Hz	250 Hz	Φ 315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	Φ 1,000 Hz	1,250 Hz	Φ 1,600 Hz	Φ 2,000 Hz	Φ 2,500 Hz	Φ 3,150 Hz	4,000 Hz	5,000 Hz
Control	0.1343 B	0.1383 B	0.1452 B	0.1614 B	0.1729 B	0.1876 B	0.1960 B	0.2025 B	0.2317 A	0.3397 B	0.4893 A	0.6085 A	0.6440 A	0.5261 A	0.4140 A	0.3658 B
M10	0.0945 A	0.0926 AB	0.0887 A	0.0952 AB	0.1082 A	0.1187 A	0.1160 A	0.1187 A	0.1678 A	0.1785 A	0.2988 A	0.4257 A	0.6108 A	0.6213 A	0.3855 A	0.2541 A
M20	0.1081 AB	0.1056 A	0.1027 A	0.1009 A	0.1059 A	0.1079 A	0.1191 A	0.1388 A	0.1923 A	0.2280 AB	0.3935 A	0.5260 A	0.5477 A	0.4623 A	0.3240 A	0.2556 A
M30	0.1093 AB	0.1075 AB	0.1046 A	0.1045 A	0.1007 A	0.1059 A	0.1081 A	0.1331 A	0.1802 A	0.2291 AB	0.3656 A	0.5020 A	0.6540 A	0.5839 A	0.4230 A	0.3370 AB
M40	0.1050 AB	0.1067 A	0.1065 A	0.1075 A	0.1094 A	0.1190 A	0.1428 A	0.1903 B	0.1947 A	0.2293 AB	0.3940 A	0.5360 A	0.6518 A	0.5322 A	0.3725 A	0.2947 AB
Levene's test statistic and Significance	3.148 0.0640	4.866 0.019	3.017 0.071	5.044 0.017	2.518 0.108	1.979 0.174	2.319 0.128	1.281 0.348	3.854 0.038	3.270 0.059	5.900 0.011	6.705 0.007	6.002 0.010	4.799 0.020	2.012 0.169	3.015 0.071

Tukey's post hoc test procedure in SPSS version 27 (International Business Machines Corporation, Armonk, New York). The results showed that the control was statistically significantly higher than all the other treatments at an alpha level of 0.05 when testing the entire data set at the frequencies of 250 Hz, 400 Hz, 500 Hz, and 630 Hz (Table 4). There was a limitation of some of the statistical results involving data sets grouped by each frequency where Levene's test showed a statistically significant finding with a P value <0.05, which reveals that the data in those columns violated the assumption of equality of error variances. For those results that violated the assumption of equality of error variances, the Games-Howell post hoc test method was used and the results for these frequencies are shown in Table 4 and denoted with the Φ symbol. At the 800-Hz frequency level, the MRP 40 percent was not significantly different from the control. At the 1,000-Hz, 1,600-Hz, 2,000-Hz, 2,500-Hz, 3,150-Hz, and 4,000-Hz frequencies, none of the treatments had a significantly different sound absorption coefficient as compared with the others at an alpha level of 0.05.

The ability for the micronized rubber particles to reflect soundwaves instead of absorbing them is likely due to the monolithic topography of the structure and being unable to break up the soundwaves on account of the composite's smooth morphology. Zhao et al. (2010) showed that larger rubber particle sizes increased the transmission loss overall at frequency ranges of 160 to 1,000 Hz. The 5-mm rubber crumbs had a much larger transmission loss than the 1-mm rubber crumbs when included in a wood–rubber composite. Chandran et al. (2018) also showed that larger waste-tire particles allowed for greater energy absorption when compared with natural rubber composites using smaller waste-tire particles.

The sound absorption coefficient of only using barium titanate/nitrile butadiene rubber (BT/NBR) performed by Jiang et al. (2018) compared well with this study. However, when using BT/NBR as a multilayered material with polyurethane, the combination of layers of the polyurethane and rubber caused there to be better sound absorption than when only compared with the polyurethane at frequency ranges of 200 to 800 Hz. Liu et al. (2019) also showed a similar effect. Therefore, the composite used in this study will likely better perform in a similar configuration, when stacked in multiple layers with polyurethane.

A study performed by Xu et al. (2018) also showed that to improve the sound absorption coefficient of the pine–rubber composite, holes could be drilled into the material, which would break up the soundwaves. They found that by adding perforations to the material that high sound adsorption coefficients could be realized, especially at frequencies lower than 1,000 Hz. When the frequencies were above 1,000 Hz, the size of the holes were not as crucial to sound absorption as was the overall perforation rate used to break up the soundwaves.

Conclusions

Based upon statistical analysis, the particleboard containing MRP resulted in a decrease in MOE as compared with the control particleboard. This increase in elasticity was expected with the addition of MRP. Particleboards containing MRP result in a product that is less resistant to deformation. A similar statistical analysis revealed that control particleboard MOR mean values did not differ significantly from the other treatment groups containing MRP. There is no apparent difference in the modulus of rupture for particleboard composites containing MRP when compared with pure particleboard.

The sound absorption coefficient, a measure of the amount of sound waves absorbed by a material at a specific frequency, was compared. At the 1,000-Hz, 1,600-Hz, 2,000-Hz, 2,500-Hz, 3,150-Hz, and 4,000-Hz frequencies, none of the treatments had a significantly different sound absorption coefficient as compared with the others at an alpha level of 0.05. The statistical results also revealed that the plain particleboard (control) yielded a sound absorption coefficient that was statistically significantly higher than all the other treatments at an alpha level of 0.05 when testing the entire data set at the frequencies of 400 Hz, 500 Hz, and 630 Hz. At these frequencies, the samples containing MRP tended to reflect sound waves more than those that did not contain MRP. This study showed an increased amount of sound energy reflected by the MRP composite particleboards as compared with the control, and the MRP addition to particleboard would be appropriate in applications where more sound energy reflection is the desired effect at these frequencies. Steps to improve the sound absorption coefficient include adding perforations to the composite material, stacking the composite material to form multiple layers of particleboard and particleboard–rubber composite, and increasing the particle size of the rubber material used to form the wood–rubber composite.

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