Acoustic and Thermal Evaluation of Palm Panels as Building Material

Cristina C. Ferrández-García, Clara E. Ferrández-García,* Manuel Ferrández-Villena, M. Teresa Ferrández-García, and Teresa García-Ortuño

Acoustic and thermal properties were determined for boards made from Washingtonia palm tree pruning waste. Three types of boards with different particle sizes (0.25 to 1.00 mm, 1.00 to 2.00 mm, and 2.00 to 4.00 mm) were obtained from the rachis of the palm fronds. To bind the particles, 8% urea formaldehyde resin was used *via* hot pressing at 120 ºC for 6 min at 1.6 MPa. Three types of panels were generated to evaluate the influence of particle size. Analysis of their physico-mechanical properties showed that their mechanical performance was superior to the existing insulating boards used in the building industry. The average thermal conductivity of the panels was 0.062 W/(K·m) and did not depend on the size of the particles. At frequencies of 125 and 250 Hz, the experimental boards were classified as class D acoustic panels. The manufactured panels had high values of sound transmission loss (TL), despite the thinness of the panels, which indicates that they have good acoustic insulation capacity. Acoustic properties could be improved by increasing the thickness of the boards. Due to their mechanical, thermal, and acoustic properties, these panels could be used as lining and as false ceilings.

Keywords: Building materials; Panel properties; Particle size; Thermal performance; Sound absorption coefficient; Sound transmission loss; Washingtonia palm

*Contact information: Department of Engineering, Escuela Politécnica Superior de Orihuela, Universidad Miguel Hernández de Elche, Spain; *Corresponding author: cferrandez@umh.es*

INTRODUCTION

The introduction of "sustainable" building design has led research towards the development of thermal and acoustic insulating materials using natural or recycled materials. Some, such as kenaf or wood fibers, are already commercialized, but their applications could be further improved, as their performance is similar to the synthetic ones (Asdrubali *et al.* 2015). Vegetable fibers have been used traditionally in construction as an insulating material, until they were replaced by technical materials that consume a lot of energy in their development. The use of sustainable materials is now becoming a common practice for the noise and heat-transfer reduction in construction and civil engineering due to the increasing health risk concern associated with materials such as glass and mineral-fiber (Fatima and Mohanty 2011). One vegetable material used as an acoustic and thermal absorbent is wood and, in particular, woody fiber- and particle-boards. Due to wood shortages, alternative boards made from rice stems (Yang *et al.* 2003), coconut fibers (Zulkifli *et al.* 2009), bamboo (Karlinasari *et al.* 2012), corn cobs (Faustino *et al.* 2012), and farm waste (Sampathrajan *et al.* 1991) have been investigated.

In general, vegetable materials are porous, good noise absorbents, and they have good acoustic insulating properties across a wide range of frequencies. However, the increase in the percentage of vegetable fibers as a raw material in the development of building materials produce a significant decrease in the material density and in their thermal conductivity (Belkharchouche and Chaker 2016). Vegetable fibers are cheaper, lighter, and more environmentally friendly than synthetic fibers in the acoustic context (Yorozu *et al.* 1987). In the same way, recycling natural resources and vegetable waste contributes to environmental improvement.

Yang *et al*. (2003) evaluated acoustic panels of rice stems, with a density of 0.4 and 0.6 g/cm^3, indicating that they were suitable as an insulating material for sound absorption in wooden constructions. The tests showed a decrease of the sound absorption coefficient for mid frequencies and an increase of the sound absorption for the range of low and high frequencies. They found no differences due to the particle size of the rice stems fibers. Kalinasari *et al.* (2012) tested fast-growing tropical species, recommending them for architectural acoustics in building constructions at low and high frequencies. Faustino *et al.* (2012) demonstrated that a panel made of corn particles had an interesting acoustic behavior for building uses.

The greatest challenge working with vegetable fibers is their great variation in thermal properties and characteristics dependent on their complex structural geometric architectures (Lü *et al.* 2013). In most studies, the use of vegetable fibers decreases the thermal conductivity; for example, the inclusion of palm fibers in brick making improves the thermal properties (Mekhermeche *et al.* 2016). An increase of the fiber fraction of the bricks resulted in a decrease in thermal conductivity, specific heat, heat capacity, and an increase in thermal resistance; the thermal performance of reinforced tiles with sisal and eucalyptus fibers were acceptable substitutes for fiber-cement sheets (Roma *et al.* 2008). The addition of palm fibers to gypsum improved the thermal insulation of buildings (Chikhi 2016).

Tao *et al*. (2016) measured the effect of the addition of vegetable fibers in polyurethane on the acoustic and thermal insulation properties and concluded that increasing the fiber proportions improved insulating properties. The acoustic and thermal properties of different fiber panels from the palm oil trunk were studied by Kerdtongmee *et al.* (2016) and from the date palm (Khidir *et al.* 2014; Mekhermeche *et al.* 2016). New treatments and techniques may improve the insulating properties (Zhu *et al.* 2014; Wu *et al*. 2016).

In this study, the use of Washingtonia palm tree fibers is proposed as a raw material for the construction of acoustic and thermal insulation panels. Commonly known as Mexican fan palm, it is a fast-growing plant, especially in permeable and nutrient-rich soils, where it can reach heights of 30 m. They are widespread in Spain and usually used for gardening and landscaping. The old leaves are pruned at least once a year, producing an average of 30 kg of palm fronds (RH 8%), according to measurements made on the palm trees used in this study. Normally, these wastes are disposed of in landfills when they could have another use.

The main objective of this work was to evaluate the acoustic and thermal properties of boards made from Washingtonia palm pruning waste and to assess the influence of the particle size on the physical and mechanical properties of the experimental particleboards.

EXPERIMENTAL

Materials

The rachis of the fronds were obtained from the pruning of the Washingtonia palm trees in the gardens of the University Miguel Hernández of Elche (Elche, Spain). The leaflets were removed from the fronds and then left to dry for 6 months in the open air. The fronds were defibrinated by a blade shredder, and the particles were classified by their dimensions as they crossed the sieves of a vibrating screening machine.

Commercial urea formaldehyde was used as a binder, with a solid content of 64 to 66%. Eight percent of the binder was used, based on the weight of the palm particles, and 4% of ammonium sulfate was used as a hardener.

Manufacturing Process

Three types of boards with different particle sizes (0.25 to 1.00 mm, 1.00 to 2.00 mm, and 2.00 to 4.00 mm) were obtained from the rachis of the Washingtonia palm, as shown in Fig. 1. Particles were blended in an IMAL blender (Model LGB 100, Modena, Italy) for 5 min. The resin containing urea formaldehyde (8%) was sprayed using nozzles.

Fig. 1. Particles obtained from the rachis of the Washingtonia palm tree

To prepare the boards, the mat was manually formed in a mould of dimensions 400 mm × 600 mm and then subjected to a hydraulic press using heated plates at a pressure of 1.6 MPa and a temperature of 120 °C for 6 min. The resulting boards had an average size of 600 × 400 × 6.5 mm and were cooled upright for 24 h. Five boards of each type were manufactured, and the samples were cut to the appropriate dimensions following the standards for each laboratory test as shown in Fig. 2.

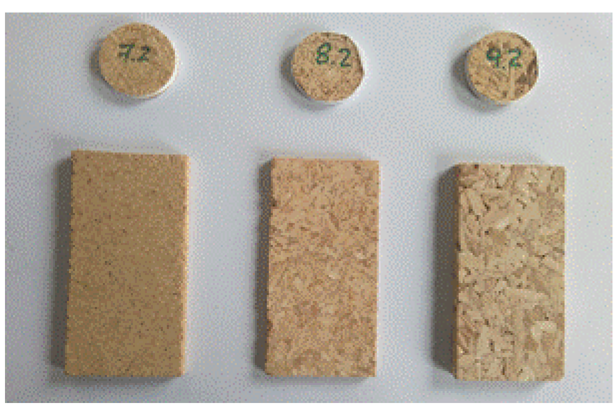

Fig. 2. Acoustic and bending tests samples (circular shape for the acoustic tests and rectangular shape for the bending tests) of the three types of panels (from left to right: particle size 0.25 to 1.00 mm, 1.00 to 2.00 and 2.00 to 4.00 mm)

Methods

Experimental laboratory tests were carried out in accordance with the European standards applicable to particleboards. The density test was carried out according to EN 323 (1993) using 3 samples of each board with dimensions 50 × 50 mm. The mechanical properties were determined with a universal testing machine (IMAL Model IB600, Modena, Italy), which complies with the speed indicated in the standards for each test. To obtain the modulus of rupture (MOR) and the modulus of elasticity in flexion (MOE), the test was performed according to EN 310 (1993). To determine the internal cohesion (IB) or tensile strength test, EN 319 (1993) was used, which states that the load is applied perpendicular to the face of the sample and at a constant speed throughout the test.

The thermal conductivity was also determined using the method of the heat flow meter (EN 12667 2001). Tests for the thermal conductivity were performed on a heat flow meter instrument (model HFM 436/3/0, NETZSCH -Gerätebau GmbH, Selb, Germany). The samples used in this test had dimensions of 300 × 300 × 6.5 mm.

The acoustical properties measured were the sound absorption coefficient and the transmission loss. The method to determine the sound absorption coefficient of a material under normal incidence used an impedance tube, two microphone positions, and a digital signal analysis system, according to EN ISO 10534-2 (2002). This technique requires a prior correction procedure to minimize the differences in amplitude and phase characteristics between the two microphones. To perform the tests, the Acupro Spectronics impedance tube was used, with a frequency ranging from 50 to 6300 Hz. Some of the test samples with a diameter of 34.9 mm and a thickness of 6.5 mm are shown in Fig 2.

The principle of the test method is as follows: The test sample is mounted at one end of the impedance tube. Plane waves are generated in the tube by a sound source, and the sound pressures are measured at two locations near to the sample. The complex acoustic transfer function of the two microphone signals is determined and used to compute the normal-incidence complex reflection factor, the normal-incidence absorption coefficient, and the impedance ratio of the test material. The quantities are determined as functions of the frequency with a frequency resolution which is determined from the sampling frequency and the record length of the digital frequency analysis system used for the measurements. The usable frequency range depends on the width of the tube and the spacing between the microphone positions. The two microphones technique requires a pre-test or in-test correction procedure to minimize the amplitude and phase difference characteristics between the microphones; however, it combines speed, high accuracy, and ease of implementation. The signal processing system consists of an amplifier, and a two-channel Fast Fourier Transform (FFT) analysing system. The system is required to measure the sound pressure at two microphone locations and to calculate the transfer function between them. A generator capable of producing the required source signal compatible with the analyzing system is also required. The loudspeaker is located at the opposite end of the tube from the test sample holder.

The first step in the measurement of the acoustic properties is the specification of the reference plane (x=0). Typically this coincides with the surface of the test specimen After this and before starting a measurement, the velocity of sound in the tube shall be determined, after which the wavelengths at the frequencies of the measurements shall be calculated. The measuring method is based on the fact that the sound reflection factor at normal incidence r can be determined from the measured transfer function between two microphone positions in front of the tested material. Once the r is calculated, the normal incidence sound absorption coefficient can be determined as a function of the sound reflection coefficient.

In order to calculate the transmission loss (TL) the test sample is placed at the end of the tube with the back open to obtain three measurements of the transfer function. Another three measures of the transfer function are obtained with the end closed. Then the software calculates the transmission loss in function of the frequency.

Data for each test were analyzed statistically using SPSS v.22.00 software the IBM SPSS statistic base (IBM, spss 20, NY, USA). From the average results, the standard deviation was obtained, and an analysis of variance (ANOVA) was conducted. Duncan test calculations ($P < 0.05$) were used to compare the differences between types.

RESULTS AND DISCUSSION

Physical and Mechanical Properties

During the laboratory tests, the specimens were kept at a controlled atmosphere with a temperature of 20 °C and a relative humidity of 65%. The average values are shown in Table 1. The density values obtained ranged from 677.1 to 885.8 kg/m^3, which classifies them as medium density boards. According to the statistical analysis there were significant differences between the boards with different particle sizes.

Table 1. Physical and Mechanical Properties of the Experimental Panels

Particle Size (mm)	Density (kg/m^3)	MOR (N/mm^2)	MOE (N/mm^2)	IB (N/mm^2)
0.25 – 1.00	885.8^c (51.0)	17.95^c (2.68)	1550.5^c (146.7)	0.98^a (0.16)
1.00 – 2.00	746.3^b (54.1)	12.24^b (0.96)	1170.8^b (230.6)	1.06^a (0.05)
2.00 – 4.00	677.7^a (28.2)	7.21^a (0.31)	665.1^a (61.9)	1.06^a (0.07)
( ) standard deviation.$^{a, b,..}$ Duncan test $p < 0.5$				

The density obtained with the three types of boards was not equal due to the use of different particle sizes, having kept the thickness constant. A bigger density was obtained with the smaller particle size due to the stronger capacity of compression.

The values of the modulus of rupture in flexion (MOR) for particles of 0.25 to 1.00 mm reached 16.95 N/mm^2, decreasing with larger particles. The flexural strength depended on the particle size. The modulus of elasticity in flexion (MOE) also depended on the particle size. The MOE values ranged from 1550.5 to 665.1 N/mm^2. The internal cohesion (IB) values achieved were not influenced by the particle size. The IB results were high (0.98 to 1.06 N/mm^2). The panels with higher densities had better mechanical properties.

The boards manufactured by hot-pressing at low temperature (120 °C) using the smaller particle size (0.25 to 1.00 mm) can be classified as grade P1 for general uses because they met the mechanical requirements of EN 312 (2010). The minimum requirements for a P1 type panel (thickness from 6 to 13 mm) are a MOR value of 12.5 N/mm^2 and an IB value of 0.28 N/mm^2. Therefore, only the particleboards made with particles of 0.25 to 1 mm fit in this category and could be implemented in general applications.

Thermal Properties

The results of thermal properties (conductivity, resistance, and gradient) of the experimental panels are shown in Table 2. The boards had good thermal insulation properties, with an average thermal conductivity of 0.062 W/(K·m), an average thermal resistance of 0.108 K·m^2/W, and an average thermal gradient of 2950 K/m. The Duncan test indicated that there were no significant differences among the panels, which means that the thermal properties of these panels are not dependent on the density nor the particle size.

Table 2. Thermal Properties of the Washingtonia Palm Tree Particleboards

Particle Size (mm)	Thermal Conductivity W/(K·m)	Thermal Resistance K·m^2/W	Thermal Gradient K/m
0.25 to 1.00	0.059[a] (0.006)	0.107[a] (0.005)	2989.3[a] (693.2)
1.00 to 2.00	0.062[a] (0.007)	0.108[a] (0.004)	3019.4[a] (447.8)
2.00 to 4.00	0.062[a] (0.004)	0.108[a] (0.002)	2831.6[a] (484.6)
Values in parenthesis are standard deviations; Means which do not share a letter are significantly different ($p<0.05$)			

The average value of thermal conductivity achieved by the panels manufactured from the Washingtonia palm tree is shown in Table 3 as well as those of other wood types used as insulating building materials for comparison purposes. The thermal conductivity value was much smaller than that of woods with a density in the range of the densities obtained in this study, and somewhat larger than the cork and wood boards with lower density. Therefore, Washingtonia palm tree particleboards can be considered a good thermal insulating material.

Table 3. Thermal Conductivity of Different Materials for Comparison Purposes

Material	Density (kg/m^3)	Thermal Conductivity [W/(K·m)]
Washingtonia palm tree panels (present study)	746	0.062
Cork (Boards)	120	0.042
Wood fiber sheets	200	0.047
Maple wood (*Acer sp.*)	750	0.349
Ash wood *(Fraxinus sp.)*	750	0.349
Beech wood *(Fagus sp.)*	800	0.143
Oak wood (*Quercus sp* .)	850	0.209
Mineral wool	<100	0.037

Acoustic Properties

Figure 3 shows the average sound absorption coefficient values of the three specimens of each board. A high sound absorption value was obtained for very low frequencies (at 50 Hz the absorption coefficient is 0.45), and this value decreased for higher frequencies to very low values. There were no significant differences between the different types of boards, as all values ranged from 0.05 to 0.10.

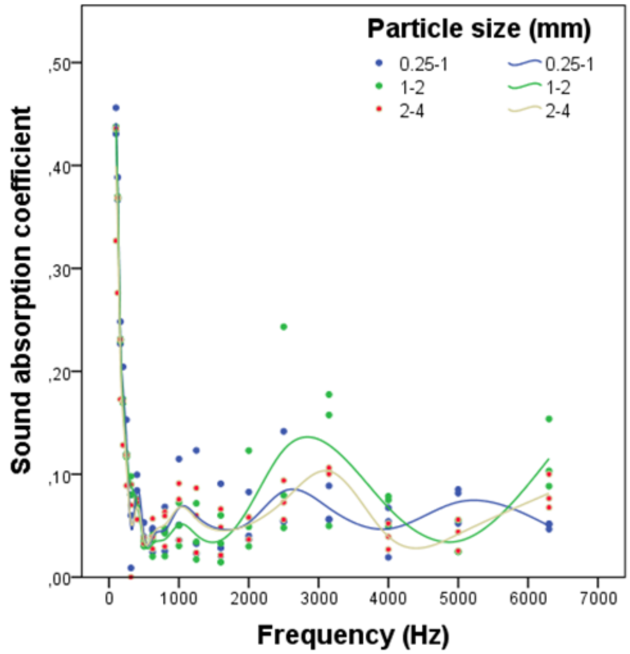

Fig. 3. Acoustic absorption coefficient as a function of frequency

Table 4 shows the sound absorption coefficients as a function of the normalized center frequencies for octave bands. The results obtained have been referred to these frequencies because they are the most used in architectural acoustics and in the majority of the consulted works and studies. Doing so facilitated the subsequent comparison of the results with the values obtained for other materials of the same density commonly used in construction and thus classify them according to ISO 11654 (1997).

Table 4. Sound Absorption Coefficients

Material	Particle Size (mm)	Board Thickness (mm)	Frequency (Hz)					
			125	250	500	1000	2000	4000
	0.25 to 1.00	6.5	0.45 (0.04)	0.31 (0.01)	0.10 (0.03)	0.07 (0.02)	0.06 (0.01)	0.05 (0.01)
	1.00 to 2.00	6.5	0.44 (0.00)	0.32 (0.01)	0.10 (0.03)	0.05 (0.02)	0.07 (0.01)	0.07 (0.02)
	2.00 to 4.00	6.5	0.40 (0.06)	0.30 (0.04)	0.10 (0.01)	0.07 (0.02)	0.05 (0.01)	0.06 (0.01)
Wood		50	0.15	0.11	0.10	0.07	0.06	0.07
Plywood		10	0.28	0.22	0.17	0.09	0.10	0.11
ISO 11654 (Insulation classes)			D	D	-	-	-	-
Values in parenthesis are standard deviations								

The sound absorption coefficients obtained had an average value for frequencies lower than 400 Hz. For higher frequencies low values were obtained. The results indicated that they are better absorbents of noise than commercial plywood and the panels of equal density for low frequencies, whereas for medium and high frequencies similar values are obtained. According to ISO, for frequencies less than 250 Hz, they could be classified as "D" category, up to 400 Hz classifies as an "E" category, and for higher frequencies, they would not be considered acoustic absorbers.

The statistical analysis showed that there were no significant differences with regard to the particle size used. Yang *et al.* (2003) studied the influence of the particle size on the sound absorption coefficient in panels made with rice stem fibers and observed that this property was influenced by the density because boards made with a lower density are more porous and therefore better acoustic insulating materials. On the contrary, Karlinasari *et al*. (2012) verified that in bamboo panels a higher sound absorption coefficient was obtained with the smaller particle size. Zulkifli *et al*. (2009) stated that panels made of coconut fiber, with bigger thickness, the sound absorption coefficient was increased after being perforated.

Because the sound absorption coefficient depends on the thickness of the panels, (the panels tested had an average thickness of 6.5 mm), increasing the thickness would improve the sound absorption properties.

The sound transmission loss (TL) is a parameter expressed in decibels (dB) that depends on the frequency and the thickness, and its value indicates how much the incident sound energy attenuates when passing through a material. Figure 4 shows the average TL values obtained in the test of three samples of each board. The highest values were reached at a frequency of 450 Hz up to 50 dB, then the values decreased with a frequency close to 30 dB. No influence of particle size was observed. These values indicated that the Washingtonia palm tree panels with a 6.5 mm thickness had a good acoustic insulation capacity.

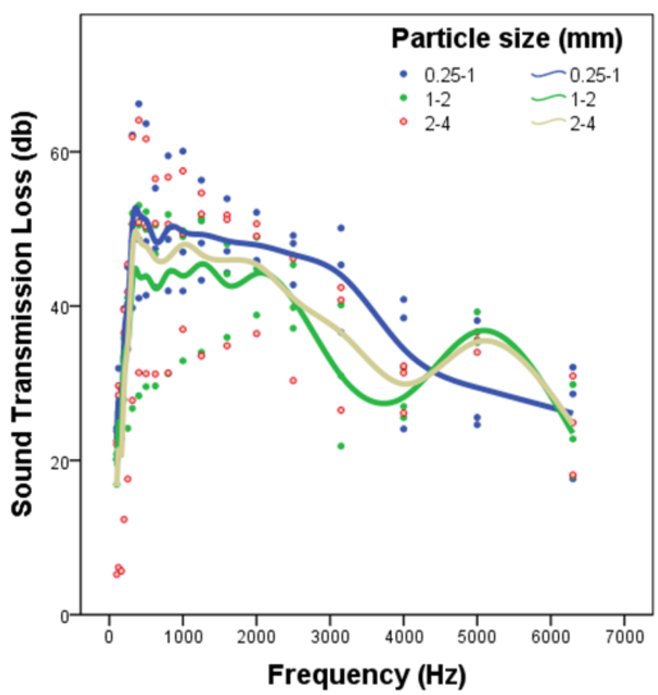

Fig. 4. Sound transmission loss as a function of frequency

CONCLUSIONS

1. The mechanical properties of the experimental panels manufactured from the Washingtonia palm tree depended on the particle size. With a particle size from 0.25 to 1.00 mm, boards classified as grade P1 for general uses in dry ambient surroundings were obtained. An increase in the density of the panels was found to improve the modulus of rupture (MOR) and the internal bond (IB).
2. The thermal conductivity of the studied panels had an average value of 0.062 W / (K .m) and did not depend on the size of the particles. This parameter was much smaller than that of wood in the same range of density and somewhat greater than the boards of cork and wood fiber sheets of a low density.
3. At frequencies of 125 and 250 Hz, the experimental boards could be classified as class D acoustic panels. However, the sound absorption coefficients of the Washingtonia palm boards were higher at frequencies lower than 400 Hz than those of commercial wood-based materials and plywood. There were no significant differences with regard to the particle size.
4. The manufactured panels had high values of sound transmission loss (TL), and the thinness of the panels indicated that they had good acoustic insulation capacity. Acoustic properties could be improved by increasing the thickness of the boards.
5. These boards, due to their mechanical, thermal and acoustic properties, could be used as lining and false ceilings.
6. Potentially, the insulators based on by-products of the Washingtonia palm tree could constitute an economically viable and sustainable alternative to existing materials.

ACKNOWLEDGMENTS

This work was financed by the Ministerio de Economía y Competitividad of Spain (MINECO, AGL2013-41612-R).

REFERENCES CITED

Asdrubali, F., D'Alessandro, F., and Schiavoni, S. (2015). “A review of unconventional sustainable building insulation materials,” *Sustainable Materials and Technologies* 4, 1-17. DOI: 10.1016/j.susmat.2015.05.002

Belkharchouche, D., and Chaker, A. (2016). “Effects of moisture on thermal conductivity of the lightened construction material,” *International Journal of Hydrogen Energy* 41(17), 7119-7125. DOI: 10.1016/j.ijhydene.2016.01.160

Chikhi, M. (2016). “Young’s modulus and thermophysical performances of bio-sourced materials based on date palm fibers,” *Energy and Buildings* 129, 589-597. DOI: 10.1016/j.enbuild.2016.08.034

EN 310 (1993). “Wood-based panels. Determination of modulus of elasticity in bending and of bending strength,” European Committee for Standardization, Brussels, Belgium.

EN 317 (1993). "Particleboards and fibreboards. Determination of swelling in thickness after immersion in water," European Committee for Standardization, Brussels, Belgium.

EN 319 (1993). "Particleboards and fibreboards. Determination of tensile strength perpendicular to the plane of de board," European Committee for Standardization, Brussels, Belgium.

EN 323 (1993). "Wood-based panels. Determination of density," European Committee for Standardization, Brussels, Belgium.

EN ISO 10534-2 (2002). "Acoustics - Determination of sound absorption coefficient and impedance in impedances tubes - Part 2: Transfer-function method. (ISO 10534-2:1998)," European Committee for Standardization, Brussels, Belgium.

EN ISO 11654 (1997). "Acoustics. Sound absorbers for use in buildings. Rating of sound absorption," European Committee for Standardization, Brussels, Belgium.

EN 12667 (2001). "Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Products of high and medium thermal resistance," European Committee for Standardization, Brussels, Belgium.

Fatima, S., and Mohanty A. R. (2011). "Acoustical and fire retardant properties of jute composite materials," *Applied Acoustics* 72, 108-114. DOI: 10.1016/j.apacoust.2010.10.005

Faustino, J., Pereira, L., Soares, S., Cruz, D., Paiva, A., Varum, H., and Pinto, J. (2012). "Impact sound insulation technique using corn cob particleboard," *Construction and Building Materials* 37, 153-159. DOI: 10.1016/j.conbuildmat.2012.07.064

Karlinasari, L., Hermawan, D., Maddu, A., Bagus, M., Lucky, I. K., Nugroho, N., and Hadi, Y. S. (2012). "Acoustical properties of particleboards made from betung bamboo (*Dendrocalamus asper*) as building construction material," *BioResources* 7(4), 5700-5709. DOI: 10.15376/biores.7.4.5700-5709

Kerdtongmee, P., Saleh, A., Eadkhong, T., and Danworaphong, S. (2016). "Investigating sound absorption of oil palm trunk panels using one-microphone impedance tube," *BioResources* 11(4), 8409-8418. DOI: 10.15376/biores.11.4.8409-8418

Khidir, E. A., Nik Mohamed, N. A., Nor, M., Jailani, M., Tahir, M. F. M., Zulkifli, R., and Nuawi, M. Z. (2014). "Effect of density on the sound absorption of date palm fibers," in: *Applied Mechanics and Materials* (Vol. 663), Trans Tech Publications, Zurich, Switzerland, pp. 437-441. DOI: 10.4028/www.scientific.net/AMM.663.437

Lü, X., Lu, T., Lipponen, O., and Viljanen, M. (2013). "Insulation materials made with vegetable fibres," in: *Nearly Zero Energy Building Refurbishment*, Springer London, pp. 411-455. DOI: 10.1007/978-1-4471-5523-2_16

Mekhermeche, A., Kriker, A., and Dahmani, S. (2016). "Contribution to the study of thermal properties of clay bricks reinforced by date palm fiber," *American Institute of Physics Conference Proceedings* 1758(1), 030004. DOI: 10.1063/1.4959400

Roma, L. C., Martello, L. S., and Savastano, H. (2008). "Evaluation of mechanical, physical and thermal performance of cement-based tiles reinforced with vegetable fibers," *Construction and Building Materials* 22(4), 668-674. DOI: 10.1016/j.conbuildmat.2006.10.001

Sampathrajan, A., Vijayaraghavan, N. C., and Swaminathan, K. R. (1991). "Acoustic aspects of farm residue-based particle boards," *Bioresource Technology* 35(1), 67-71. DOI: 10.1016/0960-8524(91)90083-V

Tao, Y., Li, P., and Cai, L. (2016). "Effect of fiber content on sound absorption, thermal conductivity, and compression strength of straw fiber-filled rigid polyurethane foams," *BioResources* 11(2), 4159-4167. DOI: 10.15376/biores.11.2.4159-4167
Wu, Y., Sha, T., Zhao, Z., He, Z., and Yi, S. (2016). "Influence of different pretreatments on the acoustic properties of dawn redwood (*Metasequoia glyptostroboides* Hu et Cheng)," *BioResources* 11(1), 2734-2743. DOI: 10.15376/biores.11.1.2734-2743
Yang, H. S., Kim, D. J., and Kim, H. J. (2003). "Rice straw-wood particle composite for sound absorbing wooden construction materials," *Bioresource Technology* 86(2), 117- 121. DOI: 10.1016/S0960-8524(02)00163-3
Yorozu, T., Hirano, M., Oka, K., and Tagawa, Y. (1987). "Electron spectroscopy studies on magneto-optical media and plastic substrate interface," *IEEE Translation Journal on Magnetics in Japan* 2(8), 740-741. DOI: 10.1109/TJMJ.1987.4549593
Zhu, X., Kim, B. J., Wang, Q., and Wu, Q. (2014). "Recent advances in the sound insulation properties of bio-based materials," *BioResources* 9(1), 1764-1786. DOI: 10.15376/biores.9.1.1764-1786
Zulkifli, R., Nor, M. J. M., Ismail, A. R., Nuawi, M. Z., and Tahir, M. F. M. (2009). "Effect of perforated size and air gap thickness on acoustic properties of coir fibre sound absorption panels," *European Journal of Scientific Research* 28(2), 242-252.

Article submitted: May 31, 2017; Peer review completed: August 4, 2017; Revised version received and accepted: September 6, 2017; Published: September 13, 2017.
DOI: 10.15376/biores.12.4.8047-8057