

Article

An Airborne and Impact Sound Insulation Analysis of 3D Woven Textiles on the Floor in Buildings

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Abstract

Noise has detrimental effects on mental and physical health and quality of life, especially for those living in apartment buildings. Therefore, sound insulation materials are pivotal for reducing unwanted noise as well as enhancing acoustic comfort. This study offers a hybrid approach for analyzing 3D woven textile sound insulation material effectiveness, especially in residential buildings, by simulating airborne sound insulation and testing manufactured slab samples with 3D woven textile mortars in a laboratory using a tapping machine. At the same time, the JCA model and the transfer matrix method are employed to calibrate sound absorption coefficients (SAC) and simulate its airborne sound insulation effect in buildings in Seoul, South Korea. Results indicate that the maximum mean sound pressure level (SPL) of the 3D woven textile was reduced up to 9 dB in the octave band frequencies. The thickness improvement of 3D woven textiles enhances the mid- and high-frequency sound absorption effect, most pronounced in 3D woven textiles made of double-layer (DSRM) material, which demonstrated an air sound insulation efficiency around 28.5% greater than that of traditional materials. The maximum drop in impact sound pressure level (SPL) at 2 kHz is 13 dB. The study also proposes a strategy to optimize sound insulation performance, which is used as an effective solution for noise control in buildings. These findings lay the groundwork for research on the application of 3D woven textiles for sound insulation in residential buildings and offer prospects for sustainable textile composites in architectural building applications.



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Keywords: 3D woven textile; ray tracing; control algorithm; floor impact sound; tapping machine

1. Introduction

Occupants of multi-unit residential complexes are often exposed to airborne and impact noise from various directions, such as running, jumping, loud voices, or disputes with neighbors [1]. Even in nations with strong regulations on airborne and impact sound insulation, inhabitants are nevertheless dissatisfied with the acoustic environment [2]. In South Korea, more than 60% of housing units have box-frame concrete structures, contributing to the problem of floor impact noise [3]. Among that, floor impact noise accounted for 82.6% of the complaints and 70.9% of footfall noise was included [1].

Recent studies suggest a variety of composite materials like rice husk, sheep waste wool, and wood-based goods have been developed to actively eliminate noise [4–7]. The sound-absorbing ceiling, acoustic metamaterials or wood frame construction, and cross-laminated timber (CLT) in the floor are commonly used for measuring floor impact

noise [8–11]. However, research about the effectiveness of 3D woven textile material in floors of buildings has not received much attention.

3D woven textile works well for minimizing noise in industrial fields [12], which was created about 30 years ago to replace pricy metal alloys in aviation brakes [13]. It possesses numerous advantages such as mechanical durability, lighter and more compact, cost-effectiveness, and easier to deliver for mass production process [14–17]. Arumugam et al. studied the density and surface layer structure of 12 different spacer knitted fabrics, which showed a great influence on the noise reduction coefficient [18]. Yeon et al. investigated weft-knitted spacer woven and discovered double-layer spacer textiles constructed with additional yarns which exhibited absorption coefficients larger than 0.5 above 1000 Hz and more than 0.8 above 2000 Hz [19]. Some studies also have found that the recycling prospects of the textile industry contribute to release harmful emissions and reducing negative environmental impacts globally [20]. Another advantage is that 3D woven textiles can be prepared by a specialized manufacturer, or take place on-site, while reducing transport volume and expenses [21]. By these great benefits, 3D woven textiles have superior advantages over other advanced soundproofing materials in preventing unexpected noise.

Although air-borne sound attenuation of 3D woven textile-reinforced composites were measured by a sound insulation chamber, it was combined with other natural fibers [22]. Besides, a sound reduction study of the airborne noise from 3D woven textile material is inadequate when it is confined just to sound absorption characteristics. Amitha Jayalath et al. also state how sound travels through the air and impacts sound is necessary [23]. To accurately measure noise levels and the effectiveness of noise-reducing strategies, it is important to be analysis sound insulation through both airborne and floor impact. Despite extensive research on the influence 3D woven textile composite materials, the effectiveness in reducing both airborne and floor impact sound has not been completely investigated yet. Therefore, the primary objective of this paper is to identify and determine the sound reduction effect of the 3D woven textile material on both aspects. In addition, the methods for calculating, simulating and measuring these quantities will be outlined, and the attenuation of airborne sound and impact floor sound will be presented.

The main contributions of this paper are as follows: Firstly, the effective airborne sound reduction of 3D woven textiles is analyzed through geometrical simulation in apartment buildings. Room acoustics simulation is employed by ray tracing and image-source method [24] with calibrated sound absorption coefficient (SAC) through iterative method of parameters based on JCA model and transfer matrix method (TMM) with test result. Furthermore, proposed control algorithm to optimize the solution after airborne sound insulation simulation to 3D woven textiles combined with other reinforced materials. On the other hand, floor impact sound is measured in an in-building acoustic testing laboratory by using tapping machine following by ISO 10140-3:2021 [25] and KS F ISO 717-2 standard [26]. After that, the results were gathered for evaluating the total capabilities of 3D woven textiles in sound insulation compared to common composite materials. This research offers a sustainable and effective solution for noise control in residential environments below 60 dB as required. From that, it could open up new opportunities for the widespread application of 3D woven textiles in apartment buildings.

2. Materials and Methods

2.1. 3D Woven Textile Material

3D woven textile is a major constituent of conventional concrete mortar mixtures in attaining acoustic insulation performance, which has distinct qualities in all three physical dimensions shown in Figure 1. The interface between the 3D woven textile and the mortar

was photographed by an optical microscope and a scanning electron microscope (SEM), as shown in Figure 2.



Figure 1. 3D woven textile-reinforced concrete [27].

Void structures and their influence on sound absorption performance are investigated. When taken by an SEM, the red line shows having an uneven rough surface, and it was confirmed the average 3D woven textile fiber diameter. The voids form an air layer inside the mortar, hindering vibration energy transmission and absorbing noise, thereby playing an important role in noise reduction.



Figure 2. 3D woven textile as observed by optical (a) and scanning electron microscopes (b).

Our study revealed that a decrease in porosity and an increase in density contribute to improving sound absorption. Greater thickness and density strengthen the absorption coefficient, resulting in better acoustic performance. In addition, the existence of an air gap further improves sound absorption, especially in the low-to mid-frequency range. Flow resistivity, σ is estimated using empirical Delany-Bazley models based on material properties such as fiber diameter, porosity, density, and is given by

$$\sigma = \frac{1.4 * 10^5}{df^2} \quad (1)$$

where d_f is fiber diameter (μm).

The Johnson-Champoux-Allard (JCA) model, the most popular and straightforward model for sound propagation across a large frequency range, is used for the theoretical calculation of porous sound absorption materials. This JCA model includes five fundamental parameters that are needed: porosity (Φ), tortuosity (α_∞), airflow resistivity (σ), thermal characteristic length (Λ'), and viscous characteristic length (Λ). Typically, sound absorption in porous materials is high as being dependent on pore sizes [28]. 3D woven textile materials achieve superior broadband sound absorption by means of a multi-layered and spacer, interwoven textile structure. A layer of 3D woven textile with high tortuosity can be designed to dissipate high-frequency sound at its surface, while the porosity and resistivity of the airflow are individually tailored within the core to absorb energy from lower frequencies.

Based on the JCA model, parameters could be calculated by MATLAB R2023b program to get the characteristic impedance and the complex wavenumber [29]. Equation (1) is used to estimate flow resistivity value. Besides porosity, viscous and thermal characteristic length parameters are measured by SEM to analyze the void fraction in material and tortuosity refer to literature [30] as shown in Table 1.

Table 1. The parameter of 3D woven textile.

Symbol	Parameters	Value	Unit
Φ	Porosity	0.86	
α_{∞}	Tortuosity	1.15	
σ	Airflow resistivity	56,000	Pa.s/m ²
Λ	Viscous characteristic length	60	μm
Λ'	Thermal characteristic length	110	μm

2.2. Sound Absorption Coefficient

2.2.1. Transfer Matrix Method

When sound energy hits the porous material, three transformations of reflection, absorption, and transmission take place for the sound energy as shown in Figure 3. The sound absorption coefficient (α), is used to quantify the sound energy dissipation power of porous sound-absorbing materials.

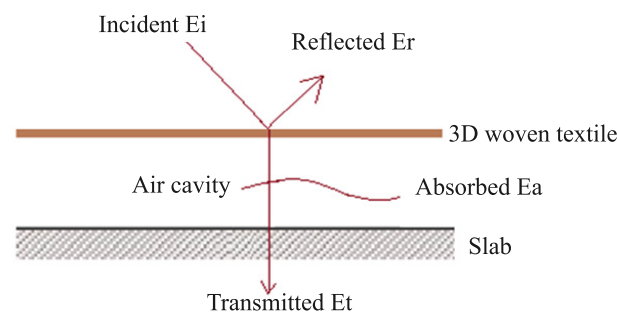


Figure 3. Sound propagates via the fabric and air layers [31].

To predict and measure sound absorption performance in porous materials, a transfer matrix method (TMM) and the Johnson-Champoux-Allard (JCA) model are used. Utilizing the TMM [32], that allows for evaluation of generic systems with arbitrary layers, the acoustic impedance along the direction perpendicular to the material interface is calculated using the continuity of the particle velocities (on both sides of the interface) and knowledge of the medium's acoustic properties (characteristic impedance, Z_c , and the wavenumber or propagation constant, k_c).

After obtaining the density and complex modulus, the characteristic impedance and wavenumber of the material could be determined using

$$Z_c = \sqrt{\rho_{(\omega)} * K_{(\omega)}} \quad (2)$$

$$k_c = \omega \sqrt{\rho_{(\omega)} / K_{(\omega)}} \quad (3)$$

where $\rho(\omega)$ is the dynamic bulk density, $K(\omega)$ is the dynamic bulk modulus of the 3D woven textiles, and ω is the angular frequency (rad/s). The transfer matrix for JCA porous layer can be expressed as follows:

$$T_{\text{textile}} = \begin{bmatrix} \cos(k_c * d_1) & j * Z_c * \sin(k_c * d_1) \\ \frac{j}{Z_c} \sin(k_c * d_1) & \cos(k_c * d_1) \end{bmatrix} \quad (4)$$

where k_c (rad/m) is the complex wave number, and d_1 is the thickness of the fluid layer.

For a fluid layer of 3D woven textiles, the surface impedance, Z_s of the material is obtained by substituting Equations (2) and (3) into Equation (5), with thickness (h), and can be calculated by

$$Z_s = -j * Z_c * \cot(k_c * h) \quad (5)$$

At normal incidence ($\theta = 0^\circ$), the sound absorption coefficient α can be calculated by

$$\alpha = 1 - \left| \frac{Z_s - \rho_0 * c_0}{Z_s + \rho_0 * c_0} \right|^2 \quad (6)$$

where ρ_0 is the equilibrium density of air (kg/m^3), c_0 is the sound speed in the air.

2.2.2. Measurement Method for SAC

The testing took place at the disaster prevention testing laboratory's, Gyeongchung-daero, Ganam-eup, Yeosu-si, Gyeonggi-do, South Korea, which has a rectangular reverberation room made of painted concrete and rendered masonry. The room is 5.2 m depth, 4.4 m width, and 2.5 m height, with a total volume of 57.2 m^3 . The samples used for the testing were 4.2 m depth by 3.3 m width, and the area of sample is roughly 14 m^2 .

This test is conducted by simultaneously introducing a broadband noise into the room at the same time for frequencies between 125 Hz and 4 kHz. The sound decay rate is tested ten times at each of the five microphone positions, and the average decay is used to find the “empty room” absorption. The test specimen is then placed in the room, and an additional 50 decays are measured. This measurement, known as “full room”, absorption with the sample installed, is illustrated in Figure 4.

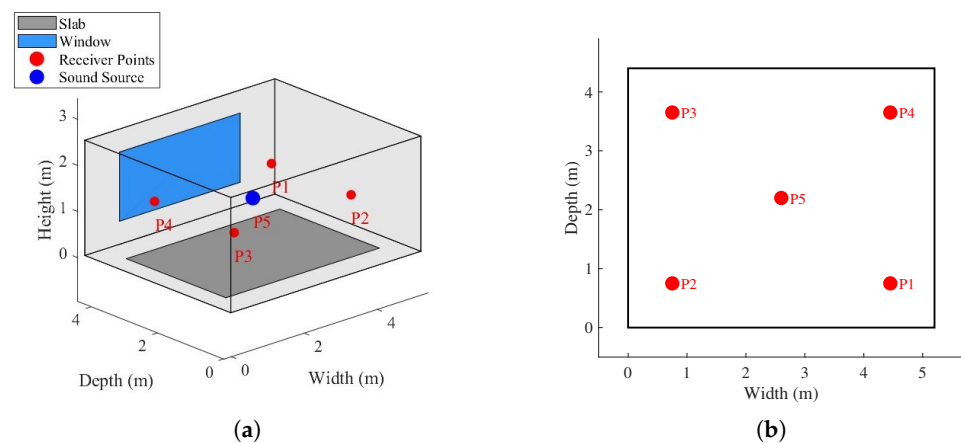


Figure 4. The installed layout (a) and spatial configuration of chambers (b).

2.2.3. SAC Comparison and Calibration

Table 1 lists the 3D woven textile parameters, which are used to calculate the normal incidence absorption coefficient using the JCA method through Equation (6). Three distinct types of 3D woven textiles were tested in a reverberation chamber in compliance with EN ISO 354:2003 [33]. In addition, the ASTM C423-22 standard [34] is frequently employed

to assess the absorption coefficient of material test specimens, relying fundamentally on the Sabine formula. The measured SAC and theoretical JCA were compared in determining the sound absorption coefficient at multiple frequency. Because of high-density, 3D woven textiles improve sound absorption in mid to high-frequency ranges (500–4000 Hz) but not at lower frequencies (0–500 Hz) [22,35], as shown in Figure 5.

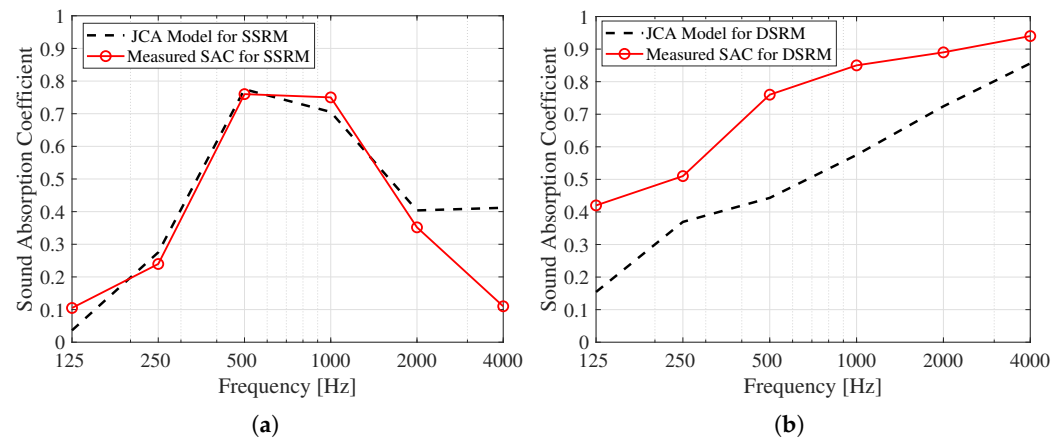


Figure 5. Comparison of theoretical JCA and measured SAC in reverberant room of (a) SSRM (b) DSRM.

In addition, when two layers of 3D woven textile (DSRM) were made thicker, the increased material depth enhanced sound absorption, leading to greater attenuation and reduced air permeability. However, beyond a certain thickness, continued propagation of sound waves into the inner layers further increases attenuation, resulting in a gradual decline in the effective sound absorption performance of 3D woven textile.

At 125 Hz, most of acoustic energy is reflected by 90% for both samples while at 500 Hz, there is a rapid increase of SAC on SSRM up to 0.8. The absorption coefficient at 1 kHz is relatively high, around 0.8, with two materials by measurement, whereas the theoretical JCA method gives a lower value under 0.7. From frequency 1000 onwards, SAC of SSRM material witnessed a sharp decrease to 0.4, whereas DSRM two layers observed a continued climb with a SAC close to 1.0 at high frequencies. This contrast highlights the differing acoustic properties of the two materials, SSRM and DSRM, suggesting that SSRM may be more effective at lower frequencies, while DSRM excels in higher frequency ranges. The sound absorption frequency of 3D woven textiles depends on the thickness of the sample; thicker samples show better absorption at higher frequencies; conversely, thinner layers provide better absorption at low frequencies [36]. Furthermore, the 3D double-layer woven textile is effective at high frequencies because sound waves enter their pores and convert energy into heat through friction. However, at low frequencies, the pores are too small compared to the wavelength, and the heat dissipation ability is poor, so the absorption ability is weaker.

An iterative method is used to fit the JCA model and measured values that are closer to the desired SAC, as shown in Figure 6. Material thickness at low frequencies has an important effect in reducing acoustic energy [37]. Therefore, increasing the thickness of DSRM generally outperforms SSRM in absorption performance at frequencies below 125 Hz and above 500 Hz. From frequency of 250 Hz onwards, the absorption coefficient of DSRM tends to increase rapidly from 0.5 to 0.8 after covering two layers of textiles, while SSRM witnesses a considerable decrease at both mid and high frequencies. Within the 125 Hz to 500 Hz range, the absorption coefficient of SSRM climbed up to 0.8, with peak performance occurring around 1 kHz, and then dropping below 0.1 at 4 kHz. This can be attributed to

the presence of multiple filament yarns in textiles like perforated holes, which allow them to absorb well while eliminating sound wave reflection.

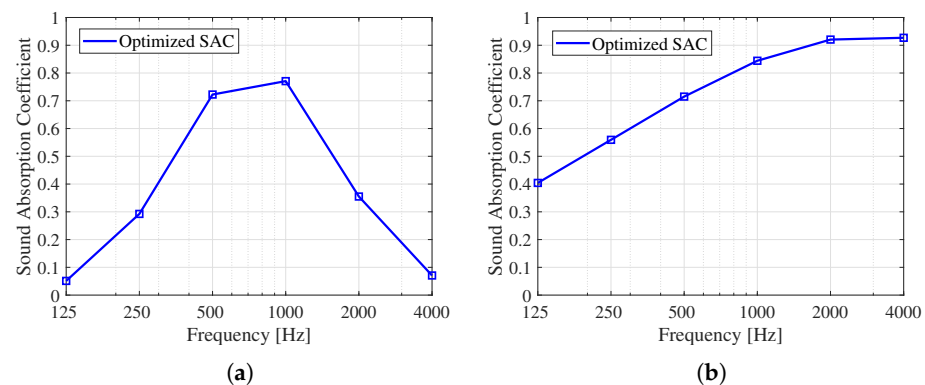


Figure 6. Sound absorption coefficient after calibration of JCA parameters: (a) SSRM; (b) DSRM.

2.3. Airborne Sound Simulation

2.3.1. Parametric Study

The case study is carried out at building 103, Gireum district, Seoul, South Korea [38], which is located between the intersection of Naebu Expressway and Gireum subway station as shown in Figure 7. The structure is 15 floors tall and made up of comparable single residential units stacked on top of one another. Besides, flat density is 6 units/floor, and one flat layout is used as an example. The floor area is roughly 140 m² which is the most common apartment building layout, and the geometry was built up in simulation software as displayed in Figure 8.



Figure 7. Location of Building 103 in Sambu building complex, Gireum district, Seoul, South Korea.

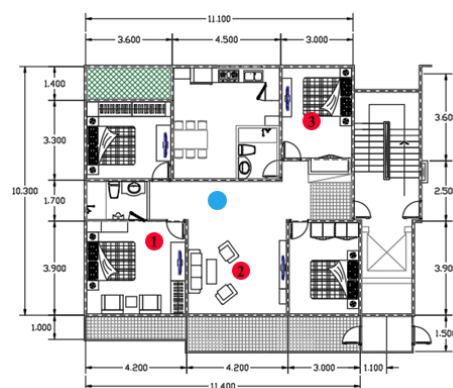


Figure 8. Typical floor plan of Sambu apartment with 3 receiver positions (red), and 1 position of the sound source (blue).

The simulation process can be divided into 3 main stages as shown in Figure 9, including stage 1, which creates geometry and determines 3D woven textile material properties; stage 2, which runs the ray tracing simulation method for one flat sample (living room and two bedrooms); and the final stage, which selects types of 3D woven textile through a control algorithm.

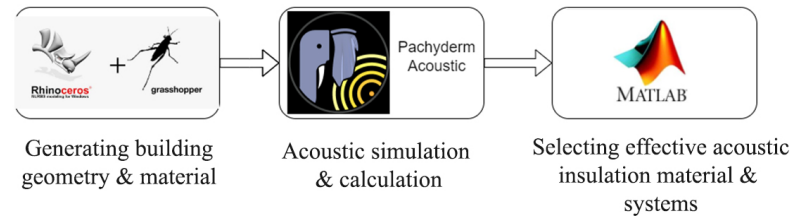


Figure 9. Simulation process.

Firstly, a geometric model of building rooms is drawn using the Rhinoceros software. Setting up shows various absorption coefficient data of materials as shown in Figure 10. When creating a model's geometry, all relevant room absorption and scattering coefficients are suggested during the simulation process for materials applied on various surfaces listed in Table 2, following ISO 10534-2 [39]. These remaining data were obtained from the manufacturer's website and earlier research.

Table 2. Acoustic absorption and scattering coefficient of materials.

Materials	Coefficient	Frequency (Hz)					
		125	250	500	1000	2000	4000
Non-3D woven textile reinforced mortar (NRM)	α	0.13	0.25	0.58	0.15	0.37	0.17
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Single side-3D woven textile reinforced mortar (SSRM)	α	0.05	0.29	0.72	0.77	0.36	0.07
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Double side-3D woven textile reinforced mortar (SSRM)	α	0.40	0.56	0.72	0.84	0.92	0.93
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Cementious cork composites	α	0.01	0.02	0.1	0.3	0.86	0.3
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Rubber composites	α	0.02	0.03	0.03	0.05	0.10	0.05
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Auxetics foam composite	α	0.03	0.03	0.03	0.07	0.21	0.15
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Wood flooring on joists	α	0.15	0.11	0.1	0.07	0.06	0.07
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Rice husk cement composites	α	0.03	0.15	0.08	0.07	0.18	0.3
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Gypsum ceiling	α	0.01	0.02	0.02	0.03	0.04	0.05
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Single pane of glass window	α	0.08	0.04	0.03	0.03	0.02	0.02
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Solid wood panels door	α	0.1	0.07	0.05	0.04	0.04	0.04
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Concrete block wall	α	0.1	0.05	0.06	0.07	0.09	0.08
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Rice straw wood wall	α	0.18	0.18	0.3	0.2	0.46	0.3
	σ	0.1	0.1	0.1	0.1	0.1	0.1
Glass wool or rock wool wall 100 mm	α	0.35	0.95	0.98	0.92	0.9	0.85
	σ	0.1	0.1	0.1	0.1	0.1	0.1

Note: The units of α is the absorption coefficients; σ is the scattering coefficients.

Using the Rhino/Pachyderm plugin, sound pressure level is calculated and obtained from the impulse response method. The sound is an omnidirectional source, and the source characteristics indicate that a point source generating noise is located in the middle of the apartment building, with a frequency spectrum ranging from 125 to 4000 Hz.

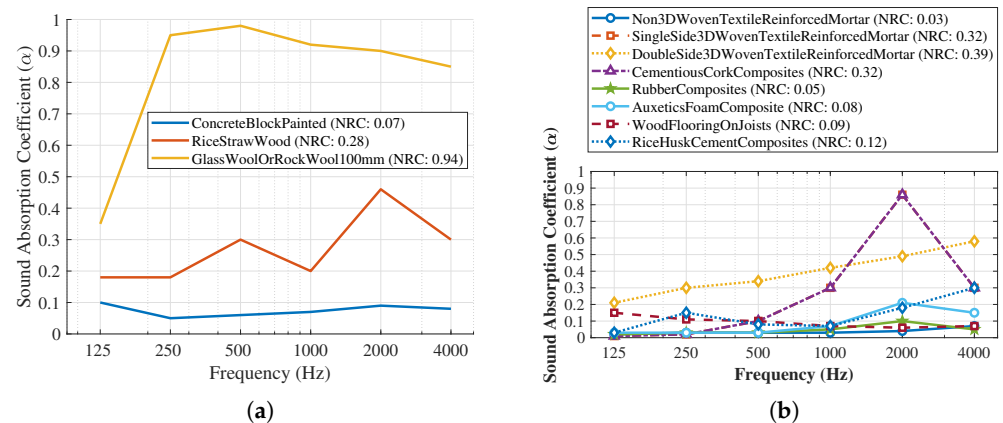


Figure 10. Sound absorption coefficient of different walls (a) and floor materials (b) [40].

The acoustic simulation process is carried out in two different ways: considering different 3D woven textile materials (NRM, SSRM and DSRM) or adding a new layer as needed. Their output usually includes acoustic metric values that are employed to quantify sound level distribution and sound propagation, respectively. A comprehensive framework is illustrated in Figure 11, which provides a diagram of the entire simulation process in the most detailed and concise manner.

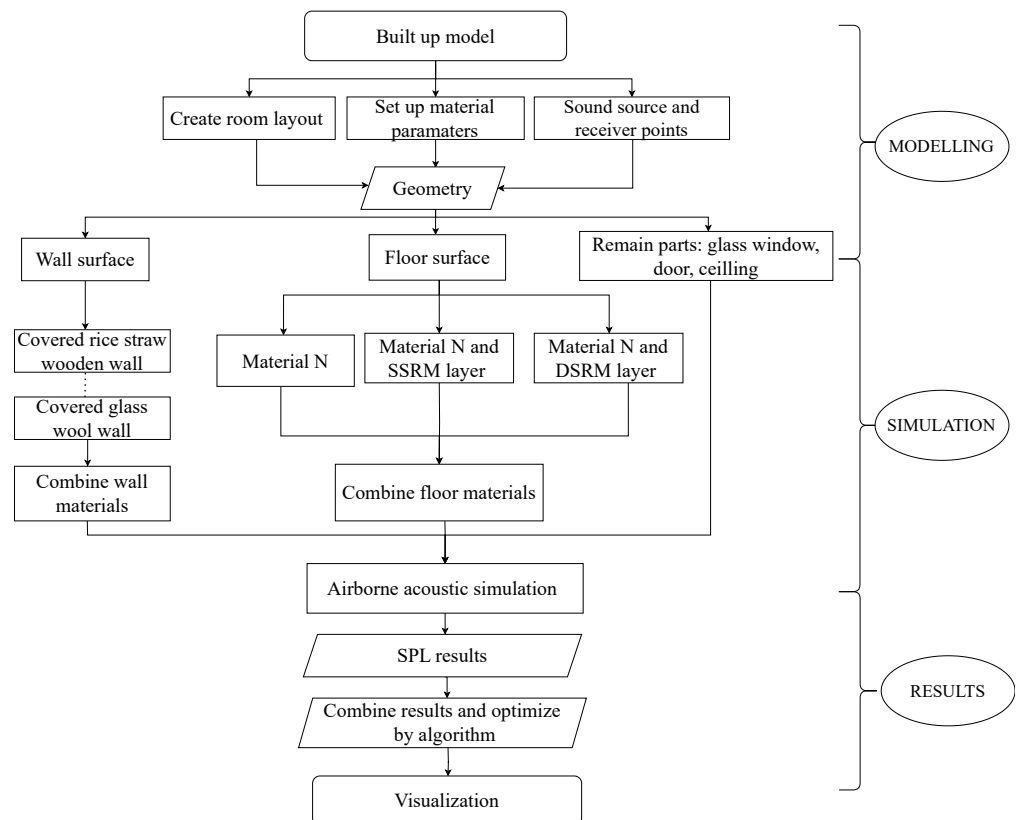


Figure 11. Acoustic optimization process.

2.3.2. Control Strategy

3D textile-reinforced concrete stands out among the materials, however, the remaining data are still higher than normal requirement, and then variable control should be set up as demonstrated in Figure 12.

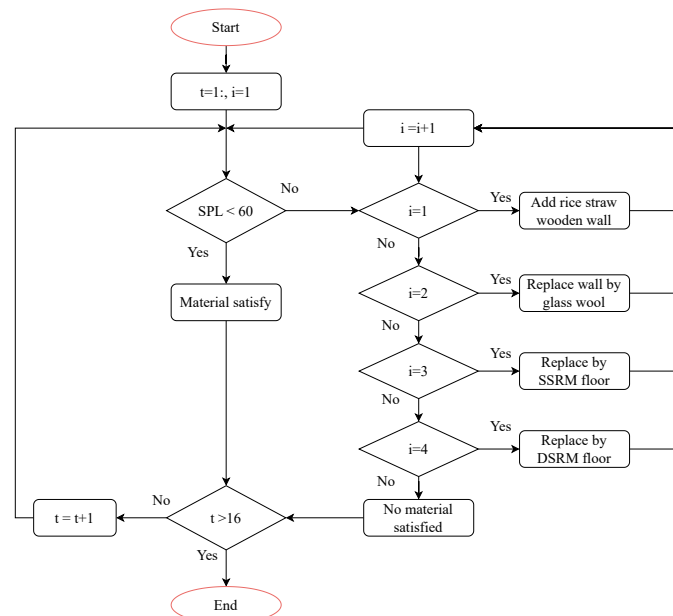


Figure 12. Algorithm of noise control.

Selecting good material could be conducted by MATLAB program with input parameters such as SPL less than 60 dB depending on space usage and belongings. This analysis is performed using JCA and transfer matrix method to achieve SAC for normal incidence, thereby assessing various absorbers. Control algorithm is customizable and can track the receiver's location, sound source, SAC across components, or other mixed control schemes can be used. Simulation process enables us to calculate and confirm the achieved or unachieved results as an expectation among these material alternatives. The input is gathered from acoustic parameter files and then transferred to the MATLAB software for computation and optimization of unsatisfactory outcomes. Combining findings allows for the identification of the most ideal values, ensuring that SPL values are required. After final result is selected, if any case is not satisfied, SSRM or DSRM of the floor layer would be proposed to increase sound insulation performance, and ultimately the results are visualized on the figures.

2.4. Floor Impact Sound Measurement

2.4.1. 3D Woven Textile Characteristics

The scope of 3D textile test floor was defined as a flat plate made of reinforced concrete with a rectangular plane and a thickness of 210 mm or more according to the Korean standard KS F 2865 [41] on measurement and evaluation method of acoustic impact noise reduction performance of apartment buildings. This evaluation method was used similarly to the impact sound generated in previous studies [19,42].

The 3D woven textile was cut to match the specimen's dimensions and applied as illustrated in Figure 13 for mortar pouring. After pouring according to the capacity of the mold, the compression and surface flattening were performed. Pouring the finished mortar, it was finished with vinyl to prevent the evaporation phenomenon of moisture, and curing was conducted for 28 days in a laboratory environment at 20 °C. After curing, an anchor was attached to the specimen to facilitate demolding of the mold and transporting it to the experimental place.



Figure 13. 3D woven textile (SSRM and DSRM) mortar specimen preparation.

The experimental test was conducted on the floor impact sound measurement room of disaster prevention testing laboratories, Gyeongchung-daero, Ganam-eup, Yeosu-si, Gyeonggi-do, South Korea, to evaluate 3D woven textile material performance, with properties as displayed in Table 3. The main structural system consists of a 210 mm thick slab, a 20 mm resilient layer made of Ethylene-vinyl acetate (EVA), and a $1700 \times 1700 \times 80$ mm floating floor layer. The top face sheet occupied the region from (0,0,0) to (5,5,10) mm, whereas the bottom face sheet extended from (0,0,0) to (0,0,10) mm, as described in Figure 14. This sample slab with 3 types of testing: non-reinforced mortar (NRM), single-side reinforced mortar (SSRM) and double-side reinforced mortar (DSRM) would be used to measure field data to improve accuracy. A limitation of this work is that our experimental scope focused exclusively on three slab samples, as demonstrated in Figure 15.

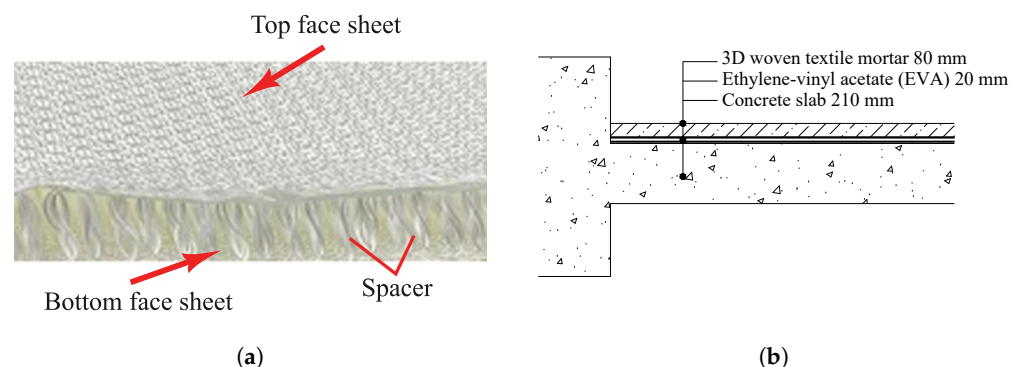


Figure 14. 3D woven textile texture (a) and reinforcement structure (b).

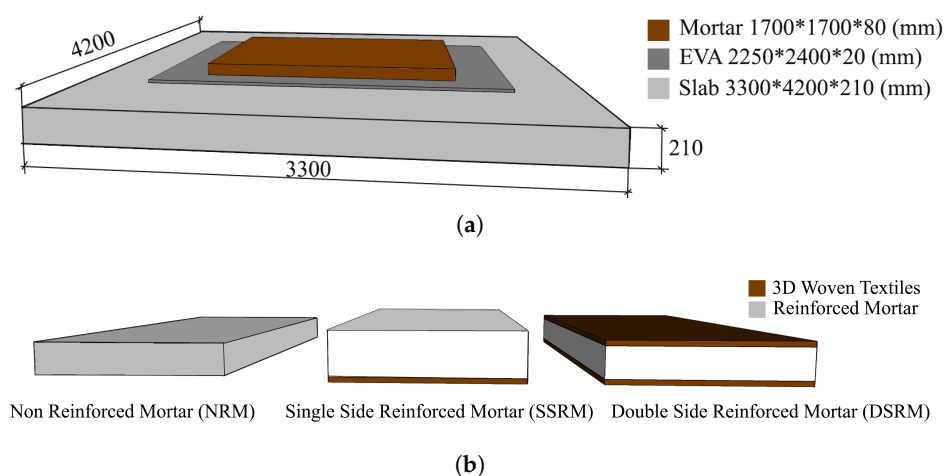


Figure 15. Structure layers (a) and three types reinforced mortar of 3D woven textile for field measurement (b).

Table 3. 3D woven textiles material properties.

Material	Density	Poisson's Ratio	Modulus of Elasticity
3D woven textiles	0.91 g/cc = 0.91 g/cm ³	0.44	1080 MPa

2.4.2. Dynamic Stiffness

An experimental test was carried out to determine the dynamic stiffness of 3D woven textile according to the ISO 9052-1 standard [43]. To achieve certain dynamic stiffness, the vertical vibration of the loading mass under external excitation was derived from the mechanical mobility function frequency response [44]. Besides, an accelerometer served as the vibration sensor, while an impact hammer functioned as the impulsive to determine dynamic stiffness. The dynamic stiffness of 3D woven textile, S' (in N/m³), could be expressed as follows [45]:

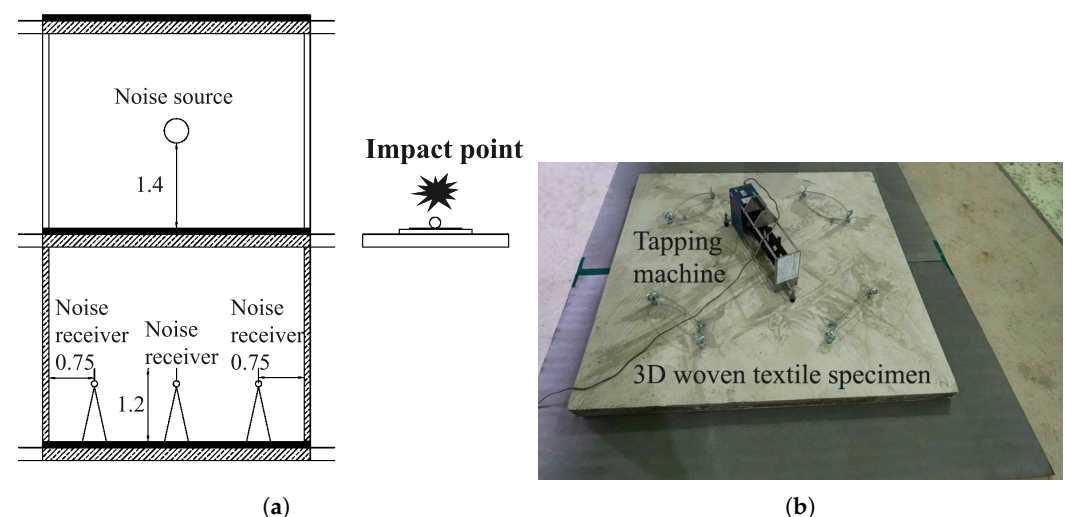
$$S' = (2\pi f)^2 * m \quad (7)$$

where S' is the dynamic stiffness of 3D woven textile (N/m), f is the natural frequency (Hz), and m is the mass of 3D woven textile slab (kg).

Dynamic Stiffness (S') and single number quantity have shown a significant effect on light weight floor impact sound. As a result, reduced dynamic stiffness was found to be beneficial for mitigating floor impact noise.

2.4.3. Measurement Method

Measurements of 3D woven textiles were conducted inside the testing laboratory. The sound reduction within the acoustic chamber during the testing of each specimen was assessed. We utilize a lightweight impact source standard like a tapping machine along with microphones and a sensor signal acquisition device. The installation method and the positions of an impact point and five receiving points are detailed in KS F 2810-1 [46], shown in Figure 16. And sound insulation is measured to conform to the KS F ISO 717-2 [26].

**Figure 16.** Microphone setting (a) and tapping machine for experiment test (b).

A tapping machine was utilized to assess the impact sound of the lightweight floor depicted in compliance with KS F 2863-1 [47] and ISO 717-2:2020 [48]. Measuring impact sound (following BS EN ISO 10140-3 [25]) was implemented as follows:

A conventional tapping machine with hammers weighing 500 ± 12 g, a speed of 0.886 ± 0.222 m/s each and a free fall 10 times per second mimics the sound source. The

effect on the floor is much more than that of typical footfall, yet it is required to provide a sufficiently high SPL in the receiving room. To ensure consistent excitation force in the measured noise impact, the test is repeatable and conducted numerous trials to analyze and determine standard deviations in noise level measurements. In addition, the basic room size ratio is chosen 1:1.2 to decrease resonances. Therefore, the chosen measuring room has a glass wool sound-absorbing substance which could avoid standing waves and undesirable reflections. Although the room modal effect is always there, its influence can be controlled by the absorbing material. Also, the microphone is 0.75 m away from the wall, and the tapping machine is measured at 3 special points in the middle of the room, near the wall, where the room modal effect is most obvious, before measuring the material experiment to avoid concentrated resonance and to select the position least affected by the room mode.

Throughout these measurements, an omnidirectional sound source was combined with a power [49]. A sound level analyzer also served as a microphone attached to the same laptop over the same audio interface and was analyzed using a custom-written MATLAB script. Five microphones were arranged to measure the sound pressure level in the receiving room to show the maximum SPL for each octave band frequency. It should be noted that the Single Number Quantity (SNQ), as specified in KS F 2863, is used as the standard method for rating floor noise in South Korea. Additionally, a narrow frequency range was chosen for the analysis since floor noise in multi-unit residential buildings is measured by SNQ, which accounts for the octave band frequency range (250, 500, 1000, 2000, and 4000 Hz). An acoustics analyzer will automatically do the averaging and present the lightweight and normalized impact sound levels.

2.5. Hybrid Approach

The results from airborne noise and impact floor sound reduction are used for optimization process. Two criteria below were employed to evaluate both stages. In first step, the proposed method initially employs JCA model and transfer matrix method to calibrate SAC for simulation process. After that, the control strategy was proposed to analyze and compare SPL with common material. This sequential combination capitalizes on the efficiency, and accuracy of airborne sound reduction for 3D woven textile more is enhanced. In second step, floor impact noise of 3D woven textile sample was tested in laboratory. By combining the two approaches, the proposed method achieves comprehensive results without compromising accuracy and time-consuming. The result demonstrate integrated method outperforms each individual approach when evaluating sound insulation materials.

2.5.1. Airborne Sound Evaluation

Each country has its own criteria for assessing airborne acoustics in buildings.

According to the Single Quantity Standard (SNQ), specified in KS F 2809, “Field measurement of airborne sound insulation of buildings” [50] in South Korea, airborne sound insulation curve calculated from SPL is used to standardize the measurement results. Following these guidelines and previous research, acoustic performance of apartment flats was evaluated using following acoustic parameters described in Table 4.

Table 4. Room acoustic metric.

Airborne Sound Evaluation	Ordinary Room	Criteria
Sound Pressure Level (SPL) [51]	≤60 dB	According to ISO 226:2023 [52], illustrates the threshold of hearing and a-weighting curve through the points at 60 dB.

2.5.2. Floor Impact Sound Evaluation

An inverse characteristic weighted normalized floor impact sound level ($L'_{n,AW}$), refers to the absorption in the receiving room, whereas the standardized impact sound pressure level, (L_{nT}), refers to a standard reverberation time. These tests are also compliant with ISO 10140-3, “Laboratory measurements of sound insulation of building elements” [25] and KS F ISO 717-2 standard [26]. The single number quantity for lightweight floor impact sound (L'_{nT}) was calculated using Equations (8) and (9).

$$L'_{nT} = L_i - 10 \log \frac{T}{T_0} \quad (8)$$

$$L_i = 10 \log \left(\frac{1}{n} \sum_{j=1}^n 10^{L_j/10} \right) \quad (9)$$

where T_0 is reference reverberation time (0.5 s) and T is reverberation time calculating in the receiving room (s). L'_{nT} is standardized impact sound pressure level (dB) and L_i is sound pressure level measurements at microphones.

3. Results

3.1. Airborne Sound Simulation Results

In Figure 17, the sound pressure level (SPL) values are required to be less than 60 dB at each receiver point.

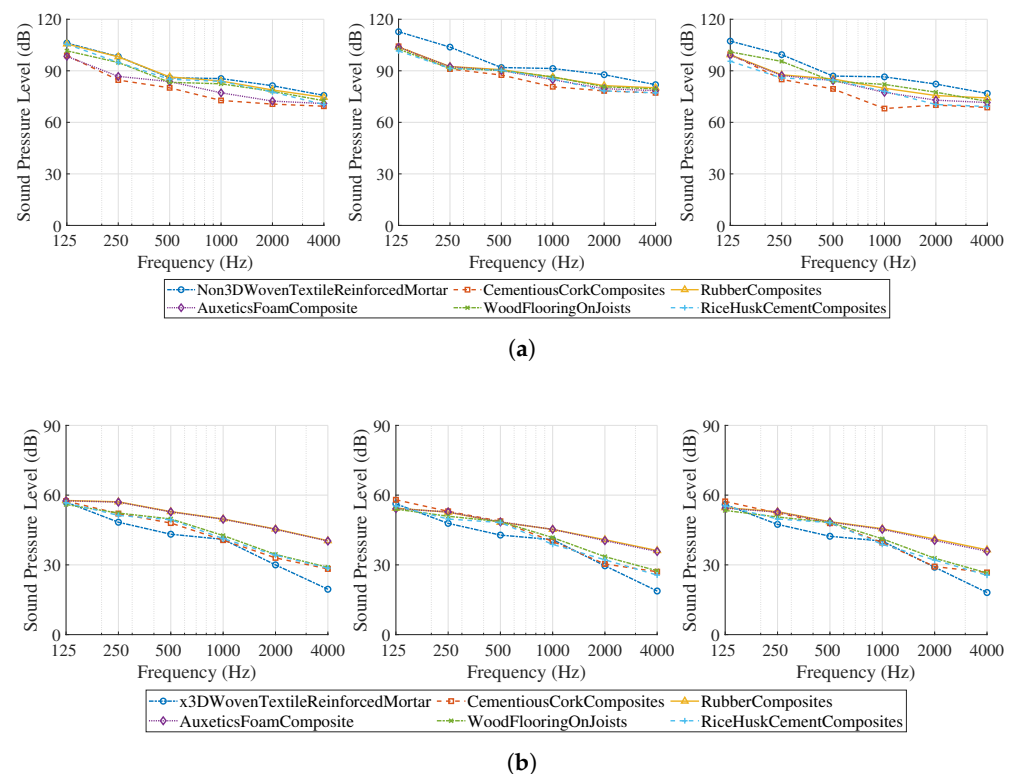


Figure 17. Sound pressure level with floor materials (a) before controlled and (b) after controlled at positions 1, 2, and 3.

For concrete walls combined with 3D woven textiles and other mixtures are good at preventing sound transmission through the slab system, yet the effective level is distinct at each position. Firstly, a normal concrete slab or one covered by other composites such as cementitious cork composites, rubber composites, auxetic foam composites, rice husk

cement composites, and wood flooring combined with a concrete wall produces a high degree of noise exceeding 90 dB. To address this problem, a complicated structural slab with 3D woven textile was recommended to reduce noise transmission level. Among of them, DSRM is still considered the most superior in sound reduction insulation performance, which dropped roundly 60 dB, representing an approximately 28.5% reduction in comparison with conventional materials.

Figure 18 presents types of composite materials having SPL reduction levels after using the 3D woven textiles. The mean SPL reduction of types of materials is taken after calculating the reduction of various 3 positions. It can be easily seen that the SSRM material combined with the above materials have SPL reduction less effective than DSRM material over the octave frequency range reaching the allowable threshold.

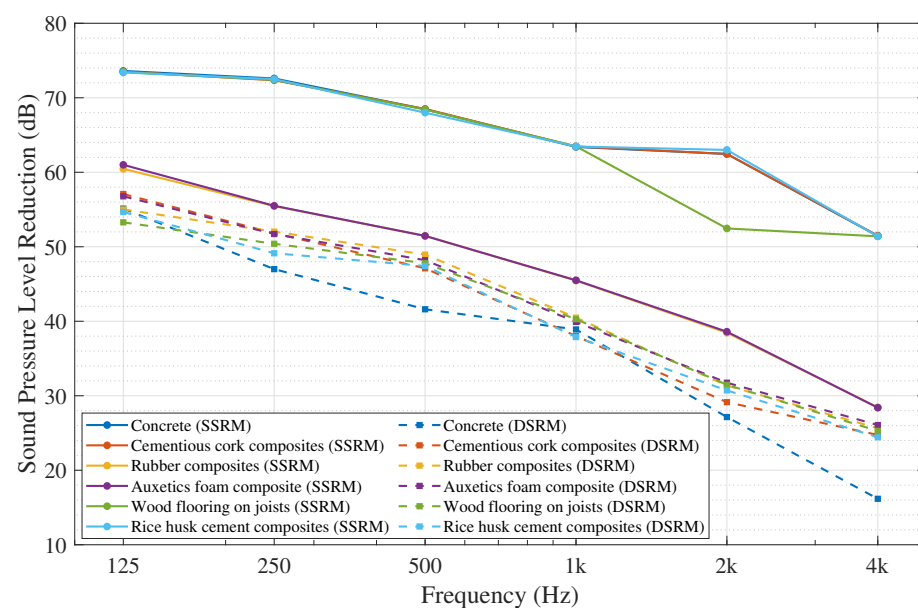


Figure 18. SPL reduction of materials when applied SSRM and DSRM.

3.2. Floor Impact Sound Experimental Results

The SPL of the floor impact sound before adding the 3D woven textile material was 58.4 dB at 125 Hz. However, after applying the single-layer and double-layer 3D woven textile, the SPL was reduced by 1.3 and 2.8 dB respectively as shown in Figure 19. From 500 Hz onward, the variation of the two SSRM and DSRM materials compared with the traditional material was clearly shown an SPL reduction of 3 dB and 3.3 dB respectively. Especially at 2 kHz, the DSRM material outperforms in terms of SPL reduction which was reduced by 13 dB. On the other hand, the SSRM material reduced only by 1 dB, indicating ineffectiveness for the high frequency. The installation of 3D woven textiles with two layers significantly reduced the noise, yet at the low frequency it could reduce less.

Experimental results at five different positions demonstrate a sharp decrease trend after 500 Hz frequency when using both with and without 3D woven textiles. Figure 19a indicates that SSRM test results follow similar trends in terms of frequency to non-3D reinforced textiles (NRM). In the instance of DSRM, it was discovered that the reduction of lightweight impact sound was good after 500 Hz, and it was proved that DSRM reduced by 13 dB when compared to traditional NRM material at 2 kHz. This demonstrates that DSRM (the arrangement of both ends of a 3D textile) has strong reduction properties in the intermediate and high frequency bands. This shows that there is a correlation between the aforementioned dynamic modulus and the lightweight impact sound. KW Kim (2009) [53] investigated the relationship between the dynamic modulus and the lightweight impact

sound, and it was discovered that the lower the dynamic modulus, the greater the decrease in lightweight impact sound. As a result, NRM and SSRM had equal dynamic modulus values, resulting in a floor impact sound level similar to each other, whereas DSRM, which had a lower dynamic modulus than NRM and SSRM, produced a light impulse sound value. The effect of reducing lightweight impact sound can be improved if 3D woven textile is used in a high-frequency band. The reduction in noise transmission to the lower story of the different frequency band is described in detail with the improvement with increasing sheet thickness as shown in Figure 19b.

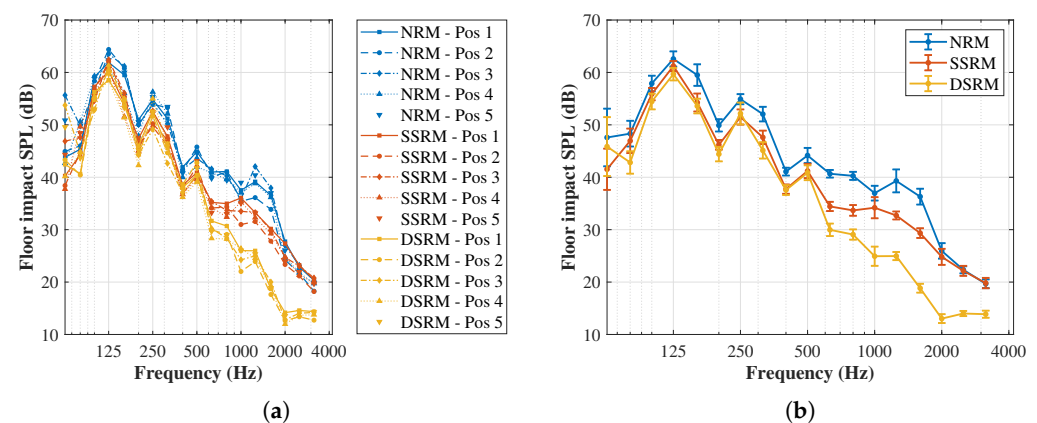


Figure 19. Comparison of measured impact SPL concrete slabs without 3D woven textiles (NRM); single side-reinforced mortar structure (SSRM); and double side-reinforced mortar structure (DSRM) (a), standard deviation (b).

In Figure 20, the results indicate that the mean SPL attenuation of DSRM is 6.45 dB, with a 95% confidence interval of [2.75, 9.01] and a variation of 10.9 dB. On the contrary, the mean SPL reduction of SSRM shows a very low, nearly 1 dB, CI [0.05, 1.89], and the variation between the maximum and minimum of SPL is 2.89 dB. The confidence interval indicates that SPL reduction contains the real values to 95% about the maximum attenuation of DSRM in the experiment which is 13 dB, whereas SSRM is just 4 dB.

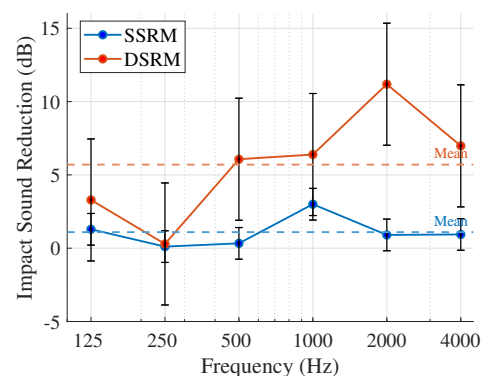


Figure 20. Comparison of impact sound attenuation caused by SSRM and DSRM sample.

4. Discussion

4.1. Airborne Acoustic Reduction

The paper examines the common materials incorporating 3D woven textile material in preventing noise from direct sound, as shown in Figure 21. The results show that The airborne noise reduction levels were different for 3D woven textiles with one or two layers (about 40% and 55%), compared to non-3D woven textile materials, as shown in Table 5. DSRM and other composites had a lower percentage reduction due to their low initial SPL.

DSRM materials showed the most variation between measurement locations, with a higher 60% reduction percentage. Meanwhile, the remaining materials showed negligible change between locations, with variations ranging around 40% at 500 Hz. SSRM had a large change rate of roundly 60% at middle and high frequencies compared to the remaining materials. While auxetic foam and rubber composites witness a lower mean percentage reduction, wood flooring and rice husk cement composites decrease uniformly from 45% to 65% at multiple frequencies. This approach is a fast and effective solution for determining the level of noise, ensuring desired sound levels in rooms below 60 dB as required, and for improving sound insulation for composite materials, especially in the early design phase.

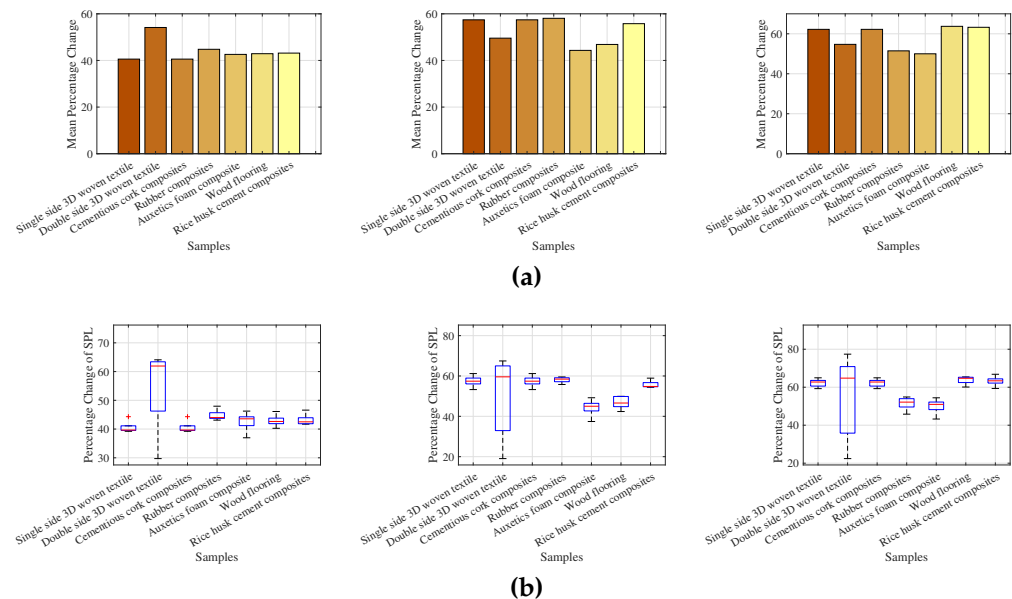


Figure 21. The mean percentage change of SPL (a) and percentage change (b) by box-and-whisker plot on each sample at 500 Hz, 2 kHz, 4 kHz respectively.

Table 5. Comparison of percentage change (%) between 3D woven textiles and other conventional composite materials at 500 Hz, 2 kHz and 4 kHz.

No	Name of Materials	Mean of SPL Change at 5 Positions		
		500 Hz	2000 Hz	4000 Hz
1	Single side 3D woven textile (SSRM)	40.57	57.42	62.23
2	Double side 3D woven textile (DSRM)	54.14	49.56	54.72
3	Cementitious cork composites	40.57	57.42	62.23
4	Rubber composites	44.78	58.07	51.47
5	Auxetics foam composite	42.60	44.32	49.99
6	Wood flooring on joists	42.89	46.86	63.74
7	Rice husk cement composites	43.15	55.77	63.25

4.2. Floor Impact Noise Reduction

The change of sound reduction performance according to the application of the 3D woven textile stands out as more apparent when compared to mortar without 3D woven textile. The floor impact sound pressure level reduces approximately 50% with DSRM and nearly 8% with SSRM at 1–2 kHz. W Chung (2024) [54] designed a rubber and cement insulation slab for residential rooms with a maximum SPL reduction of 13 dB. CW Kang [3] implied the floor's average SPL lowered by 8.6 dB while employing 10 mm thick decorative wooden floorboards. The aforementioned studies depicted the excellent acoustic insulation materials' performance in the reduction of SPL, while 3D woven textile reinforcement is also

prominent for SPL reduction of 9 dB within the confidence interval, with a maximum value of around 13 dB at 2 kHz. These results present that 3D woven textiles have sound insulation properties similar to wood flooring and other previously studied composite materials. Additionally, two-layer size of the 3D woven textiles combined with concrete mortar, results in more highly interconnected bonding of small pores, which helps to prevent sound wave transmission within the material on both sides and maximizes frictional losses, thus dissipating the acoustic energy as heat. Although single-layer 3D woven textile has a lower sound insulation level than double-layer 3D woven textile because sound waves fit into their fewer pores, they are still more effective than traditional materials at mid and high frequencies. This investigation could suggest that 3D woven textile material is also one of the promising, effective sound insulation material solutions. From a practical standpoint, this novel material shows significant promise for use in acoustic buildings.

4.3. Limitations

3D woven textile material performs effectively in the mid- to high-frequency range; however, each type has its own limitations. Firstly, the way the material absorbs sound relies on dissipating energy within its pores, but its effectiveness in reducing floor impact noise is insignificant because of low-frequency noise. Besides, DSRM is limited by the thickness of the material compared to the wavelength of the sound. To absorb a lot of sound below 500 Hz, the material may need to be thicker, which makes it hard to use for small-scale architectural projects. Secondly, airborne sound insulation is only analyzed based on simulation results at one apartment layout, and an experimental laboratory-scale sample has not been developed yet for validation. Ultimately, while cost and scalability issues are not a barrier, the fabrication of samples is limited to one slab type, and large-scale prototypes in the laboratory are challenging. The transition to mass production will require more detailed, cost-effective calculations and optimization of the manufacturing process to be competitive with natural fiber acoustic insulation materials.

4.4. Future Research

Future studies are needed to evaluate airborne sound insulation by testing to better understand how they affect airborne acoustic insulation. In parallel, the influence of 3D woven textiles on walls or other structures should be investigated and experimented in situ in residential flats with diverse floor plans. Moreover, future research hopes to reap benefits from using these data for optimizing the binder-to-aggregate ratio to mitigate the maximum impact of SPL on the specific floor system. From that, a proposal for using 3D woven textiles is combined with optimized concrete mixtures to reduce floor impact noise in apartment buildings.

5. Conclusions

Demands for embracing composite materials that uphold mechanical properties and long-term load-bearing capacity, along with superior sound insulation performance, are growing regulatory. This study proposes a 3D woven textile material solution and analyzes its sound insulation performance in the floor structure of apartment buildings. This study also serves as a reference for basic research on airborne sound insulation through simulation and floor impact sound insulation by testing with 3D woven textile specimens. An additional noise control strategy was proposed through a simulation model and optimization of sound insulation material. By utilizing 3D woven textiles with one or two layers, the airborne noise reduction levels were different (about 40% and 55%) compared to traditional materials. The floor impact sound insulation tests also showed that the two-layer 3D woven textile (DSRM) was more noticeable, with an average drop in maximum SPL of 9 dB. In

particular, the impact noise level decreased almost similarly for the two samples to 52 dB at 250 Hz. But then the reduction was significantly different, approximately 25 dB and 13 dB at 2 kHz for the SSRM and DSRM samples, respectively. Although this sound insulation material excels in the mid- to high-frequency range, it is limited at low frequencies due to the thickness of the material. In addition, the analysis was exclusively conducted on three slab types that have been fabricated for the floor impact sound insulation validation. Future works, therefore, need to extend the scope and in situ testing, as well as to adjust the thickness and material structure of 3D woven textiles to optimize the sound insulation performance. Overall, these findings could open up a wide range of potential applications for 3D woven textiles as a sustainable and noise-control alternative. 3D woven textiles are easy to construct, cost-effective, and fully compatible with existing concrete structures, while also having superior soundproofing properties, making them a good choice for various types of civil engineering applications.

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