Comparison of the Sound Absorption Properties of Acoustic Absorbers Made from Used Copy Paper and Corrugated Board

Purintorn Chanlert,* Aneeta Jintara, and Wiparat Manoma

Due to the increasing demand for eco-friendly, inexpensive sound absorbers, this study investigated composites made from recycled paper pulp and urea-formaldehyde adhesive. By varying the pulp contents, five samples from used copy paper and five samples from used corrugated board were fabricated. For the same type of porous absorber, one with a lower bulk density has a higher total porosity, resulting in a higher sound absorption coefficient (SAC) spectrum. Sound-absorbing performance of copy paper composites with bulk densities below 442.4 kg/m^3 and corrugated board composites with densities of less than 474.8 kg/m^3 can be alternatives to commercial polyurethane foam of the same thickness. The noise reduction coefficient (NRC), as well as the average SAC of all corrugated board composites at medium (α_M) and high (α_H) frequencies were greater than those of copy paper composites. However, the average SAC at low frequency (α_L) was not explicitly different for copy paper and corrugated board composites. In conclusion, corrugated board composites are a better candidate as sound absorbers than copy paper composites with the same pulp content.

DOI: 10.15376/biores.17.4.5612-5621

Keywords: Recycled materials; Corrugated board; Copy paper; Sound absorption

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INTRODUCTION

For several decades, noise has been a form of pollution that is of concern for general households, especially within urban areas. Sound-absorbing materials have been implemented in construction industries to reduce unconsented-distracting noise in the environment. Mineral wool, glass wool, and other petroleum-based polymeric foams are types of building materials generally used as sound absorbers due to their ability to absorb environmental noise (Aso and Kinoshita 1965; Uris *et al.* 1999). However, since most of them are purely synthetic and derived from the petroleum industry, they are considerably expensive and contribute to unfavorable effects on the environment, such as global warming. In addition, because of the exceptionally high shelf life and difficulty in incineration, these synthetic sound absorbers cause trouble for sustainable waste control. Researchers have been attracted to investigating environmental-friendly sound-absorbing materials, such as recycled materials derived from agricultural byproducts or household disposal (Yang *et al.* 2003; Park *et al.* 2020). Most of such sound-absorbing materials are low-cost, and some of them are biodegradable. Utilizing such materials can reduce the use of synthetic sound absorbers and reduce waste that will be landfilled or incinerated.

Taban *et al*. (2021) studied the sound absorption of acoustic panels made from date palm waste. At high frequency levels above 2,000 Hz, the materials with a thickness of 55 mm and a density of 175 kg/m^3 exhibited a random-incident sound absorption coefficient (SAC_R) of approximately 0.90 to 0.95. The sound absorption abilities of recycled denim shoddy and jute fiber were investigated by Raj *et al*. (2020). The denim shoddy with a sample thickness of 70 mm and a density of 45 kg/m^3 exhibited a noise reduction coefficient (NRC) higher than commercial glass wool, while jute fiber with the same thickness and density had a slightly lower NRC value than the commercial glass wool.

Regardless of the source, fiber is necessary for making paper. Wood is the main and original source of cellulose fiber used in the paper making industry (Małachowska *et al*. 2020). First, wood chips are processed into pulp, which is a lignocellulosic, fibrous material. The pulping process is performed chemically or mechanically. After the pulping process, some pulp is ready to produce unbleached paper. However, some pulp undergoes bleaching treatment. In general, paper made from bleached pulp has less strength than paper made from unbleached pulp. The strength and durability of paper also depends on other factors such as the wood type, the chemicals used in the process, and the paper density, among others. Since paper made from virgin pulp is considerably expensive, less-expensive recycled papers are attractive to some users.

In 2018, 67,390,000 short tons of paper waste was generated in the United States (US). Of this waste, 45,970,000 tons were recycled, 4,200,000 tons were combusted into energy, and 17,220,000 tons were landfilled (United States Environmental Protection Agency 2018). In 2020, 5,533,000 metric tons of paper packaging waste were generated in the United Kingdom (UK). Only 3,628,000 tons (65.6%) were recovered and recycled (Department for Environment, Food and Rural Affairs of the United Kingdom 2021). According to these statistics, there is still a lot of paper waste that is not recycled.

In this study, recycled pulp from corrugated board and multipurpose copy paper was made into sound-absorbing materials. The normal-incident sound absorption coefficient (SAC) spectrum, the NRC, the average SAC at low (α_L), medium (α_M), and high (α_H) frequencies of both types of acoustic materials were investigated and compared with commercial acoustic polyurethane (PU) foam. The objective of this study was to find which type of paper is more suitable for making sound-absorbing materials. By varying the pulp content, the changes in the sound absorption performance were studied.

EXPERIMENTAL

Sound-absorbing Materials Preparation

The sound-absorbing materials were prepared in two sets. The first set was made from used multipurpose copy papers from the office of the Faculty of Science and Technology, Songkhla Rajabhat University, Thailand (80 gsm; Idea Work Co., Bangkok, Thailand). The second set was made from corrugated board acquired from general domestic packaging boxes (Thailand Post Co., Bangkok, Thailand). Both sets of samples were made into a circular specimen with fixed dimensions of 28.6 mm diameter and 40 mm thickness that were suitable for normal-incident SAC measurement using a cylindrical impedance tube.

The used copy papers were torn into small pieces and soaked in 10% sodium hydroxide (NaOH) solution for 1 h. The papers were washed with water until the NaOH solution was washed out and sun-dried until the residual moisture was removed, which generally took 2 sunny days. 50 g of dried paper pieces were ground for 2 mins to make the paper pulp with a home blender machine with stirrer equipment (E-14, Sharp, Japan, 400 W, 220 V, 50 Hz). The blender motor speed is in the range of 10,000 to 15,000 RPM. The stirrer blade must be sharp. The dried pulp was mixed with urea-formaldehyde adhesive (Bosny Co., London, UK) with the mass ratios of 5, 6, 7, 8, and 9 parts of pulp and 6 parts of dried adhesive weight, as described in Table 1. The mixture was placed in a stainless-steel circular mold with dimensions of 28.6 mm diameter and 40 mm thickness. The mixture within the mold was placed in a convection oven at 90 °C for 2 h, cooled, and then taken off the mold. The manufacturing process for the sound absorbers made from the used corrugated board was similar to the copy paper. Because the corrugated board was stronger than the copy paper, the grinding process time was raised to approximately 3 mins. Finally, 10 formulas of samples were prepared. The sample information, including the bulk density and total porosity, was measured and estimated (Table 1).

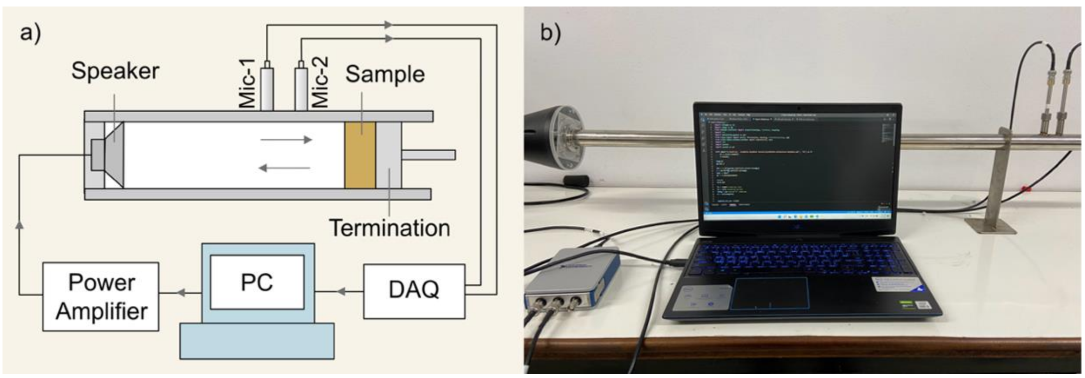

Fig. 1. a) Diagram of the cylindrical two-microphone impedance tube and b) the image of the impedance tube setup used in the measurement

The SAC Measurement

The normal-incident SAC was measured using the two-microphone impedance tube method. The construction of the impedance tube was done according to the ASTM E1050 (1990) and ISO 10534-2 (1994) standards. The diameter and length of the impedance tube were 28.6 mm and 1,000 mm, respectively. A sample was put in the sample holder at the tube end next to the microphone channels, while a speaker was placed at the other end. Laboratory-grade ¼ in microphones (GRAS 40PP; GRAS Sound & Vibration, Skovlytoften, Denmark) were sealed and placed at the microphone holders. The sound signals were collected to the computer through a data acquisition device optimized for acoustic measurement (NI-9230; National Instruments, Austin, TX, USA). The normal-incident SAC was estimated using Eq. 1,

$$\mathrm{SAC} = 1 - \left| \frac{H_{12} - e^{-jk_0 s}}{e^{jk_0 s} - H_{12}} e^{2jk_0 x_1} \right|^2 \tag{1}$$

where *SAC* is the normal-incident sound absorption coefficient, H_{12} is the transfer function of sound signals from Mic-1 and Mic-2, j is the imaginary number $\sqrt{-1}$, k_0 is the wave number of sound (frequency dependence), s is the displacement between Mic-1 and Mic-2, and x_1 is the displacement between Mic-1 and the sample. The data acquisition and interpretation were performed using the Python data acquisition module.

RESULTS AND DISCUSSION

The sound absorbers from copy paper displayed two separated colors. White was the color of the copy paper while brown was the color of urea-formaldehyde adhesive. The addition of copy paper made the sample whiter in color. The samples made from the used copy paper had an average thickness of 39.2 ± 0.9 mm, while the samples made from the corrugated board had an average thickness of 39.4 ± 0.9 mm. The average diameter of all samples was 28.6 ± 0.1 mm, which could fit inside the sample holder of the impedance tube. In this study, petrochemical-based materials including commercially available PU foam, which are designed specifically for noise absorption purpose, were used as a reference. The panel was cut into a circular shape with the same diameter and thickness as the samples.

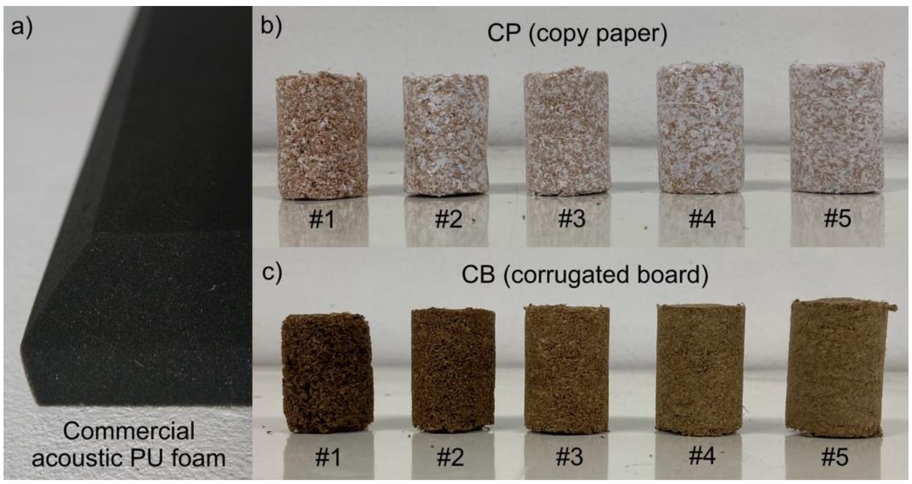

Fig. 2. Images of the a) commercial PU foam panel, b) copy paper samples, and c) corrugated board samples

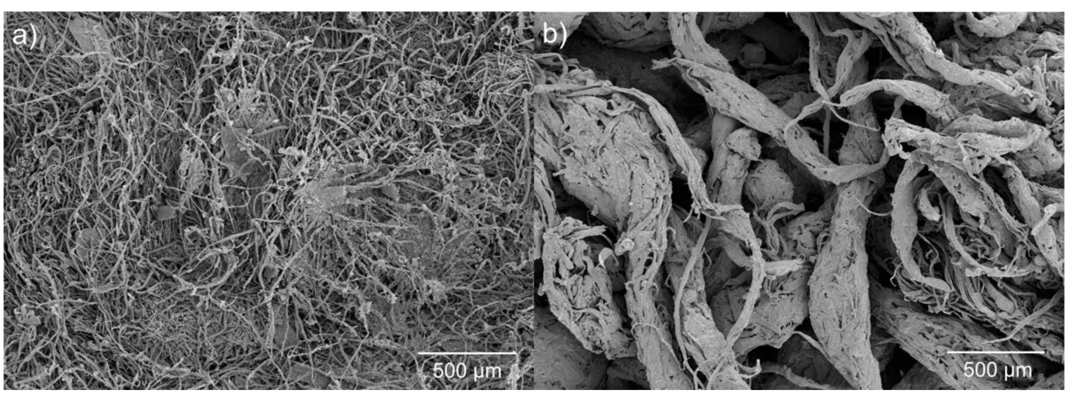

Fig. 3. Scanning electron microscope (SEM) images of a) CP#2, and b) CB#2

The sample information including the bulk density was measured and presented in Table 1. The sample name 'CP (copy paper)' and 'CB (corrugated board)' #1, #2, #3, #4, and #5, represent the samples with pulp:adhesive mass ratios of 5:6, 6:6, 7:6, 8:6, and 9:6, respectively.

Total porosity (ϕ), opened porosity (ϕ_o) and closed porosity (ϕ_c) represent the volume of the total, opened, and closed pores per volume of the specimen, respectively where $\phi = \phi_o + \phi_c$. The total porosity can be estimated from $\phi = 1 - \rho_m/\rho_f$, where ρ_m and ρ_f are the bulk densities of the specimen and fiber substance, respectively. In this study, the density of wood substance was considered uniform, with a value of 1,540 kg/m^3 (Dunlap 1914) while it was around 1,100 kg/m^3 for polyurethane substance (Baser and Khakhar 1994). The estimated total porosity of each sample is shown in Table 1. For the same type of porous absorbers, one with higher opened porosity tends to have a higher sound-absorbing ability (Allard and Atalla 2009).

Table 1. Sample Information

Sample	Mass Ratio (pulp: adhesive)	Bulk Density (kg/m^3)	Total Porosity
Commercial PU foam	-	28.4	0.97
CP#1	5:6	442.4	0.71
CP#2	6:6	487.5	0.69
CP#3	7:6	494.9	0.68
CP#4	8:6	517.6	0.66
CP#5	9:6	570.6	0.63
CB#1	5:6	417.8	0.73
CB#2	6:6	455.0	0.69
CB#3	7:6	474.8	0.68
CB#4	8:6	517.6	0.66
CB#5	9:6	557.6	0.64

** The bulk density was estimated by the average of three replicates of measurement. The average corresponding errors for bulk density of copy paper (CP) and corrugate board (CB) specimens are 14.3 and 21.3 kg/m^3, respectively.

The pulp content directly affected a sample's bulk density and total porosity. Within fixed dimensions, a sample with higher pulp content will exhibit higher bulk density and lower porosity. The CP#5 sample had the highest pulp content, resulting in the highest bulk density, and the lowest total porosity (570.6 kg/m^3 and 0.63 respectively) among the copy paper samples. Correspondingly, it was the same for CB#5 (557.6 kg/m^3, and 0.64 respectively) of the corrugated board samples. According to Table 1, the samples made from copy paper had slightly higher bulk densities and lower total porosity than those made from corrugated board with the same pulp ratio.

According to Figs. 4 and 5, CP#1 and CB#1 had the highest SAC spectra among all copy paper and corrugated board samples, respectively, with the largest total porosity. According to SEM images of two types of samples with the same pulp content (Fig. 2), the corrugated board sample exhibited more open pores than that of the copy paper. Additionally, a fibrous sound absorber with a smaller fiber diameter increases airflow resistivity (Carman 1935). In general, sound absorbers with greater airflow resistivity produce lower SAC spectra (Allard and Atalla 2009). Smaller fiber diameters may increase the likelihood of closed pores, resulting in increased airflow resistivity. Because of the smaller fiber diameter, the SAC spectra of copy paper composites ($d_f = 13 \pm 3$ μm) were lower than those of corrugated board ($d_f = 174 \pm 33$ μm) with the same pulp content.

The NRC is the rating system normally used in commercial products to describe the efficiency of sound absorption in the frequency range of common human conversation. The NRC is the average of the SAC at 250, 500, 1,000, and 2,000 Hz. According to the ISO 354 (2003) standard, the value of the NRC is reported with a resolution of 0.05.

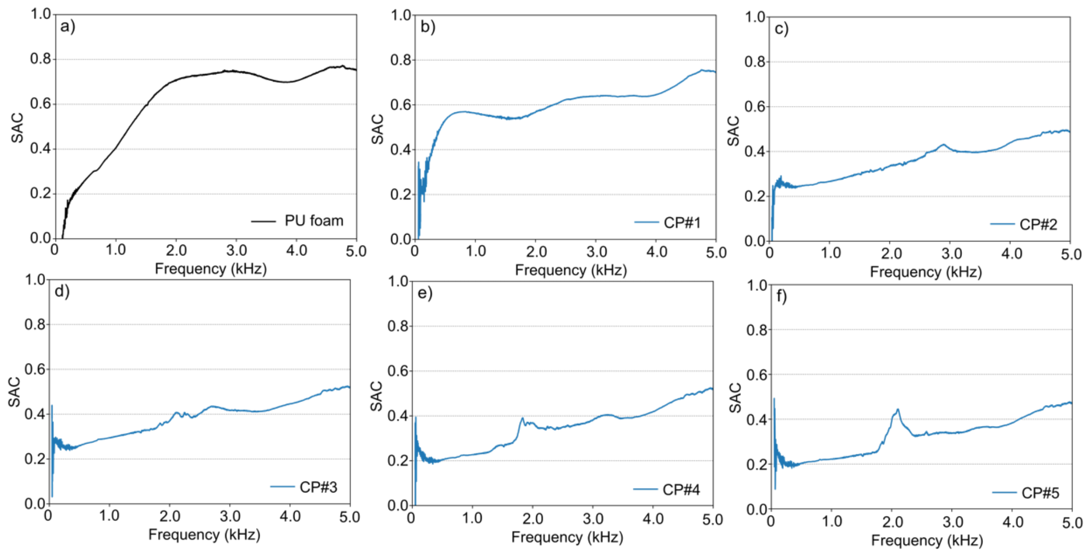

Fig. 4. SAC spectra of the a) commercial acoustic PU foam, b) CP#1, c) CP#2, d) CP#3, e) CP#4, and f) CP#5 samples

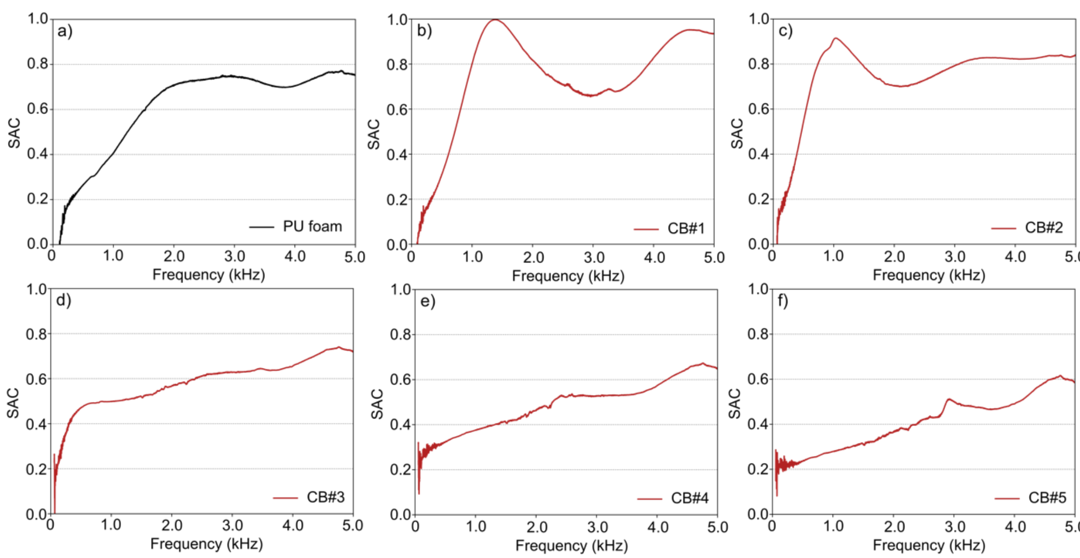

Fig. 5. SAC spectra of the a) commercial acoustic PU foam, b) CB#1, c) CB#2, d) CB#3, e) CB#4, and f) CB#5.

The ranges of the low, medium, and high frequencies are defined corresponding to the ISO 11654 (1997) standard. For the average of sound absorption at low frequencies (α_L), it can be determined from the average of SAC at the octave band frequencies between 100 and 400 Hz (100, 125, 200, 315, and 400 Hz). Correspondingly, the average sound absorption at medium (α_M) and high (α_H) frequencies can be estimated from the average SAC at the octave band frequencies between 500 and 1,600 Hz (500, 630, 800, 1,000, 1,250, and 1,600 Hz) and 2,000 to 5,000 Hz (2,000, 2,500, 3,150, 4,000, and 5,000 Hz), respectively.

Table 2. NRC and Average Sound Absorption Coefficients at the Low (α_L), Medium (α_M), and High (α_H) Frequencies

Sample	NRC	α_L	α_M	α_H
Commercial PU foam	0.40	0.14	0.40	0.73
CP#1	0.50	0.34	0.55	0.64
CP#2	0.25	0.25	0.27	0.41
CP#3	0.30	0.26	0.29	0.43
CP#4	0.25	0.22	0.23	0.41
CP#5	0.25	0.21	0.22	0.38
CB#1	0.50	0.15	0.67	0.79
CB#2	0.60	0.25	0.77	0.78
CB#3	0.45	0.33	0.50	0.64
CB#4	0.35	0.29	0.37	0.55
CB#5	0.25	0.22	0.27	0.47

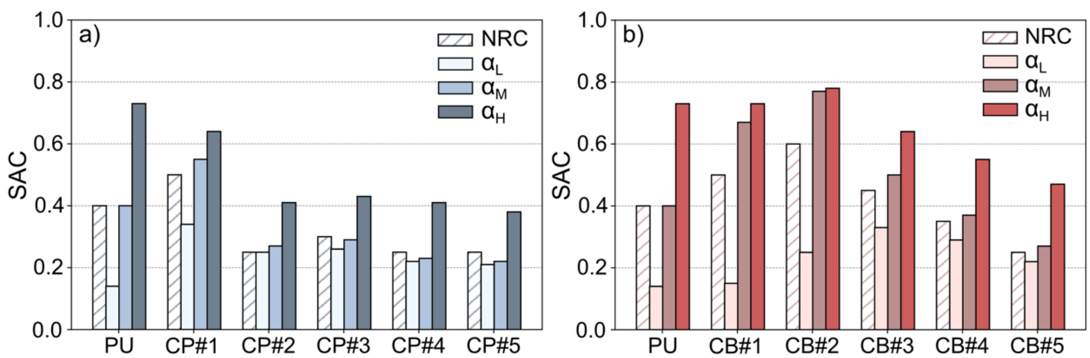

Fig. 6. NRC and average SAC values at the low (α_L), medium (α_M), and high (α_H) frequencies for the a) copy paper and b) corrugated board samples

According to Fig. 4, CP#1 sample had the highest SAC spectrum among the copy paper samples. Its spectrum was slightly lower than that of the PU foam even though its NRC was higher. The NRCs for CP#2 - #5 samples were similar, as they were between 0.25 and 0.30, which was lower than the PU foam. For SAC at low frequency, all the copy paper samples had higher α_L values than the PU foam. At the medium frequency range, the α_M of CP#1 was 0.55, which was notably higher than that of the PU foam (0.40). CP#2 - #5 samples had average α_M values of 0.25 ± 0.03, which was lower than the PU foam. At the high frequency range, the CP#1 sample had α_H much higher than the other copy paper samples. CP#2 - #5 samples had similar α_H values of 0.41 ± 0.02. CP#2 - #5 samples demonstrated remarkably lower α_H values than the PU foam. Overall, it can be concluded that the CP#1 sample, which had the lowest density and highest total porosity among copy paper samples, shows remarkably higher sound-absorbing ability than other samples with higher pulp contents and can be an alternative sound absorber to the PU foam.

CB#1, #2, and #3 samples had higher NRC values than the PU foam. At a low frequency, the CB#1 sample had the lowest α_L value among corrugated board samples, while it was still higher than α_L for the PU foam. On the other hand, CB#3 sample had the highest α_L value (0.33) among the corrugated board samples. At a medium frequency, CB#1, #2, and #3 samples possessed higher α_M values than the PU foam, as seen in Fig.6. The CB#2 sample had the highest α_M (0.77), while the CB#5 sample had the lowest α_M (0.27). At a high frequency, the CB#1 and #2 samples had higher α_H values than the PU foam. The samples with higher pulp contents (CB#3, #4, and #5) had α_H values that gradually decreased as their pulp content increased. However, the decreasing rate of the α_H values was not as exponential as the change of α_H between the CP#1 and #2 samples.

As can be seen in Fig. 6, the samples made of the corrugated board clearly showed superior sound-absorbing ability compared to those made from copy paper. The average NRC, α_M, and α_H of the corrugated board samples were 0.45 ± 0.15, 0.52 ± 0.21, and 0.65 ± 0.14, respectively. These were notably higher than those from the copy paper (0.32 ± 0.10, 0.31 ± 0.14, and 0.46 ± 0.11, respectively). However, there was little difference in their average α_L value, at 0.25 ± 0.07 for the corrugated board and 0.26 ± 0.05 for the copy paper.

Sound absorbers from recycled pulp are potential substitutes for commercial sound absorbers such as PU foam. By considering the NRC, some copy paper composites (< 442.4 kg/m^3) and corrugated board composites (< 474.8 kg/m^3) can be deemed alternative sound absorbers to commercial PU foam at the same thickness, despite their bulk densities being around 15 to 21 times higher than the PU foam. As mentioned by Park *et al.* (2020), the use of inexpensive, and eco-friendly sound absorbers is expected to increase. The use of recycled materials in this study has environmental and economic benefits to society through the substitution of petrochemical-based sound absorbers like PU foam.

CONCLUSIONS

1. For the same type of porous absorber, one with a lower bulk density tends to have a greater total porosity, resulting in greater sound-absorbing ability. Considering the noise reduction coefficient (NRC), copy paper composites with bulk densities less than 442.4 kg/m^3 and corrugated board composites with densities below 474.8 kg/m^3 can be deemed alternative sound absorbers to commercial polyurethane foam of the same thickness.
2. The sound absorption coefficient (SAC) results correspond to those of the preceding studies. The sound-absorbing ability of fibrous-porous absorbers with a larger fiber diameter is higher. The SAC spectra of composites of corrugated board ($d_f = 174 \pm 33$ µm) were higher than those of composites of copy paper ($d_f = 13 \pm 3$ µm).
3. NRC, the average SAC at medium ($\bar{\alpha}_M$) and high ($\bar{\alpha}_H$) frequency of all corrugated board composites were higher than those of copy paper composites. However, it was not explicitly different for the average SAC at low frequency ($\bar{\alpha}_L$) between copy paper and corrugated board composites. In summary, corrugated board is a more suitable material for sound absorbers than copy paper with the same pulp content.
4. In future studies, it might be worthwhile to investigate a more mathematical approach, as mathematical models are effective for predicting the sound absorption capabilities of similar materials. Furthermore, additional variations of corrugated board are required to expand the study of this type of fibrous-porous absorber.

ACKNOWLEDGMENTS

The authors are grateful for the equipment and instrument support from the Faculty of Science and Technology, Songkhla Rajabhat University, Thailand.

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Article submitted: April 13, 2022; Peer review completed: July 17, 2022; Revised version received and accepted: August 3, 2022; Published: August 5, 2022.
DOI: 10.15376/biores.17.4.5612-5621