

Sound Absorption Properties of Shredded Paper Wastes as Indoor Building Sound Absorber

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The sound absorption properties of shredded paper wastes (SPW) were evaluated. Two impedance tubes (large and small) were used to measure the sound absorption coefficient of different thicknesses of SPW sound-absorber (20, 40, 60, 80, and 100 mm). As the thickness of the SPW sound-absorber increased, the optimum sound absorption coefficient was shifted to a lower frequency direction. Based on the KS F 3503 (2002) standard, the sound absorption coefficients were 0.3 M for 20 mm, 0.5 M for 40 mm and 60 mm, and 0.7 M for both 80 mm and 100 mm. The sound absorption properties of this SPW showed comparable or better performance than other eco-friendly fibrous sound absorbers. SPW has not been previously considered for recycling applications. The findings imply that SPW has good sound absorption properties and can thus be employed as a cost-effective and environmentally friendly sound-absorbing material.

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INTRODUCTION

Wood-based materials can play an essential role in climate change mitigation strategies because they can reduce greenhouse gas (GHG) emissions when they are used in place of concrete, steel, or plastics (Ahn *et al.* 2021). In recent years, the use of wood has been encouraged in various fields, including architecture and furniture. Research on the use of wood as a sustainable and environmentally friendly resource is also increasing (Dirna *et al.* 2020; Kim and Kim 2020; Yang *et al.* 2020; Han and Lee 2021; Lee *et al.* 2021; Liu *et al.* 2021; Oh 2021).

In addition, as social interest in suppressing the use of single-use plastics increases, the use of paper as a substitute plastic is increasing (Chauhan and Meena 2021). In the case of recycling 1 ton of waste paper, it is known that there is no need to cut down about 20 trees that are 30 years old (Ahn and Seo 2017).

According to the Korea Paper Association, domestic paper supply and demand in 2020 was about 11 million tons, of which about 2.3 million tons of printing paper were counted (Korea Paper Association 2020). Although electronic documents are being introduced mainly by public institutions and companies, the use of printing paper has not decreased significantly over the past decade.

Recently, it has become commonplace for government agencies, corporations, and even individuals to cut and discard papers that are sensitive to information security by using a paper shredder. Waste paper is a sustainable recycling resource. However, recycling shredded paper wastes (SPW) is difficult because the SPW is too light and floats on the water during dissociation (the process of separating foreign substances and fibers) in the recycling process. Paper recycling companies in Korea are restricting the import of SPW. Therefore, most SPW is classified as general waste and is landfilled or incinerated (Gangnam-gu Office 2020). In this study, it was assumed that the recycling process of SPW omits the dissociation step and produces a mat-like form by simply compressing the material and wrapping it with a nonwoven fabric-like fiber. Although it was impossible to find accurate statistics on shredded paper among waste paper, it is reasonable to think that the SPW is increasing as the paper shredder market is expanding (Business Research Insights 2019). Therefore, this study focused on reusing the SPW. Paper is an eco-friendly porous material made of pulp (Jang *et al.* 2018). Moreover, the SPW is small. When these are aggregated, they form porous granules. This structure can be excellent sound absorption performance.

Various researchers have already proposed natural materials, such as hemp fiber, coconut fiber, kenaf fiber, cane fiber, sheep wool, solid wood, and wood-based materials, as eco-friendly sound-absorbing materials (Berardi and Iannace 2015; Jang and Kang 2021b, 2022). Their sound absorption performance was comparable to that of commercial sound absorption materials. In addition, candidates for eco-friendly fibrous porous sound-absorbing materials recently investigated are as follows. Raj *et al.* (2020b) investigated the sound-absorbing properties of areca nut leaf sheath fibers as a green sound-absorbing material. Its maximum sound absorption coefficient was 0.78 at 54 mm thick with 50 mm air back cavity. Jung *et al.* (2021) evaluated the sound absorption ability of air-dried leaves of evergreen broadleaf trees. Their sound absorption performance showed an average sound absorption coefficient ranging from 0.28 to 0.59, depending on the size and thickness of the sound-absorbing material. Jang (2022) reported pine pollen's sound-absorbing properties. Pine pollen has a rough surface and a structure that overlaps wide and thin scales, which is beneficial for sound absorption. Based on KS F 3503 (2002), the sound absorption performance of pine pollen sound-absorber was 0.3 M (60 to 80 mm thickness) to 0.5 M (100 to 120 mm thickness) class.

In this study, the porous structure of SPW and the spaces between SPW were expected to produce a sound absorption effect. The primary purpose of this study was to examine whether SPW can be utilized as a natural fibrous, granular sound-absorbing material. If shredded paper waste has a sufficiently good sound-absorbing effect, then it will no longer be a waste but will be valuable as a wood-based resource.

Cellulose insulation derived from recycled paper also exhibits low thermal conductivity, which makes it well-suited for energy-efficient building applications (Pathak and Mandavgane 2019). Notably, SPW is non-toxic and does not emit harmful substances during installation, helping to maintain healthy indoor air quality. Beyond these advantages, the material is more cost-effective than conventional insulation products and may qualify for eco-certification. Its intrinsic soundproofing and moisture-regulation capabilities further support its viability as a sustainable construction material.

EXPERIMENTAL

Sample Preparation

Table 1 provides the specification of SPW for this study. The SPW were collected for about one month at Sambo Scientific Co, Ltd. (Seoul, Korea). All SPW were made of fine paper (Hankook Paper, Seoul, Korea). Their basis weight was 80 g m⁻². The pore size of the fine paper was measured using a capillary flow porometer (CFP-1200AE, PMI, USA) based on ASTM F316-03 (2019). The SPW's skeletal density was measured using a gas pycnometer (PYC-100-A, PMI, USA) based on ISO 12154 (2014). The porosity of SPW was calculated in Eq. 1. Their moisture content was measured using KS F 2199 (2016). The porosity was calculated as follows,

$$\phi = 1 - \frac{\rho}{\rho_{\text{skeletal}}} \quad (1)$$

where ϕ is porosity (%), ρ is bulk density (g cm⁻³), and ρ_{skeletal} is skeletal density (g cm⁻³).

Table 1. Specification of SPW

Samples	SPW
Photo	
Basis weight (g m ⁻²)	80
Dimensions (mm)	47.04 (W) × 4.52 (D) × 0.1 (H)
Bulk volume (cm ³)	17.67
True volume (cm ³)	1.17
Porosity (%)	90.32
Maximum pore size (μm)	3.45
Mean pore size (μm)	1.77
MC (%)	4.66

Scanning Electron Microscopy (SEM) Analysis

The surface structure of the SPW was observed by SEM (Genesis-1000, Emcraft, Korea). The SPW were dried in a laboratory oven at 50 °C for about 2 h before SEM imaging to remove surface moisture. The samples were then coated with a thin layer of gold to prevent surface charge during SEM photography. The SPW's surface was then

examined at magnifications of 200 and 500 by high vacuum mode. Acceleration voltage of 15 KV was applied.

Analysis of the Sound Absorption Coefficient

Among the two methods (reverberation chamber method and transfer function method) to evaluate the sound absorption coefficient of sound-absorber, this study selected the transfer function method by an impedance tube (Type 4206, Brüel & Kjær, Denmark) as per KS F 2814-2 (2002).

Figure 1 shows an experimental setup of impedance tube. The SPW were measured using two impedance tubes. For a large impedance tube (99-mm diameter), the sound absorption coefficient was measured at 100 to 1600 Hz, and for a small impedance tube (29 mm diameter), the sound absorption coefficient was measured at 500 to 6400 Hz.

The authors calibrated the volume of both microphones from a standard calibrator prior to measurement. In addition, background and microphone position corrections were performed on the impedance tube.

The SPW were filled with a thickness of 20 to 100 mm vertically in the impedance tube, maintaining the density at 0.1 g/cm³. To maintain the density of SPW at 0.1 g/cm³, the required mass was calculated for each sample height. The impedance tube was filled with SPW in its natural, uncompressed state according to the calculated mass. In cases where the actual sample volume was insufficient and the mass did not meet the target value, the SPW was slightly compressed to match the intended height.

Moreover, the top was covered with thin Korean traditional paper (Hanji). In this manner, the structure simulates a sound-absorbing mat in which the shredded paper waste is wrapped within the Hanji paper. It is assumed that thin Hanji paper does not significantly affect the sound absorption performance of SPW (Jang *et al.* 2018). The thickness of the Hanji was approximately 0.4 mm, with a pore size of approximately 10 µm.

In the industrial setting, a sound-absorber's sound absorption ability is measured using a single-number index called the noise reduction coefficient (NRC) according to ASTM C423 (2022). This standard should calculate the NRC based on the sound absorption coefficient using the reverberation chamber method. However, many studies also calculate the NRC with the sound absorption coefficient measured with an impedance tube (Raj *et al.* 2020a; Jang and Kang 2021a, 2021c; Kolya and Kang 2022). The NRC was calculated using Eq. 2,

$$\text{NRC} = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4} \quad (2)$$

where α_{250} is the sound absorption coefficient at 250 Hz, α_{500} is the sound absorption coefficient at 500 Hz, α_{1000} is the sound absorption coefficient at 1000 Hz, and α_{2000} is the sound absorption coefficient at 2000 Hz.

A large impedance tube and a small impedance tube were employed, providing a frequency overlap between 500 to 1600 Hz. The authors took the absorption coefficients measured from a large impedance tube for 250, 500, and 1000 Hz and those from a small impedance tube for 2000 Hz.

KS F 3503 (2002) is a Korean industrial standard that defines the procedures for evaluating the sound absorption performance of building acoustic materials such as rock wool, glass wool, soft fiberboard, wood wool board, and perforated gypsum board. As

shown in Table 2, KS F 3503 (2002) classifies the sound absorption capability of sound-absorber into four classes depending on the NRC. The SPW sound-absorbers were also evaluated according to this criterion.

The environment during the sound absorption coefficient measurement was as follows: an atmospheric pressure of 1037 hPa, a temperature of 18.8 °C, and a relative humidity of 32.0%, a velocity of sound of 342.5 m/s, the density of air of 1.235 kg/m³, and the characteristic impedance of air of 423.1 Pa/(m/s). All measurements were performed three times at each height.

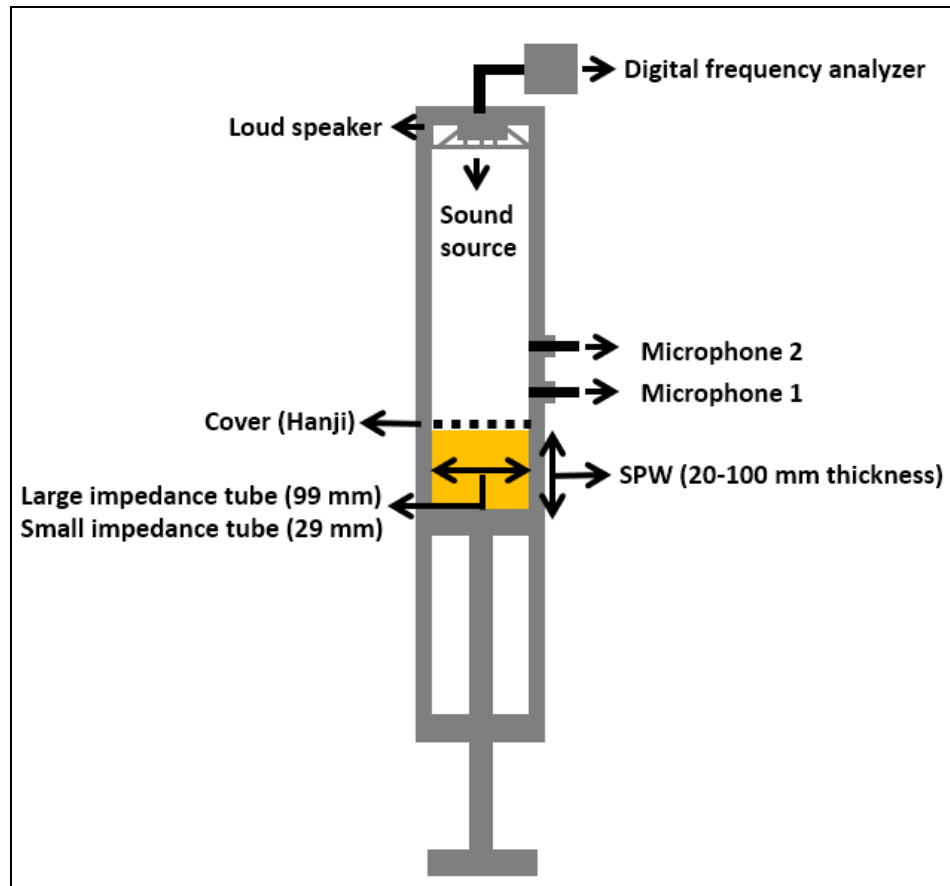


Fig. 1. Schematic diagram of the impedance tube

Table 2. Sound Absorption Capability of Sound-absorber KS F 3503 (2002)

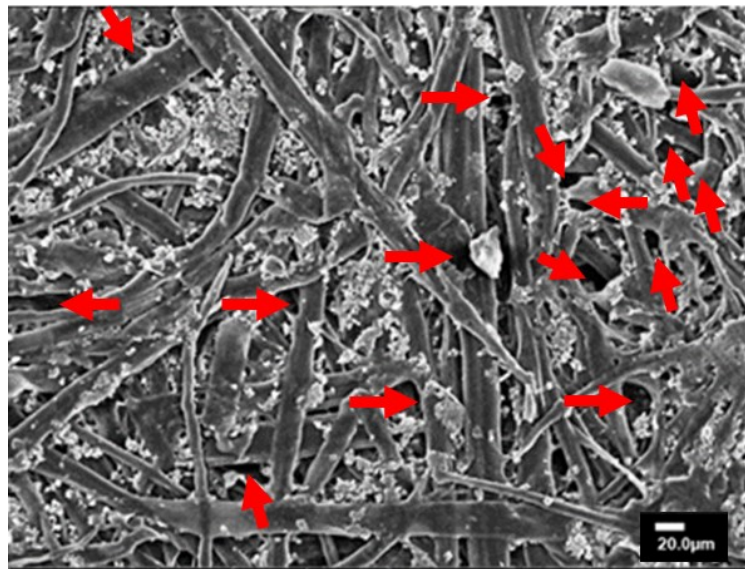
Class	NRC
0.8M(M)	Above 0.81
0.7M(M)	0.61 to 0.80
0.5M(M)	0.41 to 0.60
0.3M(M)	0.21 to 0.40

Note: M, if no rear air space is applied to the sound-absorbing material, and S if the rear air space is applied

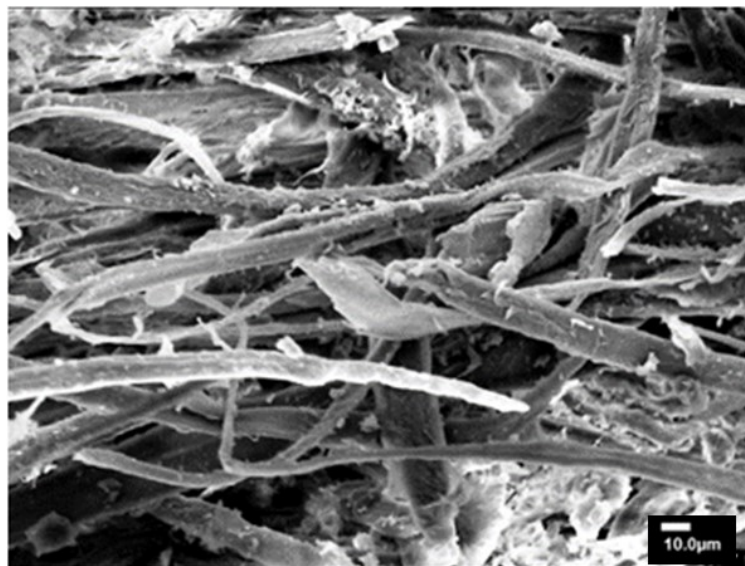
RESULTS AND DISCUSSION

SEM Images

Figure 2 depicts the surface of the shredded paper waste. The number of fibers in the machine direction (MD) was higher than in the cross direction (CD). Most fibers were generally arranged in MD rather than CD in the fine paper produced by a paper machine (Yoon 2015). The fiber diameter obtained after statistical averaging of the measurements on SEM images was $20.1 \pm 5.9 \mu\text{m}$. Additionally, small pores were observed between the fibers. The micropores between the fibers can influence the sound absorption behavior (Na *et al.* 2018).



(a) 500x (Red arrows indicate micropores)



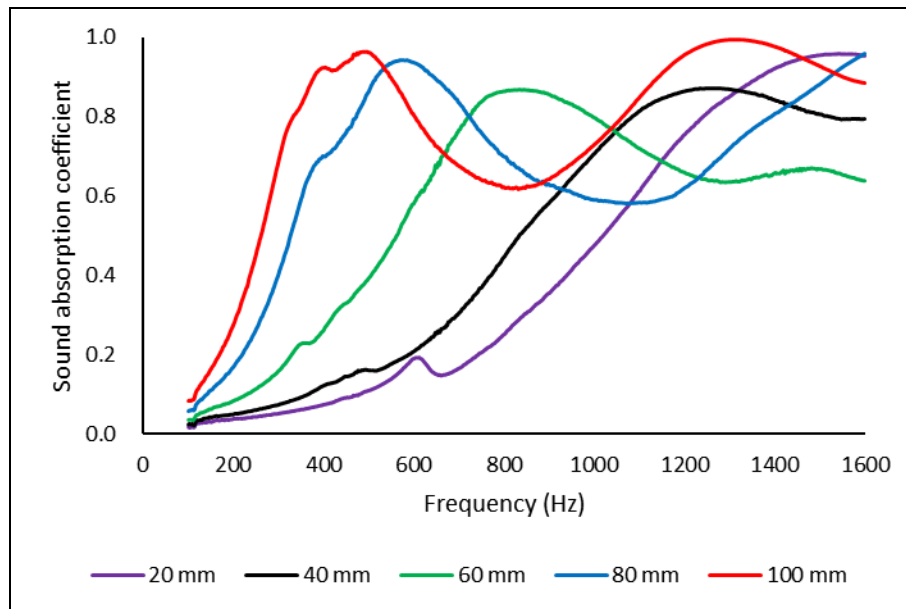
(b) 1000x

Fig. 2. SEM images of SPW

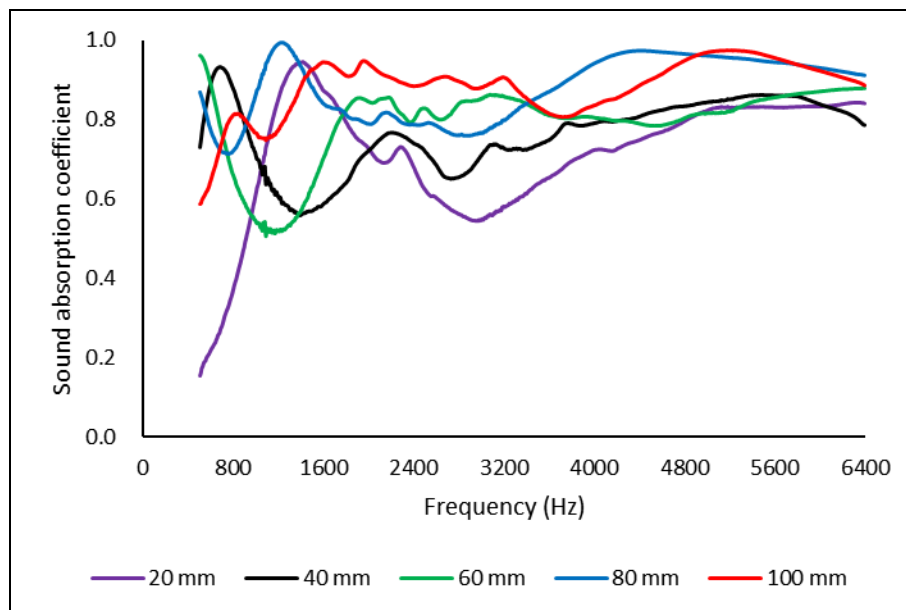
Sound Absorption Properties

Figure 3 demonstrates the sound absorption curve of SPW. Figure 3a shows the sound absorption curve at 100 to 1600 Hz measured from the large impedance tube, and Fig. 3b depicts the sound absorption curve at 500 to 6400 Hz measured from the small impedance tube.

The first maximum sound absorption coefficient was 0.960 at 1542 Hz for a 20 mm thickness. In contrast, that of SPW with 100 mm thickness was 0.694 at 462 Hz (Fig 3a). The first maximum sound absorption coefficient moved to low frequencies direction as the thickness of the SPW sound-absorber increased.



(a) Large impedance tube



(b) Small impedance tube

Fig. 3. Sound absorption curves of SPW sound absorber depending on thickness

The sound absorption peaks increased as the thickness of the SPW sound-absorber increased at high frequencies above 1000 Hz. The sound absorption coefficient of the 20 mm SPW sound absorber was 0.5 at 1000 Hz, and it tended to increase as the frequency increased. In contrast, the sound absorption coefficient of the 100 mm SPW sound absorber was 0.767 at 1000 Hz. The sound absorption coefficient at 3200 Hz was 0.899, and after that, it decreased slightly to 0.809 at 3800 Hz, and after that, the sound absorption coefficient increased again as it progressed to higher frequencies.

The high-frequency sound absorption performance of SPW can be attributed to the synergistic effects of resonance phenomena and the intrinsic damping characteristics of porous fibrous media. At intermediate-to-high frequencies, partial reflection may occur due to acoustic impedance mismatch between the fibrous structure and the surrounding air, resulting in reduced absorption. As the frequency increases further, the wavelength approaches the characteristic dimensions of the pores and fiber spacing, allowing more efficient penetration of acoustic energy.

Table 3 provides the NRC of SPW sound-absorber with 20 to 100 mm thickness. The NRC increases as the thickness of the sound-absorber increases. According to KS F 3503 (2022) sound absorption performance classification, the SPW sound absorber with 20- and 40-mm thickness was 0.3 M, its 60 mm thickness was 0.5 M. Finally, the SPW sound absorber with 60- and 80-mm thickness was 0.7 M

Table 3. The Sound Absorption Coefficient and NRC

Thickness (mm)	Sound Absorption Coefficient @ Frequency (Hz)				NRC
	250	500	1000	2000	
20	0.042	0.109	0.475	0.728	0.338
	(0.002)	(0.015)	(0.105)	(0.123)	(0.061)
40	0.060	0.161	0.707	0.723	0.413
	(0.002)	(0.036)	(0.090)	(0.168)	(0.074)
60	0.114	0.393	0.798	0.846	0.538
	(0.007)	(0.029)	(0.023)	(0.056)	(0.029)
80	0.264	0.864	0.590	0.791	0.627
	(0.017)	(0.015)	(0.012)	(0.010)	(0.013)
100	0.452	0.961	0.729	0.942	0.771
	(0.026)	(0.020)	(0.020)	(0.026)	(0.023)

Note: The parentheses are the standard deviations

Figure 4 shows the comparison of the NRC of various eco-friendly materials investigated in Berardi and Iannace (2015) and SPW in this work. Overall, the sound absorption performance of SPW showed equal or better sound absorption compared to the eco-friendly sound absorption materials investigated in previous studies.

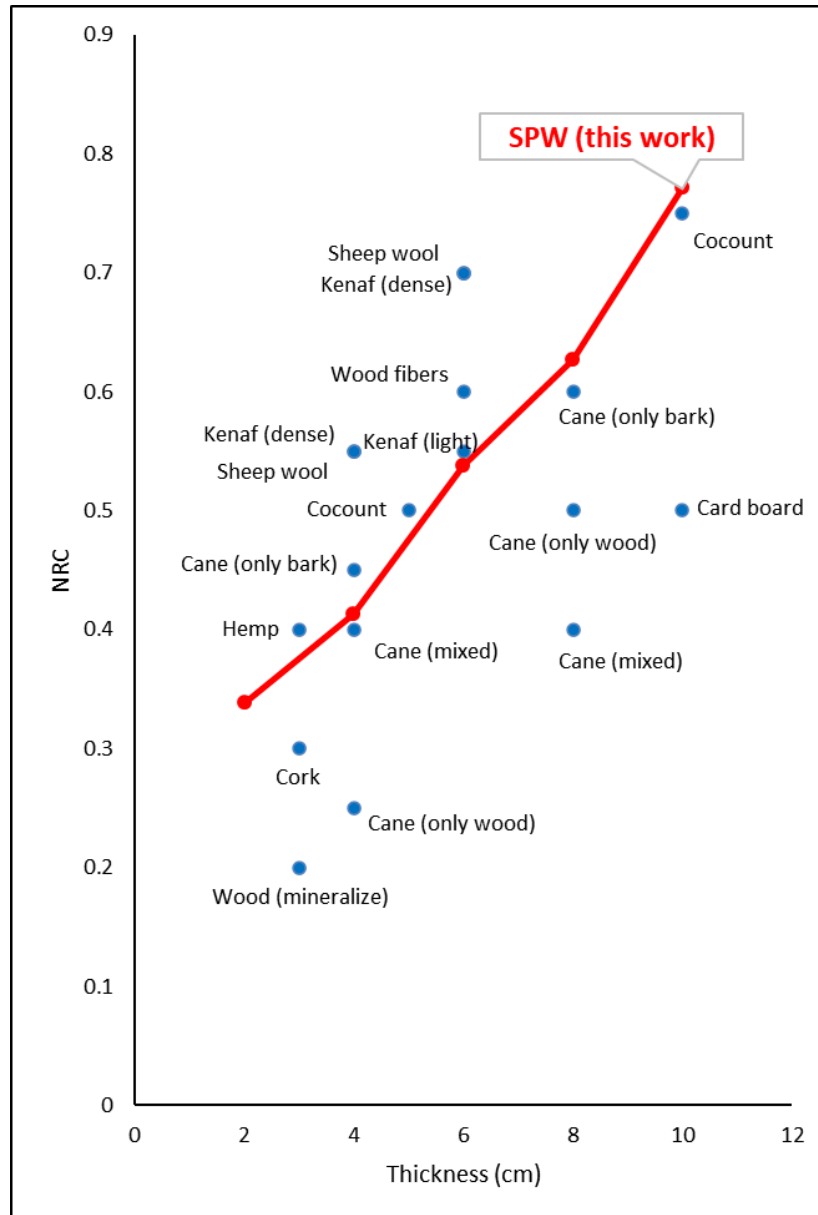


Fig. 4. Comparison of NRC of various eco-friendly materials (Berardi and Iannace 2015) and SPW sound-absorber depending on the thickness

This investigation was the first approach to the sound absorption capability of SPW. However, the sound absorption properties in this study were only measured by the absorption coefficient at normal incidence using an impedance tube. In the future, it is necessary to investigate the random incident sound absorption using the reverberation chamber. Typically, random incident sound absorption provides a higher sound absorption coefficient than vertical incident sound absorption (Berardi and Iannace 2015). Therefore, it can be expected that the SPW sound-absorber can have greater sound absorption capability in the reverberation chamber method. To better assess the practical acoustic performance of SPW, the envisioned future research will evaluate its absorption characteristics under diffuse sound field conditions—such as those found in open-plan offices, classrooms, and other realistic architectural environments.

In this study, it was assumed that SPW exists in the form of mats without adhesives. In the future, it is necessary to evaluate sound absorption performance, physical properties, and insulation properties after fabricating them in the form of boards with adhesives. It is expected that the sound absorption effect will be better in the mat form than in the board form because the adhesive blocks the paper's pores and blocks the space between the SPW, making it difficult for sound waves to scatter. Furthermore, paper is a flammable material. Therefore, a flame-retardant treatment is required for use as a building material. Flame-retardant treatment may decrease sound absorption performance, as it may block the pores in the paper. It is also necessary to evaluate the sound absorption characteristics of the flame retardant SPW in the future.

Recently, various natural materials have been proposed as candidate materials for eco-friendly sound-absorbing materials. However, even natural materials with good performance cannot be used as commercial sound-absorbing materials if their continuous supply is not guaranteed. A continuous supply of shredded paper waste may be possible. This is because shredded paper waste is continuously discharged from most companies and government offices. Therefore, it is possible to collect shredded paper mainly from companies and government offices and manufacture it as a sound-absorbing material. Reusing shredded paper waste, which was thrown away as general waste, as a sound-absorbing material was thought to be a beneficial way to contribute to realizing a sustainable green society.

CONCLUSIONS

1. As the thickness of the SPW sound-absorber increased, the sound absorption capability at low frequencies was improved.
2. According to KS F 3503 (2022) sound-absorbing performance classification, the SPW sound-absorbing material of 20- and 40-mm thickness was 0.3 M, and the thickness of 60 mm was 0.5 M.
3. The 80-mm- and 100-mm-thick SPW sound-absorber was 0.7 M, which is equivalent to or better than other eco-friendly fiber sound-absorbing materials.
4. The highest NRC recorded for SPW was 0.771 at a thickness of 100 mm.
5. SPW, continuously generated by companies and government offices, as sound-absorbing material, can contribute to building a sustainable green society.

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Authors' Contributions

Conceptualization: ESJ, Methodology: ESJ, Formal analysis: ESJ, Writing - original draft: ESJ, Writing - review & editing: ESJ, HJP, Corresponding: HJP, Supervision: HJP. All authors read and approved the final manuscript.

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