"Panels of Eco-Friendly Materials for Architectural Acoustics"

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ABSTRACT

The objective of this work is the study of the acoustic and mechanical properties of environmentally friendly materials manufactured through the process of resin infusion made with different types of fibres: some biodegradable coming from renewable resources and others from recycled textile waste. The materials studied are composed of fibres of jute, hemp, coconut, biaxial linen and textile waste. The modulus of elasticity and the airborne sound insulation are determined through dynamic and acoustic tests, respectively.

The behaviour of these innovative materials is compared to some traditional materials commonly used in architectural acoustics. The acoustic study of these environmentally friendly materials is carried out considering them as light elements of a single layer for their application to insulation of walls. The results are compared to plasterboards, considered as the most commonly used light material in buildings for airborne sound insulation.

In conclusion, these materials are a real and effective alternative to the traditional composites of synthetic matrices and reinforcements of glass fibres and there is a reduction in the production cost compared to the usual porous synthetic media that have expensive production processes.

Keywords: natural fibres, textile waste, eco-friendly materials, bioresin, airborne sound insulation.

1. Introduction

Nowadays, noise pollution is one of the most important problems in modern societies. Different sound sources, such as electronic appliances, planes, traffic, and many others occur, both inside and outside buildings, generating high sound pressure levels.

According to these conditions, new materials with natural fibres are being investigated for their application in architectural and automotive acoustics [1][2]. Eco-friendly materials present very good properties to be applied as sound barriers. In the last two decades, the research in the application of natural fibres as reinforcements like sisal, jute, lignin, raffia, pineapple-leaf and linen has noticeably increased [3][4], and some advantages can be found over synthetic fibres since natural fibres are renewable, non-abrasive and economic, and there are plenty of them in nature, and also as crop waste. In addition, they are easy to manufacture and offer non-polluting processing.

The polymeric materials have supposed a considerable advance for the society, manufacturing a high amount of products of low cost and massive utility. Traditionally, composites manufactured from a thermoplastic or thermosetting matrix and glass fibres are used [5]. However, due to its resistance to biodegradation, it generates serious environmental problems derived from the management of its waste. Its recycling, as well as incineration are not optimal solutions to solve the aforementioned problems.

However, the development of biodegradable materials present an effective and innovative solution for the management of waste [6]. Currently, most of the studies carried out in this field are focused on the design of biodegradable polymers [7] from renewable resources [8].

The environmentally friendly materials represent an alternative to the use of fossil resources from oil, allowing the finish of the life cycle of the product, while enhancing the development of the agricultural sector, specially the non-food industry sector.

Composites generally use short fibres (mat) as reinforcement and conventional resins as matrix [9][10][11][12][13][14] and only some with bioresins of natural origin [15][16][17][18]. To increase the mechanical properties of composites, long fibre reinforcements have traditionally been used as fabrics, oriented in specific directions. The works related to composites with natural fibre fabrics are relatively new [19] because of the lack of these technical fabrics in the market.

To manufacture the thermostable matrix composites, which use long natural fibres or fabrics as reinforcement, there are not many references for laminated processes with vacuum resin infusion. Other manufacturing process used is the Resin Transfer Moulding Process (RTM) [20].

Within the group of the innovative eco-friendly materials, some are manufactured from wastes of other manufacturing processes, from natural fibers or from recycled materials. All of them can become acoustic materials with applications for building acoustics [21][22][23][24].

For these materials to be applied in the field of acoustics, their properties of sound absorption and insulation must be analysed and compared to the acoustic properties of the most commonly used materials in architectural acoustics. Other applications are in the field of acoustics for the automobile industry [25] [26].

The materials reinforced with natural fibres have certain advantages in front of the traditional ones because they come from renewable resources, they are largely available, light, and they are not harmful in their processing. In addition, the reinforcements do not produce irritations or other effects on safety and health during management. Moreover, some natural fibre composites present quite good mechanical properties [27].

In front of mineral fibres, these materials are very difficult to recycle at 100%, and they can be obtained from waste of different types of manufacturing processes. It is interesting to note that, compared to fiberglass, the cost related to the production of natural fibres is lower and the polluting emissions are reduced.

From the environmental point of view, the energy consumption of the production of a mat of linen fibre (9,55 MJ/kg), which includes its farming, crop and separation of the fibre, is approximately the 17% of the energy needed to produce a fiberglass mat (54,7 MJ/kg).

At the end of their lifespan, both the polymer matrix and the different fibres of the eco-composites can be reutilised. There is a wide range of natural fibres that can be used as reinforcement, being linen and hemp the most used for their excellent mechanical properties and because they are also grown in Europe.

With the manufacturing of the materials, it is intended to obtain new innovative materials that contribute to improve their behaviour, producing a decrease in the cost of the raw materials. This can be achieved by replacing the mineral reinforcing fibres of traditional composites by lignocellulosic natural fibres and others from the textile waste.

In the field of environmental and building acoustics, one of the most important aims is to reduce the noise levels in a room. The acoustic insulation allows reducing the effect of noise in different areas.

Currently, there is a range of research works focused on materials manufactured from the recycling industries or vegetable fibres [28][29].

The requirements of the European Union regarding climate change, energy efficiency and use of raw materials (H2020) have led to an increase in the development of new materials in different areas, like building acoustics.

The viability of manufacturing eco-composites made of different types of natural fibres is studied, which will reduce the airborne noise, and will be respectful with the environment accomplishing the requirements of the current regulations [30][31][32].

2. Materials

2.1 Sample preparation

A selection of materials suitable for manufacturing eco-composites and a search for different biodegradable resins [33] that are commercialized in the market have been chosen for this work. In this investigation the fibers used to reinforce the matrices are lignocellulosic natural fibres and textile waste [34][35][36].

Composites with biodegradable matrices are called with the acronym “Bio” and composites with polyester matrices are called “EP”.

Figure 1 shows the fibres that will be used for manufacturing the composites by vacuum infusion process.

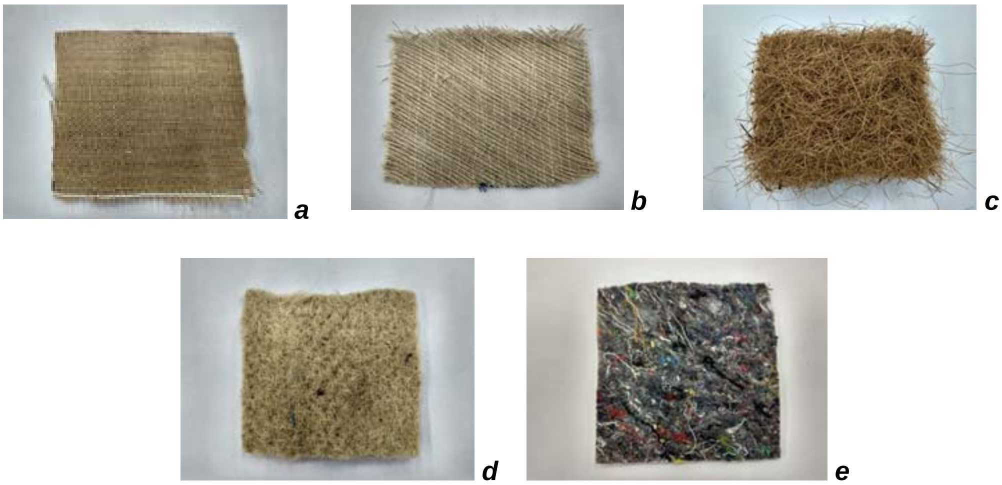

Figure 1. Fibres used to manufacture the eco-materials: a) Jute fibre (J), b) Biaxial Linen Fibre (Lb), c) Coconut fibre (Co), d) Hemp fibre (He) and e) Textile Fibre waste (T).

The preparation of the different lignocellulosic fabrics comes from rectangular samples of 900x600 mm composed of different layers with a thickness between 4 to 5 mm. The eco-composites will be manufactured by means of the vacuum infusion process [37][38], which allows the production of relatively large samples, not requiring the use of double-sided moulds, what supposes an economic advantage in front of other types of processes. The infusion equipment consists of a vacuum pump of the pallet type, model VL with a power of 0,75 kW which provides a flow of 20 m^3/hour and a resin bucket model RB 451 designed to collect the additional resin during the process of transferring the resin to the mould assisted by vacuum.

The density is measured on a scale model Scaltecde METROTEC, S.A. in order to obtain the mass per unit of volume of the material with the recommendations of the standard ISO 1183-2: 2019 [39].

The samples of composite materials are manufactured at 25ºC in all cases through the process of resin infusion. In this work, two types of resin (polyester and bioresin) are used in order to compare the properties of the layers.

The resins are used in the proportion provided by each manufacturer, which is related to the characteristics of the fabric or fibre, since the density of the fabric has an influence in the distribution of the resin in the layers. An experimental calculation of the proportion of resin can be made depending on the type of fabric or fibre. The properties obtained from the manufactured plates are described in tables 1 and 2, for bioresin and polyester matrix, respectively.

Table 1. Properties of composite layers made with bioresin matrix.

Reference	**Reinforcement**	**Number of layers**	**Thickness (mm)**	**Fibre weight (g)**	**Apparent density (g/cm^3)**
BioLb	Biaxial Linen (45º)	6	4,80	1,223	0,47
BioJ	Jute (90º)	6	4,50	1,043	0,43
BioTex	Textile waste	5	7,50	618	0,15
BioCo	Coconut	1	6,50 - 10	788	0,17
BioHe	Hemp	1	5	655	0,24

Table 2. Properties of composite layers made with polyester resin (EP) matrix.

Reference	Reinforcement	Number of layers	Thickness (mm)	Fibre weight (g)	Apparent density (g/cm^3)
EPLb	Biaxial Linen (45º)	6	4,80	1,280	0,49
EPJ	Jute (90º)	6	4,50	1,046	0,43
EPTex	Textile waste	5	7,50	693	0,17
EPCo	Coconut	1	6,50 - 10	789	0,17
EPHe	Hemp	1	5	672	0,24

Figure 2 shows the result of the biocomposite panels after the curing stage [40].

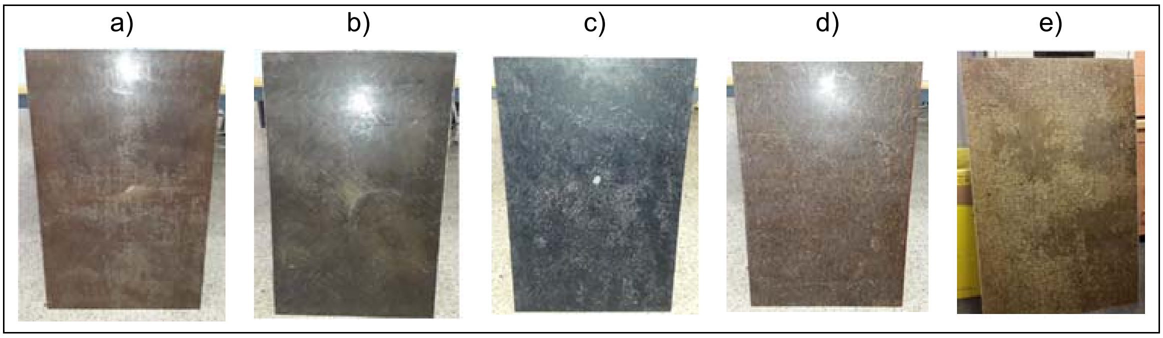

Figure 2. Biocomposite panels; a) Biaxial Linen fibre, b) Jute fibre, c) Textile waste, d) Coconut fibre, e) Hemp fibre.

The properties of the panels obtained after the curing time are shown in Tables 3 and 4.

Table 3. Properties of composites with biodegradable matrix (Bio).

Reference	Volume of the fibre (%)	Ratio of fiber mass (%)	Thickness (mm)	Panel weight (g)
BioLb	0,76	0,51	5,10	2 421,00
BioJ	0,70	0,43	5,10	1 043,00
BioTex	0,73	0,27	4,90	2 300,00
BioCo	0,64	0,22	8,14	3 580,00
BioHe	0,70	0,32	4,20	2 030,00

Table 4. Properties of the composites with polyester resin (EP).

Reference	Volume of the fibre (%)	Ratio of fibre mass (%)	Thickness (mm)	Panel weight (g)
EPLb	0,70	0,45	4,35	2 850,00
EPJ	0,60	0,38	4,72	2 718,00
EPTex	0,71	0,26	4,61	2 670,00
EPCo	0,58	0,17	7,46	4 590,00
EPHe	0,60	0,26	4,44	2 550,00

As it can be seen in Tables 3 and 4 the final thicknesses of the panels have values between 4,20 mm and 5,10 mm, except from the coconut whose thickness is higher with values between 7,46 mm and 8,14 mm. The weights of the final panels of the composites with polyester resin are higher than the same plates with the bio resin.

By measuring the weight of the sample outside and inside a fluid, in this case distilled water (ρ = 1 g/cm^3), the density of the solid can be determined by the equation:

$$\sigma = \frac{W_a - \sigma_{fl}}{W_a - W_{fl}}$$

Where:

- σ, density of the solid (g/cm^3).
- σ_{fl}, density of the fluid (g/cm^3).
- $W_{(a)}$, weight of the solid outside the water (g).
- $W_{(fl)}$, weight of the solid inside the water (g).

Table 5 shows the values of the density of the tested composites.

Table 5. Values of the density of the tested composites.

Reference	Density Hydrostatic (g/cm^3)
BioLb	1,18
BioJ	1,08
BioTex	1,07
BioCo	1,03
BioHe	1,15
EPLb	1,22
EPJ	1,12
EPTex	1,23
EPCo	1,01
EPHe	1,13

It can be observed that there is not a great difference in densities regardless of the type of the fibre and resin used in manufacturing the composite.

2.2 Scanning Electronic Microscope (SEM)

The study of the morphology of the fibres and microfibres that compose the fabrics analysed in this work has been carried out using the scanning electron microscope model S-3000N of the manufacturer Hitachi Ltd. Japan.

In Figure 3, the image with the values of the diameters of the biaxial linen fibre is shown. The sizes correspond to a thread of fibre, composed of several microfibers.

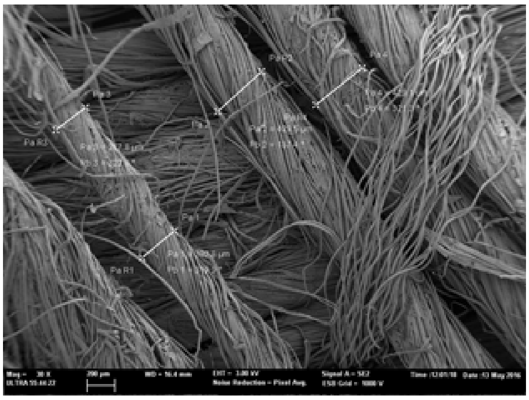

Figure 3. SEM microscopy of the diameters of biaxial linen fibre.

In Figure 4, the SEM image show the values of the diameters of the jute fibre. These diameters are threads composed of several fibres.

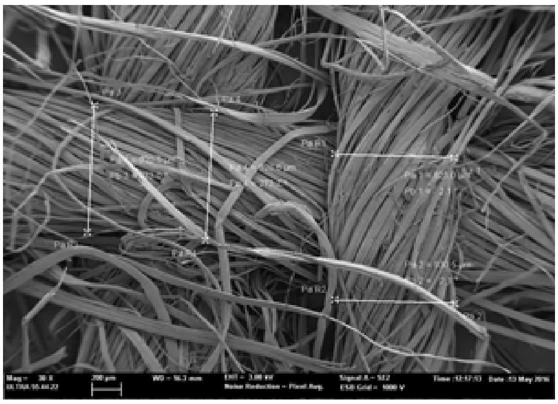

Figure 4. Jute SEM microscopy.

Figure 5 shows the diameters of the coconut fibres. In this case, the observed diameters correspond to the unattached and individual fibres that compose the material.

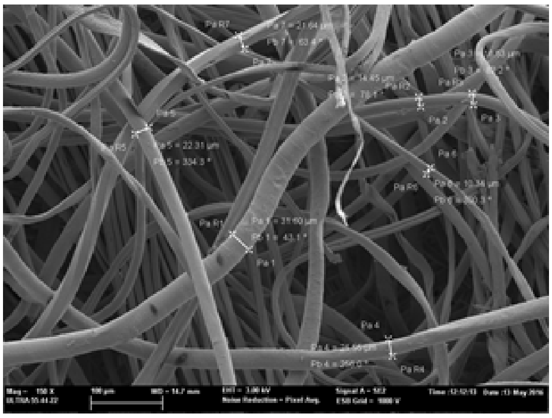

Figure 5. SEM microscopy of the coconut fibers.

In Figure 6, the image obtained by SEM microscopy of the diameters of the hemp fibre is shown. This type of fibre is very irregular.

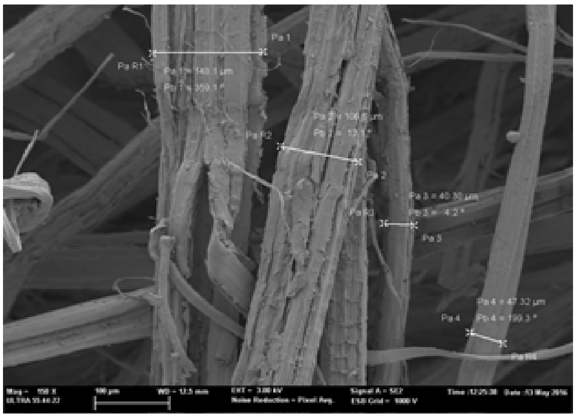

Figure 6. SEM microscopy of the hemp fibers.

Figure 7 shows the SEM image of the diameters of the textile fibre. It is observed, in this case, that the textile is composed of different fibres, although they are similar and homogeneous.

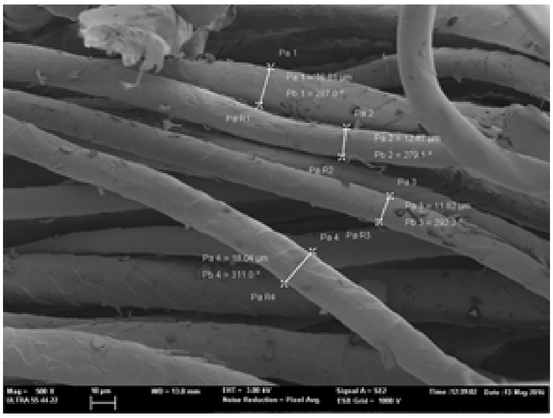

Figure 7. SEM microscopy of the diameters of the textile fibres.

Table 6 shows the average values of the fibre diameters.

Table 6. Average diameters of the fibres used as reinforcement.

Fibres	Fibre Diamter (μm)
Jute(J)	18,40
Biaxial Linen (Lb)	20,07
Textile waste (T)	14,83
Coconut (Co)	21,25
Hemp (Ca)	40

3. Experimental

3.1 Vibration test

The free vibration test is conducted according to the recommendations of the ASTM Standard C1259-15 [41]. The equipment consists of a Brüel & Kjær free field microphone, an electronic National Instruments frequency card and the Matlab software for processing the data. The purpose of studying the dynamic behavior of the eco-composites is to find out the vibration properties, which are related to the modulus of elasticity of the materials.

Within the dynamic methods, the cantilever beam test (free vibration) is carried out to determine the modes of vibration. Samples of 200 mm length and 20 mm width are fixed at one end and are free at the other. The sound is generated by a forced vibration at the free end and registered by a microphone to obtain the modes of vibration.

Figure 8 shows the experimental set-up to fix the samples and record the vibration by a microphone.

Figure 8. Experimental set-up for the vibration test.

A spring and a mass, as a theoretical approach to the modal analysis (Figure 9), can represent the cantilever beam system.

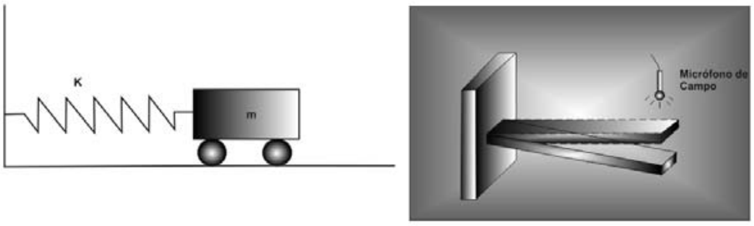

Figure 9. Scheme of the free vibration test and the analogy system.

The sound emitted is recorded by the free-field microphone and analyzed by an electronic card that transforms the acoustic signal into a Frequency Response Function (Amplitude - Frequency) through the Matlab software (Figure 10).

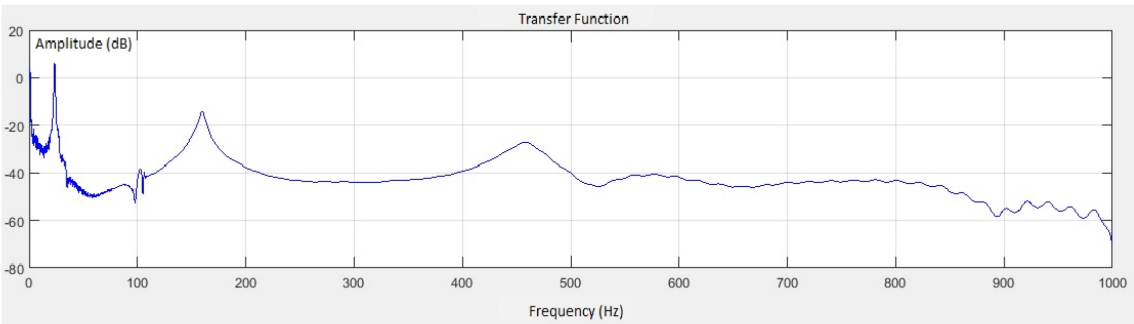

Figure 10. Frequency Response Function obtained with the free vibration test.

The values of the first mode frequencies obtained after the free vibration test of the different samples are shown in Table 7.

Table7. First mode frequencies

Reference	Natural Frequency (f_o) (Hz)
BioLb	26,00
BioJ	31,00
BioTex	25,30
BioCo	21,80
BioHe	24,70
EPLb	16,60
EPJ	27,80
EPTex	19,50
EPCo	18,00
EPHe	18,40

The highest value is for the jute composite with bio resin (material BioJ).

3.2 Acoustic Transmission

The standard UNE EN ISO 10140-2: 2011 allows obtaining the airborne sound insulation of the samples. It is an expensive equipment, both for construction and maintenance. In addition, according to the specifications of the standard ISO 10140-1:2016 to evaluate the airborne sound insulation in a vertical enclosure, at least 10 m^2 sample is required. For the analysis of the materials presented in this work, a scale reverberation chamber has been used for small samples, which in many cases will not exceed one square meter under certain limitations [42] Through this test, the value of the sound reduction index, R (dB), can be obtained from 400 Hz.

The acoustic transmission chamber is composed of two coupled enclosures in which the acoustic airborne insulation of certain materials or constructive solutions can be studied. This system guarantees that the lateral transmissions are practically negligible. Figure 11 shows a scheme and a photograph of the scale transmission chamber.

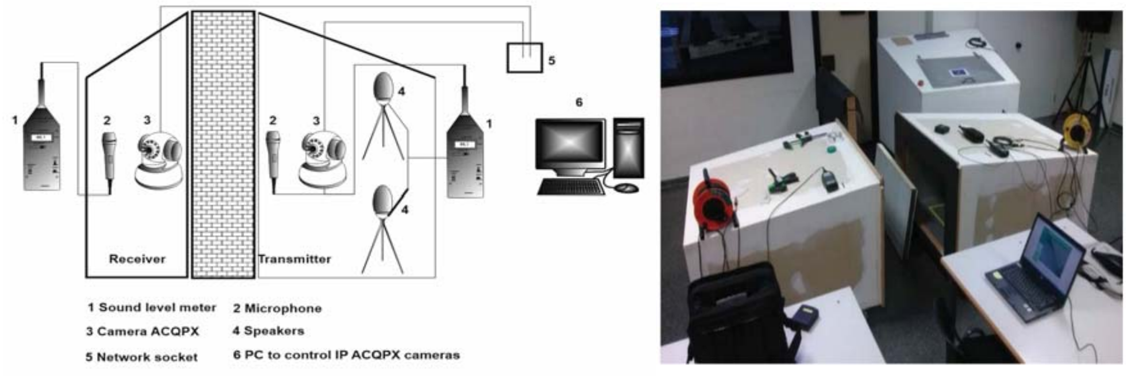

Figure 11. Scale transmission chamber.

In each test, the reverberation time in the receiving room is measured by the interrupted noise method. For that, one loudspeaker is used as a source of noise. In addition, in each test the background noise is checked in the receiving room and it is 15 dB lower than the noise received during the test.

The values are recorded from 500 Hz, since at lower frequencies it cannot be assured that the values obtained are comparable to standardized tests due to the modal density in the transmission chamber of reduced size. It is not possible to guarantee the homogeneity in the frequency response necessary to conduct an insulation test in the transmission chamber below a critical frequency. This critical or limit frequency of validity for the test depends on the reverberation time in the chamber and its amplitude.

4. Results

4.1. Vibration test

To obtain the modulus of elasticity from the frequencies, the following mathematical equation based on the standard E 756 - 05: 2017 is applied [43]:

$$E = \frac{12\,\rho\, L^4 {f_n}^2}{H^2 Cn^2}$$

Where:

E, modulus of elasticity of the material (Pa); f_n, resonant frequency (Hz); H, thickness (m); L, length (m); ρ, density (kg/m^3); 12, numerical constant; C_n, cantilever model coefficient for mode n (for the first mode is 0,55959).

Table 8 shows the values obtained through the equation.

Table.8. Modulus of elasticity values of the different composites.

Material	Modulus of Elasticity (MPa)
Bio Jute (BioJ)	6 954,81
Bio Hemp (BioHe)	4 059,68
Bio Linen (BioLb)	4 103,77
Bio Textile (BioTex)	3 562,63
Bio Coconunt (BioCo)	2 603,25
EP Jute (EPJ)	5 689,92
EP Hemp (EPHe)	4 552,97
EP Linen (EPLb)	4 083,65
EP Textile (EPTex)	3 615,56
EP Coconunt (EPCo)	2 962,82

The samples with the highest modulus of elasticity correspond to jute composites (EPJ and BioJ).

4.2. Acoustic transmission (Airborne sound insulation)

Acoustic insulation tests are carried out in a scale transmission chamber for small samples. The transmission chamber consists of two horizontally coupled enclosures (sender enclosure and receiver enclosure). The samples to be tested must be located between the sender enclosure and the receiver enclosure. Figures 12 and 13 show the values of the airborne sound insulation that are obtained for samples of small size of the panels with biodegradable resin and polyester resin, respectively. The graphs include the results of the laminated plasterboard as a reference.

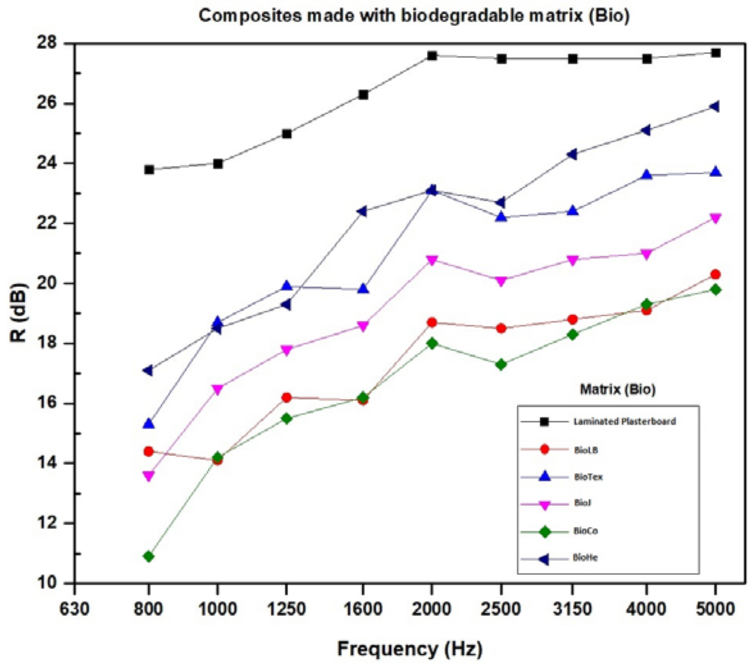

Figure 12. Airborne sound insulation, R (dB), of the biodegradable matrix samples (Bio).

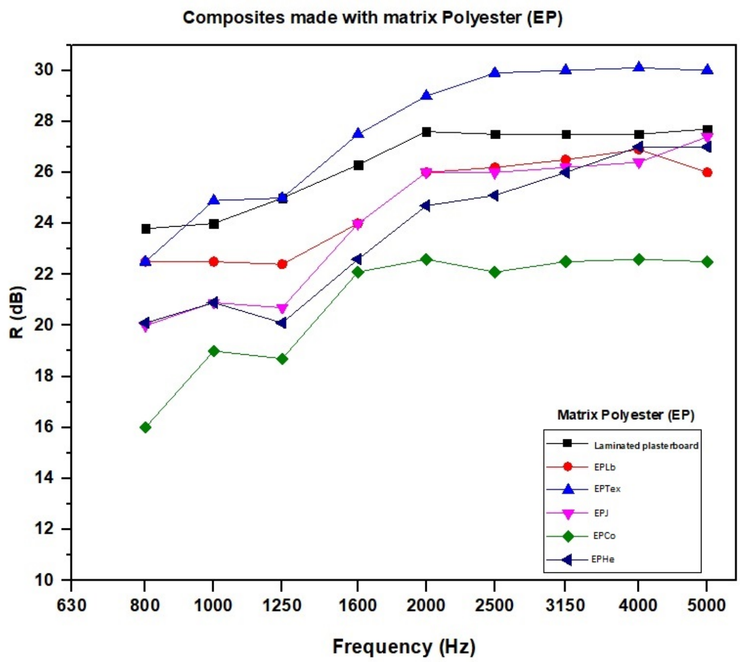

Figure 13. Airborne sound insulation, R (dB), of the polyester matrix samples (EP).

The critical frequency for the transmission chamber used in this work is the third of the octave of 500 Hz, where the panels made of textile waste, both with biodegradable matrix (Bio) and polyester matrix (EP) have the highest acoustic insulation value followed by the biaxial linen and jute, respectively.

Tables 9 and 10 detail the obtained values of airborne sound insulation, which are compared to a 13 mm thickness laminated plasterboard obtained in the same transmission chamber.

Table 9. Results of airborne sound insulation in the transmission chamber for the composites manufactured with the biodegradable matrix versus plasterboard.

R (dB)						
Frequency (HZ)	**BioLb**	**BioTex**	**BioJ**	**BioCo**	**BioHe**	**Plaster Board (13 mm)**
800	14,4	15,3	13,6	10,9	17,1	23,90
1000	14,1	18,7	16,5	14,2	18,5	24,00
1250	16,2	19,9	17,8	15,5	19,3	24,80
1600	16,3	19,8	18,6	16,2	22,4	26,00
2000	18,7	23,1	20,8	18	23,1	27,20
2500	18,5	22,2	20,1	17,3	22,7	27,10
3150	18,8	22,2	20,1	17,3	22,7	27,05
4000	19,1	23,6	21	19,3	25,1	27,05
5000	20,3	23,7	22,2	19,8	25,9	27,25

Table 10. Results of airborne sound insulation in the transmission chamber for the composites manufactured with the polyester matrix versus plasterboard.

R (dB)						
Frequency (HZ)	**EPLb**	**EPTex**	**EPJ**	**EPCo**	**EPHe**	**Plaster Board (13mm)**
800	22,5	22,5	20,0	16,0	20,1	23,90
1000	22,5	24,9	20,9	19,0	20,9	24,00
1250	22,4	25	20,7	18,7	20,1	24,80
1600	24,0	27,5	24,0	22,1	22,6	26,00
2000	26,0	29,0	26,0	22,6	24,7	27,20
2500	26,2	29,9	26,0	22,1	25,1	27,10
3150	26,5	30,0	26,2	22,5	26,0	27,05
4000	26,9	30,1	26,4	22,6	27,0	27,05
5000	26,0	30,0	27,4	22,5	27,0	27,25

As shown in Tables 9 and 10, the airborne sound insulation values of composites with biodegradable resin are lower than those of plasterboard, while the composites made with polyester resin present higher values. However, it must be considered that the thicknesses of the composites are between 4,20 mm for hemp and 8,14 mm for the textile waste, compared to the 13 mm for the plasterboard.

The results are obtained from the frequencies determined in the tests in the transmission chamber according to the standard UNE EN ISO 717-1: 2013.

6. Conclusions

New environmentally friendly materials have been analysed, which differ in the type of the base fibre for its production (five different fibres) and in the type of resin used for their manufacturing (biodegradable epoxy resin and polyester). The fibres used are lignocellulosic (linen, jute, coconut, hemp) and fibres from textile waste.

Once the panels are manufactured by means of the resin infusion process, it is observed that the densities and thicknesses of the composites, with the exception of the coconut (higher initial thickness), have similar values.

The values obtained from the modulus of elasticity of the biocomposites are higher in general (except from hemp), than those obtained for the panels of composites with polyester resin.

Regardless of the type of matrix used in the composite, the panels made of jute fibre are those with a higher modulus of elasticity given the larger diameter of the thread formed by the microfibres, as seen in the SEM images.

The modulus of elasticity of jute is similar to the one of laminated wood. The modulus of elasticity of the rest of composites are higher compared to the expected values in thermostable polymers.

The acoustic characterization has been carried out to determine the airborne sound insulation in a transmission chamber for small samples, being able to analyse samples of one square meter.

When studying the influence of the type of resin, it is observed that the values of the acoustic insulation are higher for the samples made of polyester resin.

The values of the airborne sound insulation are similar to those obtained for 13 mm thickness plasterboard. The panels made of textile fibres with biodegradable matrix (Bio) and polyester matrix (EP) have the highest values of airborne sound insulation.

The use of non-destructive tests with dynamic methods permits to have alternatives for the characterization of new materials. The comparison of the static and dynamic tests are valid tools for the characterization of a material, avoiding the fracture of the material.

The use of bioresin as a matrix material is a good alternative in general, although the value of the raw material to produce biocomposite panels increases by approximately 20%.

Finally, it can be stated that the eco-materials studied in this work offer new possibilities in the field of building acoustics. Future research will be focused on combining these composites in a multilayer way to evaluate the improvement in the mechanical and acoustical parameters.

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