Quest Journals
Journal of Research in Mechanical Engineering
Volume 11 ~ Issue 3 (May – June 2025) pp: 01-10
ISSN(Online):2321-8185
www.questjournals.org

Research Paper

Comparative Study of Acoustic Materials for Sound Absorption in Anechoic Chambers

Shivaraj Naik [1], Rachayya Arkerimath [2], Santosh P Bhosle [2]
[1] M. Tech. Student, Mechanical Engineering, JSPM's Rajarshi Shahu College of Engineering, Tathawade, Pune, Maharashtra, India*
[2] Professor, Mechanical Engineering, JSPM's Rajarshi Shahu College of Engineering, Tathawade, Pune, Maharashtra, India

Abstract
This study explores the sound absorption capabilities of different materials in an anechoic chamber through a combined approach of simulation modeling and experimental testing. As the demand for quieter spaces grows whether in consumer products or industrial settings understanding how materials perform acoustically has become increasingly important. In this research, three commonly used materials polyurethane (PU) foam, felt cloth, and glass wool were tested across a frequency range of 125 to 2500 Hz. To simulate real-world acoustic environments, wedge-shaped absorbers were designed following Leo Beranek's low-frequency optimization guidelines. Experimental measurements of the Sound Absorption Coefficient (SAC) were conducted using the Transfer Function Method in an impedance tube setup. In parallel, Simulation SAC values were predicted using the JCA Model in Ansys, which accounts for factors like material density, porosity, and flow resistivity. The results reveal that felt cloth is particularly effective at absorbing lower-frequency sounds (125–500 Hz), while PU foam and glass wool outperform in higher-frequency ranges (1000–2500 Hz). All three materials exhibited an upward trend in SAC with increasing frequency. A side-by-side comparison of experimental and theoretical data shows strong agreement, especially for felt cloth, which recorded the lowest deviation—making it a reliable material for acoustic modeling. These findings provide useful guidance for selecting effective materials in designing anechoic chambers and other noise-sensitive environments, enabling more efficient noise control and better acoustic performance.

Keywords: *Anechoic chamber, Frequency, Absorbing Material, polyurethane foam, felt cloth, Glass-wool, Impedance Tube Methods, transfer matrix method*

R**eceived 25 May., 2025; **R**evised 06 June., 2025; **A**ccepted 08 June., 2025 © The author(s) 2025. **P**ublished with open access at **www.questjournas.org

I.INTRODUCTION

Anechoic chambers are specially designed environments that eliminate sound reflections and external noise to allow for precise and reliable acoustic measurements. The effectiveness of such chambers largely depends on two critical factors: the sound absorption coefficient (SAC) of the materials used in their construction, and the geometrical design that aids in dissipating acoustic energy. For effective performance across a broad frequency range, materials with high SAC values are essential, making the choice and optimization of acoustic materials a key aspect of anechoic chamber design.

Fig 1: Anechoic Chamber

However, achieving optimal sound absorption is a complex challenge. Numerous interrelated parameters influence the SAC of a material, and these can vary widely depending on the type of absorber be it foam, felt, or fibrous panels and how they are arranged within the chamber. Important physical characteristics such as material thickness, flow resistivity, porosity, density, tortuosity, and characteristic lengths all play significant roles. Some of these factors may work against each other, and their combined influence must be thoroughly understood to strike the right balance between performance, cost-effectiveness, and structural integrity. This study undertakes a comprehensive comparative analysis of sound absorption in anechoic chambers by combining numerical simulations, and experimental validation. Specifically, the Johnson–Champoux–Allard (JCA) model is employed for simulating the acoustic behavior of porous materials. The outcomes from these simulations are then benchmarked against experimental results to assess accuracy and reliability. The primary objective is to identify the most effective material configurations and property sets that maximize sound absorption across targeted frequency bands. The insights gained from this study are expected to inform better material selection and design practices not only for anechoic chambers but also for a wide range of noise-control applications in architecture, product testing, and industrial acoustics.

1.1 Literature review and research gap:

Čurović et al. (2024) This study introduces a hybrid method combining decay time measurements with finite element modeling to estimate sound absorption coefficients at modal frequencies in small rooms. By solving inverse problems, the approach effectively determines surface impedances and absorption coefficients, offering improved accuracy in low-frequency acoustic assessments.

Shi et al. (2025) The authors present meta-MPPs, a novel class of metamaterial sound absorbers based on microperforated panels. These absorbers achieve ultrabroadband near-total sound absorption from 0.37 to 10 kHz, surpassing traditional MPPs in performance and robustness, and offering tunable angular responses suitable for diverse noise control applications.

Wang et al. (2023) This research focuses on optimizing micro-perforated panel absorbers using a combination of transfer function models and simulated annealing algorithms. The optimized three-chamber structure exhibits excellent sound absorption over 8.6 octave bands, with theoretical and finite element analyses showing a relative error of just 3.68%.

Emmerich et al. (2025) A data-driven approach employing a neural network is proposed to estimate the sound absorption coefficient of porous materials using two-microphone measurements. Trained on numerical data, the model accurately predicts in-situ absorption coefficients, aligning well with theoretical and impedance tube results, and enhancing measurement reliability in practical settings.

Hashemi et al. (2023) The study investigates how non-flat surface geometries affect the performance of perforated acoustic absorbers. Using finite element simulations, it was found that certain surface shapes can enhance sound absorption, providing insights into designing more effective acoustic materials for various applications.

Zhang et al. (2021) This paper examines factors influencing the sound absorption coefficient in reverberation chambers, highlighting discrepancies in measurements across different chambers. The findings underscore the need for standardized testing procedures to ensure consistent and accurate acoustic material assessments in engineering applications.

Baghel et al. (2024) The authors develop a novel portable anechoic chamber utilizing ultra-thin 2D microwave absorbers, aimed at industrial applications. The design offers a compact and efficient solution for noise control, demonstrating significant potential for use in Industry 5.0 environments.

Li et al. (2025) This research explores a pressure-resistant sandwich structure supported by carbon fiber trusses and embedded cavities in a rubber core. The study reveals that such configurations can achieve enhanced broadband sound absorption, particularly at low frequencies, making them suitable for demanding acoustic applications.

Yang et al. (2025) The study introduces an interlayer parallel connection of multiple Helmholtz resonators to achieve optional broadband low-frequency sound absorption. Experimental results confirm the effectiveness of this configuration, offering a promising approach for designing efficient acoustic metamaterials.

Cai & Xin (2024) Investigating compact anechoic coatings under hydrostatic pressure, this study combines theoretical analysis and experimental validation to enhance low-frequency and broadband sound absorption. The findings contribute to the development of effective underwater acoustic materials.

Wang & Li (2023) This paper presents the design of low-frequency broadband acoustic metasurface absorbing panels. The proposed structures demonstrate significant absorption capabilities, offering innovative solutions for noise reduction in various engineering applications.

Irvani, Hassan et al.(2024) The study evaluates the sound absorption coefficient of natural bamboo fiber composites through theoretical and laboratory-based approaches. Results indicate that bamboo composites possess favorable acoustic properties, highlighting their potential as sustainable and eco-friendly sound-absorbing materials.

Ikpekha & Simms (2025) This research assesses the effect of acoustic absorber type and size on sound absorption in a full-scale reverberation chamber. Findings suggest that both factors significantly influence absorption performance, emphasizing the importance of careful selection and design of acoustic materials.

Fang et al. (2024) This study investigates the low-frequency and broadband sound absorption characteristics of compact anechoic coatings under hydrostatic pressure. The results demonstrate the coatings' effectiveness, contributing to advancements in underwater acoustic applications.

1.2 Research Gap and Objectives

While sound absorption technology and material science have come a long way, there are still some important gaps that need attention. Many existing studies tend to focus on individual materials or specific designs, but there's a lack of in-depth comparisons between experimental results and widely accepted models like the Johnson-Champoux-Allard model, especially across different frequency ranges. Also, varying testing methods like impedance tubes versus reverberation chambers often lead to inconsistent results. Very few studies look at how factors like material shape, layers, and structure interact together in actual anechoic chambers. Moreover, research into eco-friendly or bio-based materials that could match the performance of synthetic ones is still limited. Closing these gaps is key to creating better, more sustainable soundproofing solutions

Absorption material design:

Creating a truly reflection-free environment inside an anechoic chamber requires lining the walls with materials that can absorb nearly all the sound that hits them ideally around 99% within the desired frequency range. When a sound wave hits the surface of an absorber, some of the energy bounces back, a little might pass through, but most of it gets absorbed and turned into heat. How well this happens depends on properties like the material's density, porosity, and how easily air can flow through it (known as flow resistivity). The effectiveness of this absorption is measured using a value called the sound absorption coefficient, which compares the absorbed sound to the incoming sound and can be determined using standard testing methods.
Common absorber types include:

1. **Porous absorbers** – e.g., mineral wool, foam, fabric.
2. **Resonator absorbers** – e.g., membrane-based or Helmholtz resonators.

Wedge design:

In designing sound-absorbing wedges for anechoic chambers, the length of the wedge plays a key role it's the most important factor when targeting low-frequency sound absorption. The size of the wedge is directly based on the lowest frequency you want to absorb effectively. To ensure that nearly all sound is absorbed (meaning the absorption coefficient, α, is close to 1), the wedge needs to meet a specific size condition related to that frequency.

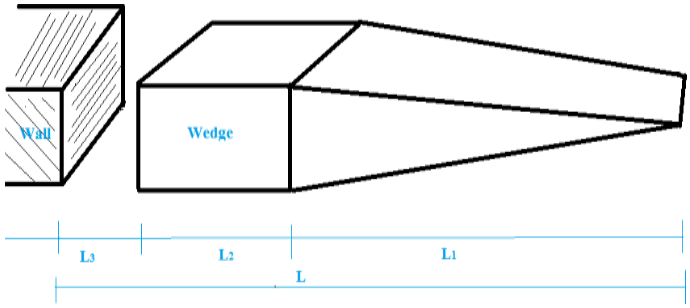
$(L/\lambda) \geq 0.25$

For a minimum frequency of 125 Hz, wavelength is:

$\lambda = (C / f) = 343/125 = 2.744$ m.

Taking the air gap into account, the minimum required wedge length comes out to 686 mm. To ensure a practical design, a total length of 730 mm was chosen. The rest of the wedge dimensions were determined using Beranek's design plots..

Fig 2: wedge Geometry



Entities	Values
Chamber Dimension	
Min frequency [Hz]	125
Max frequency [Hz]	2500
Length of the room in meter	7.3
Height of the room in meter	4.6
Width of the room in meter	5.5
Wedge Dimensions (mm)	
Air gap (L3) Base length (L2) Taper length (L1) Total Depth (D)	70
	110
	550
	730

Table 1: Calculated room dimensions and wedge dimensions using Beranek's design plots

II.METHODS AND MATERIAL

Acoustic materials are essential for controlling noise in various settings, including automobile interiors, factories, and workshops. They play a key role in passive noise control, helping to reduce unwanted sound that can affect both health and productivity. Since noise covers a wide frequency range (200 Hz to 6.5 kHz), finding a single material that performs well across all frequencies is difficult. Instead, selecting materials based on their effectiveness at specific frequencies becomes crucial.

In automotive applications, mechanical components generate a significant amount of noise, making efficient acoustic shielding necessary. Research continues to develop new materials with improved porosity, absorption, and reflectivity to enhance sound control. Understanding how materials behave acoustically across different frequencies is essential for their optimal use.

For analyzing the sound absorption coefficient in wedge design, the following materials are considered:

- Polyurethane foam
- Glass wool
- Felt cloth

2.1 Simulation Method

To find the Sound Absorption Coefficient (SAC) using the Johnson-Champoux-Allard (JCA) model in ANSYS, the porous material is first defined by inputting key parameters such as porosity, tortuosity, flow resistivity, and the viscous and thermal characteristic lengths. A suitable 3D acoustic model is then created, typically consisting of the porous sample backed by a rigid surface within an air domain to simulate wave propagation. The JCA model is applied to the porous material within the ANSYS Acoustic module, allowing the software to calculate the effective acoustic properties such as density and bulk modulus. An incident acoustic wave is introduced in the air domain, and appropriate boundary conditions, including rigid backing, are set. The model is meshed with sufficient resolution to capture the acoustic behavior over the frequency range of interest, and the frequency domain solver is used to compute the acoustic pressure fields. From the simulation results, the reflected and incident pressures are extracted to determine the reflection coefficient, and the SAC is calculated as one minus the squared magnitude of the reflection coefficient. Finally, the numerical SAC results can be validated against experimental data or literature values for accuracy.

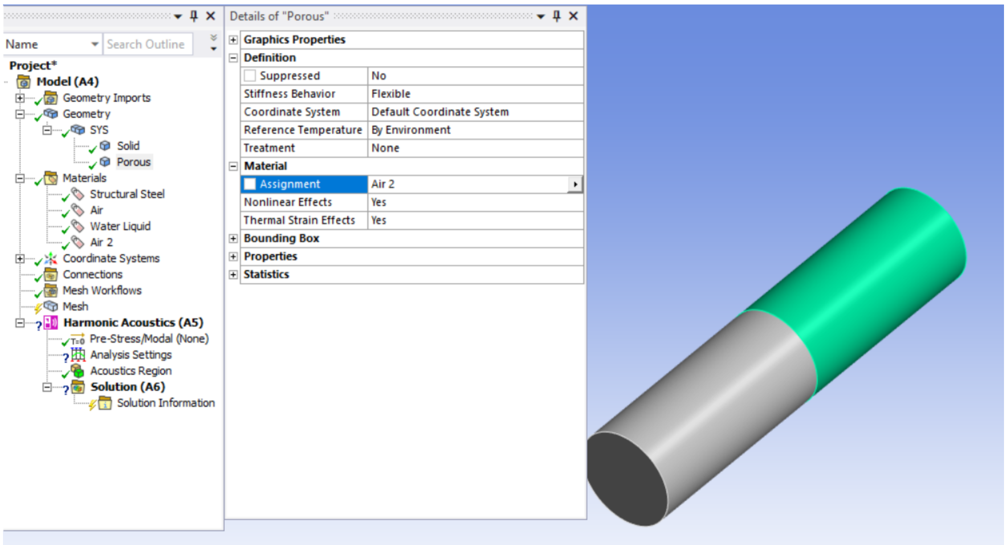


Fig 3: Simulation using Harmonic Acoustics in Ansys

Factors Affecting Sound Absorption Coefficient

The Sound Absorption Coefficient (SAC) depends on both the material's properties and how it's used. Important factors include porosity, which controls how much air moves through the material, and tortuosity, which relates to how complex the internal pathways are for sound. Flow resistivity affects how easily air flows, influencing how much sound energy is lost as heat. The size of the pores, described by viscous and thermal characteristic lengths, also impacts absorption. Material thickness matters too thicker materials usually absorb lower frequencies better. How the material is backed, like against a solid wall or open air, changes how much sound it absorbs. Lastly, different sound frequencies interact differently with the material, so SAC varies with frequency. The following material properties are selected for simulation, Where,

ρ=Density in kg/m3

σ =Flow resistivity in Rayl/m

Φ=Porasity

τ =Tortuosity

Λ=Viscus characteristics length in mm

Λ′ =Thermal characteristics length in mm

Table 2 : Material properties used for Simulation

Material	ρ	σ	Φ	τ	Λ	Λ′
PU Foam	2	12000	0.989	1.01-1.2	0.11	0.25
Felt cloth	1.6	29300	0.999	1.01-1.05	0.065	0.15
Glasswool	2.4	35000	0.97	1.01-1.05	0.065	0.15

2.2 Experimental method:

The impedance tube method is a popular way to measure how well materials absorb sound. In this setup, a sample is placed at one end of a sturdy, cylindrical tube, and a loudspeaker sends sound waves down the tube. Microphones inside the tube pick up the sound waves traveling toward the sample and those bouncing back. By comparing these sound signals, we can figure out how much sound the material absorbs at different frequencies. This technique is known for its accuracy and is commonly used in labs to test materials like foam, fabric, and other porous substances.

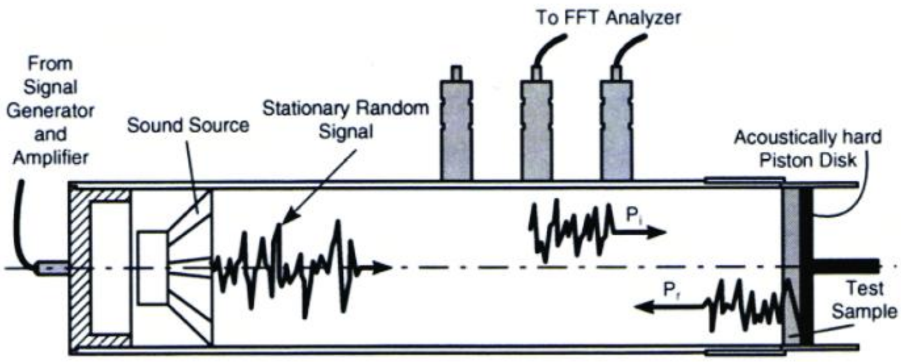


Fig 3: Experimental Setup

Specification of the apparatus as below:

Sr No	Equipment required	Sensitivity	Manufacturer
1	FFT Analyser	--	Bruel & Kjaer
2	Microphone	31.2mV/Pa	Bruel & Kjaer
3	Microphone	56.3mV/Pa	Bruel & Kjaer
4	Speaker	--	Harrgo

Table 3: Specification of equipment

Working Frequency Range: The working frequency range is: $f_i < f < f_u$

where:

- f is the operating frequency (Hz),
- fi is the lower working frequency (Hz), and
- fu is the upper working frequency (Hz).

In this study, the selected frequency range is: $125 < f < 2000$~Hz

The upper frequency limit f_u is determined by the diameter of the tube and the speed of sound, as it directly affects the onset of higher-order (non-plane) modes.

Tube Diameter: To ensure plane wave propagation inside the tube, the following condition must be met.

$$f_u < \frac{kc}{d}$$

where:

f_u=2000 Hz is the upper frequency limit,

c=346 m/s is the speed of sound,

d is the internal diameter of the tube (m),

k=0.586 is a constant ensuring plane wave propagation.

Based on this relationship, the required tube diameter is:

$$d = 0.1\ m$$

Tube Wall Thickness :The tube wall thickness is chosen as 5% of its internal diameter, is:

$$t = 0.05 \times 100 = 5\text{~mm}$$

Microphone Spacing Criteria: Increasing the spacing between microphones can improve measurement accuracy; however, the distance must always remain less than the shortest half-wavelength of the frequency being analyzed. The spacing requirement is defined as

$$f_u \cdot s \ll \frac{c}{2}$$

Solving the equation using known values, $s \ll \frac{2 \cdot 2500}{343} = 0.0686$~m

Based on this, the recommended maximum microphone spacing is set at 80% of the calculated value. Therefore, the chosen spacing is: 0.05488m= 5cm.

Transfer function method was used for calculation of sound absorption coefficient using impedance tube apparatus.

III. RESULTS AND DISCUSSIONS:

3.1 Results based on Simulation method for calculation for SAC.

Using Simulation proposed by JCA model, the following output were obtained.

Table 4: SAC for frequency range from 50 to 2500 Hz in different materials JCA Model in Ansys.

Frequency	Absorption Coefficient(PU Foam)	Absorption Coefficient(Glass wool)	Absorption Coefficient(Felt cloth)
50	0.084121	0.15219	0.13626
60	0.1158	0.19821	0.18125
70	0.1499	0.2425	0.22634
80	0.18543	0.28378	0.26994
120	0.32801	0.41275	0.41566
160	0.45505	0.49469	0.51386
200	0.5618	0.54856	0.5787
250	0.67048	0.59414	0.63217
320	0.78572	0.63646	0.67999
400	0.87527	0.66905	0.71596
500	0.93739	0.69806	0.74776
630	0.9594	0.72698	0.77845
800	0.93445	0.75995	0.8096
1000	0.892	0.7972	0.83973
1250	0.89151	0.83784	0.87147
1600	0.97151	0.87079	0.90476
2000	0.95851	0.88818	0.9261
2500	0.94272	0.91017	0.94131

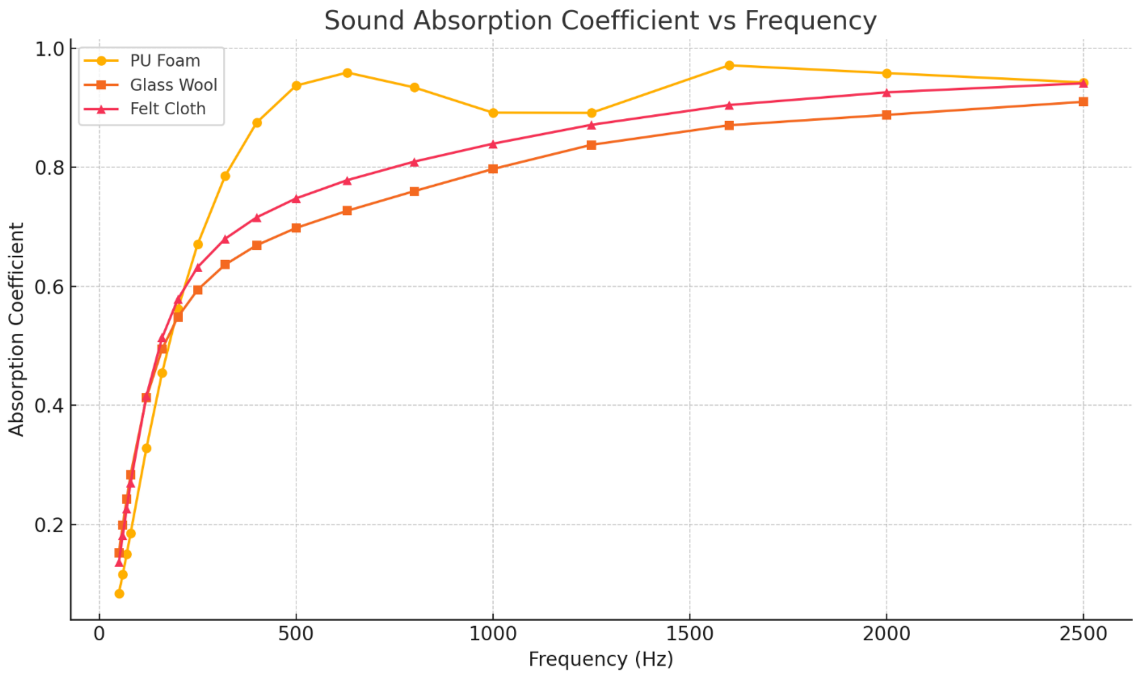


Fig 4: Multi plot visualization of Sound absorption coefficient VS Frequency for PU foam, Glass wool and Felt cloth

3.2 Results based on experimental method of calculation for SAC.

Using the impedance tube method, the following results were obtained for a comparative study to determine the most effective material across different frequency ranges. The table below presents the average values from three iterations conducted for each material.

Table 5: SAC for frequency range from50 to 2500 Hz in different materials using Impedance tube method.

Frequency	SAC- PU Foam	SAC- Glass wool	SAC- Felt cloth
50	0.0752	0.075	0.166
63	0.0918	0.092	0.178
80	0.1306	0.131	0.25
100	0.1697	0.17	0.268
125	0.2019	0.202	0.396
160	0.2621	0.262	0.427
200	0.396	0.353	0.553
250	0.4275	0.417	0.585
315	0.5745	0.511	0.674
400	0.6447	0.645	0.747
500	0.7243	0.723	0.749
630	0.75	0.751	0.751
800	0.7529	0.753	0.754
1000	0.7748	0.785	0.785
1250	0.8473	0.878	0.878
1600	0.9371	0.957	0.917
2000	0.9737	0.979	0.894
2500	0.918	0.909	0.832

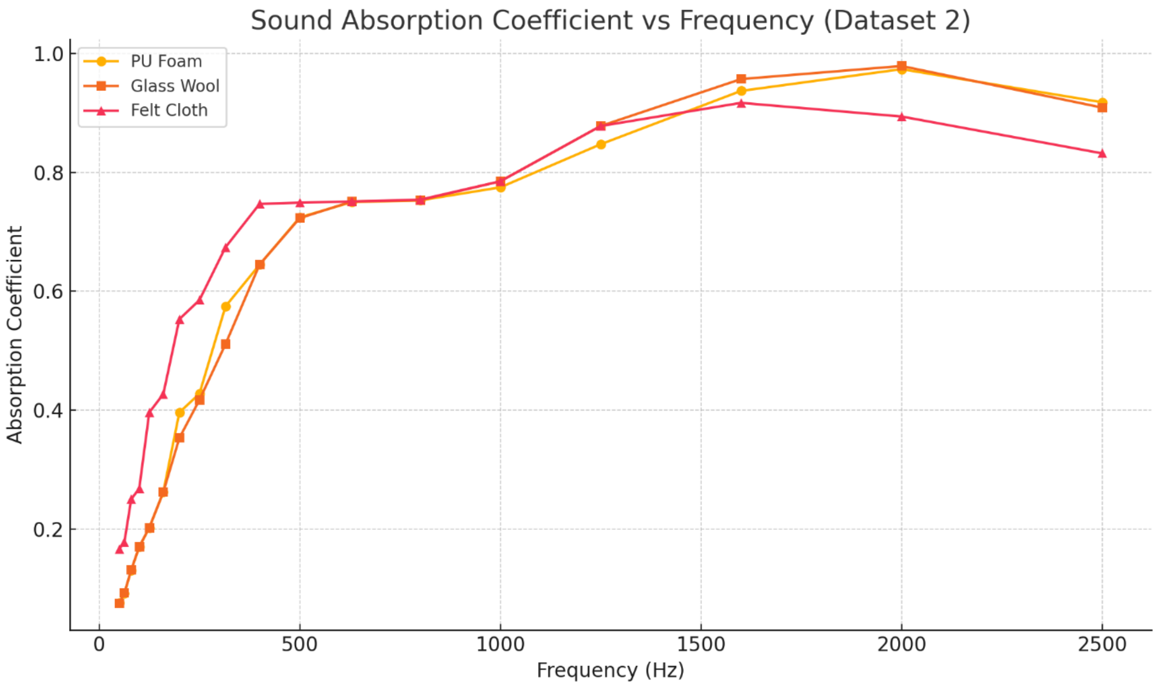


Fig 5: Multi plot visualization of Sound absorption coefficient VS Frequency for PU foam, Glass wool and Felt cloth

3.4 Discussion:

A comparative analysis of the two datasets highlights consistent trends in sound absorption behavior for PU foam, glass wool, and felt cloth across the tested frequency range (50–2500 Hz), with nuanced performance differences. Felt cloth excels in the low-frequency range (up to ~500 Hz) in both datasets, particularly in the second, where its sound absorption coefficient (SAC) reaches 0.396 at 125 Hz and 0.585 at 250 Hz, surpassing PU foam and glass wool. The first dataset shows a similar but less pronounced trend, with all materials gradually increasing in SAC through the mid-frequency range. At higher frequencies (800–2500 Hz), PU foam consistently achieves the highest SAC, often exceeding 0.9, aligning with its fine porous structure, which effectively absorbs shorter-wavelength sounds. Glass wool performs moderately well across the spectrum, competing closely with PU foam in the low to mid-range (160–800 Hz) but trailing at higher frequencies and behind felt cloth at lower ones. Both datasets show SAC increasing with frequency for all materials, consistent with expected acoustic behavior. However, variations in curve steepness and plateauing indicate material-specific sound wave interactions. For instance, in the first dataset, felt cloth's SAC rises sharply up to ~500 Hz before flattening, while in the second, it climbs steadily to ~1600 Hz before leveling or slightly declining. Error analysis reveals larger discrepancies at lower frequencies for glass wool and PU foam, whereas felt cloth shows the lowest error percentages, indicating better alignment with the theoretical Johnson-Champoux-Allard (JCA) model.

IV.CONCLUSION:

An anechoic chamber, designed to absorb ~99% of incident sound waves, provides a free-field environment critical for testing sound absorption in consumer products like automobiles and electronics. Polyurethane (PU) foam, felt cloth, and glass wool were evaluated for sound absorption coefficient (SAC) across 125–2500 Hz, a key modal range. A wedge structure (670 mm total depth, 550 mm taper, 120 mm base) was designed per Leo Beranek's research. The Transfer Function Method, using an impedance tube and FFT analyzer, was selected for its superior accuracy. Simulation using JCA model is also conducted for different materials to study comparison of simulation results from the Johnson Champoux Allard model with experimental measurements using the impedance tube method for three acoustic materials polyurethane (PU) foam, glass wool, and felt cloth. The JCA model simulations showed consistent trends in sound absorption coefficient (SAC), increasing with frequency across all materials. Experimental results, however, highlighted greater variability, particularly at lower frequencies, likely due to material inhomogeneity, edge effects, and installation variations affecting real world performance. Material-specific findings include:

Felt cloth exhibited superior low-frequency absorption (up to 500 Hz) in experiments, consistent with its dense, fibrous structure that effectively interacts with longer wavelengths. It also showed the closest agreement between JCA predictions and experimental data, with minimal percentage error, indicating the model's accuracy for this material.

PU foam achieved the highest SAC at high frequencies (above 800 Hz) in both simulation and experimental results, reflecting its open-cell structure's effectiveness for shorter wavelengths. While high-frequency experimental SAC aligned well with simulations, low-frequency deviations were notable due to challenges in modeling viscous and thermal boundary effects.

Glass wool provided consistent performance across a broad frequency range but was outperformed by felt cloth at low frequencies and PU foam at high frequencies. Experimental results showed moderate alignment with JCA predictions, with larger discrepancies below 250 Hz.

Based on conclusion, recommendations for material selection is to use felt cloth for low-frequency absorption. Choose PU foam for high-frequency applications. Select glass wool for balanced, broad-spectrum performance.

These findings guide the design of anechoic chambers, by enabling frequency-specific material choices to optimize sound absorption.

REFERENCES

[1]. Čurović, L., Murovec, J., Železnik, A., & Prezelj, J. (2024). Estimation of sound absorption coefficient at modal frequencies using decay time measurements and eigenvalue model in a small room. Building Acoustics. https://journals.sagepub.com/doi/full/10.1177/14613484241258622.

[2]. Shi, J., Luo, J., Liu, C., Chu, H., Jing, Y., Xu, C., Liu, X., Li, J., & Lai, Y. (2025). Metamaterial sound absorbers based on microperforated panels: an approach toward enhanced flexibility and near-limit broadband performance. arXiv preprint arXiv:2501.07012. https://arxiv.org/abs/2501.07012

[3]. Wang, X., Liang, C., & Mei, Y. (2023). Optimization design of a micro-perforated panel absorber with 8.6 octave bands. arXiv preprint arXiv:2305.18298. https://arxiv.org/abs/2305.18298

[4]. Emmerich, L., Aste, P., Brandão, E., Nolan, M., Cuenca, J., Svensson, U. P., Maeder, M., Marburg, S., & Zea, E. (2025). A data-driven two-microphone method for in-situ sound absorption measurements. arXiv preprint arXiv:2502.04143. https://arxiv.org/abs/2502.04143

[5]. Hashemi, Z., Fahim, A., & Monazzam, M. R. (2023).Investigation of the Effect of Non-Flat Surfaces on the Performance of Perforated Acoustic Absorber. Archives of Acoustics, 48(2), 171–181. https://journals.pan.pl/aoa/146150

[6]. Zhang, Y., Xie, X., Mei, D., & Shangguan, W. (2021). Research on Influencing Factors of Sound Absorption Coefficient in Reverberation Chamber. SAE International Journal of Advances and Current Practices in Mobility, 3(4), 2069–2077. https://www.sae.org/publications/technical-papers/content/2021-01-0359/

[7]. Al-Obaidi, A. R. (2023). Investigation of the Effect of Non-Flat Surfaces on the Performance of Perforated Acoustic Absorber. Archives of Acoustics, 48(2), 171–181. https://journals.pan.pl/aoa/146150.

[8]. Baghel, A. K., Bikrat, Y., Tavares, J., Chaves, H., Oliveira, V. U., Pinho, P., Carvalho, N. B., & Alves, H. (2024).A novel portable anechoic chamber using ultra-thin 2D microwave absorber for industrial 5.0. Scientific Reports, 14, 5358. https://www.nature.com/articles/s41598-024-55595-4

[9]. Li, K., Mao, L., Chen, Z., Huang, Z., Zhou, Z., & Li, Y. (2025). Sound absorption mechanism and characteristic of a pressure-resistant sandwich structure supported by carbon fiber truss and embedded cavities in rubber core. Applied Acoustics, 110386. https://doi.org/10.1016/j.apacoust.2024.110386

[10]. Yang, X., Li, Q., Shen, X., Zhou, B., Wang, N., Wang, E., Zhang, X., Shen, C., Wang, H., & Jiang, S. (2025). Interlayer Parallel Connection of Multiple Helmholtz Resonators for Optional Broadband Low Frequency Sound Absorption. Materials, 18(3), 682. https://doi.org/10.3390/ma18030682

[11]. Cai, C., & Xin, F. (2024). Investigation on Low-Frequency and Broadband Sound Absorption of the Compact Anechoic Coating Considering Hydrostatic Pressure. International Journal of Mechanical Sciences, 109645. https://doi.org/10.1016/j.ijmecsci.2024.109645

[12]. Wang, J., & Li, Y. (2023). Low-frequency broadband acoustic metasurface absorbing panels. arXiv preprint arXiv:2002.05325. https://arxiv.org/abs/2002.05325

[13]. Irvani, Hassan; Mahabadi, Hassan Asilian; Khavanin, Ali; Variani, Ali Safari (2024) International Journal of Environmental Health Engineering (2024). Determining the sound absorption coefficient of natural bamboo fiber composites. International Journal of Environmental Health Engineering.https://journals.lww.com/ijeh/fulltext/2024/10000/determining_the_sound_absorption_coefficient_of.2.aspx,DOI: 10.4103/ijehe.ijehe_4_24

[14]. Oshoke Wil Ikpekha and and Mark Simms, (2024) MDPI Acoustics. Effect of Acoustic Absorber Type and Size on Sound Absorption of Porous Materials in a Full-Scale Reverberation Chamber. Acoustics,7(1),3.https://www.mdpi.com/2624599X/7/1/3, https://doi.org/10.3390/acoustics7010003