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Mechanical and acoustical evaluation of bio-based composites made of cork granulates for acoustic ceiling tiles

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ABSTRACT: This work is a study about new acoustic panels made of cork granulates coming from stopper by-products to be used as acoustic ceilings tiles, providing a sustainable and environmentally friendly alternative to traditional building materials. Cork granulates were bonded with water-based epoxy and acrylic resins. The obtained panels were acoustically and mechanically tested. The results showed values of sound absorption coefficient close to 0.50 and acceptable flexural strength for their use as suspended ceiling tiles. Therefore, these bio-based panels could be used as an alternative product to the traditional materials used for noise control applications inside commercial spaces like closed entertainment areas.

KEY WORDS: Composite; Physical properties; Characterization.

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RESUMEN: *Evaluación mecánica y acústica de composites de corcho granular para techos supendidos.* Este trabajo es un estudio sobre paneles acústicos fabricados con granos de corcho procedentes de subproductos de tapones para su empleo como techos suspendidos, proporcionando una alternativa sostenible y ecológica a los materiales de construcción tradicionales. Los granos de corcho se aglutinaron con una resina epoxi de base acuosa y resinas acrílicas. Los paneles obtenidos se sometieron a pruebas acústicas y mecánicas. Los resultados mostraron valores de absorción acústica media cercanos a 0.50 y una resistencia a la flexión aceptable para su uso como placas de techo. Por lo tanto, este tipo de paneles de base biológica podrían utilizarse como productos alternativos a los materiales tradicionalmente empleados para aplicaciones de control del ruido en el interior de espacios.

PALABRAS CLAVE: Composite; Propiedades físicas; Caracterización.

1. INTRODUCTION

Nowadays, the use of green and sustainable products in the building industry has a growing interest being a common practice today as an alternative to the traditional synthetic materials such as glass wool, foams or rock wool, widely used for noise control applications (1-12). These show high efficiency in noise reduction or thermal insulation. However, these are expensive to produce and, in addition, environmental factors or health hazards must be considered.

The growing environmental awareness around the world is the main reason why many researchers have developed environment-friendly bio-composites, derived from the significant amount of waste generated globally. These wastes are ever-increasing, and their disposal is becoming extremely difficult worldwide. These developments have shown that a wide range of these by-products can be potentially applied in acoustics panels.

Buratti et al. (1) characterized sustainable panels made of recycled paper and other scrap materials, such as wool and nonwoven polyester fabric, to improve the acoustic comfort of a lecture room. Guna et al. (2) developed new biodegradable acoustic panels made of sugarcane bagasse for their uses as ceiling tile. These panels were characterized for their flexural strength, and thermal, water and acoustic resistance. Ali et al. (3) developed biodegradable natural thermal insulating and sound-absorbing materials for building walls. In the work of Guna et al. (4), two agricultural residues, namely rice husk and groundnut shell, were used to develop bio-composites for green building materials. These bio-composites showed acoustic properties comparable to commercially used gypsum ceiling tiles. Raj et al. (5) characterized the nettle fibers to obtain physical properties linked to their acoustic performance. Samaei et al. (6) studied experimentally and theoretically the acoustical and thermal properties of composites made of kenaf natural fibers when these were treated chemically with an alkaline treatment. Taban et al. (7) characterized morphological, acoustical, mechanical and thermal properties from fibers extracted from the leaves of Yucca and treated chemically. Yun et al.(8) showed the possibility of using sound-absorbing materials made of coffee waste inside commercial spaces through a novel technique for recycling this type of waste. In the work of Aly et al. (9), the acoustic and the thermal insulation performance of composites, made of jute, polyester and hybrid jute-polyester with polypropylene as the matrix, were studied. Samaei et al. (10) developed and optimized fibro-granular composites with kenaf fibers and waste rice husk granules bonded with a biodegradable polymer, polyvinyl alcohol. Taban et al. (11) studied the acoustical performance of low-cost sound-absorbing panels made of date palm waste fibers bonded with polyvinyl alcohol (PVA) solution, showing that, with their use, the acoustic performance enhanced. Yuvaraj et al. (12) developed jute fiber composite panels undergone partial perforation that had significant sound-absorbing effects. The advantages of using these sustainable products in acoustic applications, like acoustic panels, were a combination of very light mass, high physical stability, low cost, and high values of acoustic absorption. For environmental performance, these types of panels can be considered more acceptable from the health point of view and better suited to operate in an aggressive environment.

Cork, obtained from the cork oak tree (*Quercus suber L.)*, is a sustainable and natural raw material that grows extensively in countries with a Mediterranean climate, such as Portugal or Spain (13). White cork granulate is a by-product obtained from stoppers for wine, beer or champagne (14). Most of the uses of white cork granulate, due to its acoustical and mechanical properties, are associated with material researchers for different applications, where their inclusion in a high number of composite materials for building applications are also numerous: as resilient layers made from cork granulates mixed with polyurethane and epoxy resins (14), as a core element in noise barriers (15), as a lightweight aggregate for cement-based materials (16) or as a thermal insulation panel in buildings, both in facades and roofs (17).

This work is a first study to evaluate new acoustic panels made of cork granulates coming from stopper by-products bonded with a water-based acrylic resin to be used as acoustic ceilings, providing sustainable and environmentally friendly alternatives for synthetic materials.

2. MATERIALS AND METHODS

Previously, granulate cork samples were dried in an oven at 70 °C for 24 h to eliminate the possible moisture. Subsequently, cork grains were separated using five calibrated sieve sets to extract grains with sizes between 3 and 7 mm, weighed and introduced together with the binder, 25% in mass, in an industrial mixer until a complete homogenisation was achieved. Two polymers, one water-based acrylic resin (AC) with a density of 1.00 g cm^{-3} and another water-based epoxy resin (EP) with a density of 1.05 g cm^{-3}, both from Globalpaint Coating S.L., were used for manufacturing the acoustic panels. Once obtaining the homogeneous mixes, they were placed into different moulds, and in metallic nets for 24 h to let the binder percolate freely, obtaining samples with the highest porosity and avoiding the creation of impermeable layers on the bottom side of the sample (Table 1). Subsequently, the samples were placed in an oven at 60 ºC for 24 h to be cured. When the samples were cooled, they were removed from the moulds and cut to prepare the test samples.

FIGURE 1. Samples AC_5, AC_6, EP_4 and EP_5 mechanically tested (from left to right and from top to bottom).

TABLE 1. Flexural stress (σ_f), flexural strain (ε_f), flexural modulus (E_f), porosity, resonance frequency (F_L), dynamic.

Sample	Grain size (mm)	Density (kg m^{-3})	Porosity (%)
AC_3	3	162	78.1
AC_4	4	151	79.6
AC_5	5	143	80.6
AC_6	6	131	82.3
AC_7	7	121	83.6
EP_3	3	163	77.9
EP_4	4	152	79.4
EP_5	5	145	80.4
EP_6	6	133	82.1
EP_7	7	122	83.5

The flexural test was used to measure the flexural strength when applying a load at the centre of the sample. Several parameters could affect this, such as bulk density or thickness sample. Three-point bending tests were carried out using an AUTOGRAPH AG-IS 20 kN universal testing machine from Shimadzu according to the norm ASTM D7264-2021(18). The sample was subjected to a quasi-static load at its centre at a speed range from 600 Ns^{-1} to 1200 Ns^{-1}. A load-displacement curve was recorded using Shimadzu's TRAPEZIUM software. The flexural stress, σ_f (MPa), and the flexural strain, ε_f (mm mm^{-1}), were obtained and recorded for any point on the load-deflection curve for each sample according to Equations [1] and [2], and the flexural modulus of elasticity, E_f (MPa), was obtained according to the Equation [3]:

$$\sigma_f = \frac{3FL}{2bh^2} \qquad [1]$$

$$\varepsilon_f = \frac{6h\delta}{L^2} \qquad [2]$$

$$E_f = \frac{mL^3}{4bh^3} \qquad [3]$$

where F is the applied force (N), L, b and h are, the length, the width and the thickness of the sample (mm), respectively, δ is the recorded deflection at the centre of the sample (mm) and m the slope of the force-deflection curve. Samples were processed using a rectangular mould (200 mm width, 100 mm length, 40 mm thickness). Due to the possible use of these bio-composites, as suspended acoustic ceiling panels, where it is necessary to allow some deformation of these panels, their deformations were also evaluated in this work. Five different bio-based composites were prepared and tested.

To provide further information about the mechanical properties of the bio-composites, the deformability of the samples was also analysed using the failure tensile energy (G) and the resistance coefficient to cracking propagation (R). The first is strongly dependent on the maximum flexural force and can be evaluated by the area below the force *vs*. the load-deflection curves. In the latter, the force component is not taken into account, and it can be defined by the relationship between the failure tensile having the maximum flexural force ($R = G/F_{max}$).

The dynamic modulus of elasticity E_d was determined by a non-destructive methodology, the fundamental resonance frequency method, based on the standard EN 14146-2004 (19). This methodology was performed using a Zeus ZRM 2005 test machine, with the Longitudinal Resonance Frequency procedure. Measuring the transit time measurements for longitudinal ultrasound pulses, the resonance frequency of the first fundamental mode was obtained. The dynamic E_d tests were performed on five specimens for each bio-composite configuration and subsequently averaged. E_d was determined using the following expression:

$$E_d = 4 \cdot 10^{-9} \cdot l^2 \cdot F_L \cdot \rho_m \qquad [4]$$

The acoustic properties of the bio-based composites, sound absorption coefficient at normal-incidence, were carried out according to ISO standard

10534-2 (20). Figure 2 shows the experimental set-up according to (20). The loudspeaker is located at the beginning of the tube. The sample holder is located at the end of the tube, in a rigid termination. The surface of the sample is faced normal to the direction of the incoming sound waves. Random pink noise is generated into the impedance tube through the loudspeaker. Two microphones separated 5 cm, measure the sound pressure level inside the impedance tube.

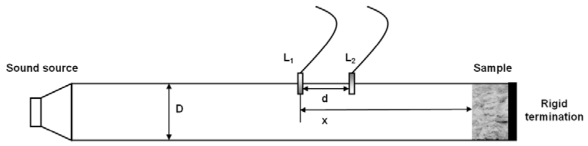

FIGURE 2. Experimental set up for measuring sound absorption spectra.

A Brüel & Kjær impedance tube type 4206T and two 1/4” Condenser Microphones Type 4187 were used. Signals were analysed with a portable Brüel & Kjær PULSE System with four input data channels (type 3560-C). This tube kit consisted of one low-frequency and one high-frequency impedance tube with diameters of 100 and 29 mm, respectively. The first was employed for measurements over the range of frequencies from 100 Hz to 1600 Hz, and the latter over the range of frequencies from 500 Hz to 6400 Hz. Previously to start any measurement, and after the sample positioning, the influencing environmental parameters (atmospheric pressure, air temperature and relative humidity) were measured and introduced in the software. The temperature inside the impedance tube needed to be stabilized. Sound velocity, c_0, and air density, ρ_a, were evaluated according to the next equations:

$$c_0 = 343.2\sqrt{T/293} \qquad [5]$$

$$\rho_a = \rho_0 \cdot \frac{p_a T_0}{p_0 T} \qquad [6]$$

where T is air temperature in Kelvin, ρ_0 = 1.186 kg m^{-3}, p_0 = 101.325 kPa, T_0 = 293 K and p_a the atmospheric pressure. Microphones calibration was accomplished by using a Brüel & Kjær calibrator type 4231 at 94 dB level at 1 kHz. The evaluation of the signal-to-noise ratio was carried out in order to obtain at least 10 dB of difference between them. Finally, the transfer function calibration for the channels phase displacements was evaluated. For each acoustic panel, five different samples were measured and subsequently averaged.

This method shows advantages and disadvantages in its use (21). As an advantage that it is a practical method because the apparatus itself is small, and only small samples are required for the tests. Two acoustical properties can be measured, the surface impedance and the absorption coefficient. As for a disadvantage, these acoustics properties are only measured for sound at normal-incidence to the sample, although it is possible to obtain approximated values of the random incidence absorption coefficient from the surface impedance values, applying a correction. When the materials are heterogeneous, some uncertainties can be introduced. It is due to the pore structure of the samples that may vary considerably when samples are taken from different regions of a large sample. Two different tubes, and samples having different sizes, were used to obtain values in a wide range of frequencies.

To evaluate the sound absorption capability of the samples, single number grading methods, which are independent of frequencies, were used. This index is useful for a practical evaluation of the performance of sound porous absorbers. For this purpose, the ASTM C423-2017 norm (22) defines the Sound Absorption Average (SAA). SAA is defined as the average of the sound absorption coefficients for 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000 and 2500 Hz, rounded off to the nearest 0.01. Six samples were tested, and the SAA averages were obtained for each grain group.

3. RESULTS AND DISCUSSION

Table 2 shows σ_f, εf and E_f, obtained at the maximum load for each sample. It should be noted that the samples with acrylic resin showed the highest values for E_f, ranging from 0.59 to 0.71 MPa, while samples with epoxy resin showed lower values ranging from 0.33 to 0.66 MPa. These values were according to the results obtained for similar bio-based composites showed in others works (23, 24). As expected, dynamic E_d values were slightly higher than the static E_f values. In the case of the rupture energy, R, the results for samples made of acrylic resin are higher than samples made of epoxy resins due to the stiffness of the epoxy resin once the latter is dried. These results ranged between 6.02 to 10.66 mm for the first, while for the latter, this range was 3.55 to 6.53 mm. As is well known, the larger the R, the larger the energy needed to produce micro-cracking in the bio-based composite, so the less probable that evolution is. For the samples under analysis, the sample AC_3 has the higher failure tensile energy and the higher resistance coefficient to cracking propagation, showing an increase of ductility just before failure. Samples made with acrylic resin revealed the highest influence on the G and R coefficients, incrementing these coefficients in comparison with the samples made of epoxy resin.

Sound absorption spectra at normal incidence for acrylic and epoxy samples, having 2 cm (solid

Table 2. Flexural stress (σ_f), flexural strain (ε_f), flexural modulus (E_f), porosity, resonance frequency (F_L), dynamic modulus of elasticity (E_d), rupture energy (G) and resistance coefficient to cracking evolution (R) for each sample.

Sample	σ_f (MPa)	ε_f (mm mm^{-1})	E_f (MPa)	*Porosity*	F_L (Hz)	E_d (MPa)	*G* (N mm)	*R* (mm)
AC_3	0.04	0.10	0.61	0.803	435	0.92	251.28	10.66
AC_4	0.04	0.09	0.59	0.793	429	0.94	176.17	7.69
AC_5	0.05	0.07	0.70	0.788	412	1.39	154.36	6.02
AC_6	0.05	0.08	0.61	0.781	435	1.02	187.10	7.68
AC_7	0.04	0.07	0.71	0.782	447	1.07	166.20	7.82
EP_3	0.02	0.06	0.33	0.850	387	0.79	57.73	3.55
EP_4	0.02	0.06	0.38	0.853	356	0.65	59.23	5.26
EP_5	0.03	0.08	0.66	0.854	407	0.84	134.74	6.53
EP_6	0.04	0.10	0.55	0.854	387	0.76	122.19	5.22
EP_7	0.04	0.11	0.43	0.857	408	0.83	128.99	4.47

line) and 4 cm (dash line) in thickness, are shown in Figures 3 and 4, respectively. It should be noted that a displacement of the first absorption maximum to lower frequencies can be observed due to the increasing thickness of the sample. Moreover, for smaller grain sizes, the values of the sound absorption coefficients were slightly greater than for larger grains. The values of the sound absorption coefficients for the first maximum ranged from 0.42 to 0.65 for samples having 2 cm in thickness and 0.53 to 0.76 for samples having 4 cm in thickness, in the case of the acrylic samples. In the case of the epoxy samples, these values ranged from 0.46 to 0.59 for samples with 2 cm in thickness and 0.67 to 0.82 for samples with 4 cm in thickness.

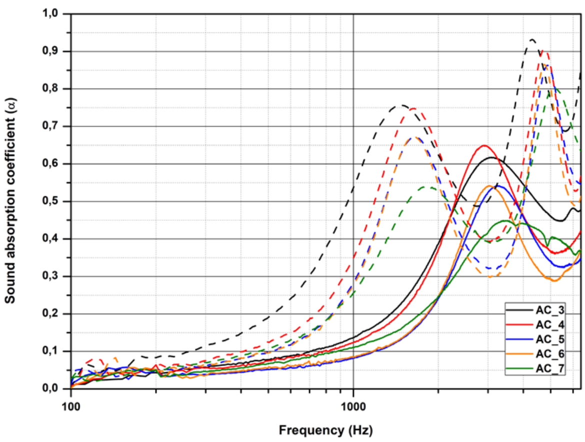

Figure 3. Sound absorption spectra for acrylic samples having thickness of 2 cm (solid line) and 4 cm (dash line).

The effect of the air gap on the sound absorption coefficient was also investigated. This technique is already known in an acoustic absorber to obtain better sound absorber performance for thin thicknesses. Figure 5 shows the effect of the air gap on the sound

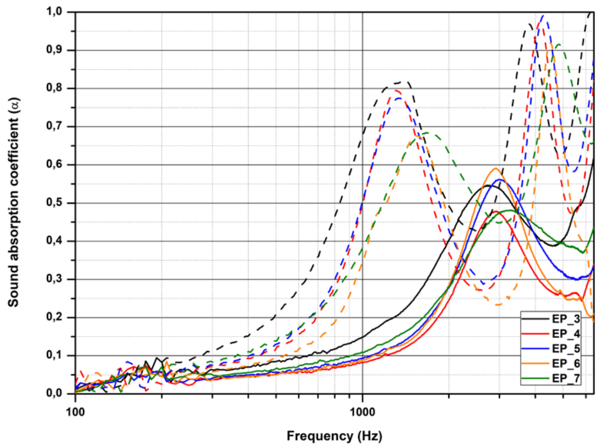

Figure 4. Sound absorption spectra for epoxy samples having thickness of 2 cm (solid line) and 4 cm (dash line).

absorption coefficient of the bio-based composites in the case of the sample AC-3. The air-back cavity between the sample tested and the back-rigid wall also led to an improvement in the sound absorption performance, mainly at low frequencies. This improvement can be observed in the absorption coefficient spectra where the first absorption maximums were shifted to lower frequencies while the values of the sound absorption coefficient become reduced. Table 3 shows the Sound Absorption Average (SAA) obtained for the samples. The air-back cavity between the sample and the back-rigid wall also led to an improvement in the sound absorption performance. This improvement can be observed in the SAA value. This is a very useful effect to improve the sound absorption at low frequencies, instead of increasing the absorber thickness. The SAA differences, in percentage, between bonded samples (BS) and bonded samples with an air-gap of 3 cm (BS-3) and 6 cm (BS-6) can be observed in Table 3. The lower the thickness of the samples, the greater the

Table 3. SAA of bio-based composites and SAA differences, in percentage, between bonded samples (BS) and bonded samples with an air-gap of 3 cm (BS-3) and 6 cm (BS-6).

Sample	Thickness (cm)	Loose	Bonded sample	Bonded sample + air-gap = 3 cm	Bonded sample + air-gap = 6 cm	Differences BS – BS3 (%)	Differences BS – BS6 (%)
AC_3	2	0.15	0.16	0.25	0.27	36	41
	4	0.34	0.39	0.42	0.44	7	11
AC_4	2	0.13	0.14	0.17	0.19	18	26
	4	0.28	0.30	0.36	0.38	17	21
AC_5	2	0.12	0.13	0.18	0.22	28	41
	4	0.31	0.32	0.32	0.40	0	20
AC_6	2	0.12	0.12	0.18	0.22	33	45
	4	0.29	0.32	0.32	0.39	0	18
AC_7	2	0.11	0.12	0.17	0.25	29	52
	4	0.25	0.26	0.30	0.35	13	26
EP_3	2	0.15	0.14	0.23	0.26	39	46
	4	0.34	0.32	0.39	0.43	18	26
EP_4	2	0.13	0.12	0.15	0.17	20	29
	4	0.28	0.29	0.33	0.39	12	26
EP_5	2	0.12	0.13	0.14	0.21	7	38
	4	0.31	0.29	0.33	0.37	12	22
EP_6	2	0.12	0.13	0.17	0.20	24	35
	4	0.29	0.26	0.31	0.35	16	26
EP_7	2	0.11	0.12	0.17	0.23	29	48
	4	0.25	0.24	0.29	0.32	17	25

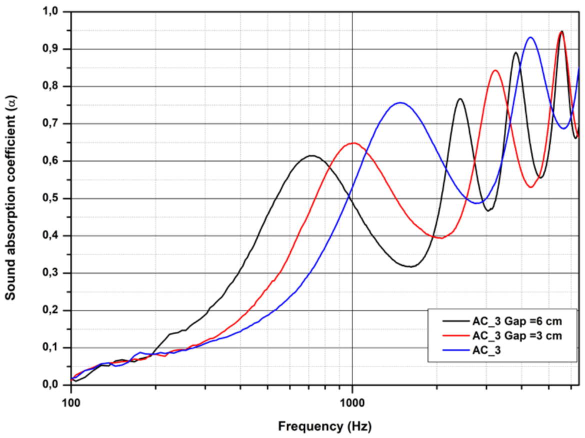

Figure 5. Effect of the air-gap on sound absorption spectra for sample AC_3.

difference is. This is more evident in samples having 2 cm in thickness where differences are up to 36 % and 52% for 3 cm and 6 cm of air-gap respectively, and more pronounced in samples having grains with lower size (samples EP_3 and AC_3).

4. CONCLUSIONS

This first research explores new avenues on using cork granulate, deriving from cork stopper processes, into acoustic panels. With the configurations used in this work, bio-based composites showed good acoustical performance, mainly at medium to high frequencies. In the case of low frequencies, the sound absorption coefficient is low. The samples reached good sound absorption average values with low thicknesses when introducing an air-gap behind the sample, leading to a considerable decrease in material quantity to be used, and therefore, in weight. Moreover, mechanical properties obtained showed acceptable values for the purpose as they were studied. Therefore, these types of bio-based panels could be used as an alternative product to the traditional materials (glass wool, foams or rock wool) used for suspended acoustic ceiling panels inside commercial spaces, such as closed entertainment areas.

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AUTHOR CONTRIBUTIONS:

Conceptualization: R. Maderuelo-Sanz, F.J. García-Cobos; Data curation: R. Maderuelo-Sanz, F.J. García-Cobos; F.J. Sánchez-Delgado; Formal analysis: R. Maderuelo-Sanz; Funding acquisition: R. Maderuelo-Sanz; Investigation: R. Maderuelo-Sanz, F.J. García-Cobos; F.J. Sánchez-Delgado; J.M. Meneses-Rodriguez; M.I. Mota-López; Methodology: R. Maderuelo-Sanz, F.J. García-Cobos; Project administration: R. Maderuelo-Sanz; Resources: R. Maderuelo-Sanz; Software: R. Maderuelo-Sanz; F.J. García-Cobos; Supervision: R. Maderuelo-Sanz; Validation: R. Maderuelo-Sanz, F.J. García-Cobos; F.J. Sánchez-Delgado; J.M. Meneses-Rodriguez; M.I. Mota-López; Visualization: R. Maderuelo-Sanz, F.J. García-Cobos; Writing, original draft: R. Maderuelo-Sanz; Writing, review & editing: R. Maderuelo-Sanz, F.J. García-Cobos.

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