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Effect of Acoustic Absorber Type and Size on Sound Absorption of Porous Materials in a Full-Scale Reverberation Chamber

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Abstract: The acoustic product development process, crucial for effective noise control, emphasises efficient testing and validation of materials for sound absorption in the R&D phase. Balancing cost-effectiveness, speed, and sustainability, the focus is on minimising excess materials. While strides have been made in reducing sample sizes for estimating random-incident absorption, challenges persist, particularly in establishing validity thresholds for smaller samples with increasing thickness, susceptible to potential overestimation due to edge effects. This study delves into analysing the absorption coefficients of widely used acoustic absorber types—polyester, fibreglass, and open-cell foam—in a full-scale reverberation chamber at Ventac, Blessington, and Wicklow. Demonstrating significant absorption above 500 Hz, these porous absorbers exhibit diminished effectiveness at lower frequencies. The strategic combination of these absorbers with different facings enhances their theoretical broadband absorption characteristics in practical applications. Moreover, the study assesses the validity threshold for reduced sample sizes, employing statistical analysis against ISO 354:2003 standard control samples of the absorber types. Analysis of Variance (ANOVA) on material groups underscores the significant influence of frequency components and sample sizes on the absorption coefficient. The determined validity threshold for 12.8 sqm ISO 354 standard control size is 7.7 sqm for the 25 mm open-cell foam. Similarly, the validity threshold of the 12 sqm ISO 354 standard control size is 9.6 sqm for the 20 mm 800 gsm polyester, 7.2 sqm for the 25 mm fibreglass, and the vinyl black on 25 mm fibreglass.

Keywords: sound absorption coefficient; full-scale reverberation chamber; reduced sample size; acoustic absorber; ANOVA analysis

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1. Introduction

Mitigation in Vehicle and Industrial Noise Control (VINC) routines primarily involve treating the noise source, where possible, and more commonly, along the noise path of the source to the receiver. Treating the noise at the source traditionally involves using dynamic absorbers and vibration isolators to reduce force amplitude, using quieter engines for the same displacement, reducing response by damping treatments, and changing the natural frequencies of components [1]. At the same time, noise treatments along the source–receiver path involve applying acoustical composite materials in the environment of the source and receiver to combat both structure-borne and airborne noise emanating from the propulsion system of these vehicles. In Internal Combustion Engine (ICE) vehicles, the noise sources typically include those from their engines, transmission system, cooling fan, intake, and exhaust. Meanwhile, electric vehicles (EVs) would mainly include noise

from the motor, gearbox, and inverter. To mitigate the noise along the source–receiver path, acoustic barrier materials such as loaded rubber, asphalt mastics, polyurethane (PU), and vinyl block the propagation of noise from the source to the receiver. Sound-absorptive fibrous (e.g., needlefelt, glass fibre) and cellular (e.g., melamine, polyurethane, open-cell foam) materials are generally applied at the source and receiver locations [2–5]. These sound-absorptive materials, or acoustic absorbers, are typically applied to source locations such as engine compartments and receiver locations like passenger or operator cabs to reduce reverberant noise. They are usually included in developing cutting-edge composites in vehicle hoodliners, headliners, floors and seats, and engine side dashes to reduce noise buildup in each environment [6]. Consequently, the sustainable alternatives of these sound-absorptive materials are hugely studied and tested in different reverberation chambers for their sound absorption performances [7–11]. In the building sector, acoustic absorber materials, such as rock wool, glass wool, polyurethane, and polyester, are usually used with sound insulation materials to create composite panels for suitable acoustic spaces. The purpose of the acoustic absorbers in the composite panels' design includes reducing the soundscape reverberation times, thus creating different acoustic environments for various purposes, including sports halls, lecture theatres, cinemas, recording studios, etc. Sustainable alternatives, like natural fibres, for these composite building materials have been, and are currently being, widely studied in different reverberation chambers for their sound absorption performances [12–14]. In the industrial noise control regimes, acoustic-absorbent constituent materials, including polypropylene, cotton fibre, cellular foams, etc., are usually employed in designing factory spaces with machinery that emits high noise levels at varying frequencies in highly reverberant spaces. When adequately used in these spaces as hanging ceiling baffles, wall liners, or free-standing absorptive panels, these materials reduce the echo and reverberation, resulting in an improved acoustic environment. In other industrial applications, wall enclosures of generators, compressors, and air-handling units are lined with these absorptive materials that aid in emanating mid- to high-frequency noise components from their associated noise sources, such as compressors and motors [15–17]. At the same time, component structures such as ducting, silencers, and attenuators comprise these materials.

Sound-absorptive materials, or acoustic absorbers, as they are also referred to, are generally classified into two categories. This includes Porous Absorbents, Fibrous and Cellular Materials, and Resonant Devices [18]. Sound propagation occurs in a network of interconnected pores in the core of Porous Absorbers so that viscous and thermal effects cause acoustic energy to be dissipated as heat. Common examples of Porous Absorbers include mineral wools, polyester, fibreglass, open-cell foams, acoustic tiles, carpets, and curtains. Acoustic absorbers are mainly effective in quelling noise at mid to high frequencies around the human hearing range; therefore, they are beneficial and effective in cutting-edge frontier Vehicle and Industrial Noise Control (VINC). However, they perform worse at lower frequencies due to their relatively low density compared to acoustic barrier materials, especially when they are too shallow compared to the wavelength. To gain lower-frequency absorption in addition to the mid- tohigh-frequency absorption provided by porous absorbent materials, as is often required in VINC routines, resonance is usually exploited [18]. This technique involves placing a perforated sheet in front of the porous absorbent to form a Helmholtz absorber or a thin sheet in front of the Porous Absorbent to form a membrane or Panel Absorber—resulting in a peak absorption at a specific bandwidth over which they operate. Exploiting both resonance and porous absorption is performed simultaneously to gain low-frequency absorption in one device in addition to mid- to high-frequency absorption. An example would include a multi-layered porous absorbent component of a fibrous material backing with a Helmholtz absorber formed with many tiny holes to aid absorption.

Membrane or panel absorbers are often employed in VINC applications to target specific frequency bands. With this, an impermeable facing such as T250, e-cloth, or aluminium foil vibrates in front of a porous fibreglass material, resulting in a peak absorption and a specific desirable bandwidth. In comparison, Helmholtz absorption, such as thin perforated metal sheets with a backing of dense mineral wool, is usually employed in building and industrial acoustic applications. In the context of this paper, porous absorbers, resonant devices, and multi-layer components are investigated to explore high-frequency, low-frequency, and broadband (low- and high-frequency) absorption, respectively.

One of the key considerations during the Research and Development (R&D) phase of sustainable acoustic products and systems for vehicle and industrial noise control includes reducing waste materials, especially during prototyping. This consideration correlates with the reduction in experimental set-up times, cost of transportation, and manufacturing material costs, amongst others. It is important to note that although typical components used in the automotive (vehicle) industry are much smaller than the building industry, they are still sent out to large-scale reverberation chambers for tests during their research and development phase. During this phase, it is essential that the evaluation process of the acoustic performances, including absorption of such materials, be fast and cost-effective [19], and it also needs to be reliable and reproducible. Studies have shown that the absorption performance of materials with the same properties varies depending on the test methodology employed [19]. There exist two main standardised methods for the estimation of the sound absorption performance of materials; these include the ISO 10,534-1:1996 and ISO 10,534-2:2023 methods [20,21], which is the determination of sound absorption coefficient in impedance tubes—with a sound source connected to one end and the test sample mounted in the tube at the other end, and the ISO 354:2003 [22], which is the measurement of sound in a reverberation room—where absorption is deduced from the effect which the presence of the specimen has on the rate of decay of sound in the reverberation chamber [23]. With the former method affording an advantage of the impedance of the material being estimated simultaneously as its absorption coefficient [18], the latter approach is, however, preferred because the internal environment in which they are measured is closer to the final practical application due to the omnidirectionality of the incident sound wave on the material [24]. Studies have also evaluated the sound absorption performance of materials utilising the random-incident absorption coefficient method in scaled reverberation chambers (SRCs) to achieve the benefits of reduced sample sizes [25–27]. However, the validity of parameters in the truncated sample sizes, without compromising the reliability of the results, has yet to be fully established, with various studies carried out to correlate the absorption coefficient using varied methodologies [25,28–30].

The volume of a standard full-scale reverberation chamber is specified according to the International Standard ISO 354 to be at least 150 m^3 or at least 200 m^3 for new construction. When the volume of the room is greater than about 500 m^3, it may not be possible to measure sound absorption accurately at high frequencies because of air absorption. Measured values of acoustic absorption obtained from standardised reverberation chamber measurements often differ across laboratories [31–36]. These discrepancies arise from non-isotropic sound incidence on the absorbing specimen, diffraction at the sample edges, and differences in the chambers' shapes and dimensions. Although measured values of acoustic absorption obtained from standardised reverberation chamber measurements often differ across laboratories, it is essential to recognise that the sound field impacting the sample is primarily influenced by the properties of the sample itself rather than solely by the room. Experimental findings have revealed substantial differences in the incident fields between empty and occupied rooms [31].

This study aimed to estimate the absorption coefficients of various acoustic absorber types, such as polyester, fibreglass, and open-cell foam, across a broad frequency range within a full-scale reverberation chamber. One of the significant aspects of this study lies in its comprehensive experimental exploration, statistical analysis, and proposal of validity thresholds for reduced-size samples from their ISO 354 standard control sizes. By conducting thorough experimentation within a full-scale reverberation chamber, the study aimed to analyse the absorption properties of these typical acoustic absorbers, offering novel insights into developing cutting-edge acoustic products. Furthermore, to create composites, the strategic combination of the analysed absorber types with different facing materials was expected to enhance their theoretical broadband absorption characteristics in practical frontier applications. The analysis of reduced sample sizes aimed to yield valid absorption coefficient estimations, with validity thresholds determined through statistical analysis against their ISO 354:2003 standardised control samples. This underscores the significant influence of frequency components and sample sizes on the absorption coefficient, ultimately establishing validity thresholds for reduced sample sizes for each absorber type.

The paper follows a structured format comprising an Introduction, Materials and Methodology, Results and Discussion, and Conclusion and Future Work sections. The Introduction segment delves into the relevant literature, explaining the noise control applications of the selected acoustic absorbers and composites, the various absorber types, the parameters of reverberation test chambers, and the test specimen sizes. The Materials and Methodology section outlines the acoustic absorbers and composites investigated and the relevant standards adopted. Subsequently, the Results and Discussion section presents the recorded data alongside the statistical analyses employed for result comparison and the interpretation of the analysed data. Finally, the Conclusion section summarises the report's objectives, delineates the findings, and provides recommendations for further research.

2. Materials and Methods

The research study was structured according to the following steps to ensure the study's clarity, understanding, and systematic progression:

- Material selection and preparation.
- Measurement of sound absorption in the full-scale laboratory according to ISO 354.
- Computation and evaluation of sound absorption coefficients.
    - Analysis of variance (ANOVA) on sample sizes.
    - Single indices of:
        - Sound Absorption Average (SAA).
        - Noise Reduction Coefficient (NRC).
        - Weighted Sound Absorption Coefficient (α_w).
    - Evaluation of threshold of validity.
- Discussion, conclusions, and future work.

2.1. Acoustic Absorber Specimen Type Tested

The absorber types were selected based on their widespread use in acoustic absorption applications and the representative nature of typical absorber types in real-world scenarios. Polyester, fibreglass, and open-cell foam were chosen, as they are commonly utilised as constituents of composite materials due to their porous nature and ability to attenuate sound waves across a broad frequency range effectively. It is essential to recognise that including a 20 mm thick polyester layer, alongside 25 mm thick fibreglass and open-cell foam, in the analyses is driven by the necessity to address material specificity and the expected prevalence of standard 20 mm polyester in practical scenarios. Evaluating its acoustic absorption

performance compared to thicker alternatives provides valuable insights into its distinctive material capacity for sound absorption, independent of thickness. This validation ensures that the study outcomes remain pertinent for real-world applications, facilitating informed decisions in material selection and design processes.

The constituent-facing materials, including perforated and embossed foil, e-cloth, and black vinyl, were selected for their variability in permeability and for transforming the composites into different composite resonant devices, as given in Table 1. Additionally, all the selected individual materials are readily available and well-characterised, making them suitable for experimental investigation. By choosing these materials, the study aimed to ensure the relevance and applicability of the findings to practical acoustic product development. Table 1 details the six acoustic material make-up (specimen) sample types (A-F), made from the four acoustic absorbers with different facing materials, analysed and tested for their variability in sound absorption properties.

Table 1. Acoustic absorber types.

	Porous Absorbent				**Resonant Device**	
	Fibrous			**Cellular**	**Membrane Absorber**	**Helmholtz Absorber**
Specimen Type	**A**	**B**	**C**	**D**	**E**	**F**
Material Make-up	800 gsm Polyester	Fibreglass	E-cloth and Fibreglass	Open Cell Foam	Vinyl Black and Fibreglass	P&E Foil and Fibreglass
Core Sample Thickness (mm)	20	25	25 *	25	25 *	25 *
Density	800 g/m^2	22 kg/m^3	-	27 kg/m^3	-	-
Control Sample Size (m^2)	12	12	12	12.8	12	12
Facing Material Type	n/a	n/a	E-cloth	n/a	Vinyl Black	P&E Foil
Manufacturer(s)	Vita Material	Harlow Agency	Marmonier & Harlow Agency	Foam Technique	Otego & Harlow Agency	Braun & Harlow Agency

* Thickness of core material only. E-cloth, P&E foil, and vinyl black facings are approximately 0.9 mm, 0.2 mm, and 1 mm thick, respectively.

The test specimens were A-mounted in the reverberation chamber following the guidelines outlined in Annex B of ISO 354:2003. This involved placing them directly on the chamber's floor, with their edges left exposed or covered by their respective facing, depending on the specimen type.

During testing, each specimen type was reduced by 20% from its standardised control sizes, shown in Figure 1, resulting in six different sizes for each test specimen type. For the open-cell foam, these sizes were 12.8 sqm, 10.3 sqm, 7.7 sqm, 5.1 sqm, 2.6 sqm, and 1.3 sqm. Similarly, for the other specimen types, the sizes were 12 sqm, 9.6 sqm, 7.2 sqm, 4.8 sqm, 2.4 sqm, and 1.2 sqm.

Each standardised control test specimen comprised five core sheets measuring 1.2 m × 2 m for polyester and fibreglass specimens and 1.2 m × 2.1 m for the open-cell foam specimen. These sheets were aligned flush and secured with black 3M duct tape with their respective facing material. This setup yielded a total absorbing surface area, including edges, of 12.40 m^2 for the polyester, 12.32 m^2 for the fibreglass, and 13 m^2 for the open-cell foam specimens, as shown in Figure 1. These measurements were utilised to calculate the absorption coefficients.

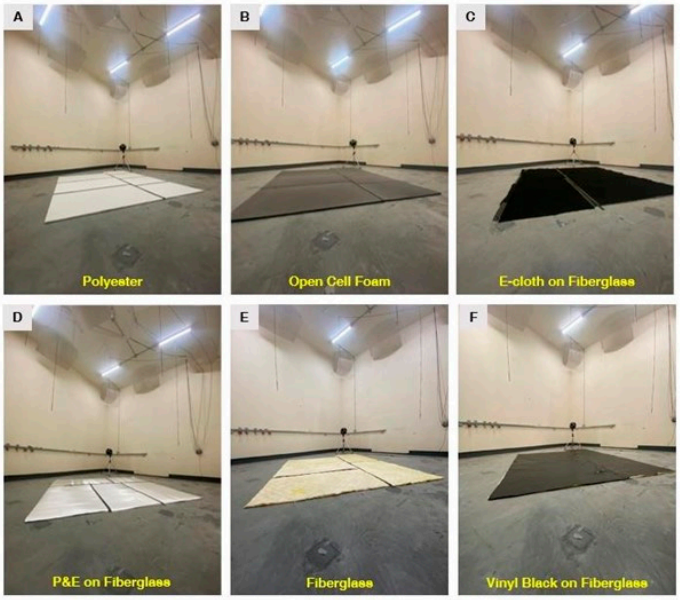

Figure 1. ISO standard control material test Specimens mounted in the reverberation chamber. Sample (**A**): 20 mm 800 gsm polyester (12 sqm surface area), Sample (**B**): 25 mm open-cell foam (12.8 sqm surface area), Sample (**C**): E-cloth on 25 mm fibreglass (12 sqm surface area), Sample (**D**): perorated and embossed foil on 25 mm fibreglass (12 sqm surface area), Sample (**E**): fibreglass (12 sqm surface area), and Sample (**F**): vinyl black on fibreglass (12 sqm surface area).

2.2. Reverberation Room Characteristics and Dimensions

Each material test specimen's intrinsic sound absorption characteristics were assessed using the Interrupted Noise Method in controlled reverberant acoustic conditions, according to the ISO 354:2003 standard for measuring sound absorption in a reverberation-diffused sound field. In this method, a burst of noise is emitted into the chamber, and the sound pressure level is measured over time, T_{60}, as the sound decreases by 60 decibels after the sound source ceases. The reverberation time is then determined using a computer-controlled recording system that analyses the decay curve of the noise level according to ISO 354. Figure 2 depicts a sample evaluation range of the reverberation time estimation, where a least-square-fit line has been employed, with the lower decibel level of the evaluation range more than 10 dB above the noise floor. It is important to note that the potential influence of reverberation times in adjacent frequency bands on the decay curve was not a concern, given that the signal bandwidth was not greater than one-third octave band.

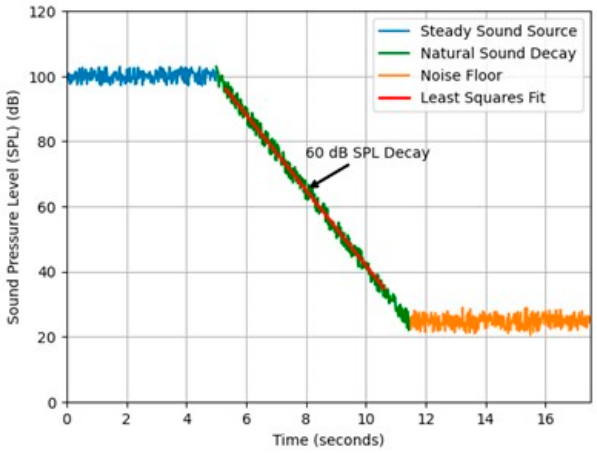

Figure 2. Sample decay curve for 500 Hz frequency.

This method uses a steady sound source with a continuous spectrum in the frequency bands of interest to drive an omnidirectional loudspeaker located sequentially in two positions in the reverberation chamber. As shown in Figure 3, each speaker position has six microphone locations. Therefore, three reverberation time measurements are taken at each microphone location, and the results are averaged arithmetically. Measurements are made at one-third octave intervals from 100 Hz to 5000 Hz.



Figure 3. Reverberation chamber showing the microphones and suspended diffusers.

The reverberation chamber's volume is approximately 283 m^3, and the oblique boundaries have approximate length, width, and height dimensions of 7.45 m, 6.46 m, and 5.88 m, respectively. Four 1 m × 1 m and eight 1 m × 1.5 m curved diffusers made from Perspex material maintained the room's diffusivity, as shown in Figure 3.

2.3. Data Acquisition and Analyses

The data acquisition (DAQ) system consisted of the Head Acoustic Squadriga III Standard System connected to 6 different ½-inchpre-polarised random-incidence condenser PCB Piezotronics ICP 377C20 microphones (426E01 preamplifiers) coupled with the 01 dB—Stell Dodecahedron Speaker AVM DO12 sound source and InterM M-700 Power Amplifier. The Artemis Suit 15.0 software was used to acquire and process the reverberation times, and the Microsoft Excel, Python Open Source, and OriginPro 2024 software were employed to complete the data analysis and presentation.

The reverberation data measurement and collection for each test specimen involved six simultaneous measurements by the six different microphones, repeated 3 times. The sound source (speaker) was positioned at two separate locations for each set of measurements. Each sample had 36 different measurements, averaged by six different receiver channels. It is important to note that all the equipment set-up, data acquisition, and analysis steps have been carried out according to the recommendations provided by ISO 354:2003.

2.4. Calculation and Estimation of the Absorption Coefficient

The Sound Absorption Coefficient (α_s) is calculated using Equation (1) in each frequency band.

$$\alpha_s = \frac{A_T}{S} \tag{1}$$

where α_s is the sound absorption coefficient, A_T is the equivalent sound absorption area of the test specimen, and S is the area of the test specimen (m^2). In Equation (1), the equivalent sound absorption area of the test specimen is given in Equation (2) as:

$$A_T = A_2 - A_1 = 55.3V\left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1}\right) - 4V(m_2 - m_1) \tag{2}$$

where V is the volume of the reverberation chamber (m^3), c_2 and c_1 are the propagation speed of sound in air in the room with and without the sample, respectively, $c_1 = 331 + 0.6t_1$, and t_1 is the air temperature, m_2 and m_1 are the power attenuation coefficients due to air absorption in the reverberation room with and without the sample in the room, respectively, calculated according to ISO 9613-1 [37], where the value m can be calculated from the attenuation coefficient α in Equation (3).

$$m = \frac{\alpha}{10\lg(e)} \tag{3}$$

T_2 is the reverberation time in the chamber with the specimen installed, and T_1 is the reverberation time in the chamber without the specimen installed.

It is assumed in the calculation of A_T that the level of relative humidity (which was approximately 57%) in the chamber remains the same when the chamber is empty and the specimen is installed, with the chamber temperature approximately 17 °C. It is important to note that the use of the subscript "s" in α_s is to avoid confusion with the sound absorption coefficient defined as the ratio of non-reflected-to-incident sound energy if a plane wave strikes a plane wall at a particular angle of incidence.

2.5. Analysis of Variance (ANOVA) and Single-Figure Index Estimation

To assess the significance of differences in the absorption coefficients among the various specimen types and sample sizes, the Analysis of Variance (ANOVA) was employed. This analysis allows for comparing means between multiple groups and identifies whether statistically significant differences exist. In this study, ANOVA was conducted separately for each material group of specimen type to determine the influence of frequency components and sample sizes on the absorption coefficient. Furthermore, Tukey's Honestly Significant Difference (HSD) post hoc tests were performed to perform pairwise comparisons amongst the different specimen types and sizes. All statistical analyses were conducted using the Origin Pro 2024 software tool with a significance level set at $\alpha = 0.05$.

In addition to analysing absorption coefficients across a range of frequencies, single-figure indices were calculated to provide a concise summary of the absorption properties of each specimen type. Commonly used indices such as the Sound Absorption Average (SAA), Noise Reduction Coefficient (NRC), and weighted sound absorption coefficient (α_w) were computed based on the absorption coefficients measured at specific octave or one-third octave band frequencies. These indices provide valuable insights into the overall acoustic performance of the materials and facilitate easy comparison between different absorber types.

3. Results

Acoustic wave energy is dissipated as thermal energy when it travels through the porous structure of absorbent materials. However, their sound absorption properties change near the edges of these materials or panels, particularly with very porous sound-absorbing materials like acoustic foams, fibreglass panels, or mineral wool. This edge effect occurs due to several factors, including the test sample's diffraction, boundary, resonance, and non-uniformity.

This study compares the sound absorption of the different control absorber types to establish the differences caused by their edge effect across the 1/3-octave centre band frequency components. Six absorber (specimen) sizes have been analysed and compared to their respective standardised control samples.

The Analysis of Variance (ANOVA) method is used to statistically determine the differences in absorption properties amongst the test samples across the different specimen types. In the analysis, absorber-type and frequency components are adopted as the independent variables, while the continuous sound absorption coefficient, α_s, is taken as the dependent variable. The Tukey's Honestly Significant Difference (HSD) test is then used to perform pairwise comparisons amongst groups to determine their differences statistically. The sound absorption average (SAA), noise reduction coefficient (NRC), and weighted sound absorption coefficient (α_w) metrics are also used to estimate further and compare the test results. These single sound absorption indices or ratings are arithmetic absorption averages at specific frequency bands: 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz for the NRC and 200 Hz to 2500 Hz for the SAA. The weighted sound absorption coefficient alpha, α_w, gives a single-number frequency-independent value, which equals the value of the reference curve at 500 Hz after shifting it as specified in the ISO 11654:1997 International Standard [38].

3.1. Results Analyses—Absorber Type Material Comparison

The standardised single-layer control sample size of all six acoustic absorbers (specimen) was employed as a comparison baseline. Taking sound absorption as the response variable and absorber type and frequency components as the independent factors, an ANOVA with a significance level of 95% ($\alpha = 0.05$) was used to estimate the difference among the different absorbers.

The result of the analysis indicated that both independent factors have a significant effect on the various sound absorption coefficients of all six specimens. The main effect of absorber type ($F(5, 540) = 2840$, $p < 0.0001$) and frequency component ($F(17, 540) = 7509$, $p < 0.0001$) were found to be statistically significant. Additionally, the interaction between material and frequency was also significant ($F(85, 540) = 607$, $p < 0.0001$); thus, all six materials were found to be significantly different in terms of their sound absorption properties.

The Tukey's Honestly Significant Difference (HSD) test, applied to the data to perform pairwise comparisons amongst the different absorber types, also indicated a considerable variance in the absorption properties of each specimen type from the rest at a significant level greater than 95%, as detailed in Table 2.

Table 2. Tukey's HSD test for absorber specimen types.

	MeanDiff	SEM	q Value	Prob	Alpha
25 mm Open-Cell Foam and 20 mm 800 gsm Polyester	0.18591	0.00261	100.81	<0.0001	0.05
E-cloth on 25 mm Fibreglass and 20 mm 800 gsm Polyester	0.13891	0.00261	75.33	<0.0001	0.05
E-cloth on 25 mm Fibreglass and 25 mm Open-Cell Foam	−0.047	0.00261	25.49	<0.0001	0.05
P&E on 25 mm Fibreglass and 20 mm 800 gsm Polyester	0.11267	0.00261	61.10	<0.0001	0.05
P&E on 25 mm Fibreglass and 25 mm Open-Cell Foam	−0.07324	0.00261	39.72	<0.0001	0.05
P&E on 25 mm Fibreglass and Ecloth on 25 mm Fiberglass	−0.02624	0.00261	14.23	<0.0001	0.05
25 mm Fibreglass and 20 mm 800 gsm Polyester	0.10108	0.00261	54.81	<0.0001	0.05
25 mm Fibreglass and 25 mm Open-cell foam	−0.08483	0.00261	46.00	<0.0001	0.05

Table 2. *Cont.*

	MeanDiff	SEM	q Value	Prob	Alpha
25 mm Fibreglass and Ecloth on 25 mm Fiberglass	−0.03783	0.00261	20.51	<0.0001	0.05
25 mm Fibreglass and P&E on 25 mm Fiberglass	−0.01158	0.00261	6.28	<0.0001	0.05
Vinyl Black on 25 mm Fibreglass and 20 mm 800 gsm Polyester	−0.08058	0.00261	43.70	<0.0001	0.05
Vinyl Black on 25 mm Fibreglass and 25 mm Open-Cell Foam	−0.26649	0.00261	144.51	<0.0001	0.05
Vinyl Black on 25 mm Fibreglass and Ecloth on 25 mm Fiberglass	−0.21949	0.00261	119.02	<0.0001	0.05
Vinyl Black on 25 mm Fibreglass and P&E on 25 mm Fiberglass	−0.19325	0.00261	104.79	<0.0001	0.05
Vinyl Black on 25 mm Fibreglass and 25 mm Fibreglass	−0.18166	0.00261	98.51	<0.0001	0.05

The graphical representation of the different absorber specimen types shown in Figure 3 concurs with their general theoretical absorption characteristics, which suggest that most porous absorbers, including all three core materials (polyester, fibreglass, and open-cell foam), achieve high absorption above 500 Hz and little absorption at lower frequencies compared to their wavelengths. This is deduced, for example, when the shallower 20 mm polyester sample performs significantly less at mid to high frequencies (above 500 Hz) compared to the other materials with 25 mm depth (thicknesses).

From Figure 4, the theoretical exploitation of resonance in achieving high broadband absorption is also deduced. The perforated and embossed foil facing on the 25 mm fibreglass core material acts as a Helmholtz absorber, thereby removing sound energy over three octaves mid-frequency, in contrast to that of the vinyl black (also on the 25 mm fibreglass core), acting as a membrane absorber that performs well at lower frequency components but at a smaller bandwidth due to the vibration of its impermeable membrane facing. It can also be deduced that the e-cloth facing on the 25 mm fibreglass performs very similarly to the lone fibreglass material, as the e-cloth is composed of a permeable material that allows sound to go through.

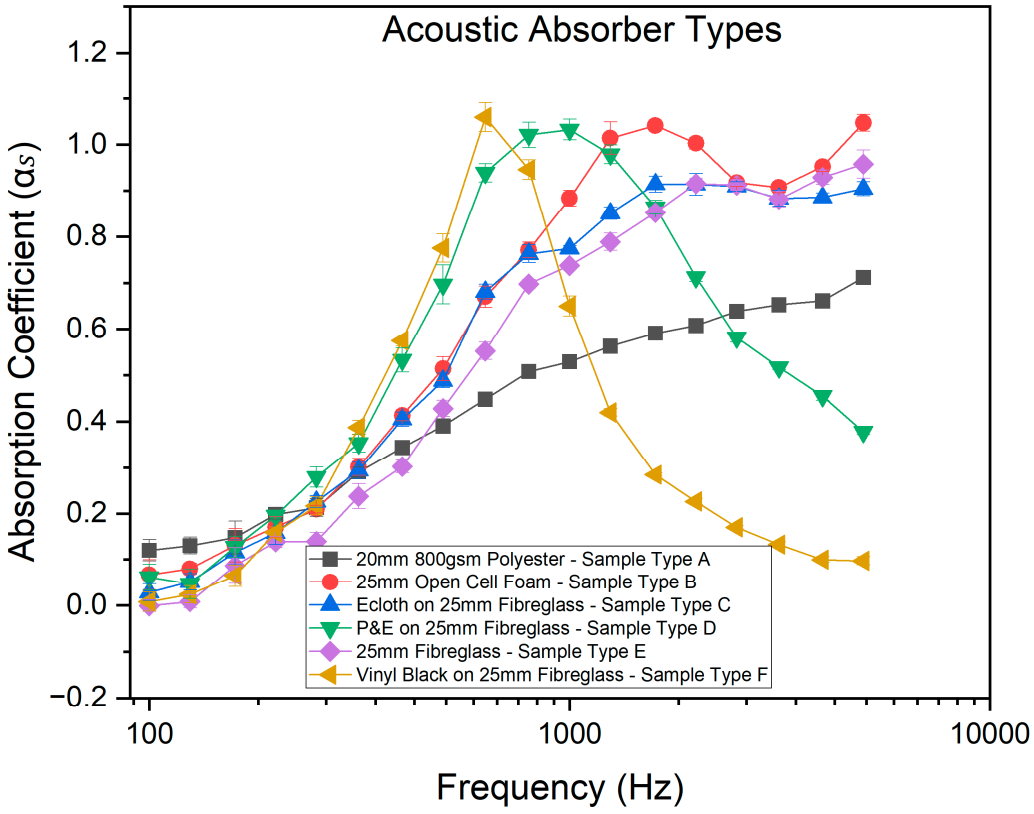

Figure 4. Measured sound absorption coefficient for 6 different absorber (specimen) types.

Table 3 gives the absorber types' single-index sound absorption coefficients: Sound Absorption Average (SAA), Noise Reduction Coefficient (NRC), and Weighted Sound Absorption Coefficient (α_W). It can be deduced that the range of specimen types each displays distinct levels of sound absorption efficacy. Notably, the E-cloth on 25 mm fibreglass and 25 mm open-cell foam demonstrate high effectiveness with Sound Absorption Average (SAA) values of 0.61 and 0.66, respectively, alongside Noise Reduction Coefficient (NRC) values of 0.60 and 0.65, and weighted sound absorption coefficients of 0.50 each. Conversely, vinyl black on 25 mm fibreglass presents lower absorption properties overall according to the single-figure indices. Still, it performs relatively well at specific mid frequencies, as evidenced by its weighted sound absorption coefficient (α_W) of 0.25 (M). Additionally, it can be deduced that the fibreglass with a P&E foil facing (Helmholtz absorber) appears to have the highest NRC value due to its exploitation of resonance, effectively absorbing lower-frequency components over a wider bandwidth.

Table 3. Comparison of single acoustic indices for each absorber specimen type.

Absorber Material Type	SAA	NRC	α_W *
20 mm 800 gsm Polyester	0.43	0.44	0.45 (H)
E-cloth on 25 mm Fibreglass	0.61	0.60	0.50 (H)
25 mm Open-Cell Foam	0.66	0.65	0.50 (H)
P&E on 25 mm Fibreglass	0.68	0.68	0.55 (H)
25 mm Fibreglass	0.56	0.56	0.45 (H)
Vinyl Black on 25 mm Fibreglass	0.49	0.47	0.25 (M)

* t is strongly recommended to use this single-number rating in combination with the complete sound absorption coefficient curve that can be obtained on request.

Comparing Figure 4 with Table 3 highlights that while the single-index sound absorption coefficient offers a convenient overall characterisation of absorption performance, it is highly recommended to complement this single-number rating with the complete sound absorption coefficient curve, as demonstrated in this study and advocated by ISO 11654.

3.2. Results Analyses—Size Effect Comparison

Figure 5 illustrates a general deduction that sound absorption increases as sample sizes decrease. This trend is attributed to the higher concentration of material near the sample edges, resulting in increased interactions and, in most instances, enhanced absorption. The observed rise in absorption with reduced sample size, particularly in acoustic absorbers, is associated with the absorption of acoustic waves at the edges. The manifestation of this phenomenon varies based on factors such as the core absorber material type, facing material, sound wave wavelength, and the characteristics of the surrounding environment, as demonstrated in this section.

Six scaled sizes of each absorber specimen type were grouped, as shown in Figure 5, with further analysis performed on each group to determine their variability in absorption coefficient influenced by their varying edge effect. Each sample size was compared to the standardised ISO 354 control sample size of 12.8 square meters (sqm) for the open-cell foam (cellular absorber type) and 12 sqm for the other samples in their respective groups.

Taking sound absorption as the response variable and sample size, frequency components, and interactions as the independent factors, an ANOVA with a significance level of 95% (α = 0.05) was used to estimate the difference among the different sizes in each absorber specimen group. The statistical analysis reveals significant effects of the different factors on sound absorption performance across the different specimen types. For instance, when considering 20 mm 800 gsm polyester, size variations exhibit a substantial impact, as evidenced by the ANOVA resulting in an F value of 97.94997 with a highly significant p-value (<0.0001). Similarly, frequency variations significantly influence sound absorption, as indicated by an F value of 376.00595 (<0.0001). Furthermore, the interaction between

size and frequency proves significant, with an F value of 3.48246 (<0.0001), suggesting a combined effect on sound absorption characteristics. Comparable trends are observed across other specimen types, such as 25 mm open-cell Foam, E-cloth on 25 mm fibreglass, and P&E foil on 25 mm fibreglass. Furthermore, it is crucial to recognise that compared to the others, the nominal disparity in thickness of the core polyester material inherently impacts the overall sound absorption, given that a larger absorption area usually confers advantages. Hence, investigating the assessment of variance in sample thickness remains imperative for future studies.

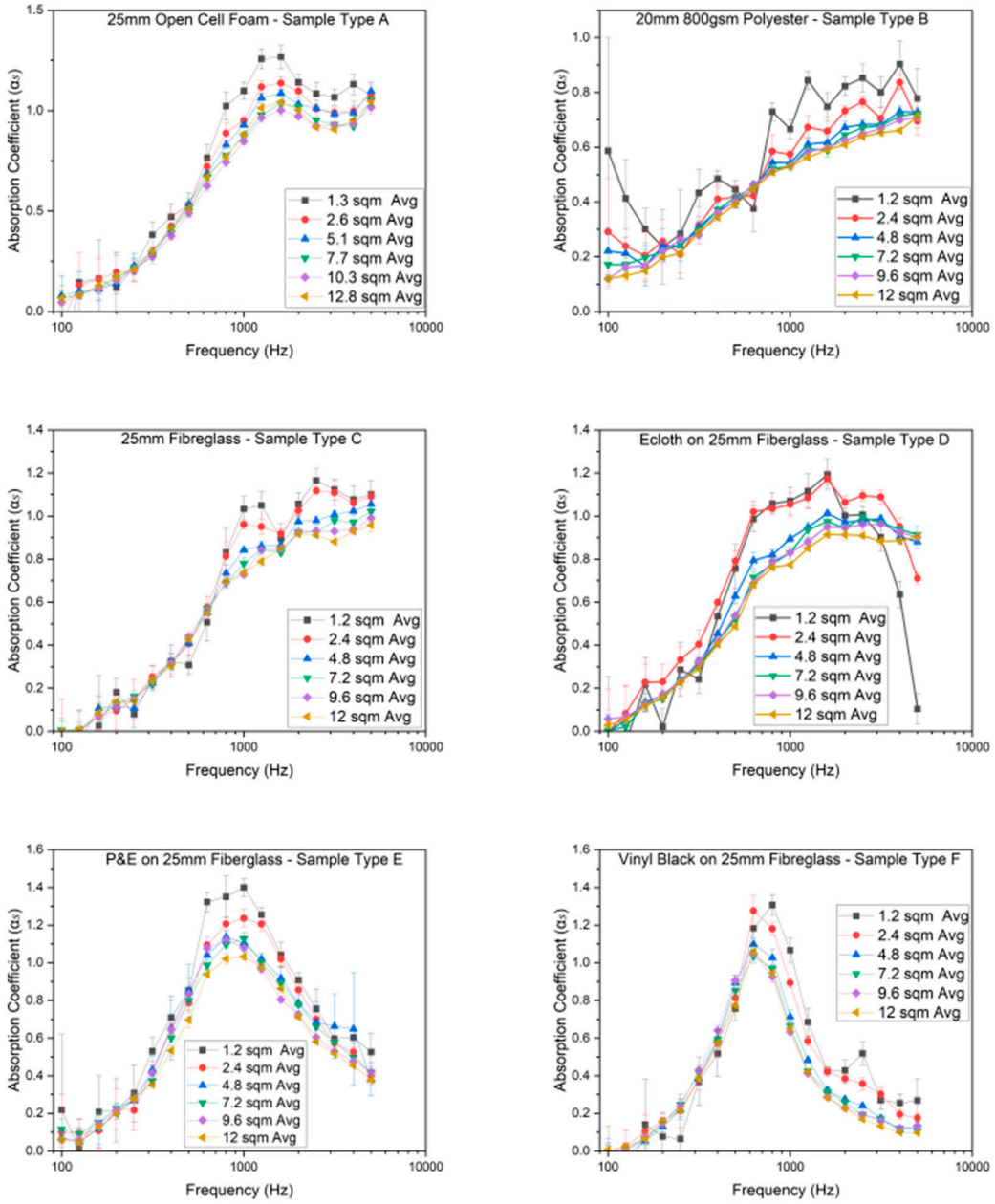

Figure 5. Absorption coefficient of 6 different size samples for the six absorber (specimen) types in a full-scale reverberation chamber.

The overall result of this analysis, shown in Table 4, indicated that for all sizes, all independent factors significantly affect the various sound absorption coefficients for all specimen types. This means the sample sizes for all six specimen types were statistically different regarding their sound absorption properties.

Table 4. Analysis of Variance (ANOVA) table for sample sizes of each absorber specimen type.

Absorber Specimen Type	Factor	DF	SS	MS	F Value	*p*-Value
20 mm 800 gsm Polyester	Size	5	1.93572	0.38714	97.94997	<0.0001
	Frequency	17	25.26456	1.48615	376.00595	<0.0001
	Interaction	85	1.16997	0.01376	3.48246	<0.0001
25 mm Open-Cell Foam	Size	5	0.79525	0.15905	39.36677	<0.0001
	Frequency	17	99.98643	5.88155	1455.7525	<0.0001
	Interaction	85	1.99107	0.02342	5.7978	<0.0001
E-cloth on 25 mm Fibreglass	Size	5	1.44329	0.28866	73.00501	<0.0001
	Frequency	17	84.52494	4.97206	1257.4935	<0.0001
	Interaction	85	6.04253	0.07109	17.97916	<0.0001
P&E Foil on 25 mm Fibreglass	Size	5	1.7951	0.35902	55.56714	<0.0001
	Frequency	17	84.06199	4.94482	765.33227	<0.0001
	Interaction	85	87.41238	0.81694	126.44116	<0.0001
25 mm Fibreglass	Size	5	0.51387	0.10277	34.56937	<0.0001
	Frequency	17	100.80642	5.92979	1994.56392	<0.0001
	Interaction	85	1.69977	0.02	6.72635	<0.0001
Vinyl black on 25 mm Fibreglass	Size	5	0.93223	0.18645	54.12847	<0.0001
	Frequency	17	75.15463	4.42086	1283.45171	<0.0001
	Interaction	85	3.35943	0.03952	11.47411	<0.0001

The Tukey's Honestly Significant Difference (HSD) test was further applied to the data to perform pairwise comparisons amongst the different-sized sample groups to determine a threshold of validity in terms of size, as detailed in Figure 6. For example, there appears to be a statistical similarity, in terms of mean sound absorption coefficient, between the standardised control 12 sqm and the 9.6 sqm sized samples for the 20 mm 800 gsm polyester material. The other sample sizes in this polyester group were statistically different from the standardised control 12 sqm sample.

The analysis presented in Figure 6 illustrates the validity threshold values needed to meet the ISO 354 standard for various material specimens. These thresholds are predicated on a control sample size of 12.8 sqm for 25 mm thick open-cell foam and 12 sqm for 20 mm thick 800 gsm polyesters, 25 mm thick fibreglass, and black vinyl on 25 mm fibreglass. Specifically, the minimum valid size for the 12.8 sqm open-cell foam is 7.7 sqm. Similarly, for materials meeting the ISO 354 standard with a control sample size of 12 square meters, distinct thresholds emerge: 9.6 sqm for 20 mm 800 gsm polyester, 7.2 sqm for 25 mm fibreglass, and 7.2 sqm for black vinyl on 25 mm fibreglass, as given in Table 5.

Table 5. Acoustic absorber types and validity thresholds.

	Porous Absorbent				**Resonant Device**	
	Fibrous			**Cellular**	**Membrane Absorber**	**Helmholtz Absorber**
Specimen Type	**A**	**B**	**C**	**D**	**E**	**F**
Material Make-up	800 gsm Polyester	Fibreglass	E-cloth and Fibreglass	Open-Cell Foam	Vinyl Black and Fibreglass	P&E Foil and Fibreglass
Core Sample Thickness (mm)	20	25	25 *	25	25 *	25 *
Density	800 g/m^2	22 kg/m^3	-	27 kg/m^3	-	-
Facing Material Type	n/a	n/a	E-cloth	n/a	Vinyl Black	P&E Foil
Control Sample Size (m^2)	12	12	12	12.8	12	12
Validity Threshold Size (m^2)	9.6	12	7.7	12	7.2	7.2

* Core sample thickness only, without facing material.

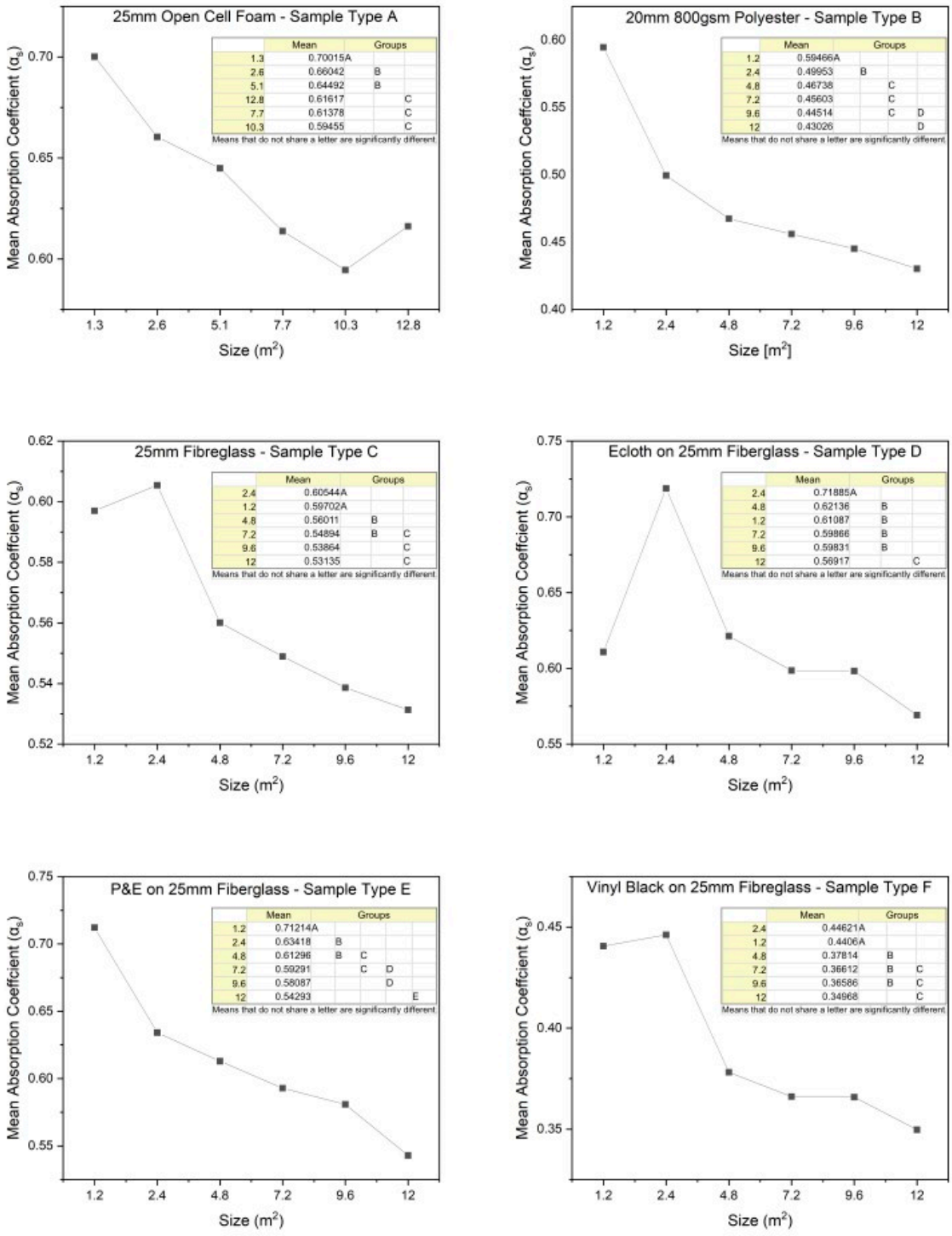

Figure 6. Mean absorption coefficient plot of the six specimen types in a full-scale reverberation chamber at six different sizes. For each group of specimen type, means that do not share a letter are significantly different, as depicted by their respective tables' inset of the graph.

Further analysis in Table 5 reveals that deviations from the standard control sample size significantly affect the statistical mean absorption of certain materials. This effect is particularly noticeable when the sample size is below the ISO 354 standard of 12 square meters, especially for materials like e-cloth on 25 mm fibreglass (porous absorber) and P&E foil on 25 mm fibreglass (Helmholtz absorber), as shown in Figure 6.

Core materials generally have a lower validity threshold than the standard control size of 12 sqm. Conversely, materials with facings typically show minimal deviations

from their standard control sizes, except for vinyl facing, which has a validity threshold of 7.2 square meters due to its sound absorption impermeability. These findings emphasise the importance of considering material composition and configuration when determining the appropriate sample size for acoustic testing protocols.

In summary, if a sample size is reduced to the threshold size (means with the same letters, as indicated in the inset in Figure 6), it will return mean absorption coefficient results statistically similar to the standardised control sample size. These would be, however, achieved given the same methodological approach in data acquisition and analyses, including equipment type, meteorological conditions, reverberant conditions, and sound absorption calculation.

4. Conclusions and Future Work

This study explored the sound absorption performances of commonly used acoustic absorbers within a full-scale reverberation chamber, including polyester, fibreglass, and open-cell foam. This involved strategically combining the analysed absorber types with different facing materials to enhance their theoretical broadband absorption characteristics in practical applications. These porous absorbers exhibited significant absorption above 500 Hz, highlighting reduced effectiveness at lower frequencies relative to their wavelengths. The practical applications demonstrated improved theoretical broadband absorption characteristics through strategic pairings of these porous absorbers with various facing materials forming composite acoustic materials.

The study further explored the validity threshold for reduced sample sizes of the acoustic absorber specimen types, employing statistical analysis against ISO 354:2003 standardised control sample sizes. Analysis of variance on specimen type groups highlighted the substantial impact of frequency components and sample sizes on the absorption coefficient across all absorber types. It reported specific thresholds of 9.6 sqm for 20 mm 800 gsm polyester, 7.7 sqm for 25 mm open-cell foam, and 7.2 sqm for 25 mm fibreglass. Additionally, it is deduced that standalone core absorbers generally have a reduced-size validity threshold from the standardised control size of 12 sqm for the 25 mm fibreglass, 20 mm 800 gsm polyester core materials, and 25 mm open-cell foam. However, core materials with facings do not typically experience this reduction in validity threshold, except the vinyl facing, which demonstrates a size validity threshold as low as 7.2 square meters due to its impermeability to sound absorption.

Future work will focus on estimating the absorption effects with reduced standardised control sample sizes of different layers or thicknesses within each absorber type group. This would serve to establish the effect of sample thickness, as in the case of the 20 mm thick polyester, where its thickness inherently impacts the overall sound absorption compared to the others. Evaluating the performance of varying sizes and layers, considering the negation of edge effects through blocking and sealing, conducting interlaboratory studies, and validating sample validity thresholds will further advance this research.

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