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Investigation of Acoustic Efficiency of Wood Charcoal in Impedance Tube for Usage in Sound-Reflective Devices

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Abstract: Charcoal is an environmentally friendly, biodegradable, and economical material. This material is usually produced by slow pyrolysis—the heating of wood or other substances in the absence of oxygen. The aim of this study was to investigate the acoustic efficiency of charcoal and design an acoustic diffuser that utilizes charcoal. Samples of different types of tree charcoal—birch (*Betula pendula*), pine (*Pinus sylvestris*), and oak (*Quercus robur*)—with different thicknesses were used for the acoustic efficiency measurements. The sound absorption and sound reflection properties of charcoal were investigated. The bulk density of charcoal was measured. In this study, an impedance tube with two microphones was employed as the measurement method. The results of the impedance tube measurements showed that the charcoal samples had high sound reflection coefficients, the highest value of which was 1. The 50 mm samples of birch had a high bulk density of 473 kg/m^3. The sample of 50 mm thick oak had the best reflection coefficient at 0.99. Reflection depended on the surface's acoustic properties, and the sound reflection coefficient increased with the increase in the density. Charcoal measurements, due to the high reflection coefficient of the material, were used for the design of a sound diffuser, which included wooden perforated plates filled with cylindrical elements of wood charcoal.

Keywords: impedance tube; wood charcoal; sound reflection coefficient; acoustic diffuser

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Citation: Khrystoslavenko, O.; Grubliauskas, R. Investigation of Acoustic Efficiency of Wood Charcoal in Impedance Tube for Usage in Sound-Reflective Devices. *Sustainability* **2022**, *14*, 9431. https://doi.org/10.3390/su14159431

Academic Editor: Jonathan Oti

Received: 4 June 2022
Accepted: 29 July 2022
Published: 1 August 2022

1. Introduction

Due to urbanization and population growth, it is important to study natural and recycled materials [1–4]. Few studies are devoted to the use of charcoal for acoustic purposes. Charcoal is a rigid, naturally porous material that has considerable sound reflection properties. The factors that influence its sound reflection properties include pore type, bulk density, and thickness. Charcoal pores range from narrow micropores to wide macropores [5]. The porosity of charcoal increases with the increase in the temperature of charcoal preparation, and the material's sound absorption properties increase with the increase in the pore size and surface area [6–8]. Acoustic materials as cement-based structural, viscoelastic, plastic, and natural fibre for sound absorption have been researched [9–12]. Using natural materials for insulation such as sheep wool, goat wool, and horse mane is one of the best ways to reduce greenhouse gases and provide better thermal comfort. Due to their porous structure and low density (for example, goat wool has a density of 269.874 kg/m^3), natural materials also have good acoustic properties [13–15]. Ayaz et al. showed that natural materials have better environmental aspects and efficiency than conventional materials. Natural materials allow for a move towards a completely sustainable energy strategy [13].

Sound absorption depends on the structure of the material; communicating open pores absorb sound better than closed ones. Therefore, sound-absorbing materials have been found to be very useful for the control of noise. The porosity of charcoal firstly depends on the source material and secondly, on the pyrolysis conditions. The size of a particle is a geometric characteristic usually assigned to material objects with sizes ranging from nanometres to millimetres. Marin and Arenas reported the effects of adding a porous layer of activated carbon on the normal-incidence sound absorption coefficient [16].

Dong Wang et al. investigated the sound absorption properties of decayed poplar wood (*Populus tomentosa*) by analysing changes in the microscopic structure, pore characteristics, and sound absorption properties. In a study by Curtu et al. on sound absorption products, biodegradable composite materials were produced using inserts of wood (flakes or fibres), textiles (wool or jute), and binders from wheat flour, clay, or ecological acrylic copolymers. Sound absorption, sound reflection, and bulk density are crucial properties of materials that often feature in research on porous sound absorption materials [17–19]. The bulk density depends on different factors such as the manufacturing process, the specific gravity of the raw material used, and the firing temperature; specifically, it tends to increase slightly with the increase in the burning temperature [20].

Charcoal is made of wood and woody agricultural products. The solid fraction of activated charcoal is used as an absorbent; it has recovering potential. Charcoal is a source of metallurgical fuel and is widely used for different purposes in arts and in medicine; moreover, it can also be used as a pollutant removal filter due to its large surface area, and it can be converted to activated carbon. In addition, charcoal improves soil productivity and sequestrates carbon from the soil. Charcoal is prepared by burning wood with a limited or controlled amount of air [5,21].

For activated carbon, the surface area is more than 500–1500 gr/m^2. Therefore, activated carbon has good sound absorption properties and high microporosity. Its density can vary between 0.2 and 0.6 t/m^3, depending on the biomass source used as the raw material. The bulk density of charcoal depends on the particle size distribution [22]. Charcoal porosity primarily varies as a function of the feedstock, and secondarily as a function of the pyrolysis conditions.

According to Suh et al. studies, charcoal has poorer absorption properties than other sound absorption materials. The sound absorption coefficient (SAC) indicates the acoustic effectiveness of charcoal. Research studies in relation to the sound absorption coefficients (α) of acoustic materials have employed the transfer function method, comprising two microphones in an impedance tube (ISO 10534-2 and ASTM E1050) [23–27]. A study was also conducted using the impedance tube measurement of the sound absorption coefficients of activated carbon nonwoven fibres. In that study, the composite with the surface layer made of nonwoven cotton fibres possessed a higher fabric density; therefore, it showed better sound insulation than composites made of glass fibres and activated carbon nonwoven fibres [28].

According to reference [29], wood charcoal is used in construction applications; for example, as an interior material (windows, doors, partition walls). Charcoal-based construction elements effectively isolate noise and improve sound insulation and the quality of internal reverberation. Charcoal is also used for cleaning atmospheric air by filtering [28].

Little research has been conducted on construction elements made of charcoal. Charcoal is a homogeneous, rigid, and porous material by which most of a sound wave can be reflected. Due to its reflective properties, this material can be used for the manufacturing of diffusers. In this case, it must be rigid enough to reflect acoustic energy, otherwise sound absorption occurs. Currently, wood is the material that is most often used for the production of diffusers because it is sufficiently rigid to reflect sound energy and is environmentally friendly. Our analysis of the literature showed that the best reflective materials ought to have a reflection coefficient of 1, which is a very high indicator useful for the creation of diffusers. This is especially interesting for experimental analyses of the reflection coefficient of charcoal [30,31]. Acoustic diffusers can be used for solving problems, such as controlling the spread of sound to achieve speech intelligibility improvements in auditoriums and concert halls. In fact, their design helps to reduce an effect known as comb filtering, and to eliminate echo [32–34]. The Schroeder acoustic diffuser is a useful tool in the acoustic treatment of spaces, such as critical listening rooms and performance spaces, to create a more even sound field or to avoid strong reflections [33,35].

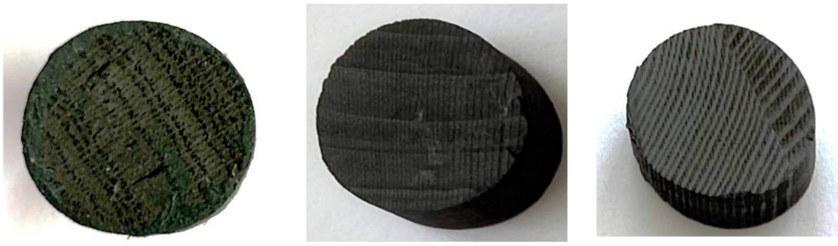
The aim of this study was to investigate the acoustic efficiency of charcoal and to study the influence of the sound-absorptive factors, such as thickness and bulk density, of charcoal materials. Simultaneously, we investigated the effects of charcoal's reflective properties on construction elements, and sound-diffusing construction elements were manufactured for this goal. It was found that the designed acoustic diffuser can help to improve the acoustics of a room and eliminate negative effects such as echo.

2. Materials and Method

2.1. Sample Preparation Method

In this research study, charcoal was manufactured from three types of wood: birch, *Betula pendula*; pine, *Pinus sylvestris*; and oak, *Quercus robur*. Wood was collected from a Lithuanian forest near Vilnius TECH university; the trees studied are widespread in this region. The samples of charcoal were prepared with thicknesses of 10, 18, 25, and 50 mm and a diameter of 30 mm.

Charcoal was manufactured by partial combustion in an E5CK-T (Lithuania, SNOL, Umega) carbonization system muffle furnace with a heating rate of 10 °C/min; burning time was 1 h under oxygen-limited conditions and under atmospheric pressure. Pyrolysis was performed at the peak temperature of 330 °C. The prepared samples of charcoal were homogeneous, solid, and isotropic, as shown in Figure 1.



(O) (B) (P)

Figure 1. Different types of wood charcoal samples: (O) oak; (B) birch; (P) pine.

The bulk densities of charcoal from different types of trees are shown in Table 1. The bulk density increased with the thickness of the sample and depended on the type of charcoal. The bulk densities of charcoal were measured according to the following formula:

$$D = M/V, \quad (1)$$

where M is the mass of soil (g) and V is the volume as a whole (cm^3).

Table 1. Bulk densities of charcoal samples.

Type of Sample	Thickness of Sample (mm)	Bulk Density (kg/m^3)
birch (B)	10	440
birch (B)	18	456
birch (B)	25	454
birch (B)	50	473
pine (P)	10	327
pine (P)	18	372
pine (P)	25	392
pine (P)	50	433
oak (O)	10	310
oak (O)	18	343
oak (O)	25	378
oak (O)	50	390

2.2. Measurement Setup and Impedance Tube Method

This research study was carried out using the impedance tube technique for determination of the sound absorption coefficient according to DIN EN ISO 10534-2 [25]. We used an AcoustiTube type III with an inner diameter of 30 mm and a frequency range of 150–6600 Hz. The AED 1000 measurement system is supported by AED 1001 analysis software. The measurements allowed us to perform the direct computation of the rated sound absorption coefficient of the material according to DIN EN ISO 11654 (ISO 11654) [26]. The impedance tube for this study is shown in Figure 2.

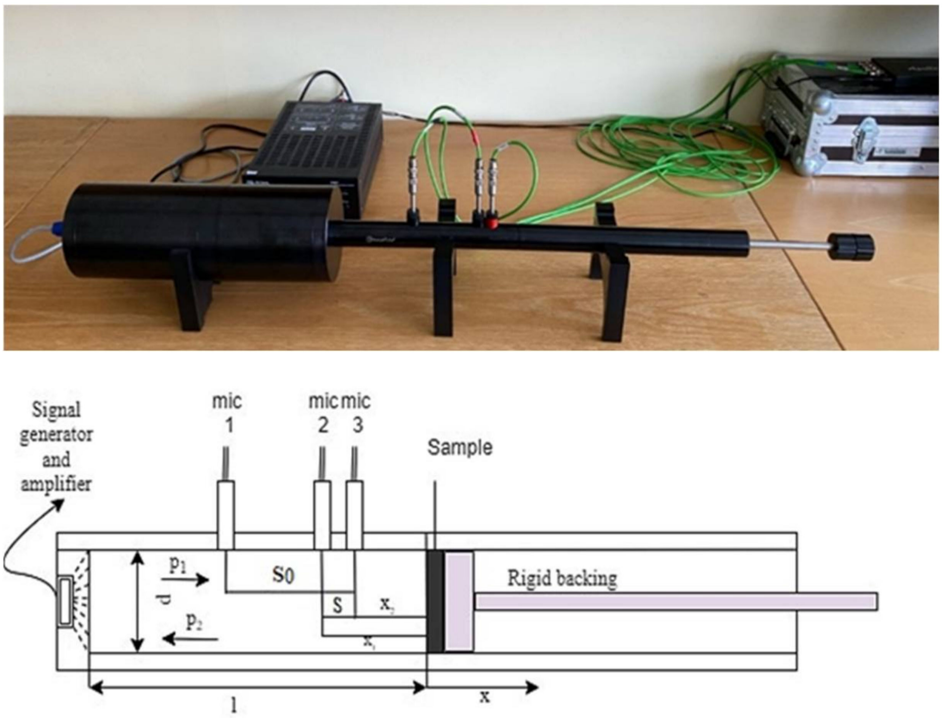


Figure 2. Impedance tube setup.

Microphones between the loudspeaker and the sample can be seen in the figure. A loudspeaker was controlled by a signal source, and a one-dimensional wave directly carried the sound energy through the sample. The impedance tube consisted of three microphones and ended with an anechoic termination. The distance between microphones 1 and 2–3 was 100 mm. The distance between microphones 2 and 3 was 20 mm. The distance from microphone 2 to the surface of the sample was 30 mm, and the distance from the sample surface to microphone 3 was 60 mm. The signal-generated excitation was the logarithmic enveloped sine in the frequency range 160–5000 Hz and the 1/3-octave-band filter, and the number of signal averages was 50. Matlab was used for the calculation of the sound absorption coefficient. The position of the third microphone with distance s0 between the point 2 and 3 microphones depended on the lower-limit frequency, fl, of the tube. The impedance tube was calibrated before the measurements to take into account the incompatibility of microphone phases. Calibration was performed by changing the position of the microphones. The ambient temperature, atmospheric pressure, and relative humidity were measured.

The tube calculation for the two-microphone transfer function method is as follows (where x_{12} is the low-frequency microphone measurement set and x_{23} is the high-frequency microphone measurement set). For the measured sound pressures, we used the following equations at each frequency employing transfer function methods [25]:

$$\text{H12} = \frac{p_2(f)}{p_1(f)}, \text{H}_{23} = \frac{p_2(f)}{p_1(f)} \quad (2)$$

$$\text{HI}_{\,(160\text{–}1000\ \text{Hz})} = \frac{p_{2I}}{p_{1I}} = e^{-jk_0(x_{12}+x_{23})}, \quad (3)$$

$$\text{HI}_{\,(1000\text{–}5000\ \text{Hz})} = \frac{p_{3I}}{p_{2I}} = e^{-jk_0(x_{23})}, \quad (4)$$

$$\text{HR}_{\,(160\text{–}1000\ \text{Hz})} = \frac{p_{2R}}{p_{1R}} = e^{-jk_0(x_{12}+x_{23})} \quad (5)$$

$$\text{HR}_{\,(160\text{–}1000\ \text{Hz})} = \frac{p_{3R}}{p_{2R}} = e^{-jk_0(x_{23})}, \quad (6)$$

where H_{12} and H_{23} are transfer functions between microphone positions 1 and 2, and microphones 2 and 3, at any frequency; p_2 is the pressure recorded by the second microphone (Pa); p_1 is the pressure recorded by the first microphone (Pa); and f is the frequency (Hz).

The sound-wave reflection was calculated with the following equations:

$$\text{R} = \frac{H_{12} - R_{I(1000-5000\ Hz)}}{H_{R(1000-1000Hz)} - H_{12}} = e^{2jk_0(x_1+x_{23}+x_{3S})}, \quad (7)$$

$$\text{R} = \frac{H_{12} - R_{I(160-1000\ Hz)}}{H_{R(160-1000Hz)} - H_{12}} = e^{2jk_0 x_1+x_{23}+x_{3S}}, \quad (8)$$

where R is the sample sound reflection coefficient; k_0 is the wave number; j is the imaginary number in the complex plane; and x_{3S} is the distance between microphone 3 and the sample (x_{3S} = 60 mm). The absorption coefficient was defined following impedance tube measurements and was calculated using the following equation:

$$\alpha = 1 - |\text{R}|^2 \quad (9)$$

where α is the absorption coefficient and R is the reflection coefficient.

2.3. Acoustic Diffuser Manufacturing Process

The constrictions of the diffuser were based on the mathematical sequence of quadratic residues derived from number theory presented by Schroeder [36,37], which is determined by the relationship:

$$s_n = n^2 \text{ modulo (N)} \quad (10)$$

where s_n is the sequence of values of the relative depth of the wells of the diffuser; n is a nonnegative integer {0, 1, 2, 3 ...}, which determines the number of the corresponding wells; and N is a prime number {2, 3, 5, 7, 11, 13, 17...}. A prime number is a number that is different from 0 and 1 and can be divided only by 1 and by itself.

Cell depth, d_n, in the design of the diffuser depended on the value of its design frequency, f_o:

$$d_n = s_n \times c/(f_o \times 2 \times N,) \quad (11)$$

where d_n is well depth of n; f_o is the design frequency of the diffuser; c is the sound velocity in the air; and N is the prime number (the order of the diffuser) corresponding to the number of wells.

A diffuser's theoretical working range is a fundamental parameter that can be predefined. The operating frequency range depends on the linear dimensions of the diffuser cells. The lower limit of the operating range, f_{low}, of the diffuser depends on the size of the deepest cell. The upper limit of the working range, f_{high}, depends on the value of cell width W [38].

In the designed triangle plywood (wood) diffuser, drilled perforations have the following characteristics: diameter, 20 mm; pitch, 30 mm; and thickness, 10 mm. In the study, the selected values of the diffuser are the optimal values for the experiment in the laboratory conditions. Charcoal has to be prepared in a muffle furnace. In the wooden acoustic diffuser, the charcoal elements are inserted and fastened within the perforations with a binder. The calculation formula of the square-hole arrangement of the acoustic diffuser, called the perforation rate, is:

$$p = \frac{\pi}{4}\left(\frac{d}{B}\right)^2 \times 100\% \quad (12)$$

where p is the perforation rate; d is the aperture (mm); and B is the pitch (mm) [39].

For calculations relative to the developed triangular, theoretical acoustic diffuser, we chose a design frequency of 550 (with which dispersion is the most effective). The values shown in Table 2 correspond to most of the mid-frequencies and significantly affect the naturalness of sound reproduction.

Table 2. Cell depth calculation results.

Number of Wells	Well Depth (cm)
1	4.5
2	17.9
3	8.9
4	8.9
5	17.9
6	4.5
7	0

The total frequency range of the acoustic diffuser was between 412.5 and 2007.3 Hz. For the estimated well width of 8.7 cm, the size of the diffuser's seven front planes amounted to a total construction width of 63 cm and a height of 120 cm. The percentage concentration of charcoal in the perforated boards was 35%.

3. Results and Discussion

3.1. Influence of Charcoal Bulk Density on Sound Absorption Coefficient

The analysis of the sound absorption coefficient measured with the impedance tube is shown in Figure 3. The sound absorption coefficient of charcoal was determined at different frequencies: 160 Hz, 315 Hz, 630 Hz, 1250 Hz, 2500 Hz and 5000 Hz.

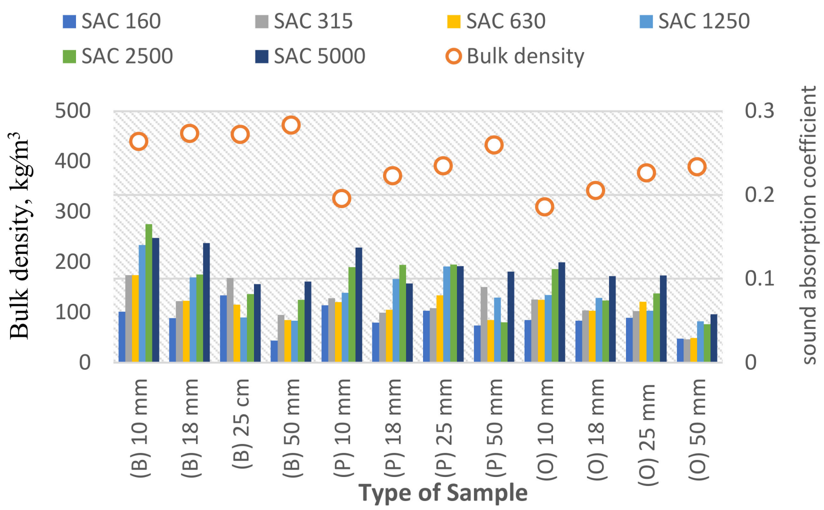


Figure 3. Influence of charcoal thicknesses and densities on sound absorption coefficient (SAC) at 160 Hz, 315 Hz, 630 Hz, 1250 Hz, 2500 Hz, and 5000 Hz in samples with thicknesses of 10 mm, 18 mm, 25 mm, and 50 mm. Types of wood charcoal samples: (O) oak; (B) birch; (P) pine.

The highest bulk density, 473 kg/m^3, was that of birch with a 50 mm thickness. The minimum value of bulk density, 310 kg/m^3, was that of the 10 mm thick oak. The bulk density of charcoal ranged between 310 and 535 kg/m^3; birch had higher bulk density, from 440 to 473 kg/m^3, than pine, from 327 kg/m^3 to 433 kg/m^3, and oak, from 310 to 390 kg/m^3. The minimum range of bulk density, from 310 to 390 kg/m^3, was that of oak. The sample of 10 mm thick birch had a density of 440 kg/m^3 with an SAC of 0.16 at 2500 Hz, which was the highest value. The sample of 50 mm thick birch had a density of 343 kg/m^3 with an SAC of 0.04 at 2500 Hz. The sound absorption coefficient increased with the decrease in density (Figure 3).

Suh et al. measured the sound absorption coefficient using an impedance tube equipment. They observed that the sound absorption coefficient of pinewood charcoal increased as the frequency increased. The sound absorption coefficient became larger when the thickness of the sample increased but was almost constant in samples with a thickness larger than a certain value [23].

In our study, the thickness of the sample had a significant effect on the absorption coefficient. The minimum absorbance values were found for birch and oak with SACs of 0.02 for 50 mm thick samples at the frequency of 160 Hz. The highest value of the SAC, 0.16, was found for the smallest specimen of birch, with a thickness of 10 mm, at 2500 Hz. SAC values increased with the increase in the absorption frequency. The 18 mm B sample showed high SAC values, 0.14, compared with the other samples at the same frequency. The lowest bulk density, 310 kg/m^3, was that of oak samples with a thickness of 10 mm. The sound absorption coefficient showed the lowest value, 0.02, at the frequencies of 160 Hz, 315 Hz, and 630 Hz for B samples of 10 mm. The sound absorption of the material was the most significant at the highest frequency, 2500 Hz, for B samples of 10 mm and corresponded to an SAC of 0.1. The highest values of absorption were found for the 10 mm thick B sample at 5000 Hz, presenting an SAC of 0.14, and for the 10 mm thick P sample, presenting an SAC of 0.13. The type of wood charcoal had no significant effects on sound absorption. As the thickness of the material decreased, the sound absorption increased.

3.2. Influence of Charcoal Thickness on Sound Reflection Coefficient

In this study, we determined the influence of the thickness of charcoal samples on the sound reflection coefficient. Figure 4 shows the sound reflection coefficients of materials of different thicknesses.

Figure 4 shows that the reflection coefficients of charcoal ranged from 0.97 to 1; as the sample's thickness increased, the sound reflection increased. The sound reflection depends on the thickness of a material and its density. The oak sample of 50 mm thickness showed better results in terms of the reflection coefficient than birch and pine. This high value could be related to oak's high density. High sound reflection can be explained by some properties of materials, such as the size of the channelling tracheids being smaller than the wavelength [23] and materials having low bulk density. The 10 mm samples had smaller sound reflection values than the samples of 50 mm thickness.

According to relevant research from Li et al., charcoal has a smaller sound absorption coefficient compared to other commonly used sound-absorbing materials such as melamine foam; this means that it has high reflective properties [40]. Such high reflective properties can be used for the creation of acoustic diffusers containing charcoal elements.

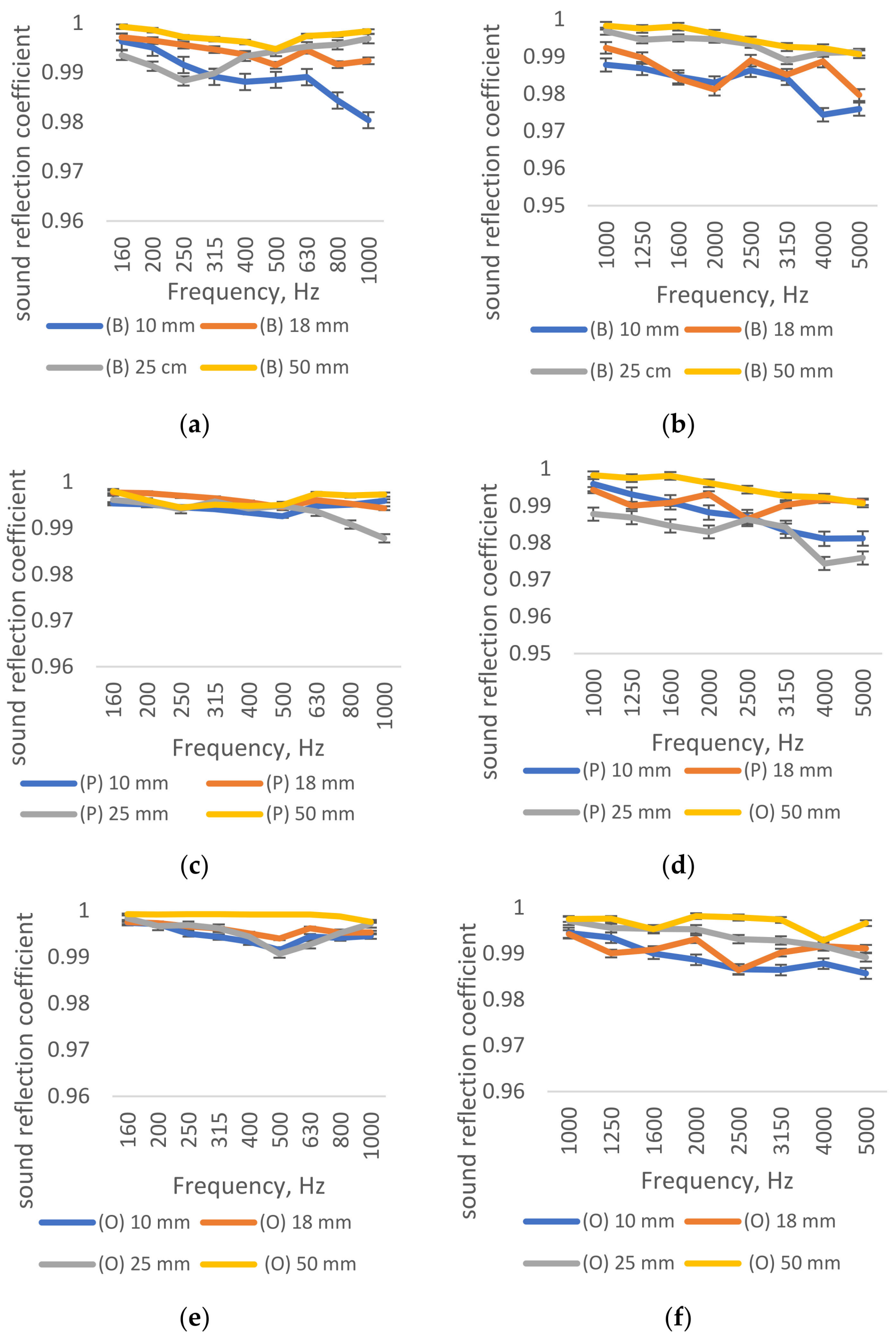
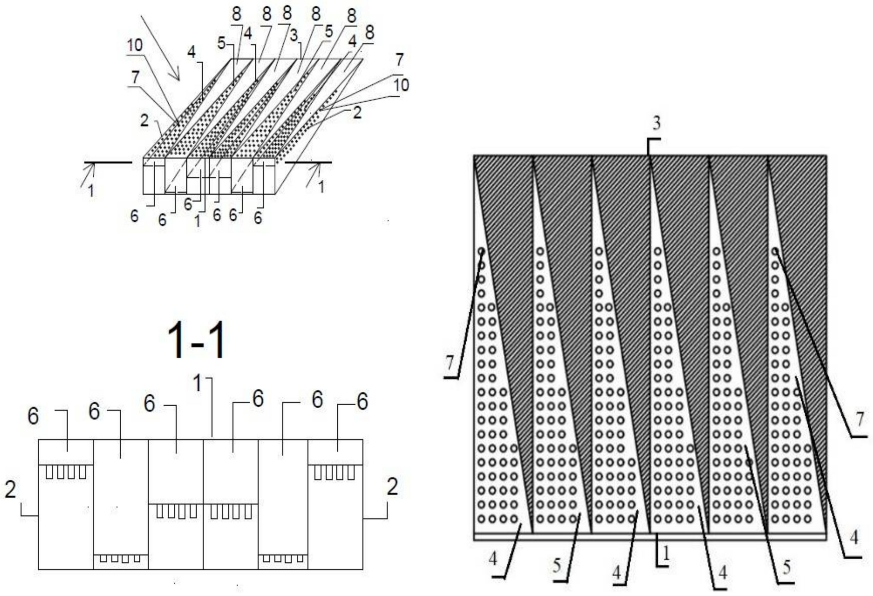


Figure 4. Sound reflection coefficient measurements using impedance tube: (**a**) birch at 160–1000 Hz; (**b**) birch at 1250–5000 Hz; (**c**) pine at 160–1000 Hz; (**d**) pine at 1250–5000 Hz; (**e**) oak at 160–1000 Hz; (**f**) oak at 1250–5000 Hz.

3.3. Designed Diffuser and Future Research

Charcoal has not yet been researched for the production of sound-diffusing construction elements and has never been used to create acoustic diffusers. The current literature has not explored the acoustic and non-acoustic properties of charcoal construction elements that can effectively improve room acoustics. Existing acoustic diffusers are wedge-shaped, rectangular planes that dissipate sound less efficiently than other forms. The designed diffuser is made of wooden triangular perforated planes filled with charcoal cylinder elements. Triangular-shaped planes distribute the reflected sound well at different positions with respect to the source and increase the diffusion of the sound field in the room. The materials on which this design is based are environmentally friendly.

The triangular, theoretical acoustic diffuser is a diffusion device that reflects sound, eliminating empty space. The device has recesses that allow different frequencies of sound (from low to high frequencies) to be dispersed. The depth of the recesses can be chosen by quadratic calculations (Equations (7) and (8)). The diffuser is essentially a device with varying cell depths. The term "acoustic diffuser" refers to a device that redistributes the acoustic energy of intense reflections via spatial and temporal dispersion. The purpose of the device is to improve diffusion and reduce reverberation in the room. The acoustic diffuser reported in this study, made of wooden perforated boards filled with cylindrical elements made of charcoal, is designed to improve acoustics. The device can be installed in auditoriums, concert halls, acoustic rooms, and museums (Figure 5).



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

Figure 5. Acoustic diffuser: (**a**) top view; (**b**) exploded view.

Our acoustic diffuser is made of perforated boards, with perforations of cylindrical elements, and has a wedge-like shape. The developed diffuser consists of a series of wells of various depths. Variable depths ensure uniform sound dispersion. The diffuser consists of a front plane: (1) a side plate; (2) a bottom plane; (3) inclined triangular planes; (4) a bottom inclined plane; (5) cells; (6) cylindrical elements made of wood charcoal; (7) a bottom plane; (8) internal elements of perforated side dividers; and (9) perforations.

4. Conclusions

In this article, the sound absorption coefficients and sound reflection coefficients of wood charcoal samples (birch (*Betula pendula)*, pine (*Pinus sylvestris),* and oak (*Quercus robur)*) were calculated based on measurements. The bulk density of charcoal was defined. The type of tree did not significantly influence the sound-reflective properties of the samples. The main influences on sound absorption were the bulk densities and thicknesses of the materials. The analysis of the experimental results showed that the highest bulk density, 473 kg/m^3, was that of birch of 50 mm thickness. The highest values of absorption were those of the 10 mm B sample at 5000 Hz, with an SAC of 0.14, and the 10 mm P sample, with an SAC of 0.13. Samples made of low-density charcoal showed better sound absorption; for example, pine of 10 mm thickness and a 323 kg/m^3 density had an SAC of 0.14 at 5000 Hz, and the pine sample of 50 mm and a 343 kg/m^3 density had an SAC of 0.11. The results of this study showed that as the thicknesses of the materials decreased, the sound absorption increased.

The investigated wood charcoal materials had high sound reflection coefficients, which were from 0.97 to 1 for wood samples of different thicknesses. The charcoal sample, where thickness influenced the sound reflection coefficient, was oak charcoal of 50 mm, which showed the highest reflection coefficients, ranging from 0.99 to 1, compared with samples of 25 mm, 18 mm, and 10 mm. Charcoal had a high reflection coefficient, which makes this material useful for the production of acoustic diffusers.

A sound-reflecting theoretical diffuser device was developed based on perforations of cylindrical elements using the acoustic efficiencies of the materials studied in the article. The calculations of quadratic residuals necessary for the design of the diffuser were based on number theory.

The scattering properties of triangle plywood (wood) diffusers should be the object of future research. In a future study, we experimentally evaluate the reverberation time in the reverberation room and calculate the sound absorption coefficient of the sound scattering coefficient of the diffuser device.

Author Contributions: Conceptualization, O.K. and R.G.; methodology, O.K.; software, O.K.; validation, O.K. and R.G.; formal analysis, O.K.; investigation, O.K.; resources, O.K.; data curation, O.K.; writing—original draft preparation, O.K.; writing—review and editing, O.K. and R.G.; visualization, O.K.; supervision, R.G.; project administration, R.G.; funding acquisition, R.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research study received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors gratefully thank H.P. Groby for suggestions for the research study.

Conflicts of Interest: The authors declare no conflict of interest.

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