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Sound Absorption Characteristics of Integrated Membrane-Fabric Materials

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ABSTRACT

Noise pollution has emerged as one of the most significant environmental issues, particularly in developing countries. Combining a membrane or panel with two or more porous materials is a practical approach to sound absorption. However, it often makes the absorber thicker, taking up more space and increasing production costs. This research proposes a new integrated sound absorber that combines a rubber membrane with fabric to absorb sound at different frequencies. The use of fabric eliminates the use of typical bulky porous material, which can save much space and cost of production. The main objective of this research is to study the characteristics of the new integrated membrane-fabric by varying perforation sizes, perforation percentages, and backed air gap distance between the material and the rigid wall. The characteristics of the integrated membrane-fabric absorber were experimentally measured in terms of Sound Absorption Coefficient by using the impedance tube method in compliance with ISO 10534-2 standard. This research has determined that the integrated membrane-fabric material exhibits exceptional sound absorption performance across a wide frequency range, which is influenced by several factors, including the diameter and ratio of perforations and the depth of the air cavity. Furthermore, the investigation revealed that the positioning of the fabric also plays a crucial role in determining the material's absorption performance.

1. Introduction

Acoustic design has become an important aspect in most building design, construction, and operation because a poor acoustic environment is known to have a negative impact on human physical and mental health [1]. Therefore, building acoustics must be optimized to create a pleasing atmosphere and increase human comfort levels. Installing an acoustic absorber is the most favorable solution to an acoustic problem since it is both effective and inexpensive. Sound absorbers are able to prevent and reduce the strength of reflected noise effectively by converting sound energy into heat energy, thus preventing sound from building up, especially in confined spaces, and lowering the volume of the reflected sound.

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Porous and fibrous absorbents have been widely used due to their absorption performance and low cost compared to other sound absorbers. However, for porous materials to be effective, they need to be very thick. Additionally, the open pores can become clogged with dust and release harmful fibers into the air, which is unhygienic and bad for health. As a result, these drawbacks have spurred interest in natural fibers. Natural fibers have been shown to be more environmentally friendly and safer, and have better sound absorption performance [2-4]. However, it is important to note that porous-type sound absorbers have limitations when it comes to absorbing low-frequency sound. Their ability to absorb sound is mostly limited to mid-high frequencies, which may make them less effective in enclosed spaces where low-frequency sound absorption is necessary. This limitation can pose a problem in such situations. Therefore, the attention begins to shift toward the panel or membrane absorber. Panel or membrane absorbers are known to have the capability of absorbing sound at the mid-low-frequency range and can be the best solution to overcome this problem.

As an alternative to porous materials, micro-perforated panels (MPPs) have been introduced by Maa [5,6] due to their features and performance in absorbing sound. MPP absorbers are known to be durable, fiberless, and aesthetic materials. Since then, MPP sound absorption has been intensively investigated. However, MPP relies solely on the Helmholtz resonator type of sound absorption. The MPP has a narrow absorption bandwidth, and its absorption is limited to the middle-frequency region unless it has been properly designed. In order to improve and produce an efficient sound-absorbing system with a wide range of sound absorption, another absorption mechanism needs to be introduced.

MPP with a combination structure is preferable over MPP with extremely small perforations. This is due to the difficulty and high expense involved in fabricating MPP with such small perforations, especially for large areas. The most popular combination structure consists of MPP and porous material. However, the combination of materials often makes the sound absorber thicker, occupying more space and becoming more expensive. Furthermore, the presence of porous materials is unsuitable in certain environments that require high levels of hygiene restrictions.

Based on the promising sound-absorption performance of MPP, the idea arose to utilize this concept for creating a new sound-absorbing structure with a broader absorption range. This research involved the selection of flexible materials to replace typical rigid materials, considering the vibration effects that MPP neglects. In addition, the membranes were perforated to create a Helmholtz-type absorption mechanism. Thus, sound energy dissipation of perforated membranes occurs through both the vibration of the membrane and the friction between air particles and the surface of the perforated hole. This differs from conventional MPP, which relies solely on the oscillatory movement of sound waves around the perforated hole area and neglects the effects of vibration.

The performance of membrane materials is usually governed by their material properties, such as mass density, thickness, depth of air cavity, and perforation. Previous studies have shown that a membrane with high mass density improves absorptivity and shifts the absorption peak towards the low-frequency range [7,8]. Adjusting the air cavity depth can alter the sound absorption peak and the resonance frequency of the membrane [9-11]. Membrane thickness also significantly influences sound absorption performance [12,13]. Perforation creates a Helmholtz resonator type of absorption on the membrane [14]. Additionally, multi-layered membrane absorbers have more absorption and give higher absorptivity in a broad range of frequencies than single-layer membrane absorbers [15-17].

This research introduces the integration of a rubber membrane with a fabric (porous material) to create a novel sound-absorbing material. By using fabric, it eliminates bulky porous materials, saving space and production costs. This integrated membrane-fabric material combines all types of sound absorbers (resonant absorber and porous absorber) into one absorptive material. As there hasn't been much related work on this material integration reported yet, this new idea of using an integrated membrane with fabric is presented. This research aims to study the sound absorption characteristics of the integrated membrane-fabric material. This research also investigates the effects of perforation size, perforation ratio, and air cavity depth on the proposed material. The sound absorption performance, in terms of the Sound Absorption Coefficient (α) are presented.

2. Theory and Formulation

2.1 Membrane Sound Absorption Mechanism

A membrane absorber works by absorbing sound through a mass-spring resonance system. When sound energy hits the surface, the vibrating sheet acts as a mass, and the enclosed space cavity acts as a spring. Mass vibration against the spring converts sound energy into mechanical energy, which is then dissipated as heat energy. Typically, these absorbers are placed over an air cavity at some distance from the solid backing. Figure 1 shows the schematic diagram of a membrane backed by a rigid wall with an air gap in between.

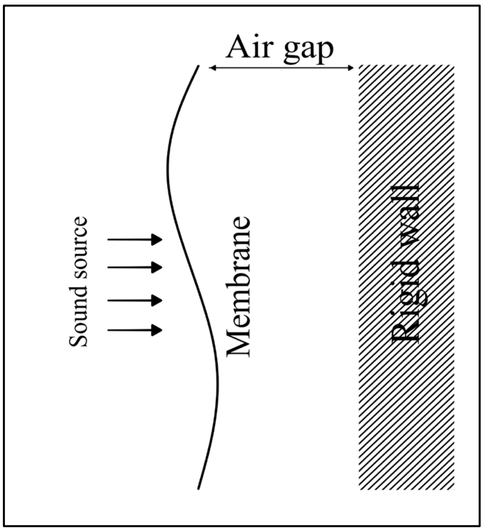

Fig. 1. Schematic diagram of membrane absorber backed by rigid wall

2.2 Sound Absorption Coefficient

The efficiency of a material in absorbing sound can be measured by its sound absorption coefficient, $\boldsymbol{\alpha}$, which can be calculated using a formula expressed as

$$\alpha = 1 - \frac{I_R}{I_I} \quad (1)$$

where:
$\boldsymbol{\alpha}$ = Sound absorption coefficient
I_R = Reflected sound intensity
I_I = Incident sound intensity

The sound absorption coefficient, $\boldsymbol{\alpha}$, is a dimensionless value ranging from 0 to 1 that indicates the level of sound absorption efficiency of a material. A value of $\boldsymbol{\alpha}$=0 signifies perfect reflection of sound waves with no absorption, whereas $\boldsymbol{\alpha}$=1 represents complete absorption of all incident sound waves with no reflection.

2.3 Air Flow Resistivity of Fabric Materials

The airflow resistivity of a porous absorber is one of the most important factors that play a role in determining the sound-absorbing capabilities of the material. It is a measurement that determines the amount of resistance that airflow encounters within a structure and how quickly air can enter a porous absorber. Once the airflow resistivity has been determined, a number of models, either theoretical or empirical, can be used to make predictions regarding the impedance and absorption coefficient of fibrous material. The airflow resistivity of the fabrics can be calculated based on empirical equation by Garai & Pompoli [18]

$$r = A\rho_{\mathrm{m}}{}^{\mathrm{B}} \tag{2}$$

where *r* is the air flow resistivity (pa.s/m$^{2)}$, *A* = 25.985 and *B* = 1.404. A and B are free parameters. The density, ρ_{m} was calculated using weight and thickness values.

$$\rho_{\mathrm{m}} = \frac{m}{t} \tag{3}$$

where ρ_{m} is the density (kg/m$^{3),}$ m is the mass (g/m^2) and *t* is the thickness (m).

3. Material and Measurement

3.1 Material Selection

For this research, three commercial rubber and fabric types were selected to ensure the study's validity across a broad range of membrane and fabric types. The material selection is based on their wide availability in the market and their use in various applications. The chosen membrane materials include Nitrile butadiene rubber (NBR), silicone, and Ethylene-propylene-Diene-Monomer (EPDM), while the three fabric types used in this research are polyester, linen, and velvet. Tables 1 and 2 provide material properties of the membrane and fabric samples used in this study.

Table 1
Material properties of membrane samples

Samples	Thickness (mm)	Weight (g)	Density (g/mm^3)
M1	0.5	8.2	2.08 x 10^{-3}
M2	0.5	5.8	1.47 x 10^{-3}
M3	0.5	4.8	1.22 x 10^{-3}

Table 2
Material properties of Fabric samples

Fabric	Thickness (mm)	Density (kg/m^3)	Air Flow Resistance (Kpa.s/m^{-3})
F1	0.19	815.8	318.1
F2	0.32	862.5	344.0
F3	0.34	488.2	154.7

3.2 Sample Preparation
3.2.1 Unperforated membrane, fabric and integrated membrane-fabric samples

Unperforated membrane, fabric, and integrated membrane-fabric samples were fabricated in two sizes: 28 mm and 100 mm in diameter in this experiment. The 28 mm specimens were used for high-frequency tests, and the 100 mm specimens were used for low-frequency tests. A sturdy holder made from Acrylonitrile butadiene styrene (ABS) filament was 3D printed using a 3D printing machine to hold the samples in the impedance tube as illustrated in Figure 2. This ABS holder plays a important role in this process as it serves as a rigid support that mounts the membrane inside the impedance tube. Without the holder the membrane cannot be positioned and oscillate properly inside the tube.

Fig. 2. Samples holder made from ABS

3.2.2 Perforated membrane samples

All of the perforations were manually punched using a puncher. The distance between each perforation was calculated and arranged using SolidWorks software based on the selected ratio to ensure that the perforations were evenly distributed. Figure 3(a) illustrates a SolidWorks model of the perforated specimen. The actual size of the perforated model was then printed out and laid on the specimen surface before manual punching. The perforation size and ratio used in this experiment were recorded in Table 3. Figure 3(b) shows the image of the completed sample.

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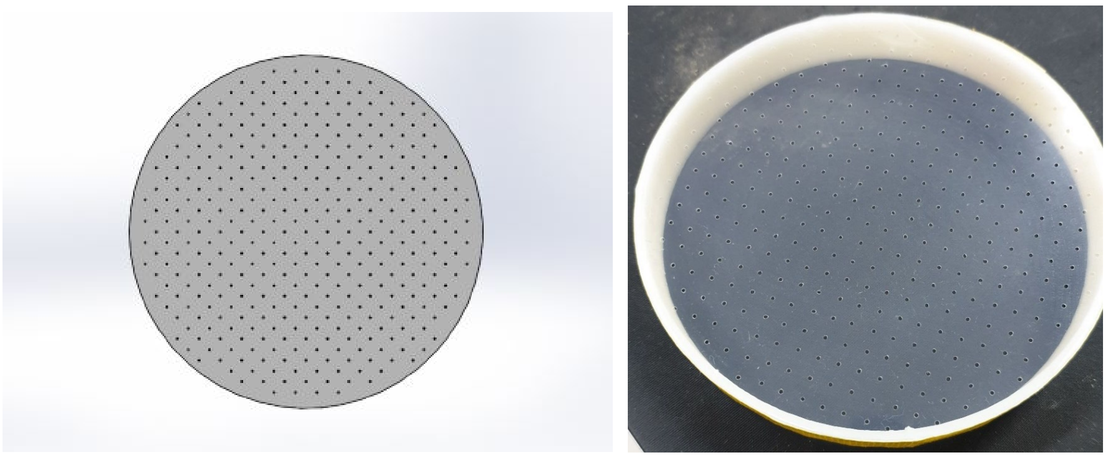

(a) (b)

Fig. 3. (a) Perforated model created in SolidWorks (b) Completed perforated sample

Table 3
Perforation sizes and ratios

Perforation size (mm)	Perforation ratio (%)
0.5	0.2
1.0	1
2.0	2
3.0	3

3.2.3 Integrated membrane-fabric samples

The integrated membrane-fabric samples were made by attaching fabric to the surface of the perforated membrane using PVA glue, as shown in Figure 4. The glue was allowed to dry before performing the test.

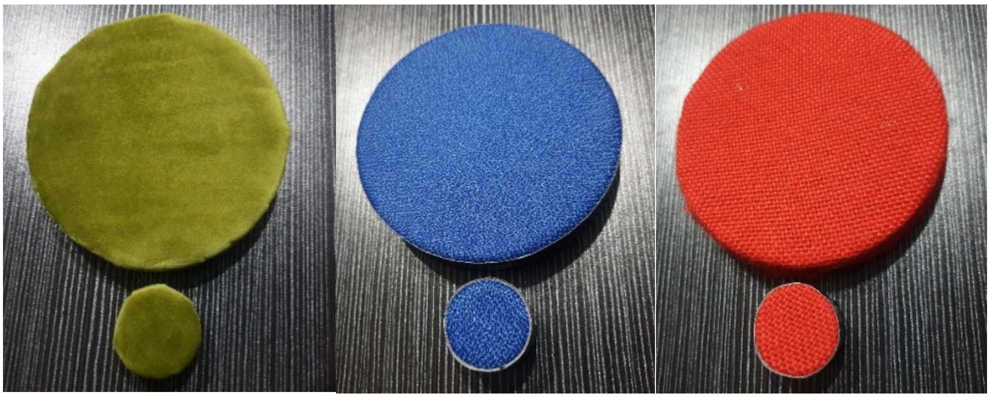

Fig. 4. Integrated membrane-fabric samples

3.3 Instrument

The impedance tube method was used to measure the sound absorption coefficients of the samples experimentally. This method involves two tube setups: a small tube with a 28 mm inner diameter for high frequency measurements between 1600 Hz and 7100 Hz, and a large tube with a 100 mm diameter for low frequency measurements between 90 Hz and 1800 Hz. The impedance tube used in this study is depicted in Figure 5. To measure the sound absorption coefficients, the two-microphone transfer function method was utilized in accordance with the ISO 10534-2 standard. This method uses a random noise source located at one end of the impedance tube and is coupled with a pair of microphones placed at fixed locations along the tube.

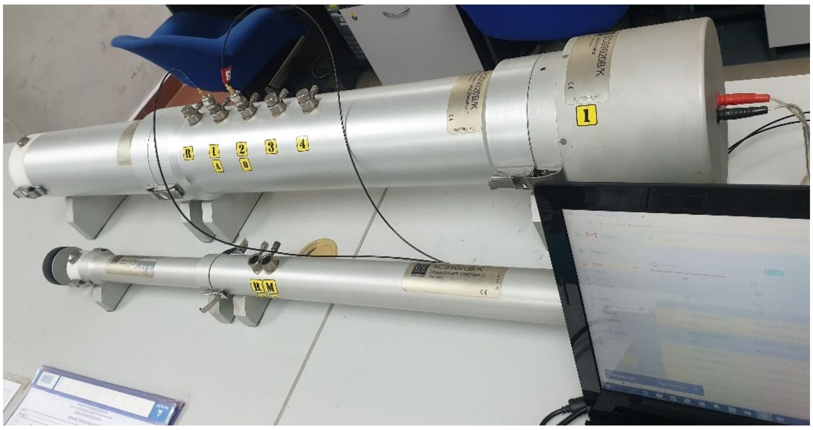

Fig. 5. Impedance tube set

4. Results

4.1 Sound Absorption Coefficient of Membrane Materials

Figure 6 presents a comparison of the sound absorption coefficients of three different membranes. The plotted graph shows that all of the samples exhibit good absorptivity in the low to middle frequency range. The results also show that the sound absorption peaks of samples M2 and M3 are almost identical. It can be observed that the sound absorption coefficient of sample M3 is quite high, reaching 0.98 within the frequency range of 350 Hz to 850 Hz. Additionally, sample M3 has slightly higher absorption in the high-frequency range compared to the other samples.

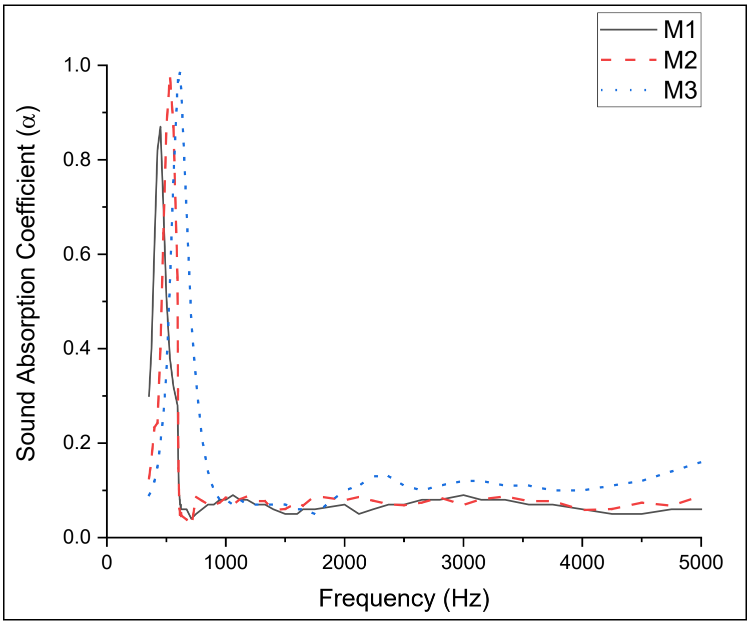

Fig. 6. Sound absorption coefficient of sample M1, M2 and M3

By referring to the graph, it can be observed that high-density results in a lower sound absorption coefficient value. The peaks of sound absorption also shift towards the mid-frequency range as the density decreases. This phenomenon can be explained by relating it to the mass-spring resonance system, where the membrane acts as a mass, and the air within the cavity acts as a spring. The low-density sample has a better sound absorption coefficient due to the decrease in its total acoustic mass, increasing to the peak of the sound absorption coefficient. The results show that samples M2 and M3, which have much lower densities than sample M1, provide optimal total acoustic resistance. This finding is consistent with previous studies [12,14,19].

High-density materials are typically more rigid and less porous than low-density materials. Consequently, sound waves tend to bounce off or reflect rather than penetrate the material. Therefore, a clear correlation exists between material density and sound absorption characteristics. From this experiment, the data implies that the surface density could determine membrane materials' sound absorption coefficient peaks and can be used to modify the absorption characteristics of a membrane. Sample M3 has shown a promising ability and potential in absorbing sound at low to middle frequency. This finding suggests that the M3 sample can be used as a membrane material in this study.

4.2 Sound Absorption Coefficient of Fabric Materials

The absorption coefficients of three different types of fabrics are shown in Figure 7. The samples were prepared and examined using a similar configuration and method as in the earlier experiment, and the material properties of all samples are listed in Table 2. Based on the data analysis, all samples effectively absorb sound in the mid to high-frequency range. The results indicate that samples F1 and F2 have nearly identical peaks of the sound absorption coefficient. Sample F1 has a slightly higher sound absorption coefficient than sample F2, reaching 0.93 between 1000 and 6000 Hz, while sample F2 reaches 0.92 with a wider absorption range, ranging from 800 Hz to 6000 Hz. The sound absorption peak of sample F3 is 0.87 within the frequency range of 1650 to 6000 Hz.

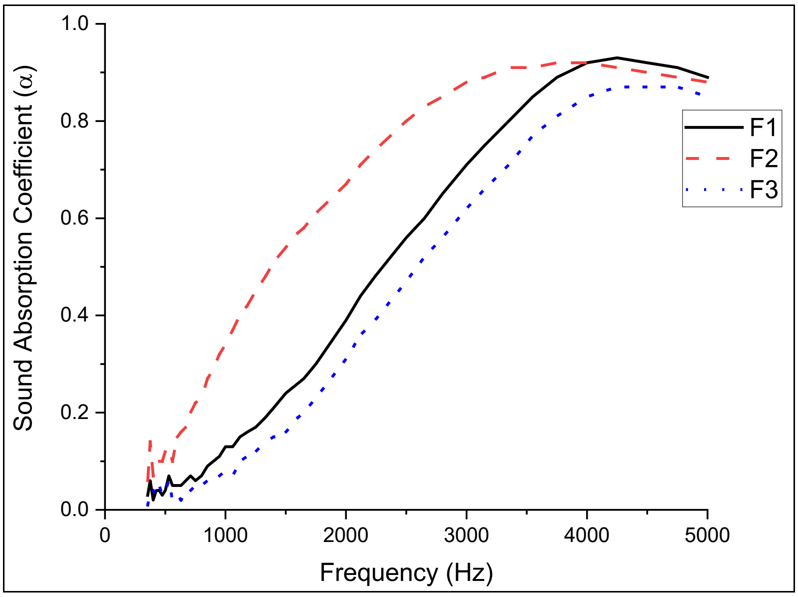

Fig. 7. Sound absorption coefficient of F1, F2 and F3 samples

In the analysis of the correlation between material properties and acoustical properties, it can be observed that the density of the fabric material is related to flow resistivity and fibre diameter. The result shows that the sound absorption performance of a material improves with the increase of airflow resistivity. However, the peak starts to decline after reaching a certain value. Similar results are also achieved by Peng [20]. This is because increased airflow resistance generates more frictional force due to the air having more difficulty passing through the sample, which converts sound energy into thermal energy and increases sound absorption. However, excessive airflow resistance can negatively impact the sound absorption performance of a sample. When airflow resistance becomes too high, it restricts air movement through the pores, reducing the material's ability to absorb sound waves. Therefore, to achieve the desired sound absorption performance, it's important to optimize the airflow resistance of the material.

In addition, the values of the sound absorption coefficient peak agree well with the fiber diameter. Sample F1 and F2 with fiber diameters lower than 20 µm promote better absorption compared to sample F3. It appears that the fiber diameter is associated with the sound absorption characteristics of the material. In comparison between the large and small diameters of fibre, a small diameter fiber can move more easily on the sound wave. Furthermore, the small fibre resulted in a more tortuous path and high airflow resistance because more fibre is required to achieve an equal volume density at a similar thickness**.**

The results also show that high density values contribute to better sound absorption. Sound absorption improved significantly in the middle to high-frequency range as density increased. This relationship is linked to the quantity of fiber in the samples. Denser samples have a higher fiber concentration per unit area, resulting in increased sound energy absorption due to greater frictional loss between the sound wave and the fiber. In the section of fabric selection, it clearly shows that the F2 is preferable for this research because it has better absorption value and range compared to other fabrics.

4.3 The Effect of Material Arrangement on Sound Absorption Coefficient of Integrated Fabric-Membrane Material

Figure 8 shows the result of two integrated sample arrangements. One has an unperforated membrane attached in front of the fabric, labeled as U-MF, and the other has an unperforated membrane attached behind the fabric, labeled as U-FM. According to the findings, the absorption peaks of U-MF and U-FM are slightly lower than the absorption of the single unperforated membrane (M3). Additionally, almost no change was observed in their resonance frequency, and absorption peak for U-MF and U-FM integrated samples. These samples exhibit almost identical absorption characteristics, particularly in the low-frequency range. However, it can be seen that the absorption of the U-FM sample in the high-frequency range is slightly higher.

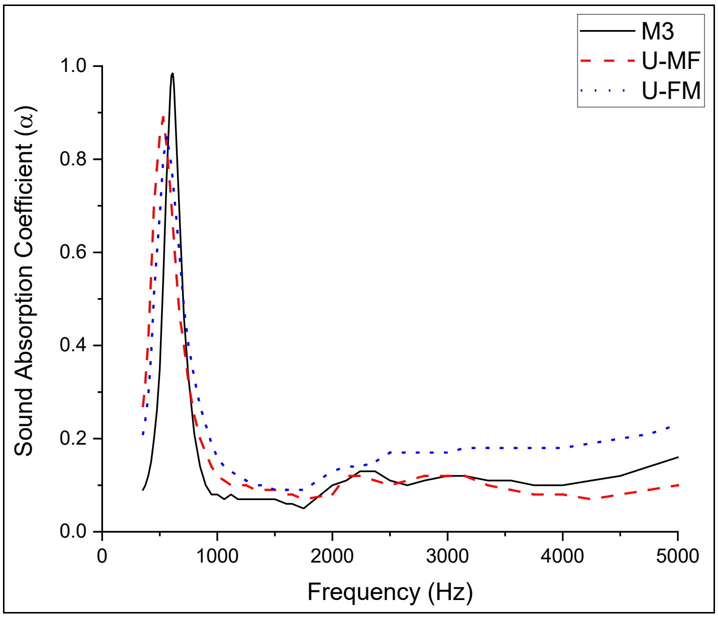

Fig. 8. Sound absorption coefficient of the integrated U-MF and U-FM samples

The U-MF exhibits comparable sound absorption properties to the M3 sample. This suggests that the fabric behind the unperforated membrane does not substantially affect sound absorption. The surfaces of the impermeable membrane prevent the sound waves from passing through and reflect most of the medium and high-frequency sounds. Therefore, the fabric behind the membrane does not play a significant role in the sound absorption of the U-MF sample.

In contrast to the U-MF sample, the U-FM sample demonstrated enhanced sound absorption at high frequencies due to the porous absorption characteristics of the fabric layer in front of the membrane. The fabric layer effectively absorbed medium and high-frequency sound waves, while the low-frequency sound waves penetrated through the fabric and were dissipated by the membrane behind it. Therefore, both layers of the U-FM sample played a role in sound absorption. The fabric layer contributed to improved sound absorption by absorbing medium and high-frequency sound, while the membrane in the back absorbed the low-frequency sound. This finding is consistent with the work of Li *et al.,* [21], who stated that a porous layer placed in the front is better than one placed in the back due to the porous layer's ability to act as an impedance-matching layer in high frequencies

4.4 Sound Absorption Coefficient of Integrated Unperforated Fabric-Membrane (U-FM) Materials

This section examines the effects of U-FM on the sound absorption coefficient. Three different fabric types were attached in front of an unperforated membrane to produce three integrated U-FM samples, identified as U-F1M, U-F2M, and U-F3M. Figure 9 shows the sound absorption coefficient of the U-FM integrated samples using three different fabrics. The standard unperforated samples, M3, were also measured to investigate the effect of the fabrics on the integrated U-FM. It is found that the resonance frequency of all samples is mainly located in the low-frequency range. The maximum peak of the sound absorption achieved by integrated U-F1M is 0.93 at 600 Hz. The absorption peaks of all integrated U-FM samples are slightly lower than that of M3. The membrane's absorption mechanism can account for the phenomenon. As there was no gap between the fabric and the membrane surface, the fabric inhibited the membrane's oscillation, restricting the absorption of sound energy.

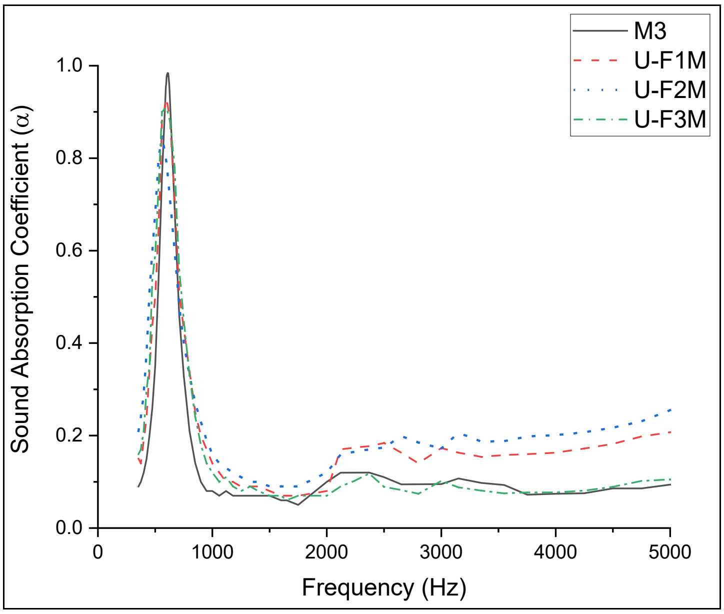

Fig. 9. Sound absorption coefficient of three integrated fabric-membrane (U-FM) samples

Interestingly, all integrated samples show increased absorption in the middle to high-frequency range, from 2000 Hz to 6000 Hz. This increase in absorption can be attributed to the porous absorption characteristics of the fabrics used in the samples. Fabrics with high airflow resistivity contribute to mid-high frequency sound absorption by adding additional damping to the membrane, which improves its absorption performance. This finding is consistent with the work of Sakagami *et. al.,* [22], who reported that porous materials play a crucial role in mid-high frequency sound absorption.

4.5 The Effect of Perforation Size on the Sound Absorption of Fabric-Membrane (FM)

Figure 10 shows the Perforated Fabric-Membrane (P-FM) sound absorption coefficient with varying perforation sizes: 0.5 mm, 1.0 mm, 2.0 mm, and 3.0 mm. The experiment used a fixed perforation ratio of p = 1%, an air gap distance of D = 15 mm, and a thickness of t = 0.5 mm. Unperforated samples were also measured as a standard to examine the effect of perforation. The results indicate that the perforation has increased the sound absorption of P-FM. Moreover, the perforation has converted the low-frequency type absorption of P-FM into a middle-high frequency type of absorption.

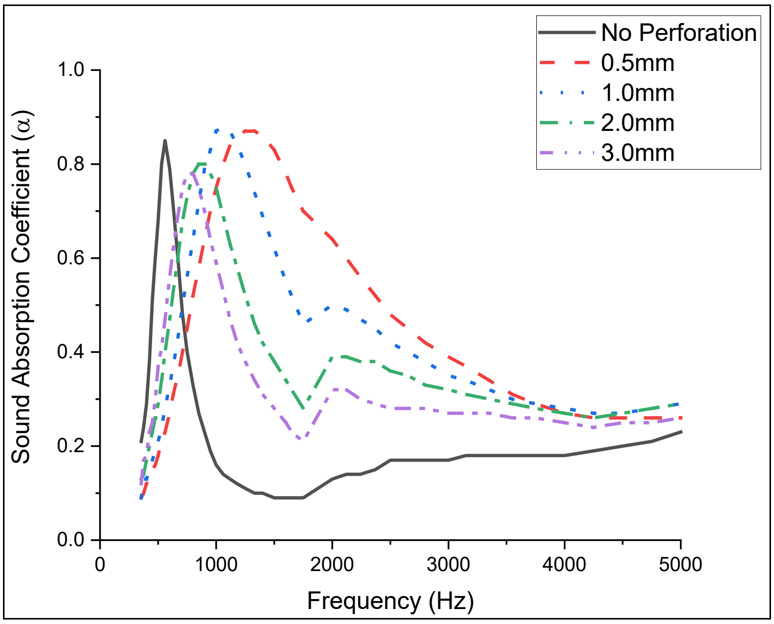

Fig. 10. Sound absorption coefficient of Integrated fabric-membrane with different perforation size

In terms of the perforation size, it clearly shows that the absorption coefficient increases as the perforation size increases. However, a significant drop was noticed in the absorption peaks as the size of the perforation increased further. The experimental results show that P-FM samples with a perforation diameter of 0.50 mm demonstrated better sound absorption performance compared to samples with different perforation diameters. P-FM samples with 0.5 mm and 1.0 mm perforation have almost similar peak values where the maximum absorption peaks for both samples only differ by 0.01. However, the 0.5 mm perforation has a wider frequency bandwidth, ranging from 630 Hz to 3350 Hz.

The increase in perforation size causes the frequency bandwidth of P-FM absorption to become smaller and shifts the peaks towards lower frequencies. This result shows a similar trend to single perforated membrane absorption, where the size of the perforation affects the frequency bandwidth and range of sound absorption. When compared to the single perforated membrane, the P-FM sample exhibits a broader range of sound absorption due to the added acoustic resistance introduced by the fibrous material. The P-FM sample demonstrates optimized acoustic resistance with a perforation size of 0.5mm. Meanwhile, for perforation sizes larger than 0.5mm, sound absorption exhibits slight increases in the resonance peak, then decrease as the perforation size increases further. This drop-in performance happens because the acoustic resistance decreases with a larger perforation size. The excessively perforations size will make the sample to loss ability to resist sound as the sound can be easily to pass through the sample without being absorbed or reflected.

Therefore, the result clearly shows that the sound bandwidth and amplitude can be controlled by the size of perforation.

4.6 The Effect of Perforation Ratio on the Sound Absorption of Fabric-Membrane (FM)

This section discusses the effect of the perforation ratio on the sound absorption of the Perforated Fabric-Membrane (P-FM). The experiment conducted by varying perforation ratios: 0.2%, 1%, 2%, and 3% with fixed d = 0.5 mm, t = 0.5 mm, and D = 15 mm. The results as shown in Figure 11 indicate that the perforation ratio has the most notable effect on absorption frequency bandwidth. The frequency bandwidth obtained from the graph shows that the sample with 3% perforation has the widest frequency band, reaching up to 2020 Hz. The resonance frequency range also moves towards higher frequencies with an increasing perforation ratio, shifting from 870 Hz to 1750 Hz as the perforation ratio increases from 0.2% to 3%.

It can be observed that as the perforation ratio increases, the sound absorption of the P-FM sample becomes more similar to that of porous material. The absorption of the fabric layer becomes dominant when the perforation ratio is above 1%. This is because the effect of the fabric layer becomes significant when the membrane does not have sufficient acoustic mass due to the increase in the perforation ratio. At this point, the viscosity and friction lost around the edges and surrounding area of the perforated holes will be insignificant. Thus, the sound is absorbed mainly by the fabric layer.

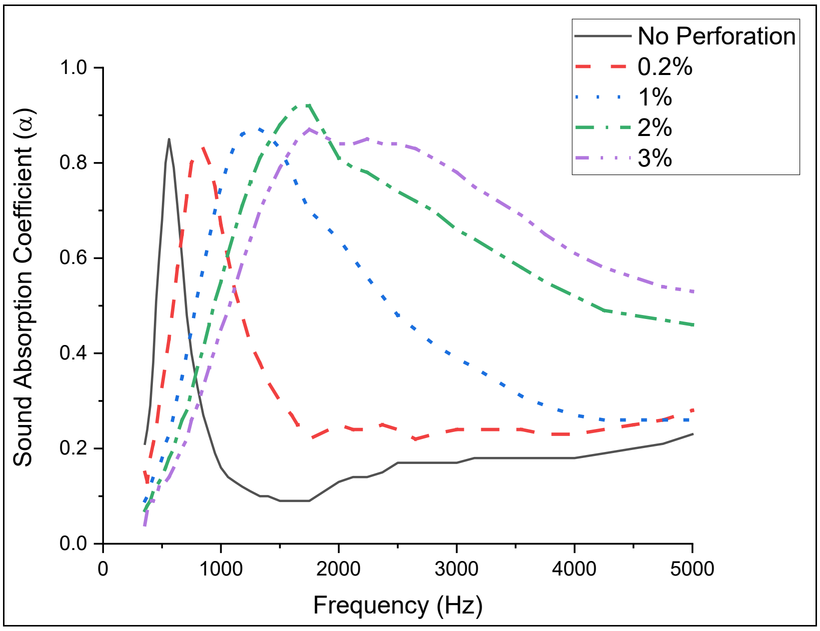

Fig. 11. Sound absorption coefficient of Integrated fabric-membrane with different perforation ratio

Based on the result, it was evident that the fabric layer improves the sound absorption of the P-FM sample when the membrane absorption is relatively low. The increases in the perforation ratio reduce the membrane absorption effect and cause the sound absorption characteristics of porous material to appear.

4.7 The Effect of Air Cavity Depth on the Sound Absorption of Fabric-Membrane (FM)

For a membrane-type absorber to effectively absorb sound energy, it is crucial to have an air gap between the rigid wall and the absorber membrane. This air-backed cavity serves as an acoustic spring, and its stiffness causes the absorber to vibrate and absorb sound energy. The effect of varying air cavity depths on P-FM sound absorption can be seen in Figure 12, where air cavity depths of 10 mm, 15 mm, 25 mm, and 30 mm were used, along with a perforation size of 0.5 mm, perforation ratio of 2%, and thickness of 0.5 mm. The absorption peak of P-FM with four different air cavity depths gradually increases from 0.86 to 0.95 as the air cavity depth increases from 10 mm to 30 mm, as shown in the comparison graph. This is because a large air gap distance between the absorber and the rigid wall allows sound waves to reflect less and travel a longer distance before reflecting back to the absorber. As a result, the absorber is able to more effectively absorb sound energy, resulting in a higher sound absorption coefficient. However, the absorption bandwidth becomes smaller as the air cavity increases further.

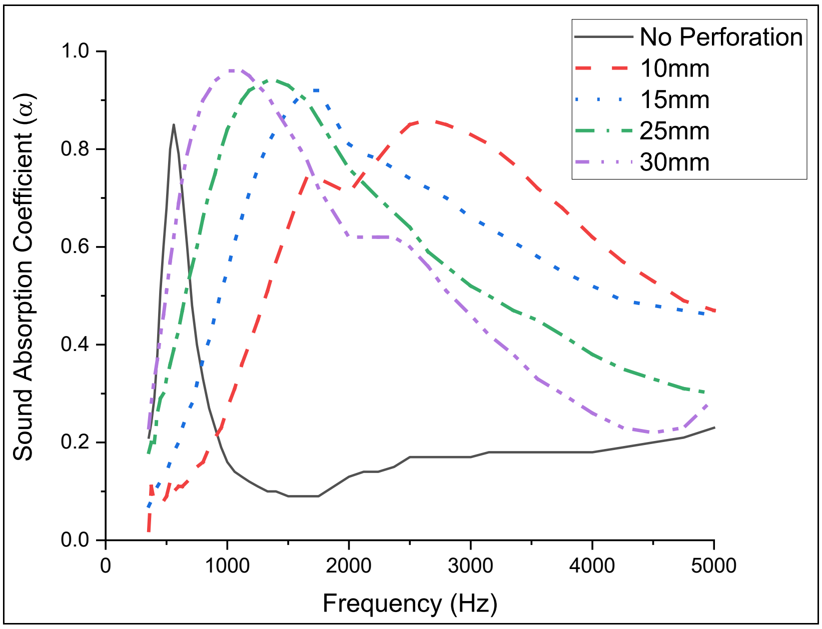

Fig. 12. Sound absorption coefficient of Integrated fabric- membrane with different depth of air cavity

The results also indicate a clear movement of the absorption peak towards lower frequencies, specifically from 2800 Hz to 1120 Hz. This shift can be attributed to the effects of both vibration and mass spring in the sound absorption system of P-FM. The absorption peak occurs when the air cavity's stiffness cancels out the acoustic mass of the holes. As the depth of the air cavity increases, the stiffness of the air cavity decreases, resulting in a shift in the resonance frequency towards lower frequencies. Therefore, it can be concluded that the air cavity depth behind the sample controls the resonance frequency of P-FM absorption.

4.8 Sound Absorption Characteristics Comparison Between Integrated Unperforated Fabric-Membrane (U-PM), Perforated Fabric-Membrane (P-FM) and Single Perforated Membrane (M3)

Figure 13 provides a comprehensive comparison of the integrated sound absorption coefficients for three different types of membrane samples: U-FM, P-FM, and Perforated membrane. The graph illustrates various peaks and troughs, offering insights into the sound absorption capabilities of these materials across different frequency ranges. Based on the data obtained, it is evident that P-FM samples exhibit higher sound absorption coefficients than both M3 and U-FM samples. The absorption peaks for P-FM, U-FM, and M3 are 0.92 at 1650 Hz, 0.85 at 600 Hz, and 0.81 at 2370 Hz, respectively. It can be seen that the P-FM sound absorption covers a broader frequency bandwidth, extending from low to high frequencies. In contrast, the sound absorption capabilities of U-FM are more specialized, focusing on low to mid-frequencies. Meanwhile, M3 samples show noticeable absorption capabilities from mid to high frequencies, making them a good fit for environments where high-frequency noise is more prevalent. While all three materials have their areas of specialization, P-FM stands out for its broader applicability across a wide range of frequencies. This makes it a more versatile choice for sound absorption in various applications and environments.

As observed, P-FM samples have higher sound absorption performance than U-FM and M3, mainly due to their porous characteristics and perforation. When fabric is attached to a perforated membrane, the peak absorption coefficient increases significantly from 0.85 to 0.95. In contrast, the integrated fabric-membrane without perforations on the membrane's surface witnesses a decline in its absorption coefficient peak, falling from 0.92 to 0.81. Based on the experiment result, the presence of the fabric provides some damping to the resonant motion of the air within the perforations. This broadens the absorption peak associated with the perforated membrane, making it effective over a broader range of frequencies.

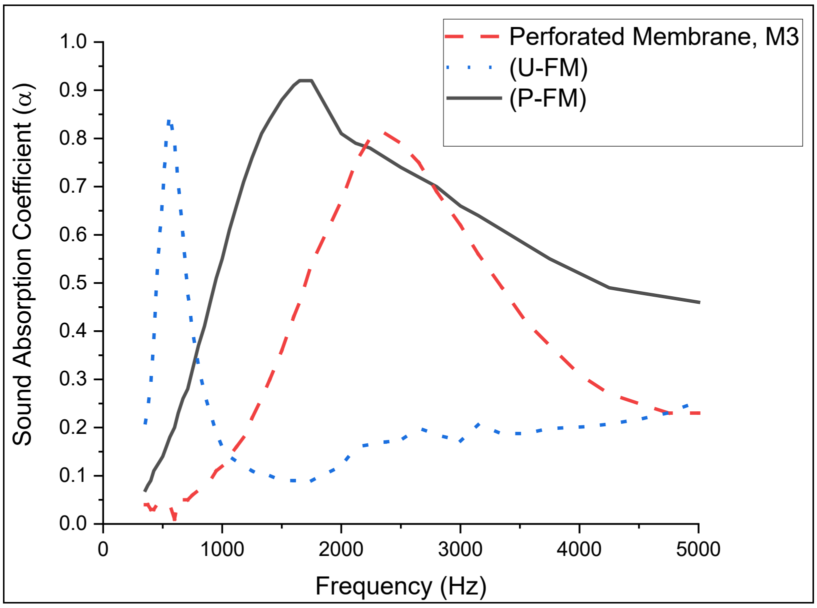

Fig. 13. Sound absorption coefficient comparison results between perforated membrane, U-FM and P-FM

However, the presence of fabric alone is insufficient to improve the sound absorption performance of the integrated sample. From the observation of absorption performance between U-FM and P-FM, the perforations play a crucial role in enhancing the acoustic properties of the fabric-membrane combination. It shows that the perforations allow for better sound wave interaction and dispersion, leading to higher absorption. However, the total acoustic resistance must be carefully selected because the absorption performance will deteriorate when the acoustic resistance of the system is beyond its optimal range. This finding shows that the P-FM offers a promising potential for enhancing acoustic absorption by controlling its perforation size, ratio, and air cavity depth.

4. Conclusions

In conclusion, the study found that material density plays a significant role in the sound absorption characteristics of both membrane and fabric materials. A lower surface density for membrane materials results in a higher sound absorption coefficient and a shift of absorption peaks towards the mid-frequency range. Sound absorption performance improves with increased airflow resistivity for fabric materials but declines after reaching a specific value. The placement of fabric material in an integrated membrane-fabric sample also influenced the sound absorption performance. The study suggests that carefully selecting material density, and airflow resistivity can improve sound absorption performance.

This research shows that P-FM has outstanding sound absorption properties over a broad frequency range, including low and high frequencies, and performs better than a single perforated membrane. Moreover, it was also found that the sound absorption effectiveness of P-FM samples is influenced by perforation size, ratio, and air cavity depth.

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