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Thermal and Acoustic Characterization of Innovative and Unconventional Panels Made of Reused Materials

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Abstract: Europe calls for a transition to the circular economy model based on recycling, reuse, the proper design of products, and repair. Recycling requires energy and chemical products for waste processing; on the contrary, reusing reduces the impact of transportation and expands the life of materials that cannot be recycled. This article highlights the characteristics of selected end-of-life materials; it aims to raise awareness among manufacturers to consider products' conscious design to facilitate their reuse in different sectors. Panels 7 cm thick, realized by assembling cardboard packaging, egg boxes, bulk polyester, and felt, have been experimentally tested to understand whether they can be installed indoors to improve thermal and acoustic comfort. The panels' equivalent thermal conductivity λ_{eq} measured through the guarded hot plate method is 0.071 W/m K. Acoustic tests have been performed in a sound transmission room and a reverberation room. The weighted sound reduction index R_w is 19 dB, the weighted sound absorption coefficient α_w is 0.30, and the noise reduction coefficient NRC is 0.64. The measured properties have been compared to those of commercial materials, and the results show that the panels have interesting properties from the thermal and acoustic points of view. They could be employed in the building sector and in disadvantaged contexts where low-income people cannot afford commercial insulating materials. Although other factors, such as fire resistance, need to be evaluated, these results show that the proposed approach is feasible.

Keywords: circular economy; thermal test; acoustic test; indoor comfort; reusing; insulating material

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1. Introduction

Europe calls for a transition from the linear to the circular economic model [1]. The linear economic model adopted for many years consists in extracting raw materials and converting them into products that are used and then disposed [2]. In an economy characterized by raw material scarcity and prohibitive energy prices, this model is no longer sustainable, and a transition to the circular economic model is needed. The circular economy model—in which a product's life is lengthened as much as possible—is based on recycling, reuse, proper product design, and repair; it aims at more durable products, money-saving, and improvement in people's quality of life. The European Commission has presented an action plan that aims at more sustainable products, waste reduction, and the empowerment of citizens through the *right to repair*. According to the European directive [1], waste ceases to be waste when it has undergone a recovery operation (including recycling) and meets specific criteria: the product must be required by the market, meet technical requirements, comply with existing legislation and standards, and must not have negative impacts, neither on the environment nor on human health [3,4]. If recycling requires energy and chemical products for waste processing, reusing reduces the amount of waste generated, the impact due to transportation (from the point of collection to the point of recycling and to the point of reuse), and expands the life of materials that cannot be recycled.

The current global situation—political uncertainties, climate changes, and rising energy prices—calls for a new approach, especially in resource-intensive sectors such as construction. When dealing with building refurbishment, energy-saving and indoor comfort are two increasingly important matters. Two main aspects, thermal and acoustic comfort, are generally developed independently, with few exceptions [5,6]. Thermal comfort is governed, among other variables, by the indoor air temperature, mean radiant temperature, and humidity. Indoor acoustic comfort can be enhanced by mitigating room reverberation time and limiting the sound transmission between confining environments.

To date, production and disposal of the insulating materials available on the market have an environmental impact, and their costs limit their application, especially in disadvantaged contexts where low-income people live: here, dwellings are generally small, overcrowded, unhealthy, and characterized by low indoor temperatures in winter and high indoor temperatures in summer. For improving the living conditions in these contexts—in which acoustic comfort is also a sore point—easily accessible and low-cost technologies should be proposed. Since end-of-life materials, such as packaging and clothes, still possess properties when discarded and turned into waste, they could be reused to realize low-cost building elements. However, to meet regulations and compare different solutions, comprehensive material characterization is required when considering the construction sector. One of the most striking cases of designing packaging also considering its reuse is the one proposed by Heineken [7], which realized square glass bottles that were used to build houses in the Caribbean islands. Also the scientific community has realized the potential of end-of-life materials [8], and several studies have investigated the properties of plastic bottles [9,10], cardboard and paper elements [11–16], Tetra-Pak panels [17], textiles waste [18–22], and egg boxes and trays [23–28]. More recently, so-called *green* and *sustainable* materials made of natural fibers have been investigated [29–36].

Even if most of the studies in the literature investigate the properties of recycled materials [37,38], reuse needs to be re-evaluated and encouraged by highlighting end-of-life materials' properties. If products' chemical composition and geometry are defined in the recycling process to meet different needs, this is impossible when dealing with reuse. A conscious packaging design should consider a product's second life to make it immediately suitable for reuse and prevent it from leaving the economic cycle. Therefore, packaging must meet the requirements of the sector for which it is made but also of the sector in which it will be reused. Packaging manufacturers could diversify their products and develop two product ranges: standard packaging, and packaging to be reused to make other items (such as building elements). For example, a box could be made of fireproof material to make it suitable also for applications where fire resistance is a must. These particular products will have higher prices, but consumers know that once used, they can return (or donate) them, and they are converted into new elements. This approach would also reduce the amount of raw material necessary to realize new products and, consequently, the dependence on commodity countries, which have recently become contentious issues in Europe. In light of this, starting the characterization of materials (such as textiles and packaging) available on the market is essential to highlight potential and critical issues, and to raise awareness of end-of-life materials' potential.

This article focuses on product reuse and aims at identifying an alternative to the disposal of end-of-life materials; it presents experimental results on materials that in the literature are analyzed only sporadically, and it proposes their reuse outside the sector for which are designed. The methodology followed is that used to certify commercial building products. Since this type of testing, especially acoustic testing, requires large samples and sophisticated instrumentation that only the best-equipped laboratories have, only a few studies in the literature analyze this type of material as extensively as proposed here. Selected end-of-life materials—cardboard elements, egg boxes, and textiles—have been assembled to realize building elements with thermal and acoustic properties, and they are intended for indoor applications (on walls and or ceilings). The panels have been tested in certified laboratories according to current standards: the equivalent thermal conductivity λ_{eq} has been determined through the guarded hot plate method, while the sound transmission loss TL and the sound absorption coefficient α have been measured in the sound transmission room and the reverberation room, respectively.

In the article, aspects to be considered when dealing with building indoor comfort and energy saving are described in Section 2, along with the description of the experimental tests. The results of the experimental campaign are then presented and discussed in Section 3. Finally, the conclusions are drawn.

2. Methods and Results

This study investigates the thermal and acoustic properties of panels realized by assembling selected end-of-life materials, such as cardboard boxes, egg boxes, bulk polyester, and felt. The cardboard elements are 4 mm thick and consist of two external liners and a fluted core. The egg boxes are made of a 2 mm paper layer, and their total thickness is 6 cm. Commercial bulk polyester and felt pads cut into small pieces have been used for filling the panels, if provided. As described in detail in the following, the panel configurations range from a simple one, consisting of a simple cardboard panel in which air circulates, to a configuration made of several elements. The thermal tests for the determination of the equivalent thermal conductivity have been performed at the EcamRicert laboratory in Vicenza (Italy), while the acoustic tests for the determination of the sound transmission loss TL and the sound absorption coefficient α have been performed at the CNR (Research National Center) in Milan (Italy). Since these experiments are time-consuming and expensive, only one test has been performed for each configuration: even though it is not possible to appreciate their variability, the results give important information on the potential of end-of-life materials.

2.1. Thermal Characterization

Building energy efficiency and indoor thermal comfort can be achieved, among other solutions, through the correct design of the building envelope. In wintertime, highly insulating building envelopes guarantee low heat flux towards the external environment and a consequent reduction in energy demand. In summertime, when the boundary conditions are non-stationary because of the considerable temperature fluctuations between day- and nighttime, the heat capacity and the position of the layers in the envelope are also influential. In this study, the focus of the thermal analysis is on equivalent thermal conductivity.

Measurement of the Equivalent Thermal Conductivity

The panels' equivalent thermal conductivity λ_{eq} has been determined through the guarded hot plate method described in the UNI EN 12667 [39] standard; it is usually employed to test homogeneous specimens with flat parallel surfaces, and thermal resistance equal to or higher than 0.5 m^2K/W.

According to Figure 1 and Table 1, 50 × 50 × 7 cm panels have been realized. Panel *T1-EB* consists of a 7 cm thick cardboard case in which air can circulate; a cardboard omega reinforcement positioned in its center prevents the crush of the panel. Panel *T2-BEB* consists of a cardboard case containing empty egg boxes. Panels *T3-BP*, *T4-BF7*, and *T5-BF20* are made of a cardboard case and egg boxes filled with different materials in different quantities: 7 g of polyester has been used to fill each egg box in *T3-BP*, 7 g of felt in *T4-BF7*, and 20 g of felt in *T5-BF20*. The egg boxes were completely stuff by 7 g of felt, but to obtain the same degree of filling, 20 g of felt was necessary. In panel *T6-BFF*, the egg boxes have been surrounded by polyester (140 g in the egg boxes, 26.2 g between the egg boxes, 130 g externally to the egg boxes, and 67.5 g in the external egg box holes).

Table 1. Details of the panels realized for the thermal tests.

Panel Name	Description	Dimensions [mm]	Textile Weight [kg]	Panel Density [kg]	Panel Weight [kg]
T1-EB	Empty cardb. box	508 × 479 × 70	-	16.2	0.44
T2-BEB	Cardb. box and empty egg boxes	506 × 485 × 75	-	48.4	0.89
T3-BP	Cardb. box, egg boxes, polyester (7 g)	505 × 505 × 82	0.16	54.5	1.14
T4-BF7	Card. box, egg boxes, felt (7 g)	505 × 505 × 78	0.16	54.5	1.14
T5-BF20	Cardb. box, egg boxes, felt (20 g)	505 × 505 × 81	0.5	65.4	1.35
T6-BFF	Cardb. box, egg boxes, polyester (full)	500 × 500 × 80	0.37	60	1.2

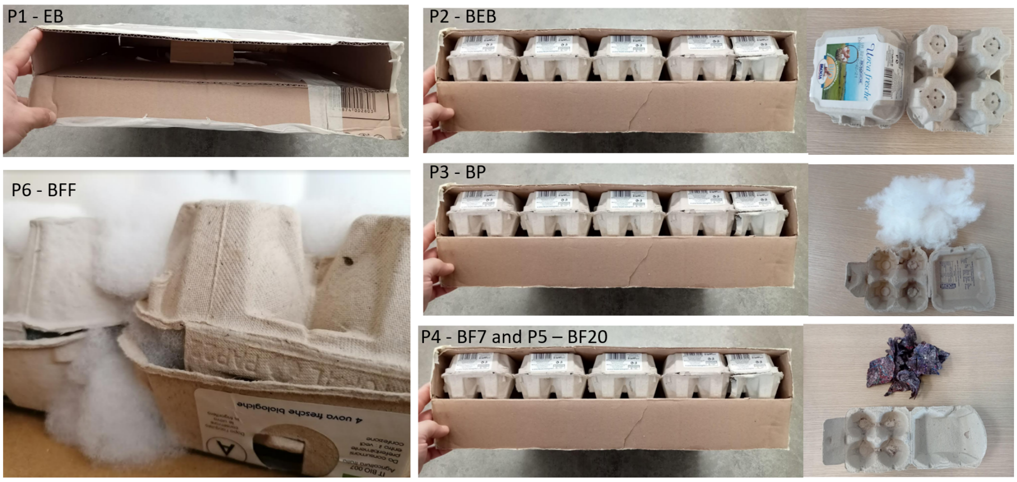

Figure 1. Panels realized for the thermal tests. All the panels are made of egg boxes, except for *T1-EB*. In panel *T6-BFF*, the egg boxes have been filled and surrounded by polyester.

Figure 2 shows the realization steps. Firstly, the egg boxes have been glued neatly onto a cardboard panel by applying hot glue on the egg box flat surface (Figure 2a,b) and, when necessary, the egg boxes on the edges and corners have been cut. Then, five holes have been drilled in each egg box cup (Figure 2c), and the egg boxes have been filled with the chosen material (Figure 2d). Finally, the external case has been completed by applying cardboard elements on the panel sides (Figure 2e). A slightly different procedure has been followed for the realization of panel *T6-BFF* for which the textile material has been inserted before gluing the egg boxes.

The test apparatus shown in Figure 3 is the Lambda Meter EP500 manufactured by Lambda Messtechnik GmbH Dresden conforming to EN 1946-2:1999 [40] standard. The instrument has a horizontal orientation with the hot element in the upper part. The panel to be tested has been placed between a heating and a cooling element. Power has been supplied through the heating element, and once the steady condition has been achieved, the heat flow rate q and the difference in temperature ΔT on the sample surfaces have been measured. The sample equivalent thermal conductivity λ_{eq} has been determined as [40,41]:

$$\lambda_{eq} = \frac{q \cdot s}{A \cdot \Delta T} \quad (1)$$

where s is the average panel thickness, and A is the area of the sample. The tests have been carried out in a controlled room at 23 ± 2 °C and 50 ± 5% in relative humidity. Results are shown in Figure 4.

Figure 2. The realization of the panels: egg boxes have been glued onto a cardboard panel (**a**,**b**); holes have been drilled in each egg box dome (**c**); the egg boxes have been filled with textile waste (in this picture, the filling is made of felt) (**d**); the external case has been completed (**e**).

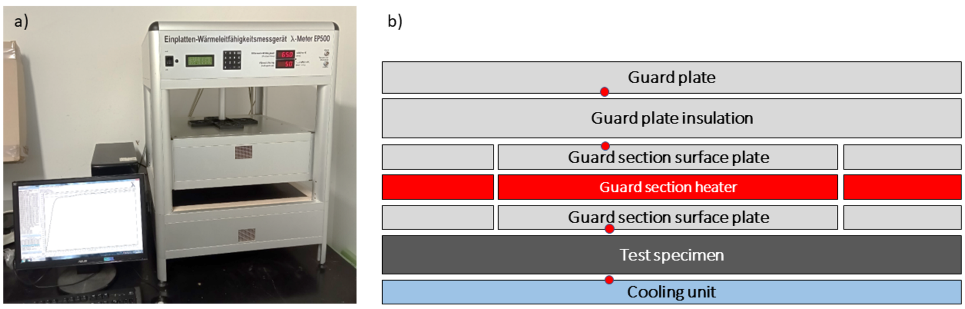

Figure 3. The test apparatus for the determination of the panel equivalent thermal conductivity (**a**) and its internal components (**b**). In the test apparatus, the section heater is in the upper part.

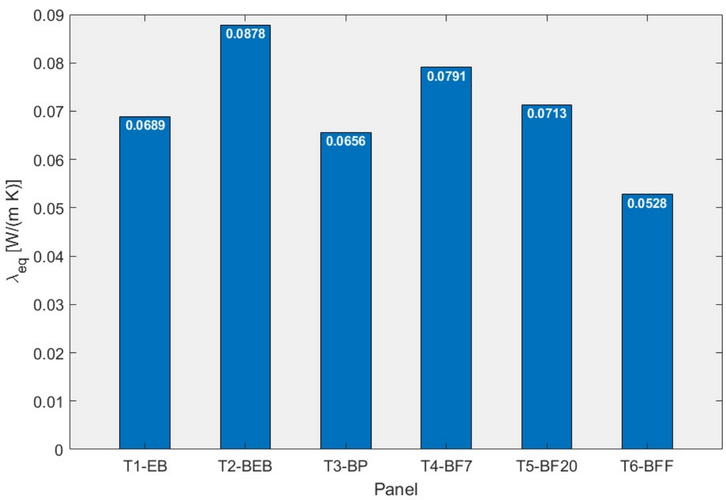

Figure 4. Panels equivalent thermal conductivity measured with the guarded hot plate method.

2.2. Acoustic Characterization

In building acoustics, the sound transmission loss TL and the sound absorption coefficient α are two important characteristics. The TL is related to the ability of a partition or material to limit the sound energy transmission between confining environments, while α represents the ability to absorb sound energy. The significance of these two quantities can be understood by considering the sound energy balance on a partition impinged by a sound wave that leads to $1 = \rho + \tau + \delta$ [42], where ρ is the sound reflection coefficient, τ is the sound transmission coefficient, and δ is the sound absorption coefficient of the partition.

The sound transmission loss TL is usually determined experimentally and is defined as [42]:

$$TL = 10 \cdot log_{10}\left(\frac{1}{\tau}\right) = 10 \cdot log_{10}\left(\frac{W_T}{W_I}\right) \quad (2)$$

where W_I is the sound energy impinging on the partition, and W_T is the sound energy transmitted. Higher TL values are representative of better sound insulation properties which depend on the structural element type: in thin single panels, thick single panels, and coupled panels, when crossed by a sound wave, different mechanisms take place.

For a thin wall, the trend of the sound transmission loss TL as a function of frequency can be divided into 3 zones. In the first zone, the decreasing TL is a function of stiffness. In the second zone—separated by the first one by the resonance frequency f_r—the doubling of the panel surface density or frequency corresponds with an increase of 6 dB per octave. It follows the critical coincidence frequency f_c at which the wavelength of the incident sound wave and the bending wavelength coincide. Above f_c, TL increases again.

Double panels, which consist of two panels separated by an air gap, are a suitable alternative to increase TL without increasing the structure density. The air gap acts as a spring characterized by its own resonant frequency that depends on the panel surface density and the air gap thickness. Below f_r the gap remains inactive and TL is governed by the panels' surface density that act as rigidly connected. At f_r the sound transmission is amplified by the first panel. Above f_r the second panel acts as a damper and TL increases by 12–18 dB per octave. When the two panels have different critical frequencies, TL reaches higher values than in the single-panel structure.

The sound absorption coefficient $\alpha = \tau + \delta$ [42] represents the ability of a partition (or material) to absorb sound energy. Sound-absorbing materials reduce the total sound pressure level L_p in a confined environment and the reverberation time T_R. Reducing the reverberation time —that is defined as the time required by the sound energy density level to decrease by 60 dB—means reducing the echo effect and, consequently, improving the intelligibility of speech. To enhance the sound absorption of a partition, different mechanisms, such as porous materials, vibrating panels, and acoustic resonators, can be coupled. Sound dissipation in porous materials is due to the contact between air and the material's fibers. The amount of dissipated sound is a function of the fiber type and size, material thickness, density, porosity, tortuosity, and airflow resistance.

Vibrating panels consist of a thin panel spaced from a rigid wall, and the resonance frequency is calculated as:

$$f_0 = \frac{60}{(m \cdot d)^{0.5}} \quad (3)$$

which is a function of the mass per unit area of the panel m, and the distance between the panel and the wall d [42].

Helmholtz resonators consist of an air cavity connected to the environment through a small duct. The compression and expansion of the air in the duct dampens sound at a specific frequency [42]:

$$f_0 = \frac{c}{2\pi}\left(\frac{S}{V \cdot L}\right)^{0.5} \tag{4}$$

where S is the area of the opening, L is the length of the neck, and V is the cavity volume. Sound absorption in these elements take place between 50 and 400 Hz, but the resonance frequency range can be enlarged by filling the cavity with absorbing material. The same mechanism is used in perforated panels that are placed at a certain distance d from a wall, and the working frequency is [42]:

$$f_0 = \frac{c}{2\pi}\left(\frac{P}{d \cdot th}\right)^{0.5} \tag{5}$$

where P is the percentage of perforation, and th is the thickness of the panel.

To understand the frequency-dependent performance in the sound diffuse field of the panels proposed in this study, a set of acoustic tests have been performed: both the sound transmission loss TL and the sound absorption coefficient α have been analyzed by means of experimental tests. The sound transmission loss TL has been measured in the sound transmission room according to the ISO 10140-4 [43] standard, while the sound absorption coefficient α has been measured in the reverberation room according to the ISO 354 [44] standard.

2.2.1. Measurement of the Sound Transmission Loss Measurement in the Sound Transmission Room

For practical reasons, among the configurations with lower thermal conductivity, *T3-BP* and *T4-BF7* have been chosen for acoustic testing since for these configurations the replacement of the filling material is easier. The panels have been tested in a sound transmission room according to the ISO 10140-4 [43] standard.

The panels are shown in Figure 5, and they are 1.2 × 1 × 0.07 m in dimensions. They are made of a cardboard case realized by placing several elements side by side and connected with adhesive tape. The case surface facing the source room has been drilled with 1420 holes 2.9 mm in diameter. The case contains egg boxes (a total of 461 domes) which have been connected to the not-drilled case surface and have been filled with 7 g of bulk polyester (panel *AC-T3-BP*) and felt (panel *AC-T4-BF7*), for a total of 1.34 kg of filling. Panel density per unit area is 4.08 kg/m^2, while the total density is 58 kg/m^3. To fix the panels to the wall, four 15 × 15 mm wooden laths and silicone have been used.

As can be seen in Figure 6, the sound transmission room consists of two rooms—one designed as the *source room* and the other as *receiving room*—separated by a wall in which the panel to be tested is installed. The room's walls are structurally decoupled to ensure that most of the sound propagates through the specimen. The test has consisted in generating a diffuse sound field in the source room by activating an omnidirectional loudspeaker at two positions, and measuring the sound pressure level in both rooms by using a continuously moving microphone with one-third-octave filters in frequencies from 100 to 5000 Hz. Then, the average sound pressure level Lp has been calculated as [45]:

$$Lp = 10 \cdot log_{10}\left(\frac{1}{Tm}\right)\int_0^{Tm}\frac{p^2(t)\,dt}{p_0^2} \tag{6}$$

where p is the sound pressure, p_0 is the reference sound pressure (equal to 20 μPa), and T_m is the integration time. The tests have been performed at 29.5 °C, 100.41 kPa, and 53.7% humidity.


a)

b)

Figure 5. Panel installed in the sound transmission room (**a**) and details of the panel core (**b**). The panel filled with polyester is denoted as *AC-T3-BP*, and the panel filled with felt is denoted as *AC-T4-BF7*.

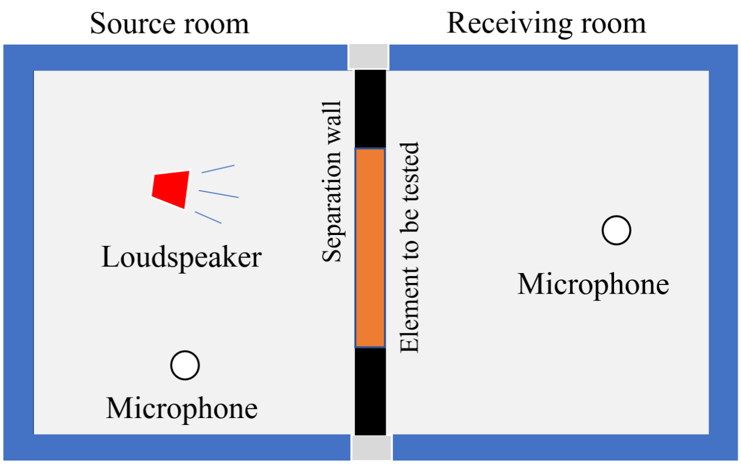

Figure 6. Plan of the sound transmission room. The *source room* is 50 m^3 in volume and 79.5 m^2 in total surface area, while the *receiving room* is 60 m^3 and 91.5 m^2. The opening in the separation wall in which the panel has been installed is 1 × 1.2 m in dimensions.

By comparing the average sound pressure level in the source room Lp_1 and in the receiving room Lp_2, the sound transmission loss TL of the panel has been calculated as [43]:

$$TL = Lp_1 - Lp_2 + 10 \cdot log_{10}\left(\frac{S}{A_a}\right) \quad (7)$$

where S is the panel surface, while the equivalent sound absorption area A_a of the receiving room is calculated as [43]:

$$A_a = 0.16 \cdot \frac{V}{T_R} \quad (8)$$

where V and T_R are the volume and reverberation time of the receiving room [46]. Results are shown in Figure 7, and the reproducibility deviation is within 1.2 and 3 dB.

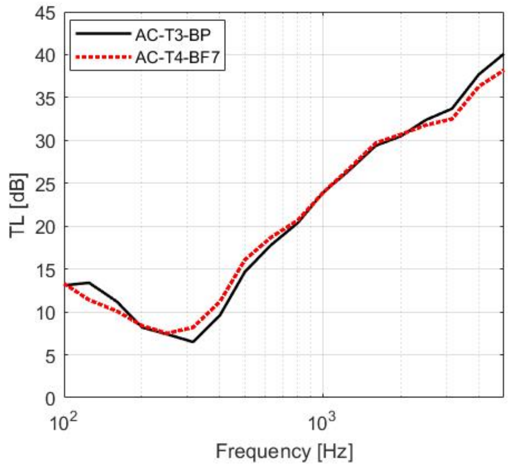

Figure 7. Sound transmission loss TL measured for panel *AC-T3-BP* filled with polyester and panel *AC-T4-BF7* filled with felt.

Weighted Sound Reduction Index

Since TL is a function of frequency and the comparison of material sound performance can be difficult, it has been calculated the weighted sound reduction index R_w representative of the acoustic performance of the partition. The term R_w is determined by comparing the measured values with a reference curve defined in the ISO 717-1 [47] standard. The curve is shifted by 1 dB toward the measured curve until the sum of unfavorable deviations is as large as possible but not more than 32 dB, and the weighted sound reduction index R_w is the value at 500 Hz of the shifted curve. Unfavorable values are considered when the measured value is less than the reference curve. Figure 8 shows the comparison of the measured and the reference curves. To describe how the panels behave with different types of noise, two additional coefficients, C and C_{tr}, are also calculated. The term C is added to the R_w value to evaluate the behavior of the partition when exposed to noise from living activities in the middle–high frequency range (talking, television, railway traffic at medium and high speed, highway road with traffic speed greater than 80 km/h, jet aircraft at a short distance, factories emitting mainly medium- and high-frequency noise). The term C_{tr} is used to calculate the sound insulation when the source falls in the low frequency range (urban road traffic, railway at low speed, aircraft, jet aircraft, disco music, and factories emitting mainly low- and medium-frequency noise). The weighted sound reduction index is R_w = 19.3 dB (−1.5; −4.3) dB for panel *AC-T3-BP* and R_w = 20.2 dB (−1.5; −4.5) dB for panel *AR-T5-BF7*.

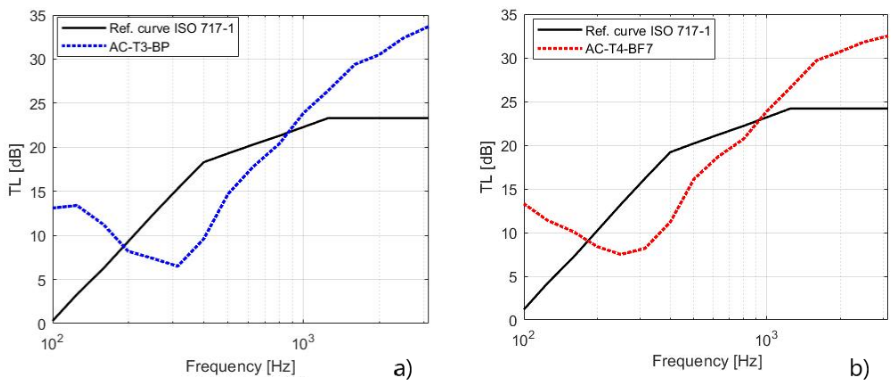

Figure 8. Comparison of the measured sound transmission loss TL with the reference curve defined in the ISO 717-1 [47] standard for the determination of the weighted sound reduction index R_w for panel *AC-T3-BP* (**a**) and panel *AC-T4-BF7* (**b**).

2.2.2. Measurement of Sound Absorption Coefficient in the Reverberation Room

To determine the sound absorption coefficient α, panel *AC-T3-BP* has been tested in the reverberation room according to the ISO 354 [44] standard. For this test, the panel is 7 m^2 and, as can be seen in Figure 9, it has been placed directly on the reverberation room floor.

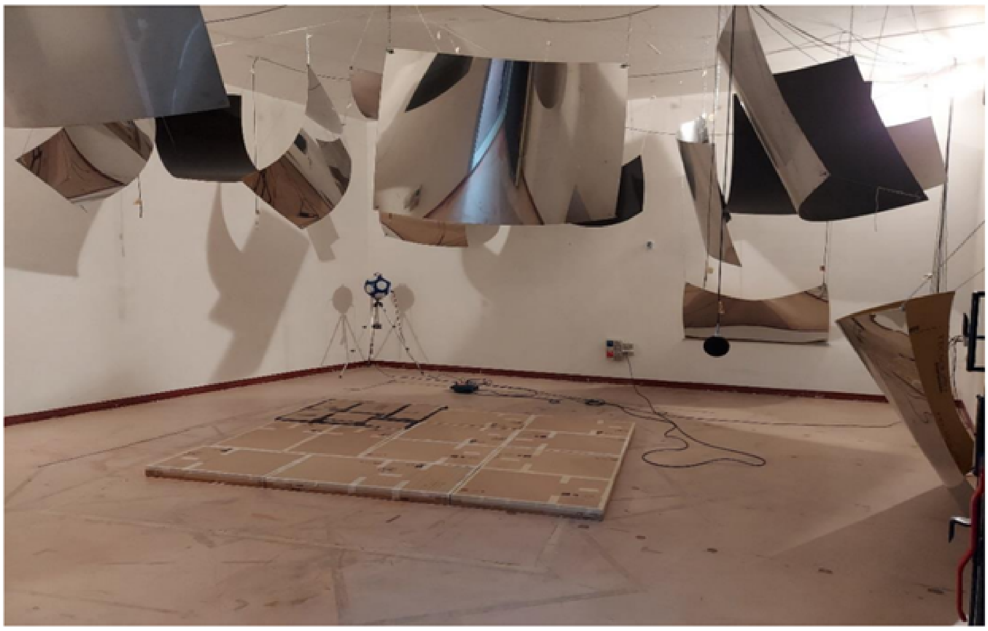

Figure 9. Panel *AC-T3-BP* has been positioned on the floor of the reverberation room for the determination of its sound absorption properties. The room is characterized by a volume of 219 m^3 and a total internal surface of 230 m^2. Twenty diffusers for a total area of 57.6 m^2 and six microphones have been used.

The test has consisted in measuring and comparing the reverberation time T_R in the room measured with and without the sample. The sound absorption coefficient has been then determined as [44]:

$$\alpha = \frac{A_a}{S} \tag{9}$$

where S is the sample surface. The room's equivalent sound absorption area A_a is defined as [44]:

$$A_a = A_{a2} - A_{a1} = 55.3 \cdot V \cdot \left[\frac{1}{c_2 \cdot T_{R2}} - \frac{1}{c_1 \cdot T_{R1}} \right] - 4 \cdot V \cdot (m_{a2} - m_{a1}) \tag{10}$$

where subscript 1 refers to the conditions with the panel positioned in the room, while subscript 2 refers to those without the panel; c is the propagation speed of sound in air, V is the volume of the room, and m_a is the sound power attenuation coefficient. Measurements have been made in one-third-octave bands in the range from 100 Hz to 5000 Hz. The test has been performed at 22 °C, 100.89 kPa, and 48% humidity. Results are shown in Figure 10, and the reproducibility deviation ranges between 0.03 and 0.11.

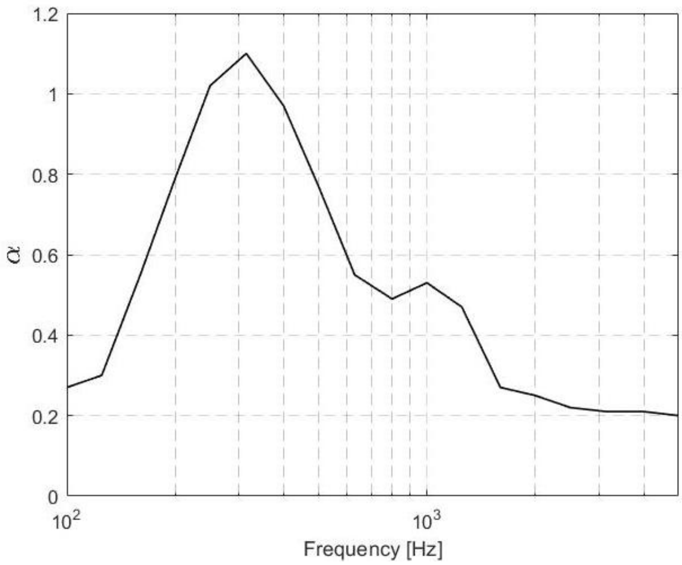

Figure 10. Sound absorption coefficient α of panel *AC-T3-BP*. A value greater than 1 indicates a not completely diffuse sound field, a typical problem encountered when sound-absorbing material is installed in the reverberation room.

Weighted Sound Absorption Coefficient

As done for the sound reduction index, a single value α_w called the weighted sound absorption coefficient has been determined according to the procedure described in the ISO 11654 [48] standard. A reference curve is shifted towards the measured curve by 0.05 until the sum of the unfavorable deviations is less than 0.1. The weighted sound absorption coefficient is the value of the reference curve at 500 Hz. Additional coefficients are indicated if the measured absorption coefficient exceeds the reference curve by 0.25 or more. Coefficient *L* indicates that the excess occurs at 250 Hz, coefficient *M* between 500 and 1000 Hz, and coefficient *H* between 2000 and 4000 Hz.

Another parameter is the noise reduction coefficient *NRC* , which is the mean value of the sound absorption at the frequencies 250, 500, 1000, and 2000 Hz. Depending on the result, an additional classification is proposed as shown in Table 2. For panel *AC-T3-BP*, the weighted sound absorbing coefficient α_w is 0.30 (LM), and the panel is classified as absorbent (class *D*). The *NRC* is equal to 0.64.

Table 2. Classification of sound-absorbent materials.

Class	α_w	Type of Sound Absorber
A	$\geq$0.9	Excellently absorbent
B	0.8–0.9	Highly absorbent
C	0.6–0.8	Very absorbent
D	0.3–0.6	Absorbent
E	0.15–0.3	Poorly absorbent
Not classified	<0.15	Reflective

3. Discussion

The results of the thermal and acoustic tests are discussed to understand whether the panels can be installed indoors for improving the indoor thermal and acoustic comfort. Measured values are also compared with data in the literature to evaluate panel characteristics and identify possible changes to improve the overall performance.

3.1. Thermal Tests

According to Figure 4, among the analyzed configurations, panel *T6-BFF* presents the lowest λ_{eq} equal to 0.0528 W/mK, which is comparable to that of commercial insulating materials such as glass and mineral fibers [30]. Since the core of panel *T6-BFF* has been filled with textiles, its orientation is not influential. Conversely, for the other configurations that present air cavities, the panel orientation affects convection and, consequently, λ_{eq}. Indeed, to reduce the effect of convection, the panels' equivalent thermal conductivity is determined through to the guarded hot plate apparatus in which the heating element is in the upper part. By comparing the results obtained for *T1-EB* and *T2-BEB*, it can be seen that for the *T2-BEB* panel, λ_{eq} is higher, and this is due to the presence of the egg boxes which, being in contact with both the panel surfaces, act as thermal bridge. The panels' equivalent thermal conductivity decreases when the egg boxes are filled with bulk textile, such as in panel *T3-BP*, *T4-BF7*, and *T5-BF20*. Despite polyester has a higher thermal conductivity (0.05 W/mK) than air (0.0252 W/mK) [30], filling the egg boxes with polyester reduces λ_{eq}. For example, the λ_{eq} measured for panel *T3-BP* is also lower than that measured for panel *T1-EB*. This is due to the presence of the egg boxes which increase the conductive heat transfer but, at the same time, reduce the radiative heat transfer. Despite felt has a lower thermal conductivity (0.044 W/mK [49]) than polyester, a higher thermal conductivity has been measured for panel *T4-BF7*, and this has been caused by the egg boxes being not completely filled with textiles. Filling the egg boxes in panel *T5-BF20* has entailed a reduction in λ_{eq}. Therefore, a better thermal performance, that is higher insulation, is achieved with the a greater filling of the egg boxes.

The comparison of λ_{eq} for typical construction material in Table 3 shows that the panels realized with end-of-life materials are less thermally insulating than commercial materials. However, the coupling of the selected materials is beneficial since the measured λ_{eq} values are lower than that of the single elements (cardboard, bulk polyester, and egg boxes). Since λ_{eq} ranges between 0.0528 W/mK and 0.0791 W/mK, the panels are considered thermal insulators, even if the panels orientation may increase the equivalent thermal conductivity because of convection. However, commercial insulation materials are generally porous and, when installed alone, do not provide good sound insulation, as explained later.

Table 3. Comparison of thermal conductivity of several materials [8]. The properties of the panels proposed in this study are in bold.

Material	Thermal Conductivity [W/mK]
Cardboard element	0.047–0.22
Panel made of reused elements	**0.0528–0.0878**
Polyester	0.041–0.053
Felt	0.044
EPS	0.026–0.056
Glass wool	0.034–0.053
XPS	0.034–0.041
PIR	0.018–0.040

3.2. Acoustic Tests

Figure 7 shows that the transmission loss measured for panels *AC-T3-BP* and *AC-T4-BF7* are comparable. The *TL* is higher than 7 dB in the entire frequency range. The configuration with polyester *AC-T3-BP* exhibits better performance at low and high frequencies; in contrast, for panel *AC-T4-BF7* better performance, albeit minimal, is detected between 300 Hz and 800 Hz. Since the employed materials have low density, sound insulation at low frequency is the most critical aspect as it depends on the mass of the elements. Based on the analytical model proposed in [50] for the prediction of *TL* for panels similar to those here anlayzed, the first resonance occurs at 315 Hz, where the sample acts as a mass–spring–mass system, where the case behaves as the mass, while the absorbent core (egg boxes filled with textile) acts as the spring. Due to the coupling of the two external panels moving in the counter phase, the air pumping in the panel core causes a reduction in *TL*. Between the first panel resonance and 1600 Hz, *TL* increases with frequency: the rate is 12 dB per octave between 315 and 630 Hz and 9 dB per octave between 630 and 1600 Hz. Between 1600 and 3150 Hz, TL decreases by 4 dB per octave.

Figure 10 shows the sound absorption coefficient α measured for panel *T4-BF7*. The values are greater than 0.2 in the entire frequency range with a peak at 315 Hz and a second minor peak at 1000 Hz. At 315 Hz, α greater than 1 indicates an insufficiently diffuse sound field, a typical problem encountered when sound-absorbing material is installed in the reverberation room [42]; indeed, in the computing of α only the horizontal projection of the panel is considered and not the entire surface panel exposed to the noise source. The resonance frequency calculated according to Equation (5) (by considering each egg box dome as a cylinder 1.276×10^{-4} m^3 in volume facing 2.36 holes in the case, the cardboard thickness equal to 0.004 m, and the total panel thickness equal to 0.065 m) is equal to 313.42 Hz and falls in the octave-band experimentally detected. At high frequencies, the sound absorption properties are not excellent due to sound reflection on the panel surface. The weighted sound absorption α_w is 0.30 (LM), and the panel is classified as absorbent (class D). Finally, the NRCs of materials employed in the building sector are compared in Table 4. Since the panel shows a higher NRC than that of typical building materials, it can be stated that the indoor application of the panel can reduce the reverberation time and, consequently, improve the acoustic comfort.

It is interesting to evaluate whether the performance of the panel is better than that of the single materials used for its realization. Carvalho et al. [25] investigated the sound absorption coefficient of egg boxes. Twenty-one configurations were tested in the reverberation room, and the influence of egg box material, position, and whether the egg boxes were open or closed was evaluated. The egg boxes were simply laid on the reverberation room floor. In the configuration called *Egg-box-down*, the flat surface of the boxes faced downward, while in the *Egg-box-up* configuration faced upwards. The obtained α ranged from 0.2 to 0.7. As can be seen in Figure 11—which compares the values measured for egg boxes such as those employed in this study—the three graphs show similar trends with prominent and minor peaks. The configurations analyzed in [25] show a peak at higher frequency, after which the sound absorption value remains higher than that measured for panel *AC-T3-BP*: this is due to the dimensions of the holes on the case that do not allow the sound wave to enter the panel. Panel *AC-T3-BP* works better at low frequencies which are those of speech. The sound absorption coefficient of polyester was measured through the standing wave method in [51], and the influence of thickness and density was evaluated. In Figure 12, polyester exhibits the typical pattern of porous materials, with high absorption at high frequencies and, as anticipated in the Introduction, the thickness as well as the density influence the sound absorption. Panel *AC-T3-BP* exhibits better performance at low and medium frequencies and is, therefore, more suitable for applications in residential environments to reduce the reverberation time. The sound absorption performance of cardboard was evaluated by means of the impedance tube in [12]: non-perforated, perforated, and perforated with multi-frequency resonators configurations were tested. The results are compared with those presented in this study in Figure 13. The non-perforated cardboard is reflective and panel *AC-T3-BP* exhibits the best sound absorption performance.

In light of this, based on the intended use, the panel proposed in this article exhibits better sound absorption properties than the individual elements/materials. The better performance is obtained by taking advantage of more acoustic dissipation modes.

Table 4. Comparison of *NRC* of several materials employed in the building sector [52]. The properties of the panels proposed in this study are in bold.

Material	NRC
Fiber glass 7 cm thick	0.95
Sprayed Cellulose Fibers 2.25 cm thick on concrete	0.88
Mineral fiber 50 mm (40–70 kg/m^3)	0.8
AC-T3-BP	**0.64**
Semi-rigid fiber glass 2.25 cm thick	0.63
Bulk polyester	0.61
Perforated cardboard	0.42
Polyurethane foam open cell 2.25 cm thick	0.30
Plaster	0.15
Wood	0.1
Painted brick	0.01
Non-perforated cardboard	0.01

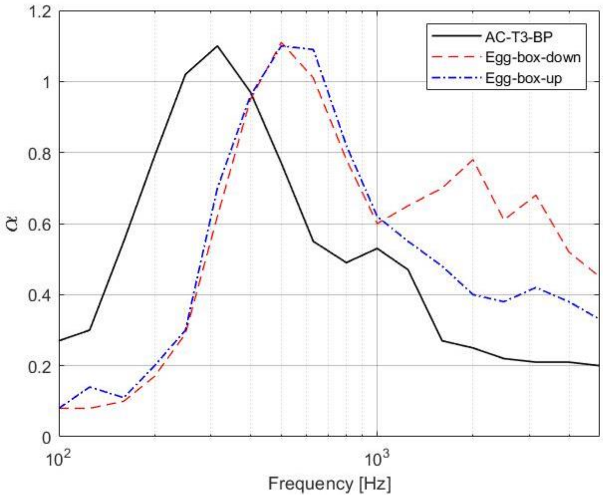

Figure 11. Comparison of the sound absorption coefficient α measured for panel *AC-T3-BP* and for egg boxes [25] similar to those employed in this study. In configuration *Egg-box-down*, the flat surface of the box is in contact with the reverberation room floor.

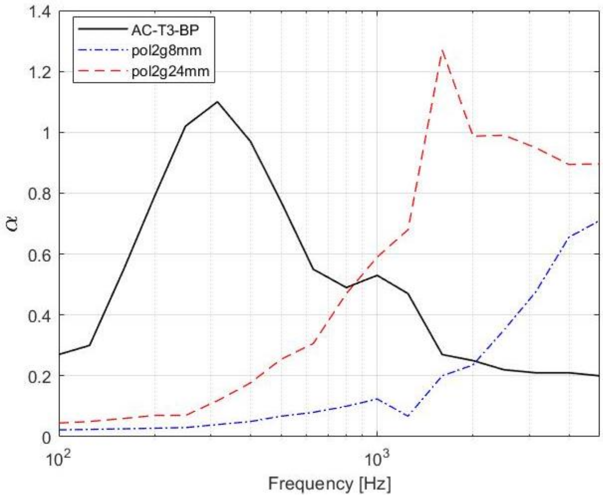

Figure 12. Comparison of the sound absorption coefficient α measured for panel *AC-T3-BP* and that measured in the impedance tube for polyester 0.2 g/cm^3 in density [51]. Sample *pol2g8mm* is 8 mm thick, while *pol2g24m* is 24 mm thick.

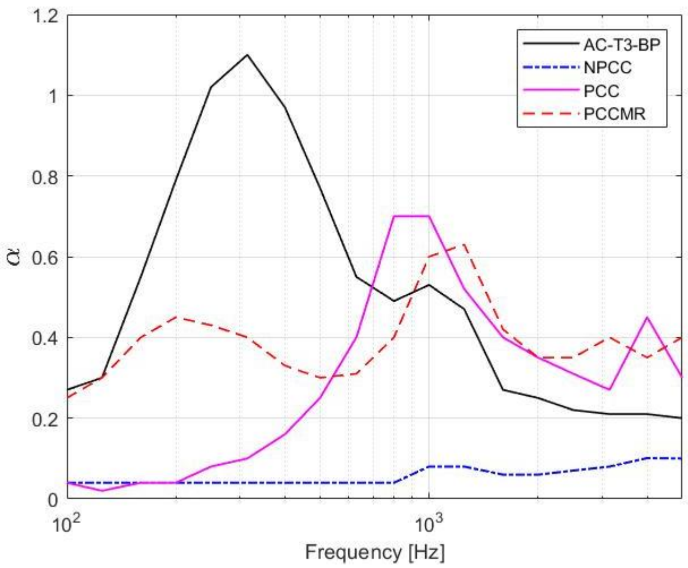

Figure 13. Comparison of the sound absorption coefficient α measured for panel *AC-T3-BP* and that measured in [12] for non-perforated cardboard element (NPP), perforated (PCC), and perforated cardboard element with multiresonators (PCCMR).

3.3. Future Works

The results show that the proposed panel has interesting thermal insulation properties. From the acoustic point of view, it is a sound absorber but sound transmission loss at low frequencies appears to be poor. Considering these results, simple modifications to the panel could improve its performance. In future works, the panel will be optimized from both the thermal and acoustic points of view through numerical and analytical analysis, and the results presented in this paper used for the models' validation.

Since any connection between the case surfaces is an acoustic bridge that limits the sound transmission loss, the surface facing the sound source will be distanced from the core to allow its vibration. To make the sound enter different cavities (in dimension and shape), the egg boxes may be placed alternately with the flat surfaces toward the sound source and the back of the panel. The thickness and material of the case surfaces will be differentiated to enhance the sound transmission loss. Aspects that may have influenced the sound absorption performance are the dimensions and positions of the holes on the case, which are uniformly distributed and of the same diameter: the holes diameter will be defined depending on the core characteristics. The accessible cavities will be filled with textiles at different densities to achieve high α values over a more comprehensive frequency range, and this expedients is beneficial also to reduce the equivalent thermal conductivity.

These results show that panels realized with end-of-life materials have interesting properties from a thermal and acoustic points of view, and they can be used in the construction sector to improve indoor comfort. For example, they can be installed in highly reverberant environments, or within prefabricated or 3D-printed walls and slabs to increase their thermal resistance. However, other factors need to be evaluated before declaring them compatible with building applications: the variability in the results depending on the operator that realizes the panels, and other aspects such as strength, fire, and condensation resistance need further investigation.

4. Conclusions

To promote the circular economy model and to incentivize products' reuse, it would be advisable to design packaging with its second use in mind. The product design should identify the characteristics that make packaging and textile suitable for being reused without undergoing recycling processes. This paper experimentally investigates the thermal and acoustic properties of panels realized by assembling selected end-of-life material.

Thermal tests show that their equivalent thermal conductivity is in the order of 0.071 W/mK and, therefore, comparable to the commercial insulating material. The NRC is equal to 0.64 and higher than that of materials typically used in the construction sector. The panel is a sound absorber since α_w is 0.30. However, the weighted sound insulation R_w equal to 19.3 dB (−1.5; −4.3) shows that the sound insulation performance is poor, especially at low frequency, and this is due to the panel low density. Expedients for improving the panel performance have been identified, and they will be further investigated through numerical and analytical models validated with the experimental results presented here. Therefore, reusing end-of-life materials for the realization of building elements is feasible, and given their low cost and ease of implementation, they are a suitable alternative to commercial insulating materials. As the construction sector requires a comprehensive material characterization to ensure regulations' accomplishment and to compare different solutions, this is a starting point essential to understand whether materials on the market can be reused in other sectors and to identify aspects that need improvement. Packaging manufacturers could diversify their products and come up with *standard packaging*, and packaging to be reused for making other products, such as building elements.

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Nomenclature

The following abbreviations are used in this manuscript:

A_a	Equivalent sound absorption area	m^2
c	Speed of sound in air	m/s
C	Sound transmission loss coefficient	dB
C_{tr}	Sound transmission loss coefficient	dB
d	Distance between panel and wall	m
f_r	Resonance frequency	Hz
f_c	Coincidence frequency	Hz
L	Helmholtz neck length	m
L_p	Sound pressure level	dB
m	Mass per unit area	kg/m^2
m_a	Power attenuation coefficient	-
NRC	Noise reduction coefficient	-
p	Pressure	Pa
P	Percentage of perforation	-
q	Heat flux	W
R_w	Weighted sound reduction index	dB
s	Thickness	m
S	Area	m^2
t	Time	s
th	Panel thickness	m
T	Temperature	°C
TL	Sound reduction level	dB
T_m	Integration time	s
T_R	Reverberation time	s
V	Volume	m^3
W_I	Incident Sound power	W
W_T	Transmitted sound power	W

α	Sound absorbing coefficient	-
α_w	Weighted sound absorption coefficient	-
δ	Sound dissipation coefficient	-
ΔT	Difference in temperature	K
λ_{eq}	Equivalent thermal conductivity	W/(m K)
π	Pi greek	-
τ	Sound transmission coefficient	-
ρ	Sound reflection coefficient	-

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