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ACOUSTIC CHARACTERISATION OF BOARDS MANUFACTURED WITH FRUIT STONES MIXED WITH COCONUT FIBRE

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Abstract

Sustainable and recycled materials are being used in a wide range of fields to solve a waste management problem and, at the same time, to confer them a second life. These materials include fruit stones of different crops: apricot, peach, cherry and olive.

Employing fruit stones as acoustic materials contributes to minimise the environmental impact and to create a new product with interesting sound-absorption properties, apart from offering aesthetic added value.

Some previous works have demonstrated the application of fruit stones panels as sound absorbers. This study aims to determine the acoustic properties of boards manufactured with a mixture of the four above fruit stone types. A coconut fibre layer is added to compare the results with and without coconut fibre.

The experimental results show that acoustic properties improve by increasing board thickness and the sound-absorption coefficient is higher when a coconut fibre layer is added. Sound transmission loss is not significantly affected by adding the coconut fibre layer.

KEYWORDS: fruit stones; acoustic characterisation; building acoustics; cherry; olive; peach; apricot; coconut fibre.

1. Introduction

Noise pollution is becoming a concern in modern societies where building standards consider comfort to be one of the main construction priorities because one of the causes of health problems is noise due to traffic, industrial machines, crowded spaces, among others [1]–[3]. A combination of regulatory measures, technological advances and social commitment to healthier living environments is needed to reduce noise pollution. Many countries have regulations to mitigate noise pollution effects [4]. These regulations often set noise level limits for different types of activities and require noise-reducing measures in certain situations [5].

The production of traditional materials used in building acoustics, such as glass fibres, involves energy and natural resources use, as well as greenhouse gas emissions. In addition, these materials can be harmful to the environment if not properly recycled.

All this is leading researchers to find solutions by applying natural materials [6]–[8]. Some of these materials present high porosity, which is a desired sound-absorption feature by allowing sound energy to be dissipated in the matrix because sound is the mechanical energy that travels through material. Those with open pores absorb more energy than those with closed pores [9], [10].

In building acoustics, employing either boards in walls and roofs to improve their acoustic conditioning and insulation properties is a common practice, or wood boards with cement [11],[12], particleboard [13] and high-density fibre boards [14], is widespread.

Currently, there is no wide variety of boards made from natural and sustainable products for acoustic applications, and the most widespread ones are agglomerates of wood chips with magnesite [15]. It is necessary to extend the use of green materials to improve environmental protection by offering products with higher added value [16].

The acoustic behaviour of all natural waste board types has been studied, such as solid-core straw boards [17], posidonia oceanica leaf boards [18], olive leaves [19], hemp fibre [20], boards made with peanut shell core [21] or almond shells mixed with resins [22]. Other studies have analysed the acoustic behaviour of recycled materials, such as cigarette butts [23], combustion bottom ash [24] or granular fibres [25]. Pruning and wood waste can be reused to build new materials with good sound-absorption properties.

One of the most important waste types generated in the agricultural industry of the Mediterranean region is fruit stones and coconut fibre. These waste types can be profitable in different applications [26]. Some researchers have conducted works into the use of olive stones mixed with polypropylene [27] and olive stones with polyester as a binding agent [28]. The authors have studied the acoustic conditioning of different types of fruit stones and thicknesses [29], [30].

Of natural fibres, coconut fibre can be applied as reinforcement for construction materials, as insulation, and even in the manufacturing process of boards [31]–[33]. Coconut fibre has a very high potential for substituting expensive synthetic fibres when manufacturing sound-absorption boards [34]. In some applications, fibrous materials are added to improve acoustic performance, and coconut fibre is one of the most widespread [34], [35]. This fibre is the part that lies between the outside shell and the core shell of coconut, which is commercially provided as mats or boards. It is classified into different types and has an apparent density within the 50-140 kg/m^3 range.

The aim of this work is to propose an alternative use of the materials obtained from the agro-food industry as sound-absorbing and sound-isolating boards to provide a solution to an environmental problem. The challenge lies in creating a panel made from a mixture of fruit stones with coconut fibres and a natural binder that is fully recyclable and has the maximum acoustic absorption by minimising panel weight and thickness. When comparing this research to other cited contributions related to fruit stones in the acoustics field, the main advantage of this work is the production of multilayer boards from different agrofood waste types that are plentiful in the Mediterranean region: coconut fibre and the mixture of cherry, olive, peach and apricot stones.

Boards are manufactured inside squared moulds. Circular samples are obtained from these moulds to run sound-absorption tests by the standing wave tube method. The results for the different thicknesses show that sound-absorption coefficients come close to 0.8 at 1,000 Hz, with sound transmission loss (STL) values of 20 dB between 500 and 1,000 Hz.

In this research work there is a detailed description of the materials, methods and results to explain the acoustic performance of the manufactured materials, completed with a conclusion and possible future research.

2. Materials

The materials used for this research are the fruit stones generated by some agricultural companies that produce fruit foods, such as juice, olive oil, cakes etc. One of the most important waste types generated in agricultural industry is fruit stones that can be profitable in different applications. Fruit and vegetable cooperatives provide an outlet for fruit that was not suitable for the fresh market or that could not be absorbed by consumers. The fruits are pre-treated by industrial processes of washing, brushing and sorting; the stone is then removed and stored in containers. According to a Spanish Ministry of Agriculture report, the percentages of the surface used to grow stone fruit are represented in Figure 1.

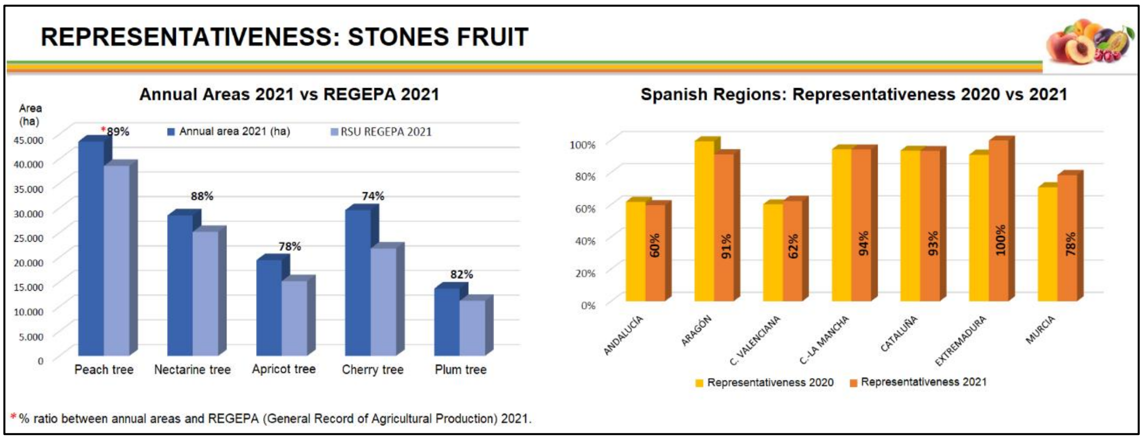

Fig. 1. Stone Fruit: Analysis of the 2021 Production Reality - Spanish Ministry of Agriculture.

Each fruit stone has unique properties in terms of size, shape, density, porosity, among others, which offer interesting properties for building acoustic applications. Fruit stone densities are calculated from the weight of each stone and the volume of the water that it displaces. To determine density, a mean value is obtained from 50 fruit stones of each type (Table 1 shows the mean density values). For weight measurements, an ACULAB scale model Atilon 423 is used with the following characteristics: capacity 420 g, readability 0.001 g, repeatability (standard deviation) ≤±g 0.0001, linearity deviation ≤±g 0.0002.

Table 1. Fruit stone density.

	Olive	Cherry	Apricot	Peach
50 stones dry weight (g)	22.67	14.26	83.74	159.32

50 stones volume (mm^3)	20.00	17.00	117.50	220.00
Density (kg/m^3)	1,132.50	838.24	712.77	724.09

Resin is made up of a water-based sustainable resin called FixGrav (total density 1.00 gr/cc, Brookfield viscosity 200 Pa·s, active ingredient 40% +/- 1%, pH 8-9 and minimum film-forming temperature (MFFT) of around 0ºC). To produce multilayer boards, a coconut fibre layer with a density of 100 kg/m^3 and a thickness of 3 mm is used. It is commercially available as a fibre roll.

Boards are prepared in the following steps:

- For a 5 kg mixture, 25% by volume of each stone type is used and 0.7 kg of resin is added until a homogeneous mixture is obtained. Table 2 shows the weight of each stone type employed in the mixture.

Table 2. Fruit stone weight.

Fruit stone	Olive	Cherry	Apricot	Peach
Weight (kg)	1.661	1.230	1.045	1.062

Figure 2 shows the mixture with a proportion of 25% volume for each fruit stone and the ecological resin.

Fig. 2. A) Weighing materials for the mixture. B) Mixture process.

- To obtain boards, a coconut fibre layer is placed at the bottom of the mould. Then the mixture is poured until the desired thickness is obtained. 20 Pa pressure is applied to compact the mixture and make the surface uniform. The mixture is left to dry for 24 hours. The total weight is reduced from 5.7 kg to 5.4 kg. Finally, boards are removed from moulds. Figure 3 shows a 20-mm panel with the mixture poured into the mould and dried.

Fig. 3. A) Mixture in the mould. B) Dried board.

- Boards with five different thicknesses are manufactured. Thickness depends on the mixture's granulometry and homogeneity by taking into account the shape and size of fruit stones. For each thickness, a circular sample of 0.1 m diameter is prepared for the acoustic tests. Table 3 shows the thickness, weight and density of each sample.

Table 3. Acoustic test specimens.

Specimen	**Thickness (m)**	**Weight (kg)**	**Apparent density (kg/m^3)**
Fruit Stones Mix-2 cm	0.02	0.057	362.87
Fruit Stones Mix-4 cm	0.04	0.099	315.13
Fruit Stones Mix-5 cm	0.05	0.174	443.23
Fruit Stones Mix-7 cm	0.07	0.212	385.72
Fruit Stones Mix-9 cm	0.09	0.270	381.98

Figure 4 shows the five different specimens for the acoustic tests.

Fig. 4. Fruit stone samples and the coconut fibre layer.

3. Methods

Acoustic properties are measured with a circular standing wave tube according to Standards UNE ISO 10534-2 [36] and ASTM 2611-19 [37] to obtain the sound-absorption coefficient and STL, respectively.

3.1. Sound-absorption coefficient

The sound-absorption coefficient is obtained by dividing the energy absorbed on the material's surface by the incident energy of a plane acoustic wave. Standard ISO 10534-2 is applied in this work to measure fibrous and porous materials' acoustic properties. The sample was placed at one end of the tube and the sound wave generator was placed at the other end. With data acquisition card NI-9234, sound pressure was measured by two G.R.A.S. model 40AO microphones placed at specific positions near the sample. The analogue input control, data processing and calculation of the complex reflection coefficient, and sound-absorption coefficient and acoustic impedance, were performed by the MATLAB software.

Figure 5 depicts the scheme of the standing wave tube test to determine the sound-absorption coefficient according to Standard ISO UNE EN 10534-2.

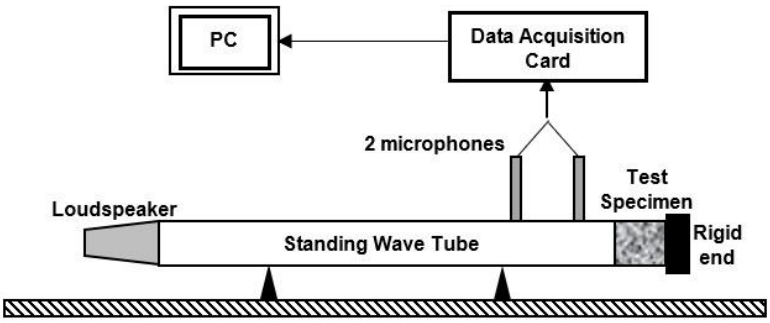

Fig. 5. Scheme of the standing wave tube to measure the sound-absorption coefficient.

Figure 6 shows the photo of the sample located on the sample holder of the tube.

Fig. 6. Sample located on the sample holder.

The reflection coefficient is defined by Equation (1):

$$r = \frac{H_{12} - H_i}{H_R - H_{12}} \cdot e^{2jk_o x_1} \tag{1}$$

where H_{12} is the transfer function from microphone positions 1 and 2, H_R, is the real part of H_{12}, H_i is the imaginary part of H_{12}, k_0 is the wave number, and x_1 is the distance between the sample and the first microphone.

Acoustic impedance is determined according to Equation (2):

$$\frac{Z}{\rho \cdot c} = \frac{R}{\rho \cdot c} + \frac{X}{\rho \cdot c} j = \frac{1+r}{1-r} \tag{2}$$

where R is the real component of impedance, X is the imaginary component of impedance, ρ·c is the characteristic impedance, r is the reflection coefficient and Z is acoustic impedance.

The sound-absorption coefficient is given by Equation (3):

$$\propto = 1 - |r|^2 \tag{3}$$

3.2. Sound transmission loss (STL)

One property used to characterise some materials' sound insulation properties is STL. According to ASTM E2611-09 [37], a given material's STL at a certain frequency band is defined as the fraction of the airborne sound power incident on a material that is transmitted through the tested material and is outwardly radiated.

The sample is mounted onto the tube. Data acquisition card NI -9234 is employed to measure sound pressure. Four G.R.A.S. model 40AO microphones are placed at two different locations on each sample side. Plane waves are generated in the tube using a broadband signal from a noise source. The MATLAB software is utilised for analogue control and data handling, and for calculating pressure and particle velocities, acoustic transfer matrix and acoustic attenuation.

STL is given by Equation (4):

$$STL = 10 \log_{10}\left(\frac{W_i}{W_t}\right) \tag{4}$$

where W_t and W_i are the transmitted and the incident sound power, respectively.

The obtained STL is expressed as decibels (dB).

Figure 7 represents the scheme of the Sound Transmission Loss (STL) test according to Standard ASTM 2611-09 (Standard Test Method for the Measurement of Normal Incidence Sound Transmission of Acoustical Materials Based on the Transfer Matrix Method).

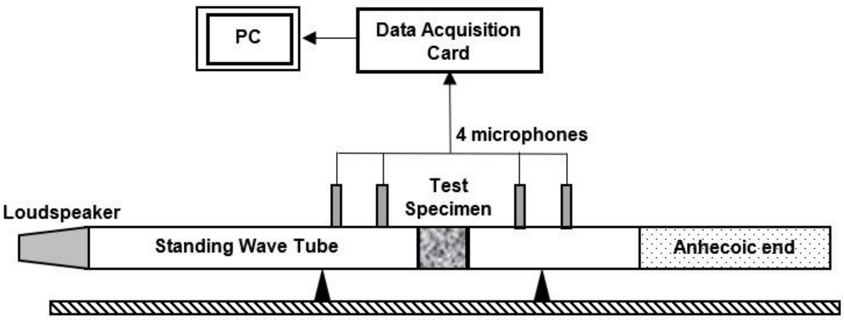

Fig.7. Scheme of the four microphone impedance tubes to measure STL.

Figure 8 shows the test of one of the samples to determine STL.

Fig. 8. The STL test.

Table 4 shows technical characteristics of the equipment employed for acoustical tests.

Table 4. Technical characteristics of equipment.

Equipment	Technical characteristics
Acquisition Card NI 9234	Four analogue input channels, ADC resolution 24 bits, Input range ± 5V
G.R.A.S. 40AO microphones	Freq. range: 3.15 Hz to 20 kHz, Dyn range: 20 dB(A) to 163 dB, Sensitivity: 12.5 mV/Pa
Impedance tube	Internal diameter 100 mm, Freq. range between 214 and 1716 Hz.
MATLAB	Release 2023, DAQ Toolbox

4. Results and Discussion

4.1 Sound-absorption coefficient

Figure 9 represents the sound-absorption coefficient of the different fruit stone samples without the coconut fibre layer. First, the acoustic absorption of coconut fibre is very low, less than 0.2, within the studied frequency range due to its low thickness value (only 0.003 m). For the fruit stones mix, acoustic absorption increases with thickness, with sound-absorption coefficients up to 0.8 between 800 and 1,200 Hz. It should be noted that the 0.02-meter thick sample has negligible sound absorption due to the material's heterogeneity because sound absorption only becomes relevant at a certain thickness.

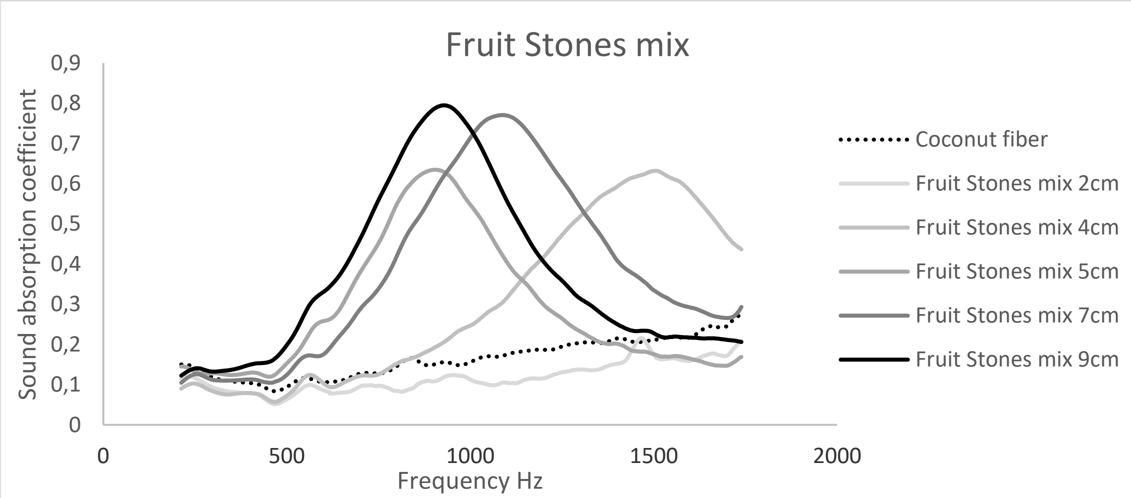

Fig. 9. Sound-absorption coefficient of the fruit stones samples and coconut fibre.

Figure 10 shows acoustic behaviour when the coconut fibre layer is added. The fibre layer modifies samples' acoustic behaviour by displacing the maximum absorption for each thickness toward lower frequencies. With the coconut fibre layer, sound-absorption coefficient values above 0.6 are obtained within the 500-1000 Hz frequency range, with a maximum of 0.82 at 520 Hz for the sample of 0.09 m thickness.

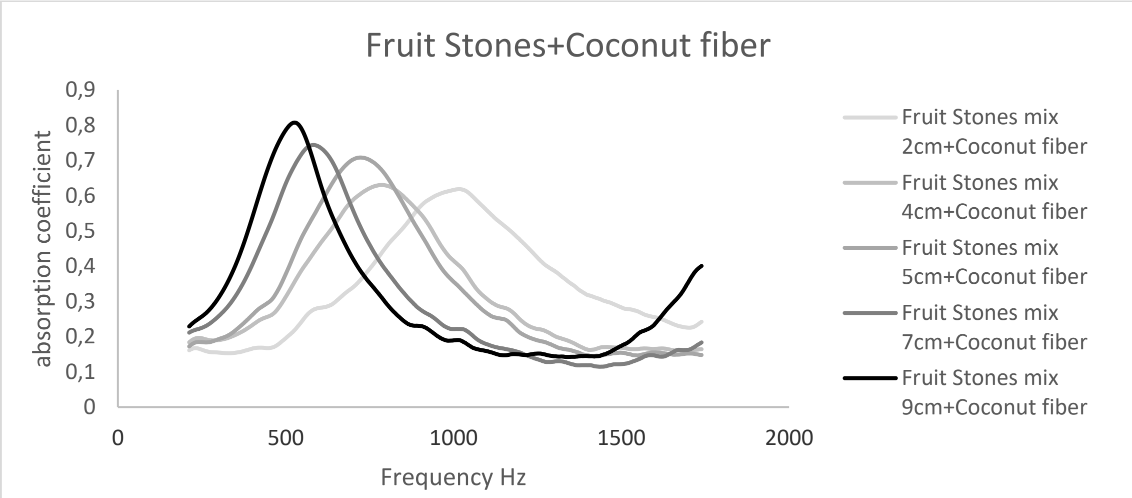

Fig. 10. Sound-absorption coefficient of the fruit stones samples with a coconut fibre layer.

4.2 Sound Transmission Loss (STL)

Figure 11 represents the STL for the different samples without the coconut fibre layer. There is a tendency for sound insulation to increase depending on thickness of all the samples within the studied frequency range. The STL values between samples are similar at low frequencies up to 400 Hz, with values between 15 and 18 dB. The differences in samples' STL become increasingly bigger between 400 and 1,000 Hz and reach a maximum value of 26 dB for thicker samples. The obtained results show similar STL values to those of the wood samples [38].

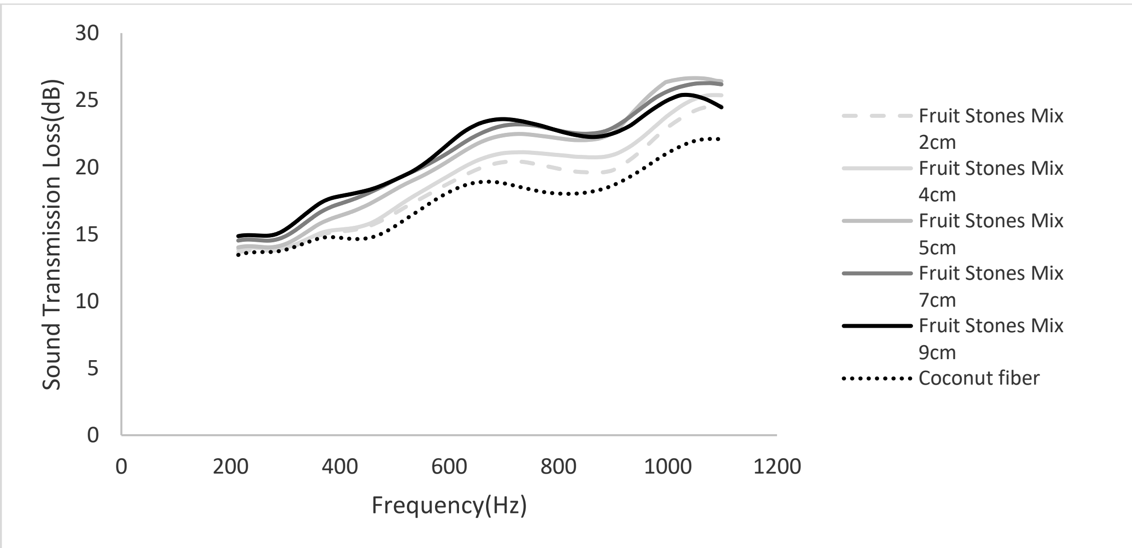

Fig. 11. STL of the fruit stones mixture samples and the coconut fibre layer.

When adding the coconut fibre layer, the STL results do not vary due to its low thickness and low density values, and to its fibrous structure. Figure 12 shows the STL values when the coconut fibre layer is added to each sample.

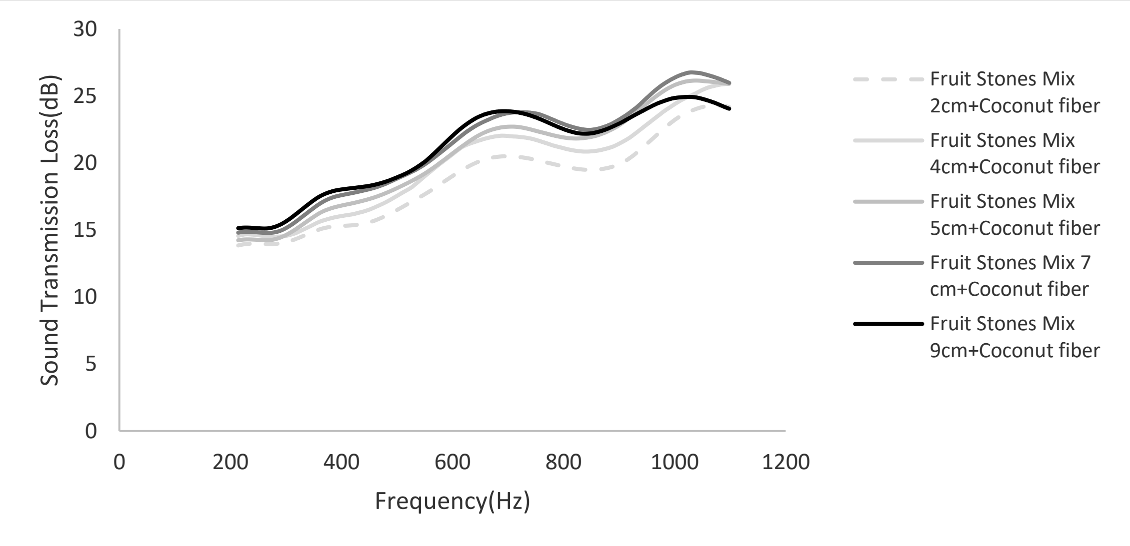

Fig. 12. STL of the fruit stones mixture samples with the coconut fibre layer.

5. Conclusions

This work focuses on enhancing the acoustic properties of an agricultural waste, improving their durability and finding efficient ways to process and utilize them. Research also explores combining different types of agricultural waste to optimize sound absorption across a broader range of frequencies. The results allow us to conclude the following advantages: sustainability, because using agricultural waste reduces the need for synthetic materials and helps manage waste effectively; cost-effective, because these materials are often cheaper than traditional sound-absorbing materials like fiberglass, rockwool or foam; biodegradability, since agricultural waste materials are biodegradable, making them environmentally friendly; renewable resource, because this agricultural waste is continually produced, providing a steady and renewable supply of raw materials.

Four different fruit stone types are selected for this study to solve a waste management problem for manufacturing acoustic boards with such waste. The use of fruit stones as sound-absorbing materials is a valid option for reducing noise and reverberation in buildings. It can also be extended to other fruit stone types. Employing such natural waste material has environmental benefits, such as conferring this agricultural waste added value.

The acoustic results demonstrate the possibilities of applying stone types as a substitute for traditional materials in acoustic conditioning and isolation building applications at specific frequencies. The sound-absorption coefficient values go up to 0.8 at 500 Hz for the 0.09 m sample with the coconut fibre layer. They reveal that it is possible to obtain STL values between 24 and 26 dB at 1,000 Hz with thicknesses of 0.07 and 0.09 m.

This work demonstrates that it is possible to manufacture acoustic panels from agricultural waste and biodegradable resins for building acoustics applications, such as sound reduction and reverberation elimination in enclosed spaces, by placing these panels on walls and ceilings.

When considering aesthetic factors, these panels confer fruit stone waste added value. The organic and natural look of these boards also makes them ideal for decoration purposes on walls and ceilings.

Furthermore, the characterisation of these boards can be extended by means of tests to determine their mechanical, thermal and fire resistance properties. Moreover, to effectively verify the performance of these materials, it would be appropriate to also carry out a simulation of the application of this material in a room, using specific software for room acoustics. Finally, this work is a starting point to manufacture acoustic boards with other agricultural waste types and different matrices of natural or ceramic origin.

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