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Virgin Natural Cork Characterization as a Sustainable Material for Use in Acoustic Solutions

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Abstract: A characterization of the sound absorption of a sustainable material with scarce current use such as natural virgin cork is presented in this paper in order to explore further possible applications in the design of acoustic solutions. Different samples of virgin cork not bonded and various decorative panel formats were tested under random sound incidence conditions in a standardized reverberation chamber. The samples in which the outer bark of the cork was facing upwards showed a better behavior as an acoustic absorber, with sound absorption coefficient values generally greater than 0.6 for frequency bands between 1 and 5 kHz. The results obtained were compared with samples of some recycled materials available in the scientific literature, such as sheep wool and PET.

Keywords: sound absorption; reverberation chamber; ISO 354; green circular economy; building material

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1. Introduction

Global warming and sustainable management of the planet's resources are two major challenges facing society today. Construction is one of the economic activities that most needs to transform production models, given the use of many non-renewable materials and the high carbon footprint of their production. Some acoustic properties of a biomaterial that usually ends up either discarded or reused, but after the addition of petroleum-based binders, are analyzed in this work. This is virgin cork, the bark of the cork oak tree is extracted for the first time.

The cork oak (*Quercus suber* L.) is a typical tree of the Mediterranean basin, cultivated due to the use of its bark for cork production. Cork oak forests are a model of agricultural exploitation, in which the tree must remain alive for the cork extraction (and, therefore, fixing carbon). Furthermore, a forest can be managed in what is known as a "Dehesa" system (ecosystem consisting of meadow or pasture artificially modified with scattered trees such as holm oaks and cork oaks), which concerns other sustainable activities such as extensive farming (with a lower carbon footprint than intensive), apiculture, mycoculture, etc. [1,2]. Cork can be an excellent product in a Mediterranean green circular economy as it is a renewable and recyclable natural material. It should be noted that its extraction does not cause any negative impact: (a) it does not require cutting down the tree and (b) it does not cause contamination, as it is done carefully by hand.

The cork oak is characterized by continuous growth of the subereous tissue that protects the inner areas of the trunk and branches. Moreover, this external layer can be extracted without the tree dying and the process can be repeated several times during the life of the tree. Cork exploitation has three stages: a first extraction of the bark, known as ordinary virgin cork; a second extraction, known as secondary reproduction cork, with a limited use; and the following extractions [3]. These last two stages are known as reproduction cork. The first two extractions (and especially that corresponding to virgin cork) are characterized by producing an irregular cork, both in structure and in thickness and density. It is also quite rough, as it develops deep fractures and cracks that extend irregularly, although generally with a longitudinal orientation. This fact is what gives cork oak trunks and branches their typical striated appearance [4,5]. In addition, virgin cork has a higher volumetric density than reproductive cork [6]. At the cellular level, the cell composition of virgin cork has a higher content of suberin and extractable compounds, such as waxes and fats [5].

The main industrial use of cork is the manufacture of stoppers for wine bottles, although recent studies have shown that the overall environmental impact of cork stoppers in wine bottles is higher than when using screwcaps [7]. Apart from the use for stoppers, other uses of cork are becoming more widespread lately, given its low density, as is the case of its use for the lightening of concrete [8] or lightweight aggregate for cement-based materials [9]. If cork is used as a stopper, a minimum thickness without excessive irregularities or fractures is necessary. This means that virgin cork is discarded for this use. However, since it shares other characteristics of cork from subsequent extractions, such as maintaining its properties over a wide temperature range [10] and not releasing toxic substances in case of fire [5], it can also be used as a thermal and acoustic insulator.

In this regard, the reduction in noise pollution in urban environments is another challenge facing today's society. The European Environment Agency (EEA) has recently published a report showing that 20% of the European population, i.e., some 113 million people, are exposed to noise levels that are harmful to their health [11]. Prolonged exposure to noise produces a variety of health effects ranging from physiological problems (varying degrees of hearing loss, disturbances during pregnancy, negative effects on the cardiovascular and metabolic system, etc.) to psychological (discomfort, altered mental health, cognitive impairment in children, sleep disturbances, etc.) [12]. The development of materials and solutions that contribute to the improvement of sound insulation of buildings with respect to both environmental noise and community noise between dwellings is an aspect that can positively influence the well-being of citizens [13,14]. There is a growing interest in the positive perception of the indoor acoustic environment of a dwelling by the building occupants and in the development of appropriate metrics to evaluate this environment [15,16]. To this must be added the growing concern in construction for the use of products that improve the acoustic sensation, but using components that either give a second life to waste materials [17–24], or are eco-friendly [25–29], as is the case of reproduction cork (obtained from the second and subsequent extractions), whose acoustic characteristics were studied in the loose granulated form [30] or compacted with the addition of resins [31].

Along the same lines, and combining both concerns, the use of waste materials and eco-friendly materials, virgin cork can be found. So far, the acoustic absorption coefficient of virgin cork remains uncharacterized, but given the macroscopic and microscopic differences that exist, it is necessary to evaluate this parameter in order to exploit this material in its natural state, as a decorative element with acoustic absorption capacity. As already mentioned, it is a material that currently has little use and therefore little economic value [6]. However, it also has a low carbon footprint, as boiling is the only process to which it is subjected in order to give it a flat shape. In this work, we present a study of its acoustic absorption without crushing it to make agglomerates and, therefore, without adding any type of resins or other binding elements. Experimental tests were carried out in a reverberation chamber to determine its acoustic absorption capacity in actual environments with random sound incidence. In addition, a study is made of the acoustic behavior of a presentation proposal for possible application in indoor environments and, if applicable, its commercialization.

2. Methodology

2.1. Cork Sample Collection and Treatment

As said before, cork oak forests play a very important role in preventing soil erosion and subsequent desertification, also acting as key elements in the preservation of biodiversity in the Mediterranean basin, helping to fix population in rural areas given the need for labor due to the scarce mechanization involved in the cork extraction process.

The age at which a cork oak can enter production depends on its radial growth. It can range from 20–25 years in normal conditions, although it can reach 30–40 years in less favorable environments. The time between two consecutive extractions also depends on the area. Thus, in Portugal and southern Spain, a thickness of about 3–3.5 cm is reached in nine years, while in northern Spain or southern France it takes more than 15 years.

The cork extraction, or cork stripping, is done manually, with two cork strippers per tree who have good technical knowledge to avoid injuring the tree. A special stripping axe with a curved cutting blade and a relatively long wooden arm is used. Some attempts have been made to mechanize the process, but they have been unfeasible for practical or economic reasons.

The cork planks are usually stacked in the field before being transported to the mill yard, although recently there has been a tendency to transport it immediately after extraction to the mill, avoiding storage in the field. Nowadays, this storage process takes about six months, although it may take longer.

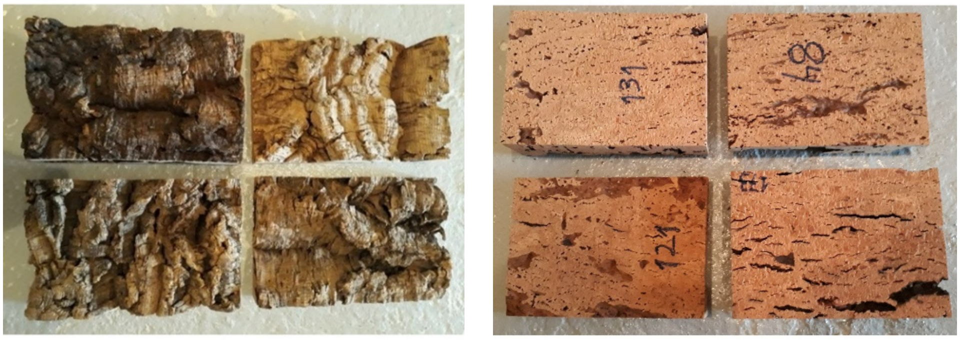
Afterward, the cork planks are treated with non-chlorinated water in a closed stainless-steel autoclave at 95 °C for 1 h. At the end of the process, these waters constitute a waste problem. Several studies have been devoted to its treatment in recent years with promising results [32–35].

The main objective of boiling is to change the mechanical properties of the cork planks to flatten them and facilitate subsequent cutting processes. After boiling, the planks are left to air dry for about 2–3 days, in what is called a stabilization step. Finally, it is passed through a cutter with a pair of rollers that leaves it completely flat on the inner side of the bark.

A more detailed description of the whole process can be found in Pereira [4].

2.2. Testing Methodology

Two alternative methods are commonly used to characterize the sound absorption of a material, the impedance tube [36] and the reverberation chamber [37]. While in the first case the incidence of sound waves is normal to the sample, it is random in the second one. The measured absorption properties in the second method are more representative of the performance of a material under real conditions in room acoustics and environmental applications [29,38]. In particular for natural virgin cork, since it presents many discontinuities of widely varying sizes when the outer bark faces upwards (Figure 1), the acoustic characterization of this material in the impedance tube using small samples could lead to misleading results. Experimental tests of different samples of natural virgin cork were carried out in this study to obtain their sound absorption coefficient (α_s) together with the practical (α_p) and weighted (α_w) sound absorption coefficients with random sound incidence following the specifications of ISO 354:2003 [37] and ISO 11654:1997 [39]. The results were compared with those obtained by alternative methods and the ASTM C423-17 standard [40].



(**a**) (**b**)

Figure 1. Different pieces of natural virgin cork where outer bark faces: (**a**) upwards; (**b**) downwards.

This study was performed in the normalized reverberation chamber located at the School of Technology of the University of Extremadura in Cáceres (Spain) [41], which was acoustically conditioned and satisfactorily complies with the requirements established in the ISO 354:2003 [37], ISO 3741:2010 [42], and ISO 3740:2019 [43]. The tests were carried out in accordance with ISO 354:2003 [37] using a Brüel and Kjær 2260 type 1 sound level meter with building acoustics software module, a Brüel and Kjær microphone type 4189, a Brüel and Kjær 4292 omnidirectional sound source, and a Lab Gruppen LAB 300 power amplifier.

The reverberation times (RT) were measured by the interrupted noise signal method using pink noise. The sound level meter was set to record data in one-third octave bands in a frequency range between 100 Hz and 5 kHz, and the average reverberation time of the 12 source-microphone combinations was obtained for each of the frequencies in the chosen range. Measurements of the reverberation time of the empty chamber were carried out on each test day. The temperature and relative humidity inside the chamber were within the ranges established by the ISO 354:2003 standard [37] during the tests (>15 °C and 30–90%).

2.3. Samples Analyzed

Different samples of natural virgin cork were configured for the tests, whose main characteristics are shown in Table 1. They were placed on the floor of the reverberation chamber in accordance with the type A mounting indicated in annex B of the ISO 354:2003 standard [37]. Samples S1 and S2 had an area of 10.2 m^2 and their edges were covered with an acoustically reflective frame. In the first case (S1), the outer bark of the cork faced upwards, while in the second case (S2), the outer bark faced downwards. Sample S3 is a decorative absorber panel proposed as a final product for possible commercialization. Its exposed side had a majority composition of sample type S1 with decorative cork elements from sample type S2. According to the ISO 354 standard [37], if the edges of the sample are commonly exposed in a real application, they should not be covered during the test. Thus, the area of the edges was considered in the total surface area of the sample, resulting in a value of 10.1 m^2. Samples S4, S5, S6, and S7 were other final product proposals for possible commercialization. They are other decorative combinations, similar to sample S3, but smaller to allow for modular installation. As in the previous case, their perimeter was not covered in the tests, and the area of the edges was considered in the total surface of the sample. Each of these four samples had a total surface area of 2.64 m^2 and were manufactured in such a way that the exposed side had a majority composition of sample S1 with different decorative patterns of cork elements from sample S2. Figure 2 shows the samples tested in the experimental tests (Figure 2a–d) and some details of the samples S4, S5, S6, and S7 (Figure 2e–h).

Table 1. Characteristics of the tested cork samples.

Sample	Area (m^2)	Average Thickness (cm)	Description
S1	10.2	6	Outer bark facing upwards
S2	10.2	6	Outer bark facing downwards
S3	10.1	4	Panel with outer bark facing upwards (S1) with cork decorative elements of S2
S4	2.64	4	Panel with outer bark facing upwards (S1) with diagonal decorative elements of S2
S5	2.64	4	Panel with outer bark facing upwards (S1) with square decorative elements of S2
S6	2.64	4	Panel with outer bark facing upwards (S1) with V-shaped decorative elements of S2
S7	2.64	4	Panel with outer bark facing upwards (S1) with horizontal line decorative elements of S2

Figure 2. Samples tested in the reverberation chamber: (**a**) S1; (**b**) S2; (**c**) S3; (**d**) S4, S5, S6, and S7; and some details of the samples: S4 (**e**); S5 (**f**); S6 (**g**); S7 (**h**).

2.4. Calculation Method

First, following the guidelines of ISO 354:2003 [37], the sound absorption coefficient (α_s) was obtained for each natural virgin cork sample using Equation (1), where A_T is the equivalent sound absorption area and S is the area of the test sample.

$$\alpha_s = A_T/S \tag{1}$$

Secondly, the weighted sound absorption coefficient (α_w) of each sample was obtained following the procedure established in ISO 11654 [39] from the sound absorption coefficients obtained in each frequency band. This standard indicates that the form factors must be given for those cases where the practical sound absorption coefficient (α_p) exceeds the value of the displaced reference curve by 0.25 or more. Thus, together with the value of α_w, the notation L, M, and H was respectively specified when the excess occurs at 250 Hz, 500 or 1000 Hz, and 2000 or 4000 Hz. From the value of α_w, the tested sample could be classified into six different classes according to its absorption capacity (Table 2).

Table 2. Classification of the samples according to the weighted sound absorption coefficient (α_w) following ISO 11654.

Sound Absorption Classes	α_w
A	0.90; 0.95; 1.00
B	0.80; 0.85
C	0.60; 0.65; 0.70; 0.75
D	0.30; 0.35; 0.40; 0.45; 0.50; 0.55
E	0.25; 0.20; 0.15
Unclassified	0.10; 0.05; 0.00

2.5. Sound Absorption Indexes According to the ASTM C423-17 Standard

In order to evaluate the sound absorption capability of the samples, single number grading methods which are independent of frequencies were used. These indexes are useful for a practical evaluation of the performance of sound porous absorbers. The ASTM C423-17 standard [40] defines the Noise Reduction Coefficient (NRC) and the Sound Absorption Average (SAA) for this purpose. NRC is defined as the average of the sound absorption coefficients for 250, 500, 1000, and 2000 Hz rounded off to the nearest multiple of 0.05. 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.

3. Results and Discussion

3.1. Samples of Standardized Size

Samples S1, S2, and S3 of natural virgin cork were tested in this section to obtain the different sound absorption coefficients. Figure 3 shows the sound absorption coefficient (α_s) in one-third octave bands (Figure 3a) and the practical sound absorption coefficient (α_p) in octave bands (Figure 3b) obtained for each of these samples, together with the expanded repeatability uncertainty for 95% confidence (U_r (95%)) calculated according to ISO 12999-2:2020 [44]. The results obtained for S1 show higher absorption than S2 at medium and high frequencies starting from the 800 Hz band, taking α_s values equal to or higher than 0.60 up to 5 kHz. However, the absorption at low and medium frequencies up to 500 Hz does not exceed the value of 0.25. In the case of sample S2, the results obtained show a behavior of the absorption coefficient with higher values in the 500 Hz one-third octave band, where α_s reaches a value of 0.65. Below the 400 Hz band, the coefficient takes values below 0.3, while, for frequencies above 630 Hz, the value ranges between 0.3 and 0.4. The differences found in the absorption curves of samples S1 and S2 would be due to the different surface structure of the top face of each sample (Figure 1a,b). Sample S1 presents a visible face with an irregular surface structure filled with cavities, compared to sample S2, which presents a much more uniform surface structure. These differences could explain the higher absorption in the 1 to 4 kHz octave bands of sample S1. However, the behavior observed in the 500 Hz octave band, where sample S2 shows a higher absorption than S1, would require future investigations, either in a test chamber or in an impedance tube, to find the reasons for these differences, that could be related to the existence of an air layer underneath and the appearance of resonant effects. On the other hand, sample S3, corresponding to a decorative absorbing panel with an area of 10.1 m^2 whose face exposed to view is composed mostly of exposed bark as in S1 with decorative cork elements as in sample S2, has a behavior closer to sample S1. However, it presents a higher absorption in the frequency bands between 200 and 500 Hz, reaching a maximum difference of 0.17 at 400 Hz with respect to S1, while the absorption curve is a little smoother in the frequency bands from 800 and 5000 Hz. Similarly, Figure 3b shows the results obtained for α_p in octave bands between 250 and 4000 Hz according to ISO 11654 [39]. In general terms, the absorption curves for α_p present a similar shape to those obtained in Figure 3a for α_s. Regarding the expanded uncertainty of α_s and α_p, there are practically no differences between samples S1, S2, and S3. They all present the maximum uncertainty value in the 5 kHz band, with a maximum value ranging between 0.08 and 0.09 depending on the sample.

Another comparison between samples S1, S2, and S3 can be made by considering global indicators of sound absorption (Table 3). First of all, if the indicators proposed by ISO 11654 [39] are considered, it is observed that the three samples show some differences with respect to the weighted sound absorption coefficient (α_w). Although S1 and S2 show the same value of 0.35, the MH form factors in the case of S1 indicate a better performance in terms of sound absorption at medium (500 Hz and 1 kHz) and high frequencies (2 and 4 kHz). In the case of S3, the sample presents an α_w value of 0.4, which is slightly higher than the previous ones, and the H form factor, which means that the α_p values at high frequencies are considerably higher than those of the shifted reference curve. Despite these differences, all three samples have the same expanded repeatability uncertainty for 95% confidence and a type D sound absorption classification. On the other hand, if the NRC and SAA indicators proposed by ASTM C423-17 [40] are considered, it is observed that samples S1 and S3 present a higher sound absorption than S2, with sample S3 being the one that obtains better values for NRC.

Table 3. Sound absorption indicators for samples S1, S2, and S3.

Sample	α_w	U_r (95%)	Sound Absorption Class	NRC	SAA
S1	0.35 (MH)	0.04	D	0.40	0.42
S2	0.35	0.04	D	0.35	0.35
S3	0.40 (H)	0.04	D	0.45	0.42

3.2. Decorative Absorber Panels

As previously indicated in the Section 2, samples S4, S5, S6, and S7 are samples of decorative absorbent panels manufactured as final product proposals for possible commercialization, but with a smaller size than sample S3 in order to allow for a modular installation. In all of them, the exposed face is mostly composed of exposed bark as in sample S1 and the only variation between samples is the decorative pattern of the normal cork elements as in sample S2. Figure 4 presents the sound absorption coefficient (α_s) in one-third octave bands (Figure 4a) and the practical sound absorption coefficient (α_p) in octave bands (Figure 4b) obtained for each of these samples, along with the expanded repeatability uncertainty for 95% confidence (U_r (95%)). It can be observed how, starting from the 250 Hz band, the absorption of these samples increases progressively with frequency up to 800 Hz and similarly, although S6 and S7 present slightly better absorbing behavior than S4 and S5 in this frequency range. Starting at 1 kHz, samples S4, S5, and S7 follow a similar trend with α_s values generally ranging between 0.6 and 0.75. However, sample S6 presents slightly lower values in this frequency range, with values between approximately 0.5 and 0.6. In the case of α_p in octave bands, the trend of the absorption curve is similar to that of α_s. The expanded uncertainty of α_s and α_p shows no differences among the four samples studied, presenting a maximum of approximately 0.1 in the 5 kHz band.

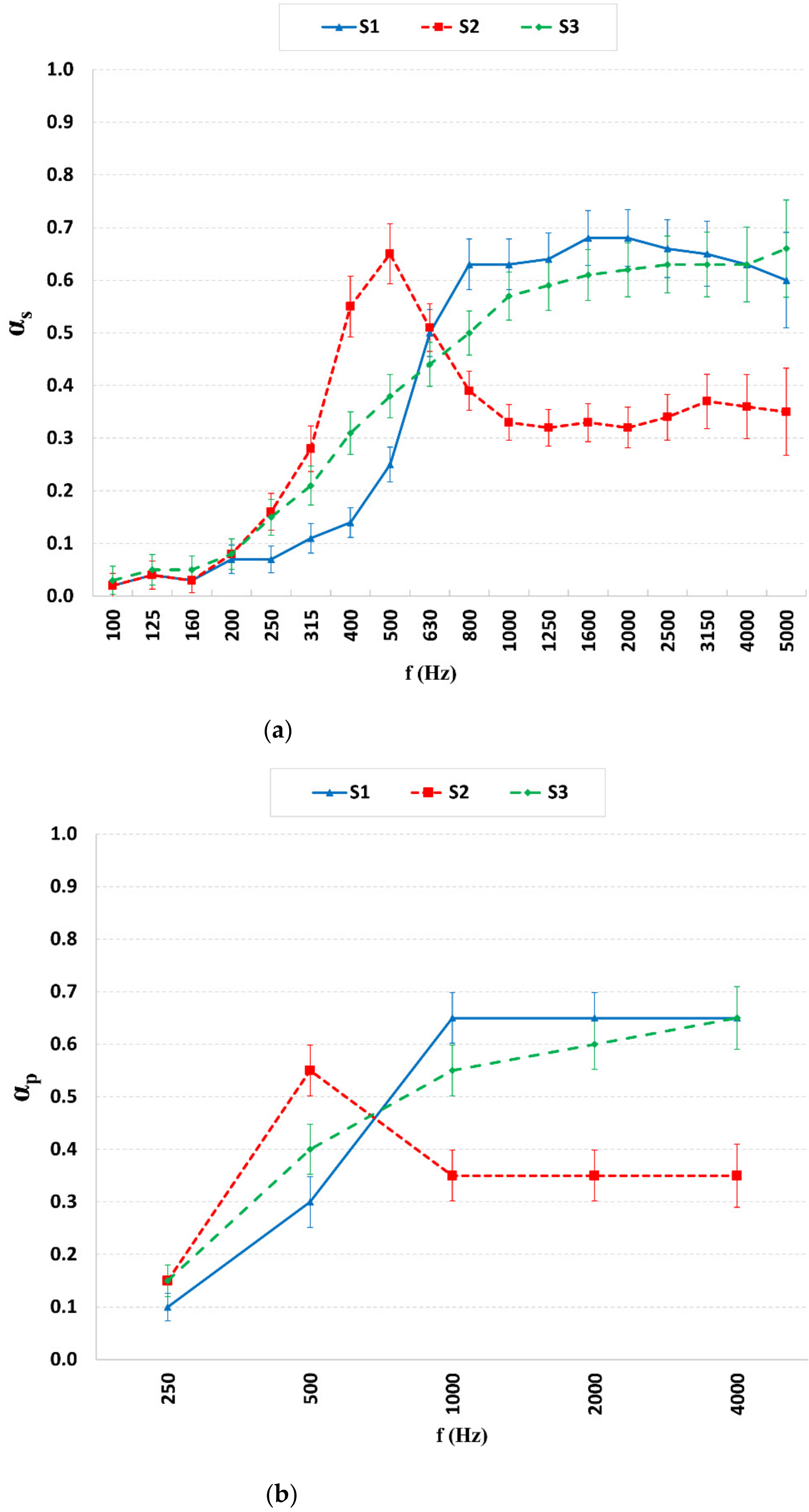
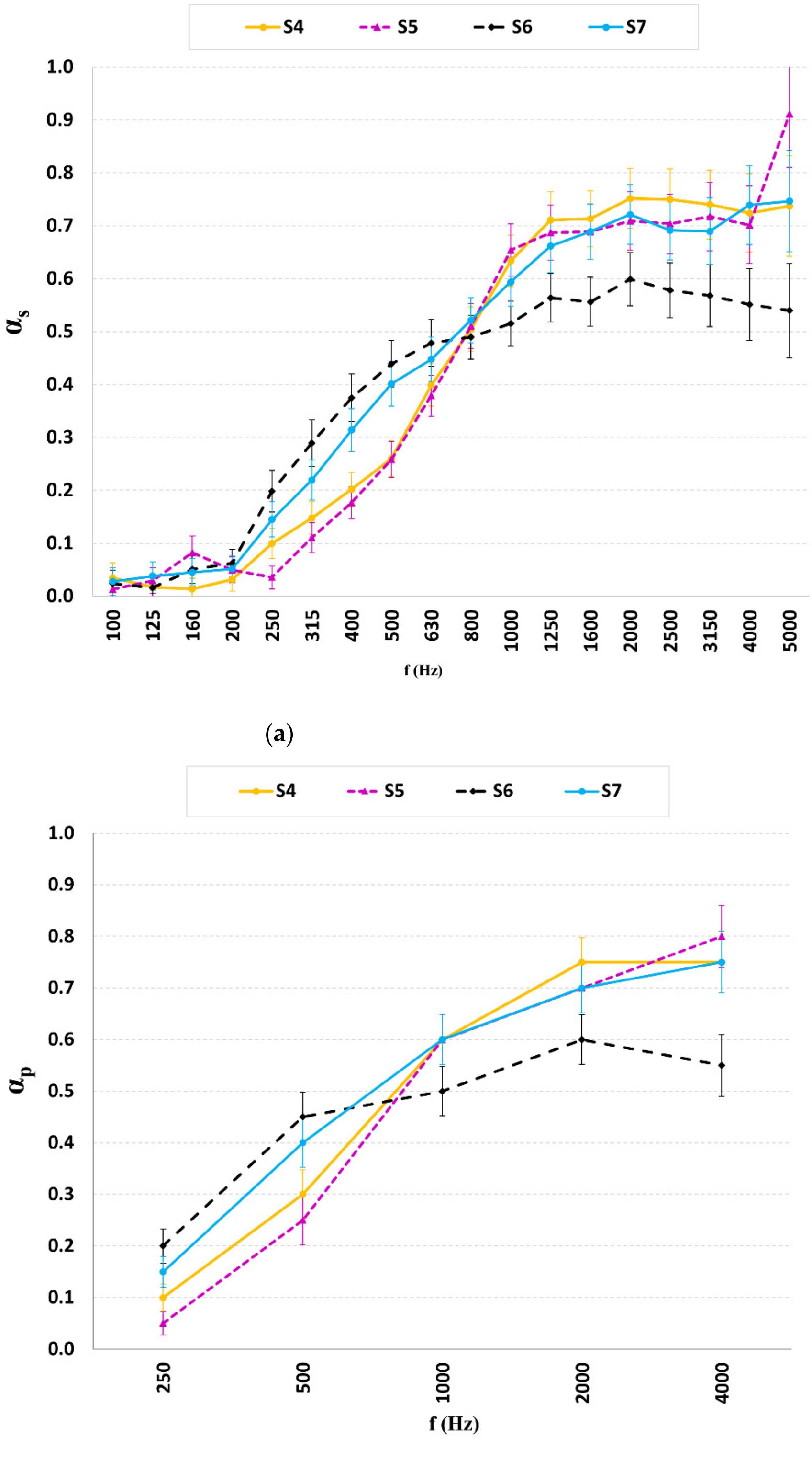


Figure 3. Sound absorption coefficients for samples S1, S2, and S3: (**a**) α_s; (**b**) α_p.



(**b**)

Figure 4. Sound absorption coefficients for samples S4, S5, S6, and S7: (**a**) α_s; (**b**) $\alpha_{p.}$

If a comparison is made between samples S4, S5, S6, and S7 from ISO 11654 [39] global sound absorption indicators (Table 4), the weighted sound absorption coefficient (α_w) of the different samples ranges from 0.3 to 0.45. Sample S6 shows the highest value, however, the form factors of the other three samples indicate that the α_p values are considerably higher than those of the shifted reference curve at medium (M) and/or high (H) frequencies, as appropriate. The differences in α_w and in the form factors of each sample do not result in a different sound absorption classification or in a variation of the expanded repeatability uncertainty. On the other hand, if a comparison is made from the NRC and SAA indicators of ASTM C423-17 [40], a more similar absorbent behavior of all samples is found. In this case, sample S7 presents a slightly higher SAA value.

Table 4. Sound absorption indicators for samples S4, S5, S6, and S7.

Sample	α_w	U_r (95%)	Sound Absorption Class	NRC	SAA
S4	0.35 (MH)	0.04	D	0.45	0.43
S5	0.30 (MH)	0.04	D	0.40	0.41
S6	0.45	0.04	D	0.45	0.43
S7	0.40 (H)	0.04	D	0.45	0.45

3.3. Comparison with Other Recycled Materials

Given the described growing need for the use of sustainable materials, it was considered of interest to make a comparison of these samples of natural virgin cork with some recycled materials tested in a standardized reverberation chamber and with similar sample sizes. Figure 5a shows the results obtained for the sound absorption coefficient (α_s) and Figure 5b shows the practical sound absorption coefficient (α_p), together with the expanded repeatability uncertainty for 95% confidence (U_r (95%)), for samples of materials such as sheep wool mixed with PET as a binder [29] and PET (40 mm thick and 1400 g/m^2) from recycled bottles [24], in addition to samples S1, S2, and S3 of natural virgin cork. We have not found any other published works in the scientific literature on natural or recycled materials studied in standardized reverberation chambers. The values of α_s (Figure 5a) and α_p (Figure 5b) show that both the sheep wool and PET samples present a better absorbing behavior than samples S1, S2, and S3 of natural virgin cork in the whole frequency range. Sheep wool also has higher absorption coefficients than PET for medium and high frequencies. It is in the high-frequency range where natural virgin cork samples S1 and S3 approach the absorption curve of PET, while sample S2 reaches values similar to those of sheep wool and PET in the 400 and 500 Hz bands. If the global sound absorption indicators of Table 5 such as α_w, NRC, and SAA are also considered in the analysis, it is observed that the sound absorption capacity of the natural virgin cork samples is lower than those of sheep wool and PET.

Table 5. Sound absorption indicators for some samples.

Sample	α_w	U_r (95%)	Sound Absorption Class	NRC	SAA
Sheep Wool	0.75	0.04	C	0.70	0.70
PET	0.70 (H)	0.04	C	0.60	0.62
Virgin cork (S1)	0.35 (MH)	0.04	D	0.40	0.42
Virgin cork (S2)	0.35	0.04	D	0.35	0.35
Virgin cork (S3)	0.40 (H)	0.04	D	0.45	0.42

Two options can be considered taking into account the actual possible applications of these materials as acoustic absorbers. On the one hand, materials with absorbing properties are usually used inside double walls in order to reduce the effect of coupling by standing waves in the cavity and, therefore, increase acoustic insulation, or within perforated panels in acoustic screens. In this type of application, considering the values of the absorption coefficients of the different materials and the final objective pursued, in general, the use of sheep wool or PET can be more interesting than the use of virgin cork. Although, in a more complete analysis, other criteria related to the on-site installation process, production costs, sustainability, etc. should also be included. In this sense, it should be noted that the virgin cork studied is a fully ecological material, not recycled, with no added agglomerating products and with little water treatment, which has been considered a waste material until now but can have a quite interesting acoustic use.

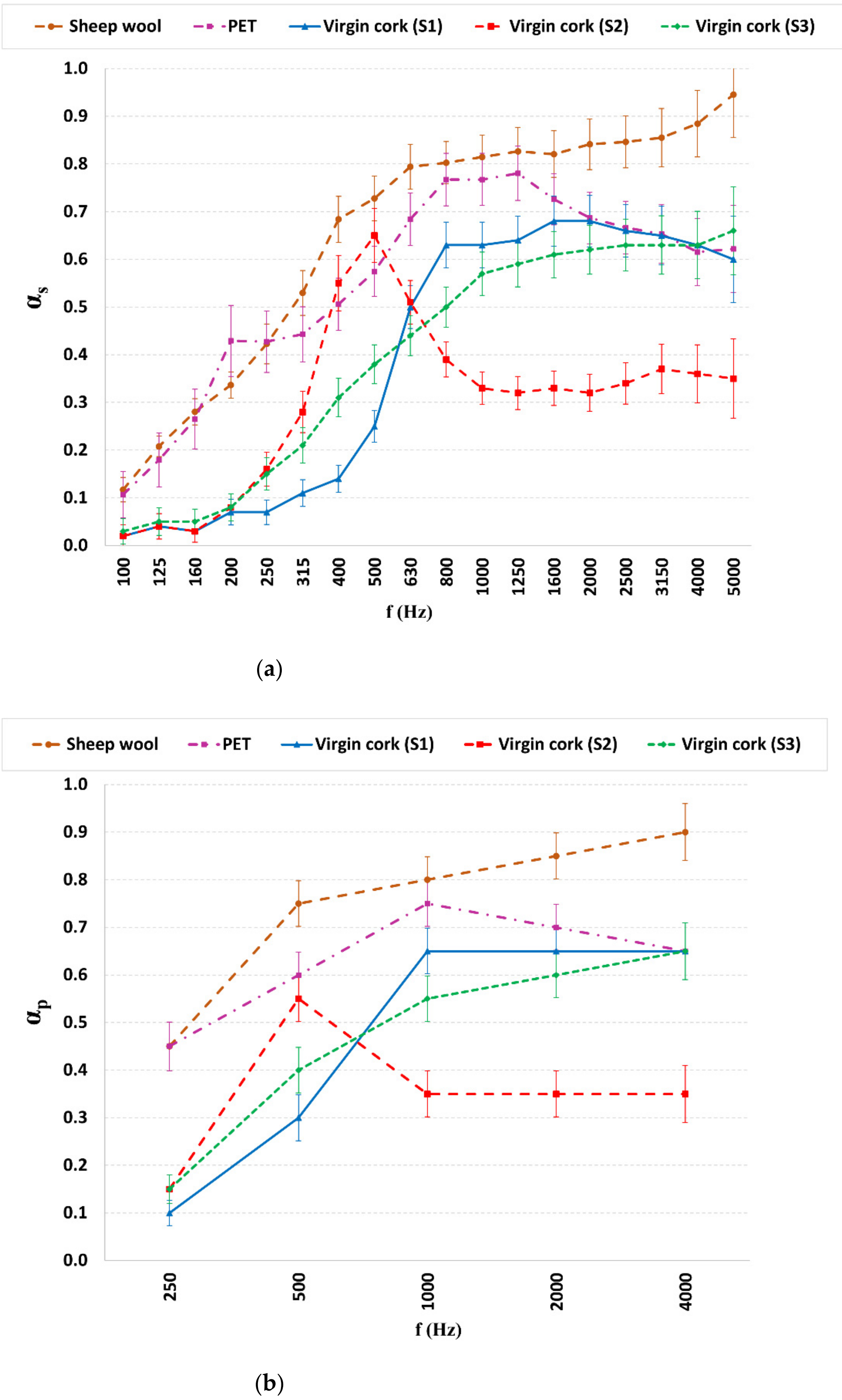


Figure 5. Sound absorption coefficients for some samples: (**a**) α_s; (**b**) α_p.

These materials are also used as acoustic absorbers in the vertical and horizontal walls of interior spaces to reduce the reverberation time and improve the sensation of acoustic comfort. Theatres, auditoriums, concert halls, conference halls, etc. are types of enclosures that require specific room conditioning according to their use. Some international standards recommend values for reverberation time in certain types of enclosures [45]. The use of absorbers in these spaces, therefore, requires a format with decorative characteristics in accordance with those of the enclosure. In this case, the natural virgin cork samples S3, S4, S5, S6, and S7 could have a greater interest of use, since they represent final proposals of absorbent decorative panels for their possible commercialization. In addition, their production process is simple and energetically sustainable since they do not require any added treatment and directly present their own aesthetics.

4. Conclusions

This article presents a study to characterize the sound absorption of a sustainable and currently little-used material, natural virgin cork, in order to explore other possible uses of this material with a low carbon footprint and reduced cost in the design of acoustic solutions for insulation, conditioning, and noise control.

Different samples of virgin cork not bonded were tested under random sound incidence conditions in a standardized reverberation chamber according to ISO 354. The samples in which the outer bark of the cork was facing upwards showed better behavior as an acoustic absorber, with values of the absorption coefficients α_s and α_p equal to or greater than 0.6 for frequency bands between 1 and 5 kHz.

Several proposals for decorative absorbent panels were also studied as final products for modular installation in those enclosures where room conditioning is desired to reduce reverberation time. Similar results were obtained for the four-panel formats studied for the absorption coefficients α_s and α_p, although with slight variations between them in the medium and high-frequency ranges.

A comparison of its behavior as an acoustic absorber was carried out with respect to other recycled materials tested in a standardized reverberation chamber, such as sheep wool mixed with PET as a binder and PET from recycled bottles. Different indicators show that the sheep wool and PET samples present a better absorbing behavior than the natural virgin cork samples in the whole frequency range. However, it should be noted that not all samples can be considered as final products for installation as an *in-situ* sound absorber, as in some cases the customization process could lead to some modifications in the absorbing behavior. In this sense, the choice of one material or another for the different types of acoustic solutions for insulation, conditioning, and noise control may depend not only on purely acoustic criteria, but also on other criteria associated with on-site installation, production costs, sustainability, aesthetics, etc.

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