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Development of Sustainable Plant-Based Sound-Absorbing Boards to Reduce Noise in Interior Spaces

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Abstract: The reduction in CO_2 emissions has become an important issue as global environmental problems have become more serious. The replacement of conventional petroleum- and mineral-derived raw materials for building materials with local plant-based resources is expected to reduce CO_2 emissions. This study examined the possibility of using compression-molded boards made from plant-based resources as sound-absorbing materials in rooms. Among plant resources, few studies have conducted detailed measurements of the sound absorption properties of boards compressed from reeds. When measuring the normal incidence sound absorption coefficient, a material layered with a reed compressed board, wood fiber insulation, and an air layer showed a peak in the sound absorption rate at approximately 850 Hz. This indicates the potential to effectively absorb noise in the frequency band of human voices (500–1000 Hz). By changing the layering of multiple sound-absorbing materials, the presence or absence of an air layer behind them, and the installation conditions of the sound-absorbing materials, and then measuring the sound absorption rate, variations were observed in the sound absorption rate and the frequency at which the peaks were observed. This provides guidelines for material configurations that exhibit sound absorption at specific frequencies.

Keywords: resource recycling; plant-based resources; unused materials; building materials; interior space; sound absorption performance

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1. Introduction

In recent years, global environmental issues have become increasingly serious, and environmental issues have gained significant attention in various fields. In particular, reducing CO_2 emissions from the building sector, which accounts for approximately 37% of global CO_2 emissions, is important for realizing a sustainable society. Accordingly, proactive efforts such as improving energy efficiency, using renewable energy, and improving waste management are required [1]. Recently, CO_2 emissions from the construction sector in developed countries have declined. In the EU, emissions were reduced by approximately 35% between 2005 and 2020 [2]. In particular, as energy conservation during operation contributes to the promotion of net zero-energy buildings, the embodied carbon in construction has gained increasing attention as the next target for the reduction in emissions [3,4].

Wood is gaining momentum as an alternative to petroleum and minerals, which are the main raw materials used in building materials. The use of wood for building exteriors and interiors, the utilization of unutilized resources such as thinned wood, and the reuse of wood waste such as bark are increasingly gaining interest [5].

The active utilization of untapped plant-based resources as building materials is related to several Sustainable Development Goals (SDGs) set forth by the United Nations and is recommended as a contribution to a sustainable society [6,7]. As plant-derived materials are recyclable resources and have carbon dioxide-absorbing properties, sustainable resource management and appropriate use are expected to contribute not only to the reduction in carbon dioxide emissions but also to the promotion of local economies, the creation of jobs, and the preservation of the global environment. Furthermore, unutilized resources other than wood, such as grass, are also attracting attention [8].

In Japan, grass resources, such as Miscanthus sinensis, reeds, and rushes, have been widely used as materials for building structures and finishing for a long time. Miscanthus sinensis and reeds, perennial grasses of the Poaceae family, have been used as traditional roofing materials in thatched roofs since ancient times. However, the use of thatched roofs has been declining in modern times, mainly because of the increasing demand for industrially produced roofing materials because of modernization, fire prevention laws, regulations associated with urbanization, and a decline in mutual support in the local community. Although skills and knowledge for constructing traditional thatched roofs are preserved by thatched roof craftsmen scattered throughout Japan, few new houses with thatched roofs have been built in Japan, and cultural heritage buildings account for approximately 80% of the demand for thatched roofs [9].

In the United Kingdom, Denmark, and the Netherlands, which also have a tradition of thatched roofs, laws and regulations are being developed to allow the introduction of thatched roofs into new buildings if certain standards are satisfied from the perspective of global environmental conservation [10]. In the United Kingdom, standards have been established to allow thatched roofs to appear on the exterior by maintaining a certain separation distance between the property line and the roof of the building and by installing a noncombustible board on the interior side of the roof and a ventilation layer on the exterior side of the board. A fire prevention measure called the Dorset Model is used to reduce the distance from the property line to the roof of a building by half [11]. In Denmark and the Netherlands, in addition to the mitigation measure of installing non-combustible boards on the interior side, as in the Dorset Model in the UK, a provision allows thatch on the interior without using non-combustible materials by using fire retardant-treated thatch that must be subjected to maintenance measures every 5 years. In Japan, the outdoor side of a roof is used as the base. In Japan, the outdoor side of the roof is covered with a non-combustible material as a fire prevention measure to prevent damage, whereas in European countries, standards are set from the perspective of preventing damage by requiring fire resistance on the indoor side of the roof, recognizing the value of traditional thatched roofs, and considering legislation to introduce it in modern architecture. Based on these European examples, we believe that in the field of architecture, it is important to examine the possibility of utilizing plant-based resources in the modern age to address global environmental issues and achieve a sustainable society.

This study aims to investigate the use of boards made by pulverizing and compressing reeds, a raw material for thatch, as sound-absorbing materials to effectively reduce noise in indoor spaces. Recycling wood by pulverizing it into chips and compressing it at a high density to form boards has become common practice. Boards compressed at high densities are expected to exhibit structural strength [12,13] and are widely distributed in the market as building materials. While these compressed boards typically have a smooth surface and a dense interior, the reed compressed boards (hereinafter abbreviated as RCB) fabricated in this study are made of porous materials with a high porosity rate, contrasting with the former. By coarsely grinding and compressing the reeds to a low density, it is possible to retain the strength of the reeds as linear materials, leave hollow layers in the formed boards, and provide a sound-absorbing mechanism. The target noise for sound absorption is assumed to be human voices in residential and office indoor spaces, and this study examines the configuration of porous sound-absorbing boards that effectively absorb sound in the low-frequency band of 500–1000 Hz.

Rayleigh's capillary theory has served as a fundamental theory for predicting the acoustic properties of porous materials [14], and many models have since been devised. Notable examples include the Delany–Bazley model [15], which derives effective prediction formulas for flow resistance, characteristic impedance, and propagation constants in fibrous materials using measured values of flow resistance, and the Biot model [16], which predicts the acoustic properties and sound absorption rates of porous materials by providing information such as material density, porosity, thickness, and pore size and shape as parameters. Previous studies on the sound absorption properties of natural wood-based materials include Wassilieff [17], who demonstrated that the sound absorption performance of wood fibers and chips can be rationally described using three parameters based on Rayleigh's model: flow resistivity, porosity, and tortuosity. Mania et al. [18] measured changes in sound absorption rates after heat treatment of various types of wood at high temperatures. Chojnacki et al. [19] designed acoustic panels that absorb sound over a wide frequency range by investigating curved shapes and hole-drilling methods applied to the wood surface. Song et al. [20] compared theoretical predictions and experimental values for the absorption characteristics of wooden panels perforated with tiny holes with diameters of 1–3 mm. To predict acoustic properties based on theoretical models, it is necessary to obtain parameter information. However, it is difficult to obtain accurate parameter information for porous materials, such as the reeds used in this study, which have uneven pore sizes and exhibit anisotropy.

Previous studies investigating the sound absorption properties of inhomogeneous and anisotropic porous materials include Asdrubali et al. [21], who compressed various uncommercialized natural and recycled materials to investigate their thermal insulation and sound absorption performance. Walter et al. [22] measured the sound absorption performance of porous materials cultivated with mycelium using waste paper as a base material. Astrauskas et al. [23] fabricated a porous panel by mixing paper sludge and clay. Su et al. [24] investigated the impact of hemp stems on sound absorption properties by combining them with polycaprolactone. Kobiela-Mendrek et al. [25] fabricated a felt-like porous material from local goat hair. Gliscinska et al. [26] measured the sound absorption effect of a concavo–convex-shaped composite material surface made of flax fiber and polylactic acid fiber. Park et al. [27] investigated the relationship between density, resin content, and sound absorption rate by fabricating a wood fiberboard by mixing wood pulverized into a fibrous form with a melamine–urea–formaldehyde resin adhesive. Tudor et al. [28] investigated changes in sound absorption properties due to particle direction and density by creating a compressed board using larch bark, a waste material, as a raw material. Zheliazkova et al. [29] investigated the sound absorption properties of sound-absorbing materials created by combining carbonized cork boards and perforated wood. A review paper by Yang et al. [30] introduced sound-absorbing materials made of natural fibers, classifying them into three categories: raw materials, fiber assemblies, and composite materials. Although many studies have investigated the sound absorption properties of various natural and recycled materials, no specific research has been conducted on the sound absorption properties of compressed boards made from reeds, particularly on the impact of porous structures formed by low-density compression. Furthermore, there has been insufficient research on the changes in sound absorption properties caused by laminating reeds with other plant-based porous materials or by providing air layers. Thus, this study aims to provide new insights into sound-absorbing boards made from recyclable plant-based resources by investigating the sound absorption performance of RCBs and changes in sound absorption performance when laminated with other porous materials or provided with air layers.

2. Methodology

2.1. Prototype Low-Density RCB

A compressed board made of reeds was developed by Nagai et al. [31], who were looking for a new way to utilize reeds. ISO 16894 [32], a standard for particleboards that can be used not only for structural materials but also for furniture and interior decorations, was used as the target performance index. The reed compression board was fabricated by processing the dried reeds into long, thin shavings using a hammer crusher, agitating a spray gun while spraying a predetermined amount of adhesive, laying the shavings in a mold, and pressurizing them to a predetermined thickness using a heat-thickness machine. Although various boards can be made depending on the target values of the length, density, and thickness of the shavings, in this study, compression boards were made using compression-molding reeds at a low density, leaving a hollow layer on the surface and inside the material (Figure 1). Their sound absorption performance was measured.

Figure 1. Manufacturing of RCBs.

2.2. Measurement of Sound Absorption Performance

The sound absorption performance of the compression board as a test specimen was measured as follows: the transfer function method, which includes an acoustic tube and two microphones, was used to measure the normal-incidence sound absorption coefficient under rigid wall contact conditions, as shown in Figure 2. To measure the vertical incidence sound absorption rate, an acoustic tube (WinZacMTX, manufactured by Japan Acoustic Engineering Co., Sumida-ku, Tokyo, Japan) capable of measuring the frequency band from 200 to 4800 Hz was used with a test specimen 40 mm in diameter. The measurements were conducted in accordance with ISO 10534-2 [33].

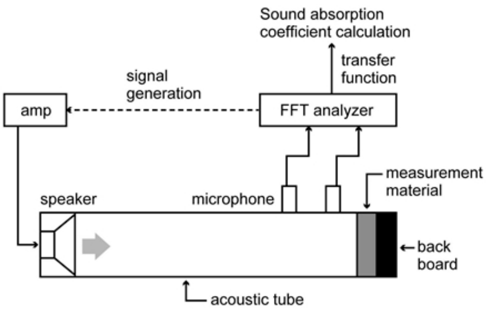


Figure 2. Measurement system for normal incidence sound absorption coefficient using an acoustic tube.

A circular piece with a diameter of 40 mm was placed in the acoustic tube as the test specimen, and the measurement was performed after sealing the circumference of the specimen with clay to prevent gaps. To account for errors owing to individual differences in the test specimens, three specimens were prepared for each material. The sound absorption measurements were conducted individually for each specimen, and the average and standard deviation of the measurement results for each specimen were calculated.

2.3. Test Specimens

Glass wool, wood fiber insulation, a bark fiber board made from cedar bark, and a carbonized cork board were used as porous materials for comparison with the RCB in the sound absorption test. The wood fiber insulation material used in this study consisted of wood chips made mainly from thinned domestic softwood, such as Abies sachalinensis and larch, which were processed into fibers and formed sponge-like shapes. The bark fiber board was made mainly of Japanese cedar bark, with bark fibers fixed on the board using a naturally derived adhesive. Table 1 presents the densities and details of the specimens.

For porous materials other than the RCB, commonly available materials were procured. Using a woodworking hole saw, samples with a diameter of 40 mm were cut out from the sheet materials and three test specimens were obtained for each material. The installation conditions for each test specimen were set according to the following three types, and the sound absorption rate of each specimen was measured (Figure 3).

(i) Single material
(ii) Porous material behind RCB
(RCB 15 mm + porous material 15 mm)
(iii) Providing an air layer at the back of (ii)
(RCB 15 mm + porous material 15 mm + back-air layer 15 mm)

Table 1. Types of specimens.

NO.	1	NO.	2
Appearance		Appearance	
Material	Reed Compression Board	Material	Reed Compression Board
Thickness	9 mm	Thickness	15 mm
Density	290 kg/m^3	Density	290 kg/m^3
NO.	3	NO.	4
Appearance		Appearance	
Material	Glass Wool	Material	Wood Fiber Insulation
Thickness	15 mm	Thickness	15 mm
Density	30 kg/m^3	Density	60 kg/m^3
NO.	5	NO.	6
Appearance		Appearance	
Material	Bark Fiber board	Material	Cork Board
Thickness	15 mm	Thickness	15 mm
Density	230 kg/m^3	Density	110 kg/m^3

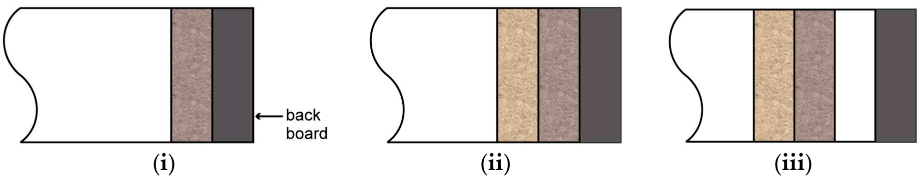
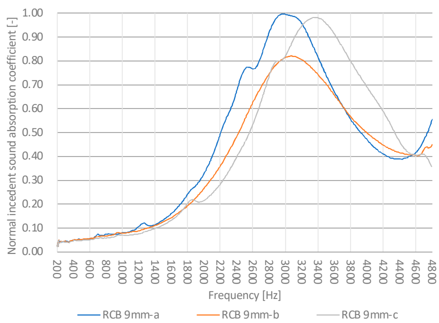


Figure 3. Installation conditions of the specimen. **(i)** Single material, **(ii)** RCB +porous material, **(iii)** RCB + porous material + back-air layer.

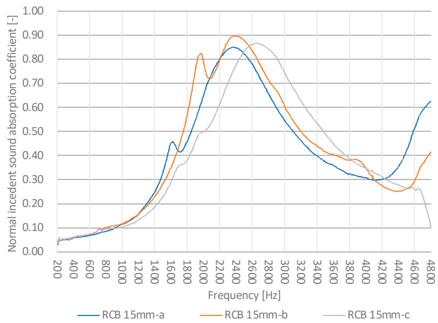
3. Results and Discussion

3.1. Sound Absorption Characteristics of Each Material

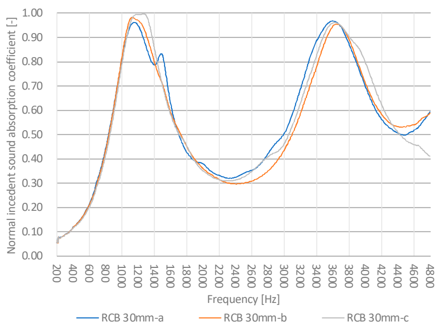
Figure 4 shows the sound absorption rate measurement results (200–4800 Hz) for the RCB according to thickness. The sound absorption rates were measured at four thicknesses: 9, 15, 30 (15 + 15), and 39 (9 + 15 + 15). To account for individual differences due to high anisotropy, measurements were conducted individually using three samples, and the data obtained from each sample are presented. Figure 5 shows the average values and standard deviation error bars for the three samples. Figure 6 presents the data showing the sound absorption rate in the low-frequency range (200–1600 Hz) targeted in this study.



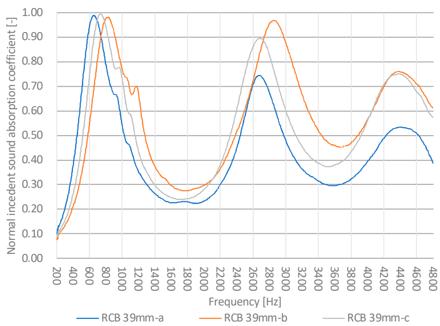
Sound absorption coefficient of 9 mm RCB



Sound absorption coefficient of 15 mm RCB



Sound absorption coefficient of 30 mm RCB



Sound absorption coefficient of 39 mm RCB

Figure 4. Measurement results of the RCBs' sound absorption coefficients by thickness.

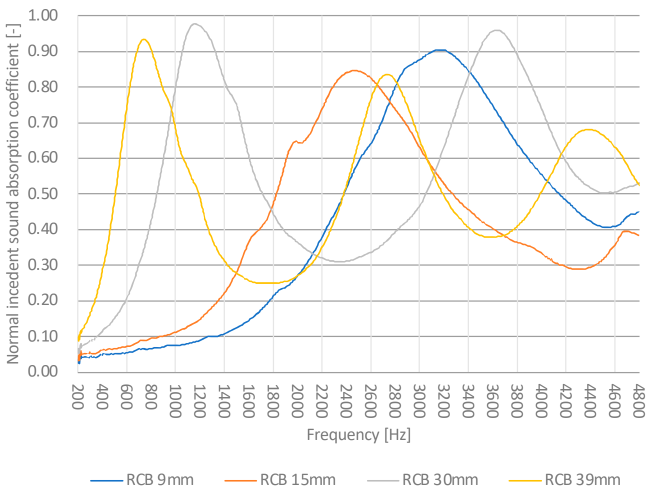


Figure 5. Comparison of measurement results of the RCBs' sound absorption coefficients by thickness (200–4800 Hz).

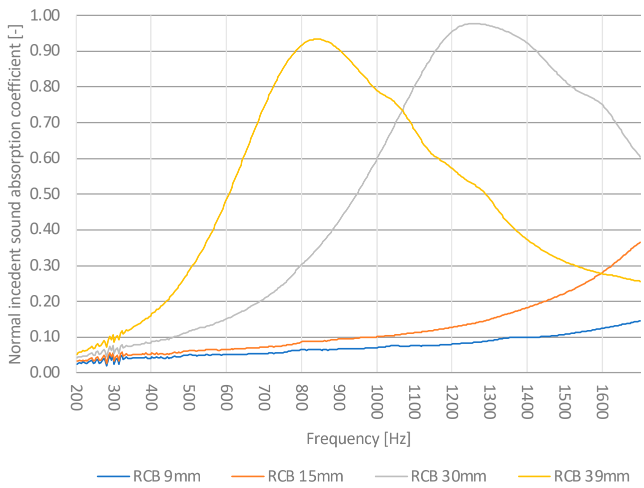


Figure 6. Comparison of measurement results of the RCBs' sound absorption coefficients by thickness (200–1600 Hz).

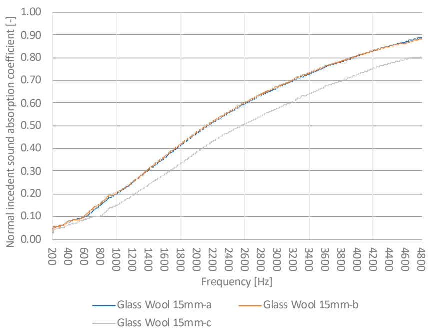
For all measured thicknesses, the sound absorption coefficient transitioned in a waveform pattern in response to changes in frequency. The frequency bands that first showed peaks in sound absorption were approximately 2800–3400 Hz for a thickness of 9 mm, 2200–2600 Hz for 15 mm, 1000–1300 Hz for 30 mm, and 600–900 Hz for 39 mm. As the thickness of the test specimen increased, the frequency decreased.

The results of sound absorption coefficient measurements for various porous materials under perpendicular incidence are presented. The sound absorption coefficients for perpendicular incidence were measured for thicknesses of 15 and 30 mm. Measurements at 15 mm were conducted individually using three samples (Figure 7). For the 30 mm measurement, two 15 mm samples were overlaid to create two samples, and measurements were taken (Figure 8). Data comparing each material, showing the average values and error bars representing the standard deviation for the frequency range of 200–4800 Hz, are shown in Figure 9. The data indicating the sound absorption coefficient for the low-frequency band (200–1600 Hz), which was the target of this study, are shown in Figure 10.

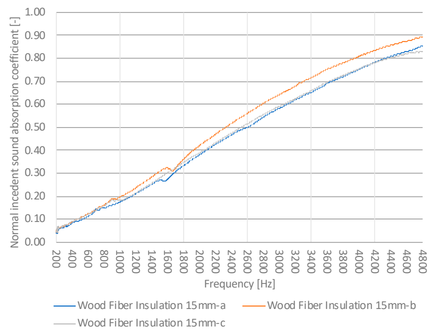
When comparing the sound absorption coefficients of porous materials with thicknesses of 15 mm and 30 mm in the frequency band of 200–4800 Hz, the sound absorption coefficients of glass wool and wood fiber insulation showed an increasing tendency as the frequency increased for the 15 mm thickness. In contrast, for the 30 mm thickness, they peaked in the 2600–3000 Hz frequency band and then gradually decreased. Increasing the thickness decreased the frequency band in which the sound absorption coefficient peaked. The RCB also showed a similar trend of the peak frequency band decreasing with increased thickness. However, the RCB exhibited a significant variation in the sound absorption coefficient across frequencies compared to other porous materials, suggesting the potential for effective sound absorption in specific frequency bands. At a thickness of 30 mm, it showed a higher sound absorption coefficient in the 900–1400 Hz frequency band than glass wool and wood fiber insulation.

3.2. Sound Absorption Coefficient of Multi-Layered Porous Materials

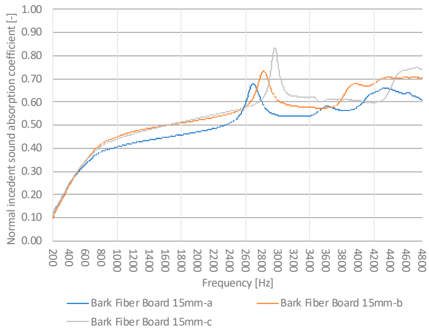
Figure 11 shows the sound absorption coefficient measurement results when the other porous materials were overlaid behind the RCB (15 mm). Two samples were prepared and tested. The average sound absorption coefficient measured from the two samples is presented, and the data comparing the sound absorption coefficient of each material for the frequency ranges of 200–4800 Hz and 200–1600 Hz are shown in Figure 12. To compare the sound absorption effects in the low-frequency band, which is the target of this study, a comparison with the sound absorption coefficient of standalone porous materials of the same 30 mm thickness is presented in Figure 13.



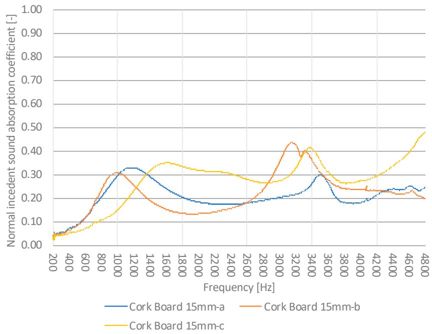
Sound absorption coefficient of glass wool



Sound absorption coefficient of wood fiber insulation

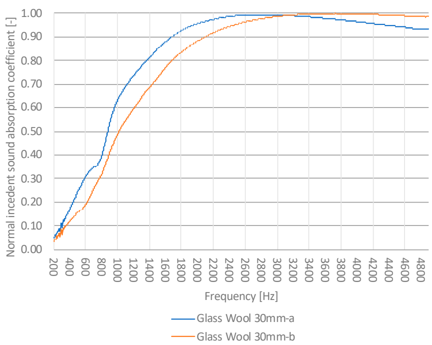


Sound absorption coefficient of bark fiber board

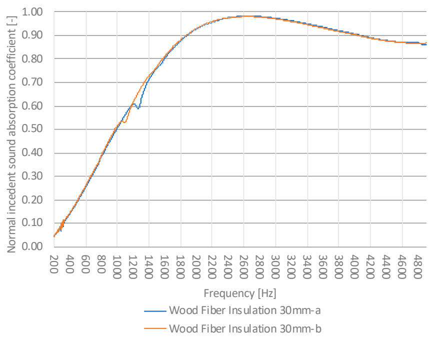


Sound absorption coefficient of cork board

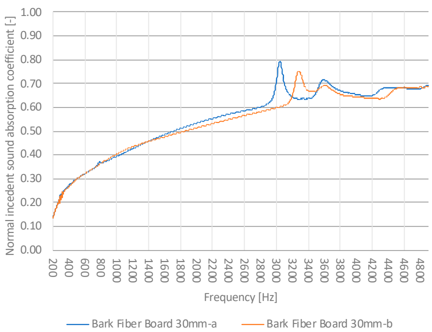
Figure 7. Measurement results of the sound absorption coefficients of porous materials (15 mm).



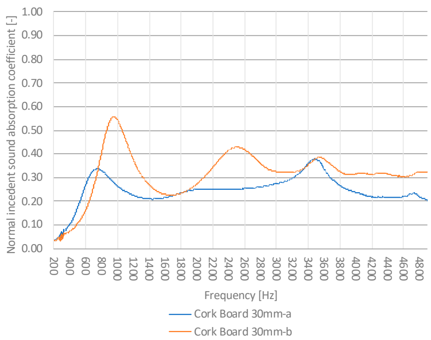
Sound absorption coefficient of glass wool



Sound absorption coefficient of wood fiber insulation

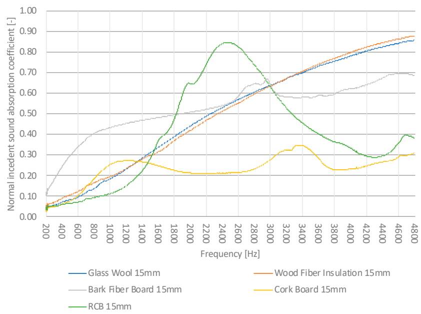


Sound absorption coefficient of bark fiber board

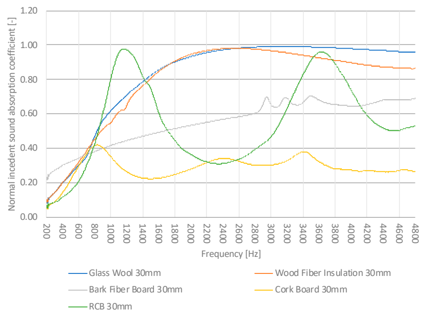


Sound absorption coefficient of cork board

Figure 8. Measurement results of the sound absorption coefficients of porous materials (30 mm).

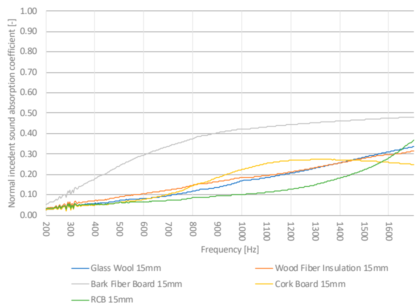


15 mm

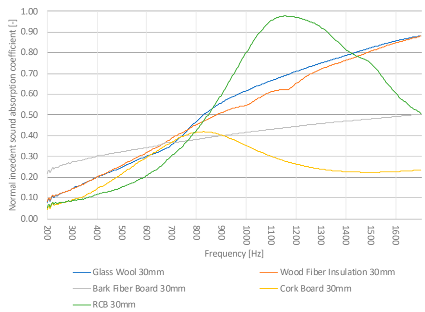


30 mm

Figure 9. Comparison of measurement results of the sound absorption coefficients of porous materials (200–4800 Hz).

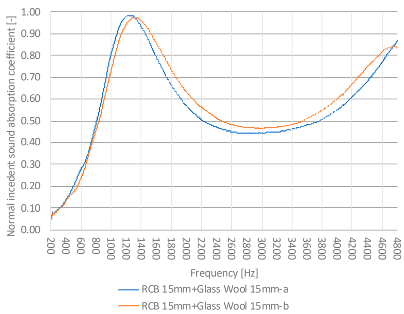


15 mm

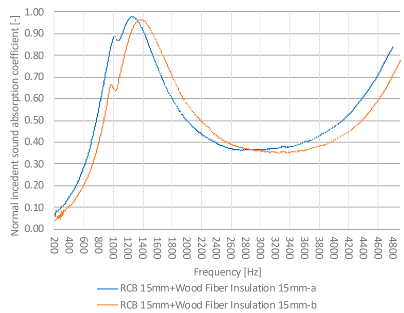


30 mm

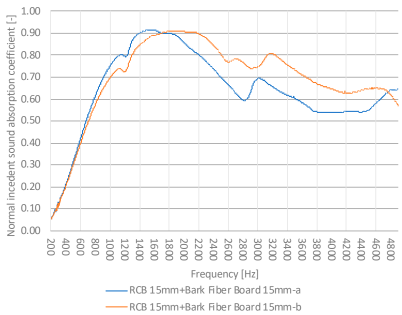
Figure 10. Comparison of measurement results of the sound absorption coefficients of porous materials (200–1600 Hz).



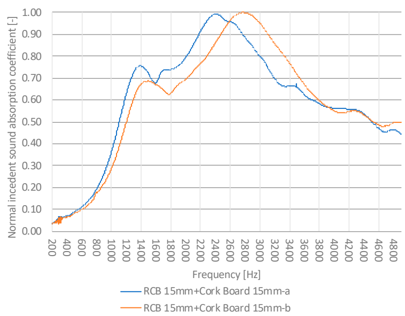
Sound absorption coefficient of
15 mm RCG + 15 mm glass wool



Sound absorption coefficient of
15 mm RCG + 15 mm wood fiber insulation

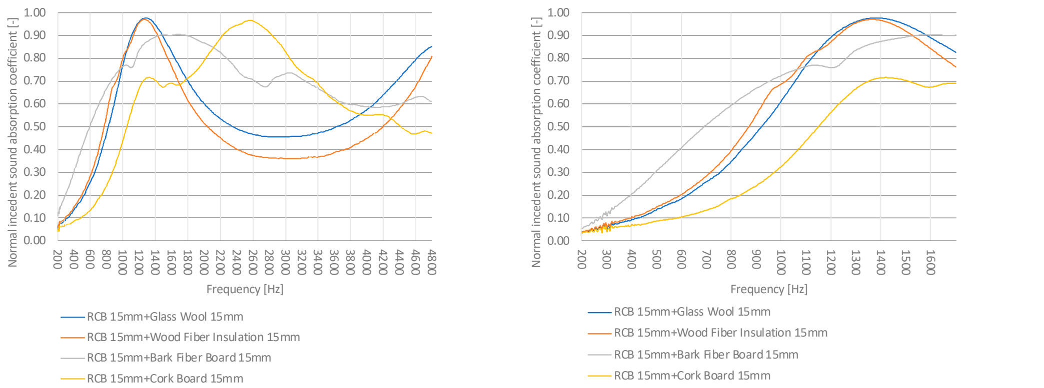


Sound absorption coefficient of
15 mm RCG + 15 mm bark fiber board



Sound absorption coefficient of
15 mm RCG15 + 15 mm cork board

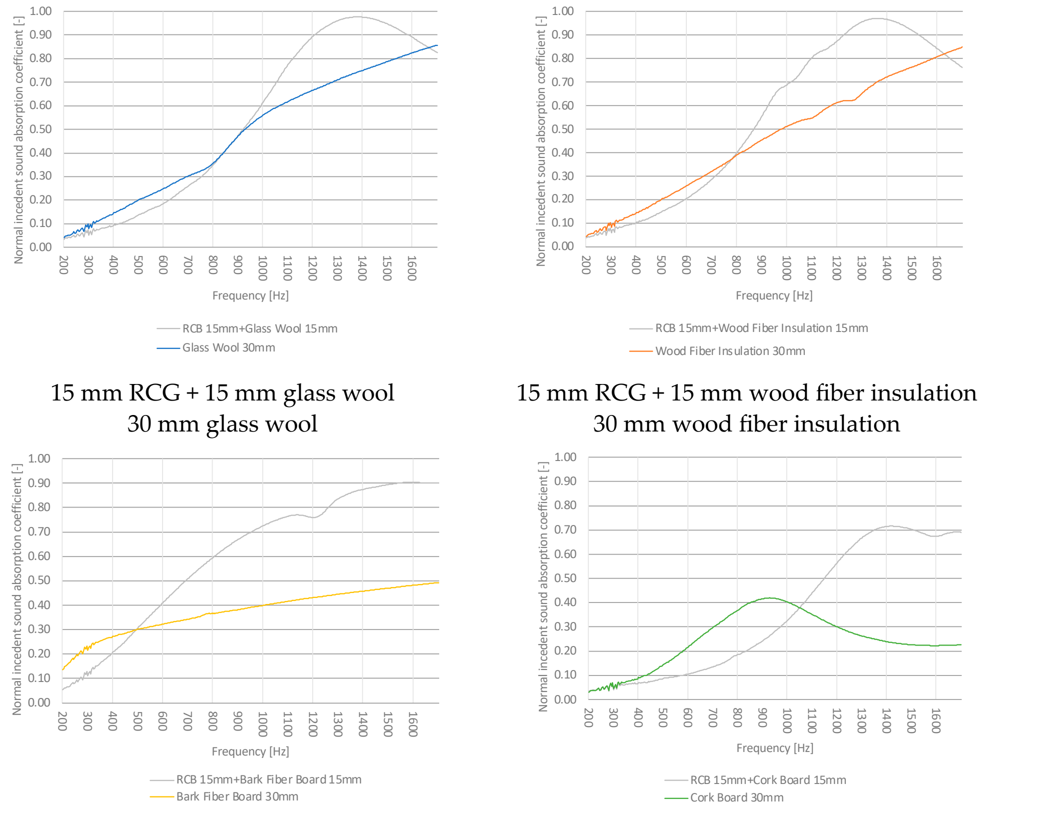
Figure 11. Measurement results of the sound absorption coefficient of multi-layered porous materials (15 + 15 mm).



200–4800 Hz

200–1600 Hz

Figure 12. Comparison of measurement results of the sound absorption coefficient of multi-layered porous materials (15 + 15 mm).



15 mm RCG + 15 mm glass wool
30 mm glass wool

15 mm RCG + 15 mm wood fiber insulation
30 mm wood fiber insulation

15 mm RCG + 15 mm bark fiber board
30 mm bark fiber board

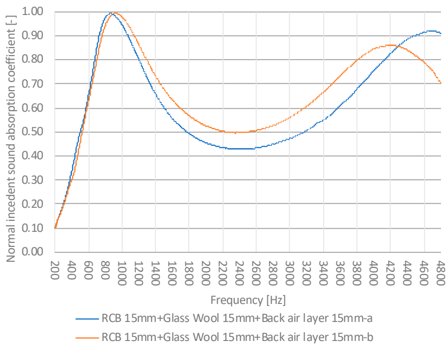
15 mm RCG + 15 mm cork board
30 mm cork board

Figure 13. Comparison of measurement results of the sound absorption coefficients of multi-layered porous materials (15 + 15 mm) and porous material (30 mm).

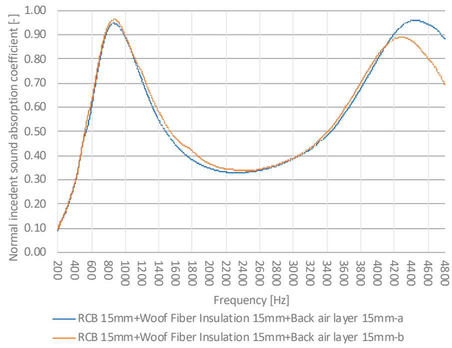
In materials layered with RCB and glass wool as well as RCB and wood fiber insulation, the first peak of sound absorption was observed in the frequency band of 1000–1600 Hz, exhibiting a high sound absorption coefficient of 0.8 or more. In this frequency band, when compared to the sound absorption coefficients of glass wool and wood fiber insulation of the same thickness (30 mm), the layered materials demonstrated superior sound absorption performance. This suggests that the RCB effectively enhanced sound absorption in that frequency range.

3.3. *Sound Absorption Coefficient of Multi-Layered Porous Materials with Back-Air Layer*

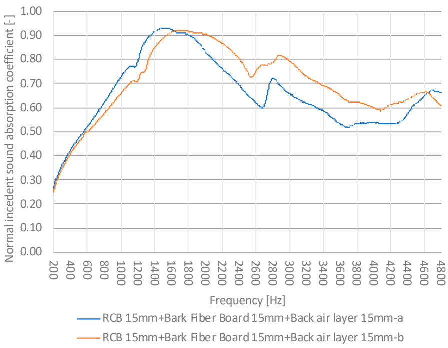
Figure 14 shows the sound absorption coefficient measurement results for materials layered with RCB and porous materials (15 mm + 15 mm) when a 15 mm back-air layer is provided behind them. Two samples were prepared and tested. The average sound absorption coefficient measured from the two samples is presented, and the data comparing the sound absorption coefficient of each material for the frequency ranges of 200–4800 Hz and 200–1600 Hz are shown in Figure 15. To determine the sound absorption effects of a back-air layer, a comparison of the sound absorption coefficients of the same material combination with and without a back-air layer is presented in Figure 16.



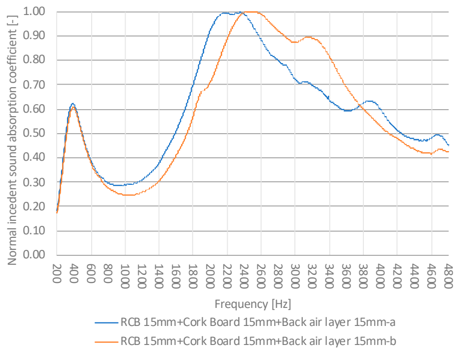
Sound absorption coefficient of
15 mm RCG + 15 mm glass wool + 15 mm back-air layer



Sound absorption coefficient of
15 mm RCG + 15 mm wood fiber insulation + 15 mm back-air layer



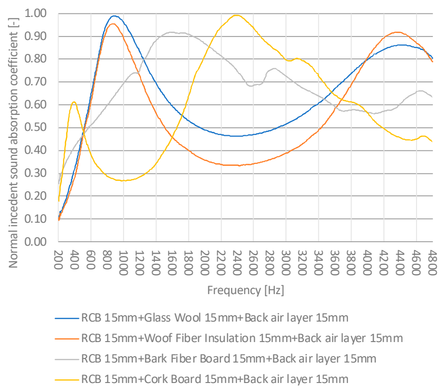
Sound absorption coefficient of
15 mm RCG + 15 mm bark fiber board + 15 mm back-air layer



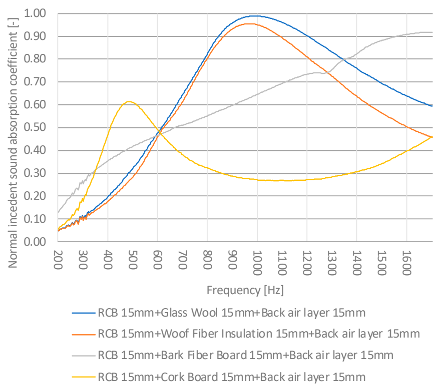
Sound absorption coefficient of
15 mm RCG + 15 mm cork board + 15 mm back-air layer

Figure 14. Measurement results of the sound absorption coefficient of multi-layered porous materials (15 + 15 mm) + back air-layer (15 mm).

By installing an air layer behind the material in materials that combined RCB and glass wool, the frequency band that initially showed a peak in the sound absorption rate shifted from 1200–1600 Hz to 700–1100 Hz, confirming effective sound absorption in the lower frequency band. Nearly identical results were obtained with the RCB and wood fiber insulations. For the bark fiber board, the sound absorption rate increased in the 200–800 Hz frequency band but was almost the same as when there was no air layer in the 800–1600 Hz range. On the cork board, a peak in the sound absorption rate shifted to the low-frequency band of 300–500 Hz, but the absorption rate remained at 0.6. The combination of RCB and glass wool and RCB and wood fiber insulation (15 mm + 15 mm) indicated that by adding an air layer (15 mm) behind them, they can effectively absorb sound in the target frequency band of 500–1000 Hz.

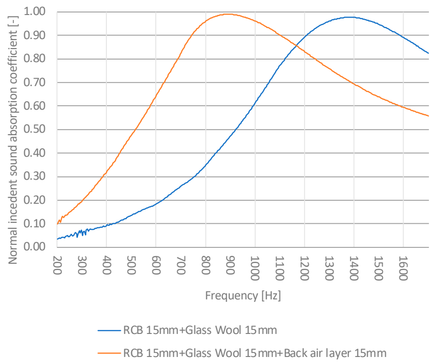


200–4800 Hz

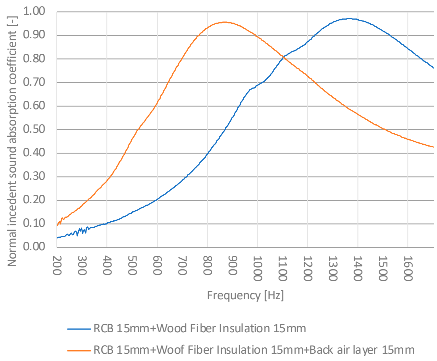


200–1600 Hz

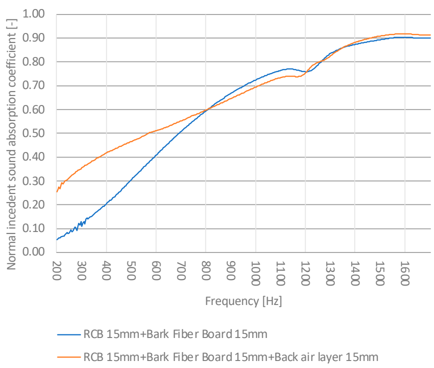
Figure 15. Comparison of measurement results of the sound absorption coefficients of multi-layered porous materials (15 + 15 mm) + back air-layer (15 mm).



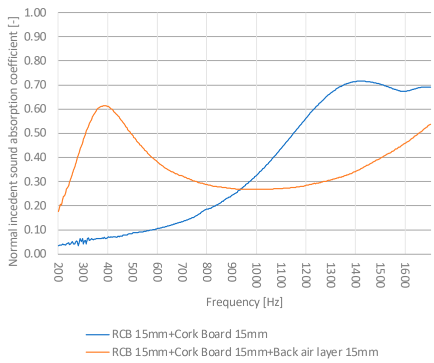
15 mm RCG + 15 mm glass wool
15 mm RCG + 15 mm glass wool + 15 mm back-air layer



15 mm RCG + 15 mm wood fiber insulation
15 mm RCG + 15 mm wood fiber insulation + 15 mm back-air layer



15 mm RCG15 + 15 mm bark fiber board
15 mm RCG + 15 mm bark fiber board + 15 mm back-air layer



15 mm RCG + 15 mm cork board
15 mm RCG + 15 mm cork board + 15 mm back-air layer

Figure 16. Comparison of measurement results of the sound absorption coefficients of multi-layered porous materials (15 + 15 mm) and multi-layered porous materials (15 + 15 mm) with back-air layer (15 mm).

4. Conclusions

The utilization of plant-based recyclable resources native to a region as building materials is an effective way to reduce CO_2 emissions and achieve a sustainable society. However, for plant-based resources to become commonly used in society, it is important to examine how they can be used to verify their performance. In this study, we investigated the inherent porous nature of plant-based resources and verified their potential as sound-absorbing materials for indoor applications. The normal incidence sound absorption of the RCB, wood fiber insulation, and bark fiber board made from cedar bark, cork board, and glass wool of the same thickness (15 mm) was measured to determine the differences in their sound absorption characteristics. When an air layer was installed, a change was observed in the frequency band, where several materials first exhibited peaks. For the combination of RCB and wood fiber insulation, which initially showed a peak in the sound absorption coefficient at 1200–1600 Hz, a peak was observed at 700–1100 Hz when an air layer was provided. This indicates its potential as an effective sound-absorbing material in the frequency band of human voices (500–1000 Hz), which was the target of this study. The results showed that porous sound-absorbing materials made from plant-based resources can effectively demonstrate sound-absorbing performance through careful examination of the differences in sound-absorbing properties between materials, the composition of multiple layers of air, and the installation conditions of the sound-absorbing materials. The sound-absorbing material developed in this study targeted the human voice for sound absorption. Therefore, it is not expected to be effective in absorbing noise in the high-frequency range and may not be suitable for use in all locations. Further experiments and analyses are required to verify whether sound-absorbing materials can address noise in the high-frequency range. Additionally, the sound absorption coefficient can vary even if the fiber quality, fiber diameter, thickness, and density are the same, depending on the arrangement of the fibers. For plant resources, which are complex porous materials with high anisotropy, it is important to understand the sound absorption characteristics of each material through actual measurements.

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