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An Experimental Study on the Performance of Corrugated Cardboard as a Sustainable Sound-Absorbing and Insulating Material

Chun-Won Kang [1], Mina K. Kim [2] and Eun-Suk Jang [1,3,*]

[1] Department of Housing Environmental Design and Research Institute of Human Ecology, College of Human Ecology, Jeonbuk National University, Jeonju 54896, Korea; kcwon@jbnu.ac.kr
[2] Department of Food Science & Human Nutrition and Research Institute of Human Ecology, College of Human Ecology, Jeonbuk National University, Jeonju 54896, Korea; minakim@jbnu.ac.kr
[3] R&D Center, Sambo Scientific Co., Ltd., Seoul 07528, Korea
* Correspondence: esjang@sambosc.com

Abstract: The continuing development of industrialization and increasing population density has led to the emergence of noise as an increasingly common problem, requiring various types of sound absorption and insulation methods to address it. Meanwhile, the recycling of resources to ensure a sustainable future for the planet and mankind is also required. Therefore, this study investigates the potential of corrugated cardboard as a resource for noise reduction. The sound absorption and insulation performance of non-perforated corrugated cardboard (NPCC) were measured, and modified corrugated boards were fabricated by drilling holes either through the surface of the corrugated board alone or through the corrugated board in its entirety. The sound-absorption/insulation performance both of perforated corrugated cardboard (PCC) and perforated corrugated cardboard with multi-frequency resonators (PCCM) were measured using the transfer function method and the transmission matrix method. To determine the effectiveness of NPCC, PCC, and PCCM in noise reduction, the sound pressure level was analyzed by applying it to a home blender. The results showed PCCM's sound absorption and insulation performance to be excellent. On the basis of these findings, we propose the use of PMMC as an eco-friendly noise-reduction material.

Keywords: eco-friendly sound-absorbing material; corrugated cardboard; perforated corrugated cardboard; sound-absorption coefficient; sound transmission loss; transfer function method; transfer matrix method; multi-frequency resonator

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1. Introduction

Because Republic of Korea is a country with small land mass and high population density, apartment housing is common [1]. Noise complaints in these apartment complexes are an unavoidable reality [2]. According to the National Noise Information System (NOISEINFO), a government agency that monitors noise problems in the country, the number of reported noise-related problems has increased exponentially, from 1829 cases in 2012 to 10,142 cases in 2019 [3].

Overall noise level reduction is necessary for maintaining an agreeable sound environment [4]. Blocking or reducing noise through sound absorption and sound insulation is a mainstream method [5]. Accordingly, a significant amount of research has been conducted in order to identify materials with excellent sound absorption and sound insulation properties [6,7]. Sound-absorbing materials typically include one or more components from porous materials [8], plate or membrane vibration materials [9], or resonators [10,11].

Traditionally, the most important metric by which a potential sound-absorbing material is assessed is its absorption ability. However, while the materials typically relied on for indoor acoustic control are typically derived from petroleum [12], recent years have seen a new focus on the utilization of sustainable green materials, including agricultural by-products, to fulfill this function [13–15]. In this spirit, a wide range of studies have been conducted of eco-friendly sound-absorption materials such as rice straw [16], rice husks [17], palm fibers [18], giant reeds [19], egg cartons [20], and wood paper [21].

Corrugated cardboard is a bio-degradable, eco-friendly paper material that is inexpensive and robust in relation to its weight [22]. Its thickness and empty middle space make it a useful sound insulating material [23]. It can be used as a resonance sound-absorbing material either by perforating only the surface of the corrugated board or by penetrating the entire thickness of the corrugated board. Its sound-absorption properties for specific frequency bands can be enhanced by modifying hole size and depth [24]. Corrugated cardboard can also be used as an interior building material and, when discarded, can be reused for pulp or paper [25]. Corrugated cardboard is known for its utility as a building material [25,26], and some studies have suggested the potential of hydrophobic treatment to avoid moisture absorption and further expand its versatility [27,28]. Moreover, it may act as a flame retardant, improving building safety [29].

With an eye toward these benefits, we set out to determine whether corrugated cardboard could be utilized as a sustainable noise-reducing building material.

Berardi and Iannace [30] measured cardboard's sound-absorption coefficient by inserting its veins in a direction parallel to the impedance tube. This resulted in excellent sound-absorption performance at medium and high frequencies but poor performance at low frequencies below 400 Hz. In short, while the material performed well in the veins of the cardboard direction, as a practical matter, it is not easy to use the material in this way.

Kang and Seo [31] investigated changes to the resonant frequency of the cardboard as a function of changes to the aperture ratio. They found no significant changes but reported that sound absorption at a specific frequency was significantly increased by perforations of a certain depth and size. Kang et al. [32] reported that applying porous polyurethane foam attached to a corrugated cardboard to a household blend reduced the sound-absorption coefficient and sound transmission loss. Polyurethane foam, however, is not an eco-friendly sound-absorbing material, and sound-absorbing performance may be improved with additional research into the corrugated board itself.

This study developed a natural sound absorber using triple-layer-corrugated cardboard whose inner surface layers were pierced with holes to enhance its resonance sound-absorbing properties. Three types of corrugated cardboard were prepared: non-perforated corrugated cardboard (NPCC), perforated corrugated cardboard (PCC), and perforated corrugated cardboard with multi-frequency resonator (PCCM). The sound absorption and insulation properties of each of these types were then measured using the transfer function method and the transmission matrix method.

To test these corrugated sound-absorbing materials, they were applied to the use case of home blenders. A home blender was selected as a noise generator since it is one of the most common noise-producing household appliances [33].

The noise level of the blender's rotor was first analyzed. After this, a Helmholtz resonator actively formed in the thickness direction corresponding to the frequency characteristics of the noise source was created on the surface of the corrugated cardboard.

An additional cavity layer was installed between the single-resonator corrugated cardboard and the NPCC, while part of the surface perforation was connected to the rear layer in order to create a multi-resonator with multiple frequencies. The noise reduction effect on the blender was evaluated by measuring and comparing the sound-absorption rate, acoustic transmission loss, and noise level of the fabricated single-resonator and multi-resonator-perforations in relation to hole diameter and perforation ratio.

2. Materials and Methods

2.1. Sample Preparation

As shown in Figure 1, triple-walled, seven-layer corrugated cardboard with 1800 g/m^2 base weight and 15.0 mm thickness was sourced from a Korean market (Daeyoung Packaging Co, Ltd., Ansan-si, Korea).

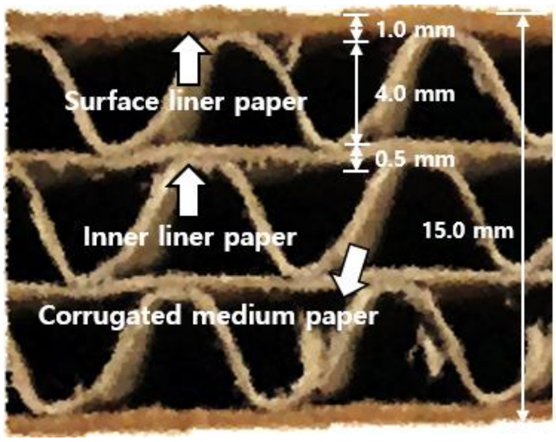

Figure 1. Triple-wall corrugated cardboard structure.

In this study, three types of corrugated cardboard were used as sound absorbers. Figure 2 shows the respective structures of the three corrugated cardboard types, while Figure 3 shows application of the cardboard to the blender. NPCC denotes non-perforated corrugated cardboard (Figure 3a). PCC denotes single-resonance sound-absorbing corrugated cardboard whose surface liner paper was pierced with 2.3 mm diameter holes at 14 mm intervals (Figure 3b).

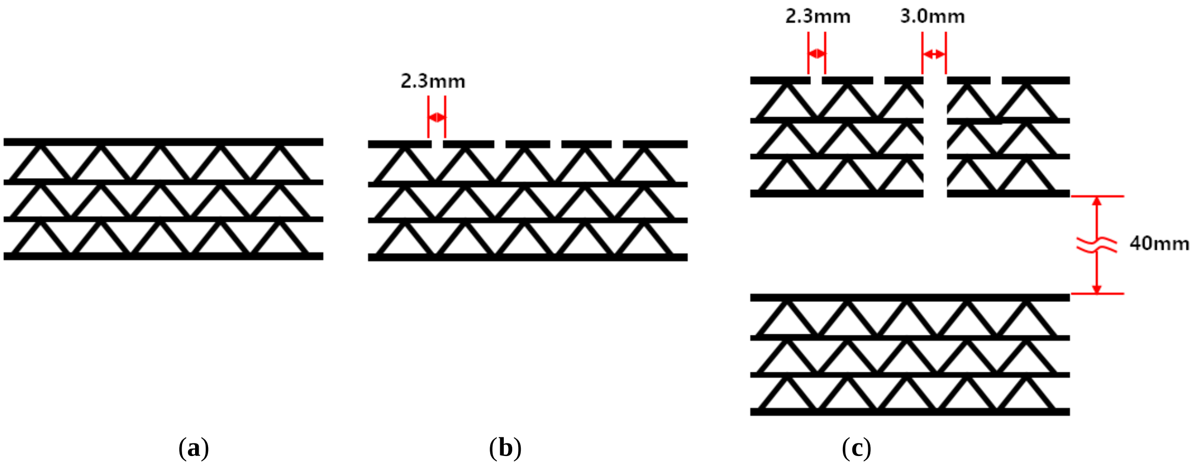

Figure 2. Three corrugated cardboard type structures. (**a**): NPCC, (**b**): PCC and, (**c**): PCCM.

PCCM denotes PCC with additional 3.0 mm diameter holes (1/4 of the number of 2.3 mm diameter holes). The 3.0 mm diameter holes pierced all 7 layers of the corrugated cardboard. There was a 4 cm air cavity at the back where we added NPCC (Figure 3c).

Resonance occurs at different frequencies depending on perforated hole diameter, surface liner paper thickness, perforated hole area, and distance from the inner liner paper. The resonance sound-absorption frequency was calculated as follows:

$$f_0 = c/2\pi(G/V)^{0.5} \tag{1}$$

$$G = s/le \tag{2}$$

$$le = l + \delta \quad (3)$$

where c: sound velocity; G: neck conductivity; V: cavity volume; s: neck surface area; le: effective neck length; l: neck length; and δ: end correction (≒ 0.8d)

Therefore,

$$f_0 = c/2\pi(s/V(1 + \delta))^{0.5} \quad (4)$$

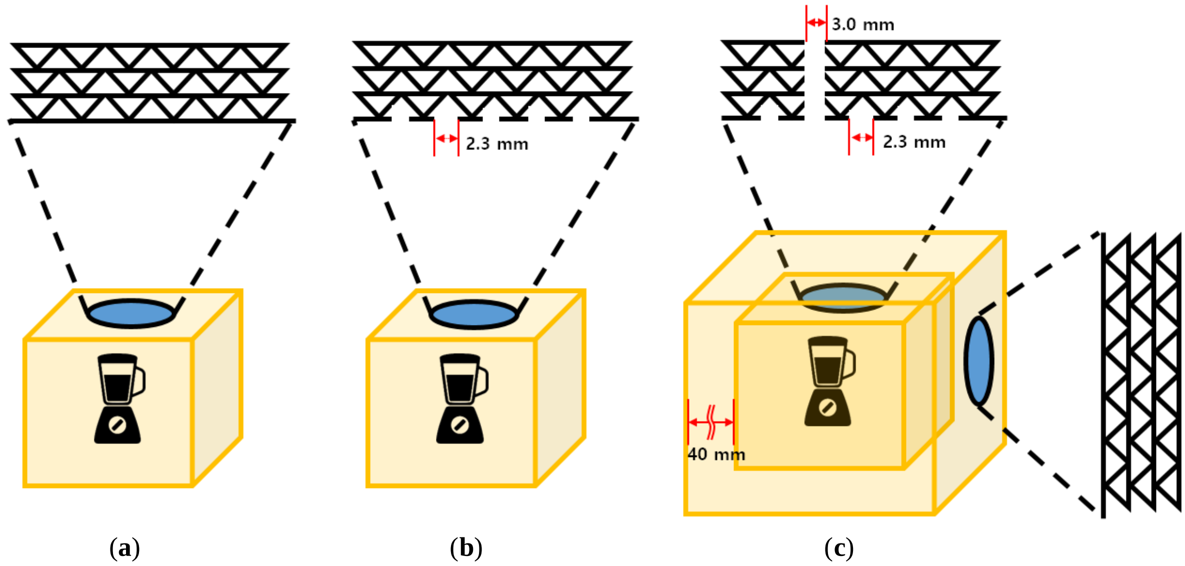

Figure 3. Three types of corrugated cardboard types for sound-absorbing materials applied to the blender. (**a**): NPCC, (**b**): PCC, and (**c**): PCCM.

2.2. *Measurement of Sound-Absorption Coefficient Using Transfer Function Method*

The sound-absorption coefficient (SAC) of the NPCC, PCC, and PCCM was measured using a B&K type 4206 impedance tube according to ISO 10534-2 [34] (Figure 4). We additionally calculated the noise-reduction coefficient (NRC) as the average of the sound-absorption rates of 200, 500, 1000, and 2000 Hz.

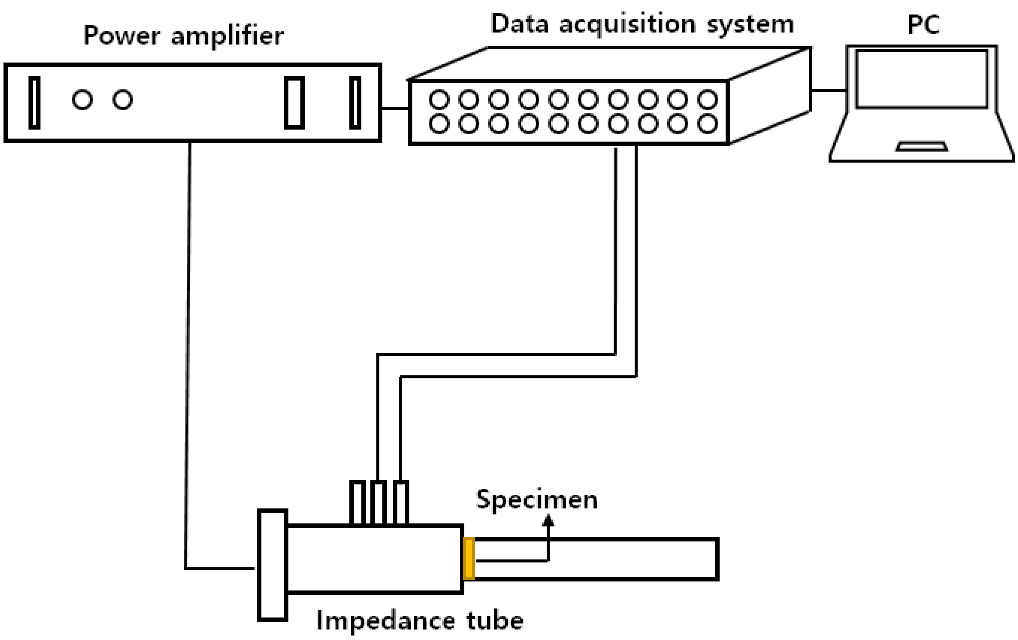

Figure 4. Schematic for B&K type 4206 impedance tube used to measure SAC.

Specimens were cut into 29 mm diameter pieces and inserted into an impedance tube. We added silicon O-rings to prevent experimental errors due to gaps between the sample and the wall of the impedance tube. SAC was measured in the 100–6400 Hz frequency range. Temperature, relative humidity, and air pressure were 25.8 °C, 53%, and 1012.00 hPa, respectively. Sound velocity, air density, and acoustic impedance were 346.62 m/s, 1.177 kg/m^3, and 408.0 Pa/(m/s), respectively.

2.3. STL Measurements Using Transmission Matrix Method

Sound transmission loss (STL), the ratio of the difference between incident sound energy to the material and transmitted sound energy to the material, represents the material's sound insulation performance. In this study, STL was measured in the 100–6400 Hz frequency band by the transmission matrix method according to ASTM E-2611 [35], using a B&K type 4206-T impedance tube to measure acoustic transmission loss (Figure 5). Temperature, relative humidity, and air pressure during measurement were 26.3 °C, 50%, and 1010.0 hPa, respectively.

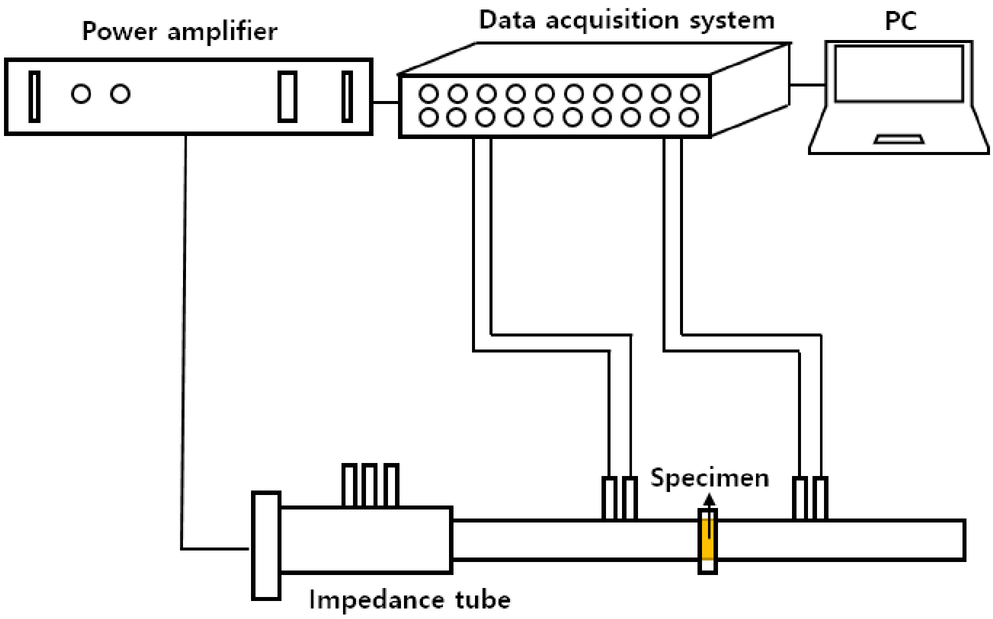

Figure 5. Schematic for B&K 4206-T impedance used to measure STL.

2.4. Sound Pressure Level Analysis

To verify the actual noise reduction effect, we fabricated a cover using NPCC, PCC, and PCCM and applied this to the blender. First, we performed a sound pressure level analysis. Sound pressure level was measured using a B&K type 2250 handheld sound analyzer in the 63–16,000 Hz frequency range with a 1/3 octave analyzer. Sound pressure level can be measured from 63 Hz. However, there is an experimental error due to noise generation below 50 Hz; therefore, it was measured at frequencies above 100 Hz [33,34]. Sound pressure was measured approximately 1 m from the top of the blender, and the sound pressure level is given as the average of the measured values over 20 s. At the blender's maximum power, the maximum noise peak was in the 1–2 kHz frequency band. Using this information, the resonance cover was optimized for the 1–2 kHz frequency band. The blender was enclosed with the NPCC, PCC, and PCCM covers, and noise levels measured. Temperature, relative humidity, and air pressure during measurements were 28.7 °C, 54%, and 1017.2 hPa, respectively.

3. Results and Discussion

3.1. SAC Results from Transfer Function Method

Figure 6 shows the SAC for NPCC, PCC, and PCCM in the 100–6400 Hz frequency range measured by impedance tube. The average SAC and NRC of NPCC were 0.062 (SD 0.010) and 0.055 (SD 0.012), respectively. This indicates almost no sound absorption. The average SAC and NRC of PCC were 0.331 (SD 0.009) and 0.346 (SD 0.007), respectively. The average SAC and NRC of PCCM were 0.362 (SD 0.017) and 0.423 (0.009), respectively.

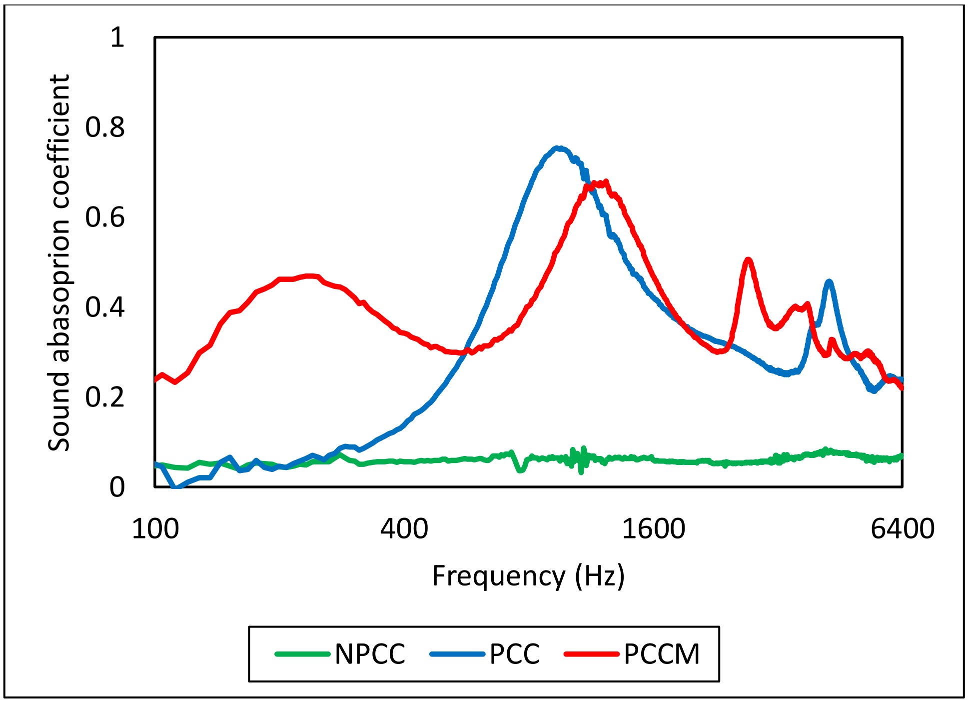

Figure 6. SAC results for NPCC, PCC, and PCCM.

As shown in Figure 2b, the PCC's void volume between the perforated surface liner paper and the inner liner paper becomes a single resonator. This is why it can resonate at specific frequencies.

The theoretical resonance frequency of PCC calculated from Equation 4 was 1102 Hz. As shown in Figure 6, the resonance frequency of the PCC obtained experimentally was 936 Hz. As Figure 2c shows, the PCCM's void volume is equal to that of the PCC, plus additional void volume between the corrugated cardboard and the rear space. This means that resonance occurs in two places, at 380 and 1050 Hz. The theoretically calculated resonance frequency and experimentally measured resonance frequency were little bit different. The cause of such an error is that the corrugated cardboard does not only absorb sound by resonance, but an effect due to weak plate vibration may be added. In addition, in this study, since the hole was drilled by the experimenter, not by a machine such as CNC, the hole size may not be constant; therefore, the frequency mismatch can be regarded as an experimental error.

As a result, the average SAC of the PCC increased approximately 5 times more than that of the NPCC, while the NRC of the PCC increased approximately 6 times more than that of the NPCC. In addition, the PCC had peak values of SAC, which were 0.754 at 936 Hz and 0.457 at 4264 Hz. The SAC of the PCC was significantly increased at a specific frequency.

The average SAC of the PCCM was similar to that of the PCC, but the NRC of the PCCM increased approximately 1.2 times more than that of the PCC. The SAC peak values for the PCCM were 0.680 at 1232 Hz, 0.628 at 2704 Hz, and 0.469 at 240 Hz. The PCCM is a multi-resonator and showed peak SAC values at various frequencies.

Compared with other NRC natural fiber composite board (Bagasse: 0.32, Bamboo: 0.35, Banana 0.40, Coir of 0.29, Corn: 0.36) [36], the PCCM demonstrated higher sound-absorption capabilities.

We also compared the sound-absorption performance against Wooden MPP (micro-perforated panels), which are an eco-friendly sound-absorbing material in wide use. We extracted raw data for the sound-absorbing graph result of wooden MPP with holes of 2 mm in diameter and 10 mm intervals in a 5 mm wooden board and the rear air cavity set to 50 mm from the previous study [37] using Engauge Digitzer software [38], and compared the performance of this material with our cardboard. In addition, we added to compare with parallel direction of NPCC from Beradi et al. [27].

As shown Figure 7, PCC's SAC absorbed sound better over 680 Hz than Wooden MPP, and PCCM generally performed better at sound absorption than Wooden MPP, with the exception of the 400–600 Hz range. The wooden MPP had a rear space of 50 mm, while that of the PMCC was 40 mm. Were the space behind the PCC and PCCM to be further increased, the SAC at low frequencies might increase even more.

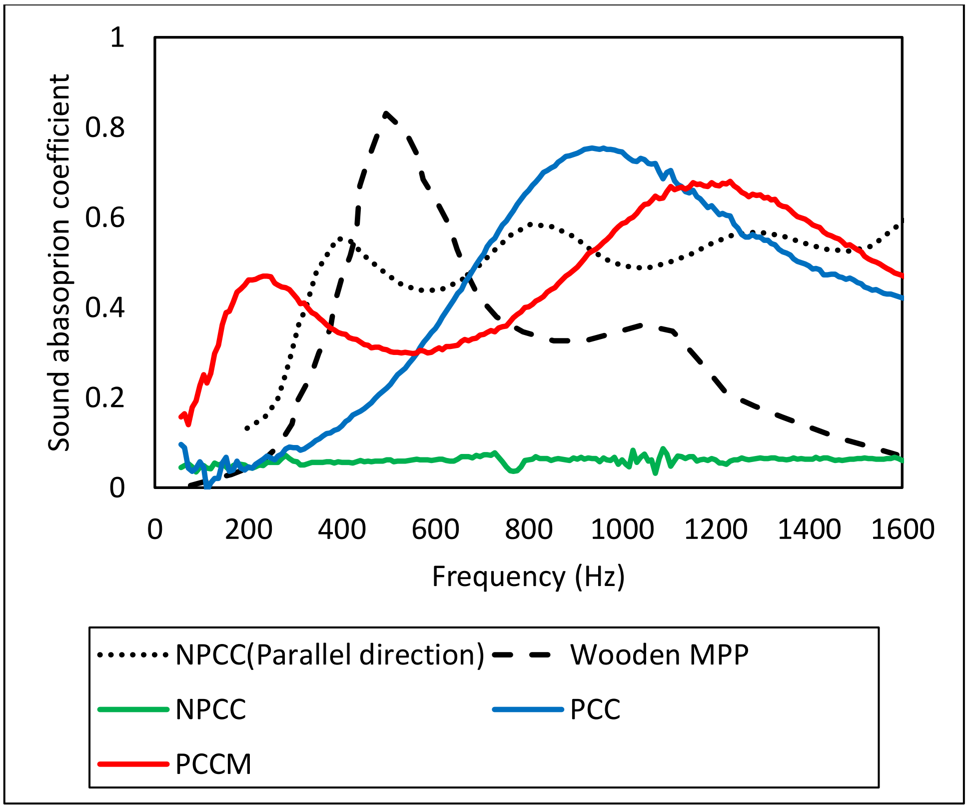

Figure 7. Compared SAC results for Wooden MPP from Song et al. [37], NPCC (Parallel direction) from Berardi et al. [27], NPCC, PCC, and PCCM from this work.

PMCC generally performed better at sound absorption than parallel direction of NPCC from Beradi et al. [27], with the exception of the 320–940 Hz range.

In sum, PCC and PMCC did not perform worse than Wooden MPP and parallel direction of NPCC. Corrugated cardboard is cheaper than wooden boards, lighter, easier to install, and easier to recycle. In addition, parallel direction of NPCC is not easy to use practically as sound-absorption material. Therefore, PCC's and PMCC's many advantages make them ideal environmentally friendly sound-absorbing materials.

In sum, PCC and PCCM did not perform worse than Wooden MPP. Corrugated cardboard is cheaper than wooden boards, lighter, easier to install, and easier to recycle; PCC's and PMCC's many advantages make them ideal environmentally friendly sound-absorbing materials.

3.2. STL Results from Transmission Matrix Method

Figure 8 shows the SLT of NPCC, PCC, and PCCM in the 100–6400 Hz frequency range.

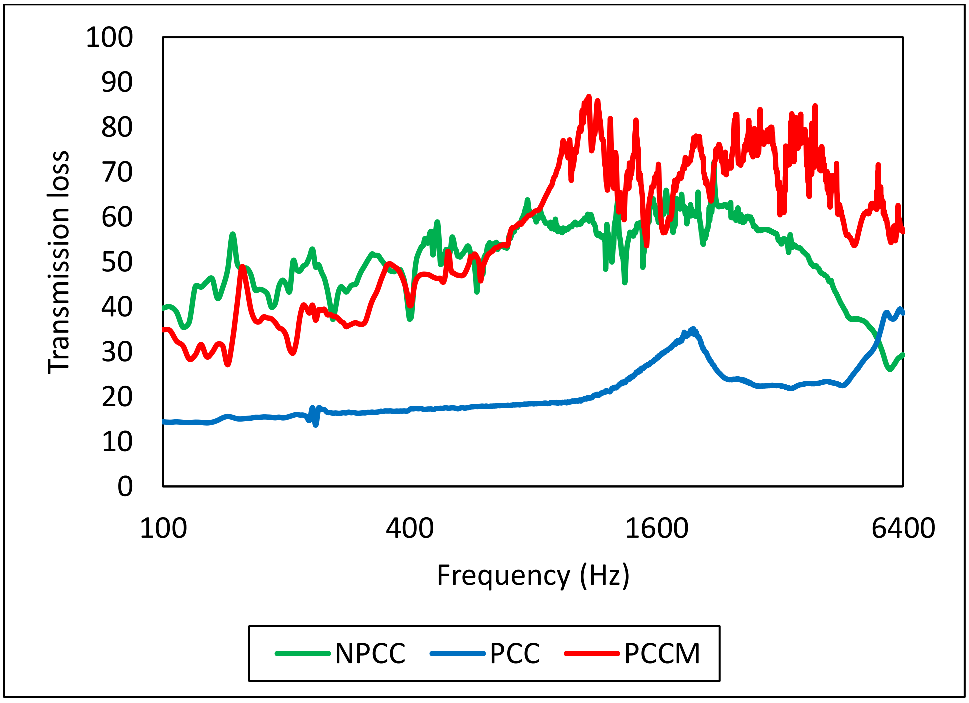

Figure 8. STL for CC, PCC, and PCCM.

The average STL of NPCC, PCC, and PCCM were 48.246 (SD 4.683) dB, 25.590 (SD 1.839) dB, and 65.011 (0.878) dB, respectively.

NPCC is a good sound insulation material in itself. The PCC's STL was significantly lower than that of the NPCC due to the surface liner paper perforations. However, the PCCM also showed good sound-insulation performance because the multi-perforated corrugated cardboard on the front side and the NPCC on the rear-side block the sound energy.

Corrugated cardboard has a low specific gravity and is thick; therefore, transmission loss is generally high. As frequency increases, transmission loss decreases. Below 1000 Hz, corrugated cardboard is a good sound-insulation material.

3.3. Sound Pressure Level Analysis

The average sound pressure level of the blender without a cover was 86.267 (SD 1.840) dB, while the levels using NPCC, PCC, and PCCM were 75.500 (SD 0.432) dB, 72.133 (SD 1.096) dB, and 64.367 (SD 0.573) dB, respectively (Figure 9).

NPCC application already reduced the blender's sound level pressure by 11 dB solely on account of its sound insulation effect. PCC application lowered the noise reduction rate by 13 dB, and the PCCM reduced the noise by 22 dB. There was no difference in the average SAC between the PCC and the PCCM, but the PCCM's blender noise reduction effect was greater than that of the PCC. This is because the PCCM's sound-absorption peak frequency range was similar to the blender's noise frequency range.

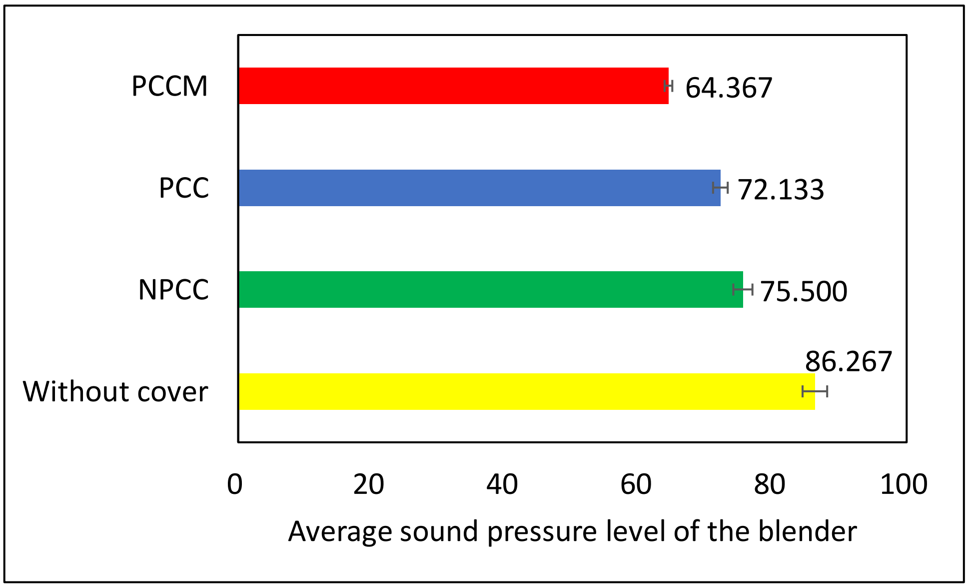

Figure 9. Sound level results of blender without cover, blender with NPCC cover, blender with PCC cover, and blender with PCCM cover.

4. Conclusions

The possibility of using corrugated cardboard as an eco-friendly sound-absorbing and insulating material was investigated. The material was applied to a blender to evaluate its noise reduction effect. The results of the study are as follows:

1. Corrugated cardboard itself had a sound insulation effect.
2. The NRC of PCC and PCCM were 0.346 (SD 0.007) and 0.423 (0.009), respectively. The average sound pressure level of the blender using NPCC, PCC, and PCCM were 75.500 (SD 0.432) dB, 72.133 (SD 1.096) dB, and 64.367 (SD 0.573) dB, respectively.
3. Compared with other NRC natural fiber composite board, Wooden MPP, and NPCC (parallel direction), and the PCCM demonstrated higher sound-absorption capabilities
4. PCCM shows considerable promise as a sustainable, eco-friendly sound-absorbing and insulating material.

On the basis of the findings in this study, it will be possible to develop a variety of sound-absorbing and sound-insulating materials using the method of corrugated cardboard perforation. In the low-carbon era, in which the recycling of resources has become a necessity for the sustainable future of the earth and humanity, corrugated cardboard is likely to become an increasingly valuable resource as an eco-friendly sound-absorbing material.

Author Contributions: C.-W.K.: conceptualization, investigation, methodology, writing—original draft, writing—review and editing. M.K.K.: conceptualization, methodology, supervision, writing—review and editing. E.-S.J.: experiment, data analysis, supervision, writing—original draft, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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