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Research Article

Tuning of Estimated Sound Absorption Coefficient of Materials of Reverberation Room Method

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Acoustical materials are usually used for architectural design, ambient noise, and traffic noise to absorb sound. The sound absorption coefficient (SAC) is often used as the performance index of acoustical materials. It is measured using the reverberation room method (RRM) and the impedance tube method (ITM). The sound source of the RRM is a random incidence in various directions, whereas that of the ITM is a normal incident. The SAC measured by the RRM is more extensive, practical, and costly than ITM. Usually, the SAC measured by RRM is used as the commercially available acoustical materials index. However, RRM requires large-area test samples for measurement and a special sound field of reverberation room for test experiments. Therefore, this study aims to use the ITM to measure SAC. The measured SAC, frequency, thickness, and material density were employed as independent variables and substituted in the obtained multiple regression model to predict SAC obtained by RRM. In addition, the measurement characteristics of impedance tubes provide varisized calibers for different frequency ranges to measure a relatively accurate SAC. Based on the abovementioned characteristics, this study proposed a dual-model for estimating the SAC of the reverberation room method to achieve the best-estimated result. After experimental validation, the dual-model estimated result was compared with SAC from the reverberation room method. It was observed that the maximum absolute value of all errors did not exceed 0.16. Most of the absolute errors were below 0.1, proving the accuracy of this method. Therefore, the method proposed in this study can shorten the acoustical material development schedule for manufacturers and save the cost of the development process.

1. Introduction

The application of acoustical materials is quite extensive, including in buildings, transportation, or offices. As a result, the performance of acoustical materials will influence the range and effect of their usages; the primary evaluation index is the sound absorption coefficient (SAC). The main evaluation methods of SAC are by measuring the reverberation time in a reverberation room [1] and the impedance tube two-microphone method. Between these two methods, the impedance tube method is rapid and convenient, whereas the reverberation room method has a relatively higher cost. In 2021, Hiremath et al. [2] adopted both the reverberation room method and the impedance tube method to measure the sound absorption coefficient of materials, reviewed the two methods' principles, and compared them by their merits and demerits. While the laboratory setup of a reverberation room has a higher cost, the evaluation and maintenance of performance are more important. In 2021, Abd-Elbassee et al. [3] adjusted and evaluated the performance of a reverberation room to guarantee the sound field diffusion property of the room. In 2018, Kang et al. [4] employed the two methods to measure the same acoustical material and found that the obtained SACs were in a positive correlation, implying considerable reference values in the two test methods.

At present, in the development process of new materials, the impedance tube method is still the preferred choice for measuring SACs, while the reverberation room method is employed for testing when the product is mature. In 2019, Bhattacharya et al. [5] adopted a self-made impedance tube and commercially available impedance tube for sound absorptivity measurements, indicating a relatively higher usage rate of impedance tubes. Besides using the impedance tube method to measure SACs of materials, Taban et al. [6] also employed the Johnson–Champoux–Allard mathematical model in 2019 to predict SACs. Further, they compared the results of the experimental data with those of the mathematical model. Considering the influence of lengths and diameters on impedance tubes, Chelidze [7] proposed a study in 2018 by using the sonic attenuation in impedance tubes to determine SACs and obtained good results. In 2017, Nandanwar et al. [8] adopted an impedance tube to measure the effect of fiberboards with different densities on SACs. In 2015, Niresh et al. [9] measured the SACs of single and multilayered porous materials in an impedance tube, compared the standing wave method with the transfer function method, and analyzed the results. In 2014, Kimura et al. [10] found that the high frequency was restricted when the existing impedance tube was employed for measuring SACs, especially in the frequency range of 8 kHz–10 kHz. Thus, they developed a high-frequency impedance tube; meanwhile, the traditional impedance tube and high-frequency impedance tube were validated and compared by taking the measurements of the two tubes with an air cavity (empty tube) and an acoustic absorber material. According to the abovementioned references, the reverberation room method for measuring SACs is more practical but costly; hence, less used. The impedance tube is extensively studied and used for its convenience, time-saving, and low cost. However, if the data of SACs are measured using the advantage of the impedance tube method and employed to estimate the result of the reverberation room method, the advantages of these two methods can be combined. By using the SAC results from the impedance tube method and the reverberation room method, McGrory et al. [11] found in 2012 a mathematical relation between the two methods. The thickness, density, and flow resistivity were adopted as the variables of a linear regression to find the relation between the two methods by using multiple regression. This study adopted multiple regression as the mathematical foundation. Considering the measurement characteristics of impedance tubes, where different frequency ranges are limited to certain tube diameters, a dual prediction model was proposed to give different mathematical models to different frequency ranges so as to increase model accuracy. Furthermore, by adjusting the weights of frequency, thickness, and density and decreasing the use of the flow resistivity as a variable, this could make calculating the variables of the regression model easier. This study greatly enhanced the accuracy and convenience of tests by adjusting the weights of variables and building a dual model. Moreover, the research findings can provide a feasible program for reducing the SAC testing cost when developing new materials.

2. Introduction to Test Method of the Sound Absorption Coefficient

2.1. Sound Absorption Coefficient. SACs can be divided into three major classes according to the directionality of the sound source [12]: (1) normal incident sound absorption coefficient, a small-scale specimen with good precision; (2) oblique incident sound absorption coefficient, with an academic property, not often used; and (3) random-incidence sound absorption coefficient, the value is more practical, often employed in the reverberation room method, as shown in Figure 1.

In the current acoustic performance evaluation, the acoustic absorptivity of materials is judged by their SACs. There are three measuring methods for the SACs of materials: (1) reverberation room method using reverberation time for measurement; (2) standing wave method using impedance tubes and a single microphone for measurement; and (3) impedance tube two-microphone method (also known as transfer function method) using impedance tubes and two microphones for measurement.

Considering economy and convenience, the extensively and presently used measuring method is the impedance tube two-microphone method, which is also the fastest among the three methods. This method employs impedance tubes as the standard acoustical environment for measuring the acoustic characteristic of materials and requires the inner space of the tubes to have a higher acoustic impedance in order to prevent the sound from being radiated. The two microphones are interchanged during the measuring procedure for correction, making this method extremely time-saving and convenient. As it only requires the test specimen area to be equal to the cross section area of the connecting tube, this method is easy to fabricate and is lower in the development cost. These measuring methods perform measurements according to some international standards. For example, the two-microphone transfer function method mainly follows the impedance tube method design specifications and the theory of the transfer function method (ASTM C384-95 [13] and ASTM E1050-90 [14]).

The SAC (α) is defined as the ratio of absorbed energy (including transmission sound energy) to incident sound energy expressed as follows:

$$\begin{aligned}\alpha &= \frac{E_i - E_r}{E_i} = 1 - \frac{E_r}{E_i} = 1 - R,\\ \alpha &= \frac{\text{absorbed energy}}{\text{incident sound energy}} = \frac{E_i - E_r}{E_r},\end{aligned} \tag{1}$$

where E_i is the incident wave sound energy and E_r is the reflected wave sound energy.

2.2. Reverberation Room Method. The reverberation room is employed for measuring the reverberation time, and SACs are measured in the reverberation room according to CNS9056 [15], ASTM-C423-17 [16], and ISO354 [17]. Due to the restriction of the cut-off frequency, the volume of the reverberation room should not be smaller than 150$\mathbf{m}^3$. If the volume of the reverberation room is larger than 500 m^3, the SAC of the higher frequency band cannot be measured correctly due to the air's sound absorption phenomenon.

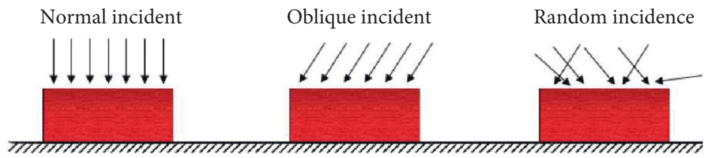


Figure 1: Schematic diagram of three types of SAC.

According to the SAC calculation of the reverberation room method based on ISO354 [17], the calculation formula of SACs is expressed as follows:

$$\alpha = \frac{55.3V}{cS}\left(\frac{1}{T_1}-\frac{1}{T_2}\right) - 4\frac{V}{S}\left(m_1 - m_2\right), \quad (2)$$

where α is the Sound Absorption Coefficient; T_1 is the reverberation time after the sample is placed; T2 is the reverberation time before the sample is placed; V is the volume of the reverberation room (m^3); S is the sample area (m^2); C is the sound velocity in the air, C 1.5 + 0.61 t, t is in Celsius degree (℃); and $m_1 m_2$ is the sound power attenuation coefficient (m^{-1}) of the reverberation room with and without a specimen. They are derived from the temperature and humidity measured during the test according to the ISO-9613-1 look-up table.

2.3. Impedance Tube Method. The impedance tube is adopted for measurement (ISO 10534-2, [18]; ASTM E1050-98, Reapproved 2006 [19]). When the sound source is generated in an impedance tube, two microphones at different positions are installed on the impedance tube wall to measure the sound pressure level simultaneously. The transfer function and the reflection coefficient are calculated according to the measured sound pressure level. Lastly, the SAC is worked out of the reflection coefficient.

As partial energy may be absorbed by the inner wall of an impedance tube and result in a small amplitude and change in phase angle of the reflected wave, the two-microphone transfer function method [20] can be employed for correction. Figure 2 shows Microphones 1 and 2, and the frequency response function measured by Microphones 1 and 2 is H_{12}^{I}. H_{12}^{II} is the frequency response function after the positions of the two microphones are exchanged. The transfer function correction coefficient H_c could be worked out of H_{12}^{I} and H_{12}^{II}, expressed as (3), where φ_c is expressed as the phase shift between H_{12}^{I} and H_{12}^{II}.

$$H_c = \sqrt{\frac{H_{12}^{I}}{H_{12}^{II}}} = \left|H_c\right| e^{j\varphi_c}. \quad (3)$$

After the correction coefficient H_c was worked out, the measured transfer function $\widehat{H}$ was corrected. The corrected transfer function H is expressed as follows:

$$H = \frac{\widehat{H}}{H_c} = H_r + jH_i. \quad (4)$$

Assuming that the plane sound wave is a normal incident and its direction is parallel to the rectangular coordinate x-axis, whereas the sound wave is from negative x-direction, this situation is shown in Figure 2.

The principle of measuring the acoustic performance of the impedance tube's materials is based on the transfer function method. If the incident wave is p_i and the reflected wave is p_r, p_i and p_r can be determined by the sound pressure measured by the two microphones installed on the tube, as shown in Figure 2. In the figure, s is the spacing between two microphones and l is the distance from Microphone 2 to the reference plane (measuring surface). The incident wave sound pressure and the reflected wave sound pressure can be expressed as follows:

$$\begin{aligned} p_i &= P_I e^{jk_0 x}, \\ p_r &= P_R e^{-jk_0 x}, \end{aligned} \quad (5)$$

where $k_0 = 2\pi f/c$ (k_0: wave numbe, f: frequency, and c: sound velocity)

In the equation above, P_I is the amplitude of reference surface p_i and P_R is the amplitude of p_r on the reference plane ($x = 0$). The sound pressures in the positions of two microphones are as follows:

$$\begin{aligned} p_1 &= P_I e^{jk_0(s+l)} + P_R e^{-jk_0(s+l)}, \\ p_2 &= P_I e^{jk_0 l} + P_R e^{-jk_0 l}. \end{aligned} \quad (6)$$

The transfer function H_i of the incident wave is as follows:

$$H_i = \frac{p_{2i}}{p_{1i}} = e^{-jk_0 s}, \quad (7)$$

where s is the distance between two microphones. The transfer function H_r of the reflected wave is as follows:

$$H_r = \frac{p_{2r}}{p_{1r}} = e^{jk_0 s}. \quad (8)$$

The transfer function H_{12} of the total sound field is derived from incident p_1, p_2, and $P_R = rP_I$.

$$H_{12} = \frac{p_2}{p_1} = \frac{e^{jk_0 l} + re^{-jk_0 l}}{e^{jk_0(s+l)} + re^{-jk_0(s+l)}}. \quad (9)$$

When the above equation is rewritten by Hi and Hr, the reflectivity r can be worked out, where the reflectivity is defined as the ratio of the reflected wave to incident wave and expressed as follows:

$$r = \frac{H_{12} - H_i}{H_r - H_{12}} e^{j2k_0(s+l)}. \quad (10)$$

Therefore, the reflection coefficient r of the reference plane ($x = 0$) can be determined by the measured transfer

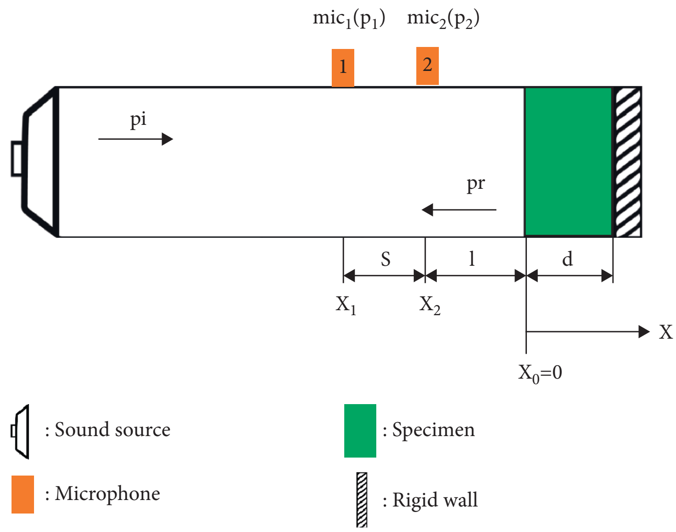


Figure 2: Impedance tube layout.

function with known distance *s*, *l* and wave number k_0. Therefore, the normal incident sound absorption coefficient α is expressed as follows:

$$\alpha = 1 - |r|^2. \tag{11}$$

3. Multiple Regression Theory

Regression analysis is a statistical method for data analysis. The purpose of this statistical method is to identify the relationship between two or multiple variables so that the obtained samples can be adopted for data fitting, and the regression equation is worked out, approaching the input/output characteristic of the data. The regression equation can estimate how much the output is changed by the input variation. Therefore, the variation can be predicted using the regression equation.

When k independent variables are imported, the mathematical model of general multiple regression can be expressed as follows:

$$Y = b_0 + b_1 x_1 + b_2 x_2 + \ldots\ldots + b_x x_k + c. \tag{12}$$

The matrix mode can be expressed as follows:

$$[Y] = [x] \times [b] + [c]. \tag{13}$$

For $Y = b_0 + b_1 x_1 + b_2 x_2 + \ldots\ldots + b_x x_k + c$, if the estimates a_0, a_1, $a_2 \ldots a_k$ of parameters b_0, b_1, $b_{2\ldots} \ldots b_k$ in the regression equation are exported using the least squares method, the estimating equation corresponding to the regression line can be expressed as $y = a_0 + a_1 x_1 + a_2 x_2 + \ldots\ldots + a_x x_k + c$. For the general multivariate regression model, the least squares method was selected. The estimated regression equation can minimize the sum of square error $\Sigma(Y_i - y_i)^2$ predicted by all sample points. The sum of square error (SSE) can be expressed as follows: $\mathrm{SSE} = \sum_{i=1}^{k} (Y_i - y_i)^2 = \sum_{i=1}^{k} (Y_i - a_0 - a_1 x_1 - a_2 x_2 - \cdots\cdots - a_x x_k)^2$. If the SSE is minimum, the following equation must be satisfied:

$$\frac{\delta \mathrm{SSE}}{\delta a_0} = \frac{\delta \mathrm{SSE}}{\delta a_1} = \cdots\cdots = \frac{\delta \mathrm{SSE}}{\delta a_k} = 0, \tag{14}$$

where a_0, a_1, $a_{2\ldots} a_k$ can be obtained; and let Y_i represent the measured value of data and y_i represent the prediction value generated by the regression line.

The frequency, density, and thickness of the glass fiber after weight adjustment and the SAC (x_4) measured by the impedance tube are employed as independent variables, whereas the SAC measured in the reverberation room is a dependent variable (y_i), as shown in Table 1. By doing so, the multiple regression equation can be established.

4. Research Structure and Measurement Result

4.1. Research Structure. This study aims to build an estimation model for SACs of the reverberation room method and to obtain SACs close to the actual values via this model. According to SACs measured by the simple impedance tube method and with the adjustment in the weights of related independent variables, a rapid, simple, and cost-cutting method was provided in this study for estimating the acoustic performance of acoustical absorbent. The analysis process is shown in Figure 3.

The process chart for building an estimation model for SACs of the reverberation room method is described as follows:

Step 1. The SACs of glass fiber were measured by the reverberation room method and the impedance tube method.

Step 2. The weights of independent variables of the regression were adjusted and combined with SACs measured by the impedance tube method for multiple regression calculation. Finally, a dual prediction model was obtained, and the absolute error between the predicted result and the SAC obtained by the reverberation room method was worked out.

Table 1: Multiple regression analysis variables.

Dependent variable (y_i)	Independent variable (x_1)	Independent variable (x_2)	Independent variable (x_3)	Independent variable (x_4)
Prediction value by reverberation room method	Frequency	Density	Thickness	Measured by impedance tube method

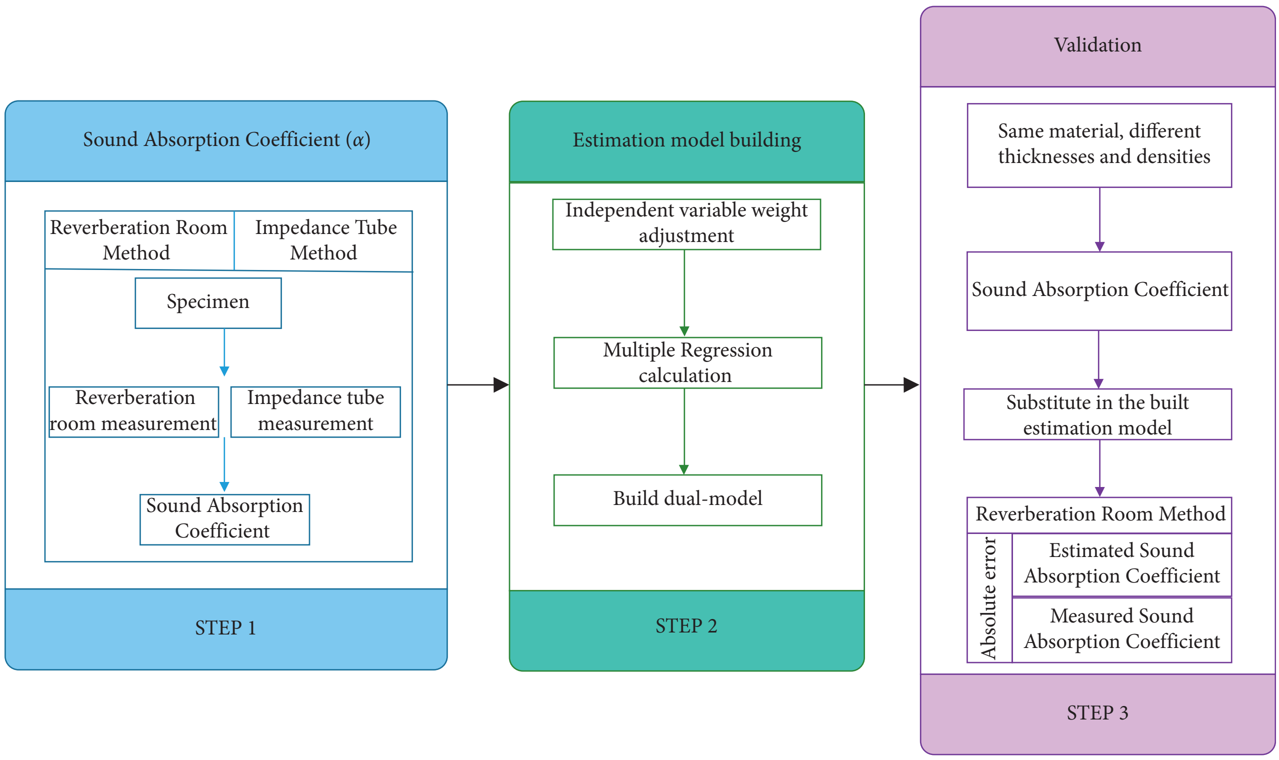


Figure 3: Analysis process chart of bearing failure diagnosis.

Step 3. A new set of SACs obtained by the impedance tube method and the reverberation room method was measured. Then, they were substituted into the built dual prediction model for validation to confirm the model accuracy.

4.2. Experimental Structure and Measurement Result

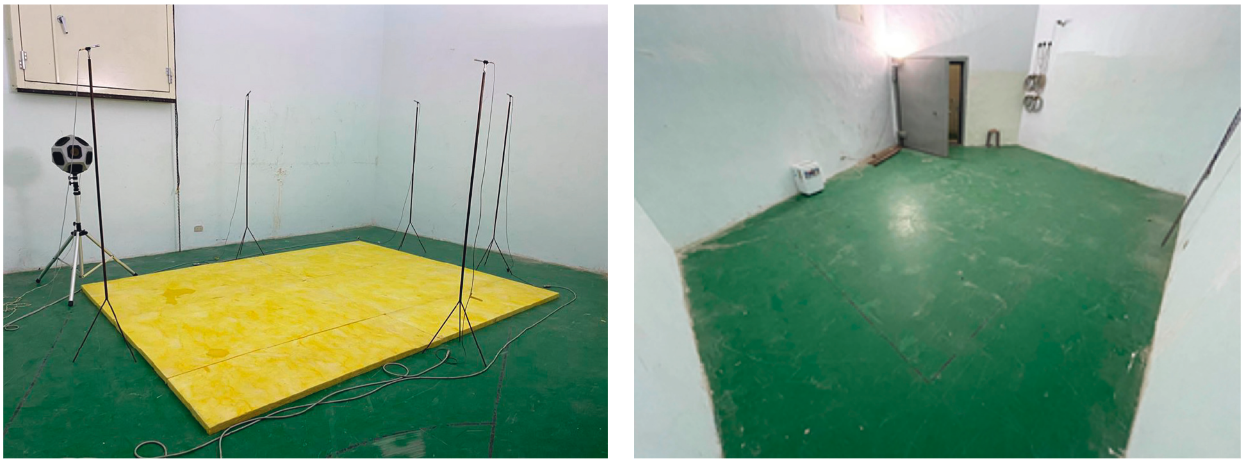
4.2.1. Reverberation Room Method Measured Sound Absorption Coefficient. Five microphones were installed around the specimen and connected to the spectrum analyzer in the master control room for receiving signals. The spectrum analyzer exported sound source and was connected to a loudspeaker in the reverberation room through the power amplifier to measure the sound source, as shown in Figure 4.

4.2.2. Impedance Tube Method Measurement. Two microphones were installed on the microphone installation site of the impedance tube and connected to the spectrum analyzer for receiving signals. The spectrum analyzer exported the sound source and was connected to a loudspeaker in the impedance tube through the power amplifier for measuring the sound source, as shown in Figure 5.

4.2.3. Experimental Measurement Result. The glass fiber was coded according to its density and thickness. There are four groups, and the corresponding coding is shown in Table 2, with the specific samples being shown in Figure 6.

The glass fiber 48K25, 96K25, 32K50, and 73K50 were measured by the impedance tube method and the reverberation room method, with the SAC results of glass fibers on various frequencies shown in Table 3. The results are compared in Figures 7 and 8.

As shown in Figures 7 and 8, the SACs obtained using the impedance tube method or reverberation room method were approximately below 1 kHz. SACs increased with frequency. After the frequency exceeded 1 kHz, the SAC increased and remained relatively stable. Therefore, if SACs measured by the impedance tube method were employed to predict its value using the reverberation room method, there would be a better correlation. As the impedance tube method was more convenient and economical than the



(a) (b)

Figure 4: Measured absorption coefficient in the reverberation room.

Frequency range: 50 Hz~1.6 kHz

(a)

Frequency range: 500 Hz~6.4 kHz

(b)

Figure 5: Impedance tube: (a) large and (b) small tube for B&K Type 4206.

Table 2: Coding of specimens of glass fiber.

Density (kg/m^3)	Thickness (mm)	Code (K)
48	25	4825
96	25	9625
32	50	3250
73	50	7350

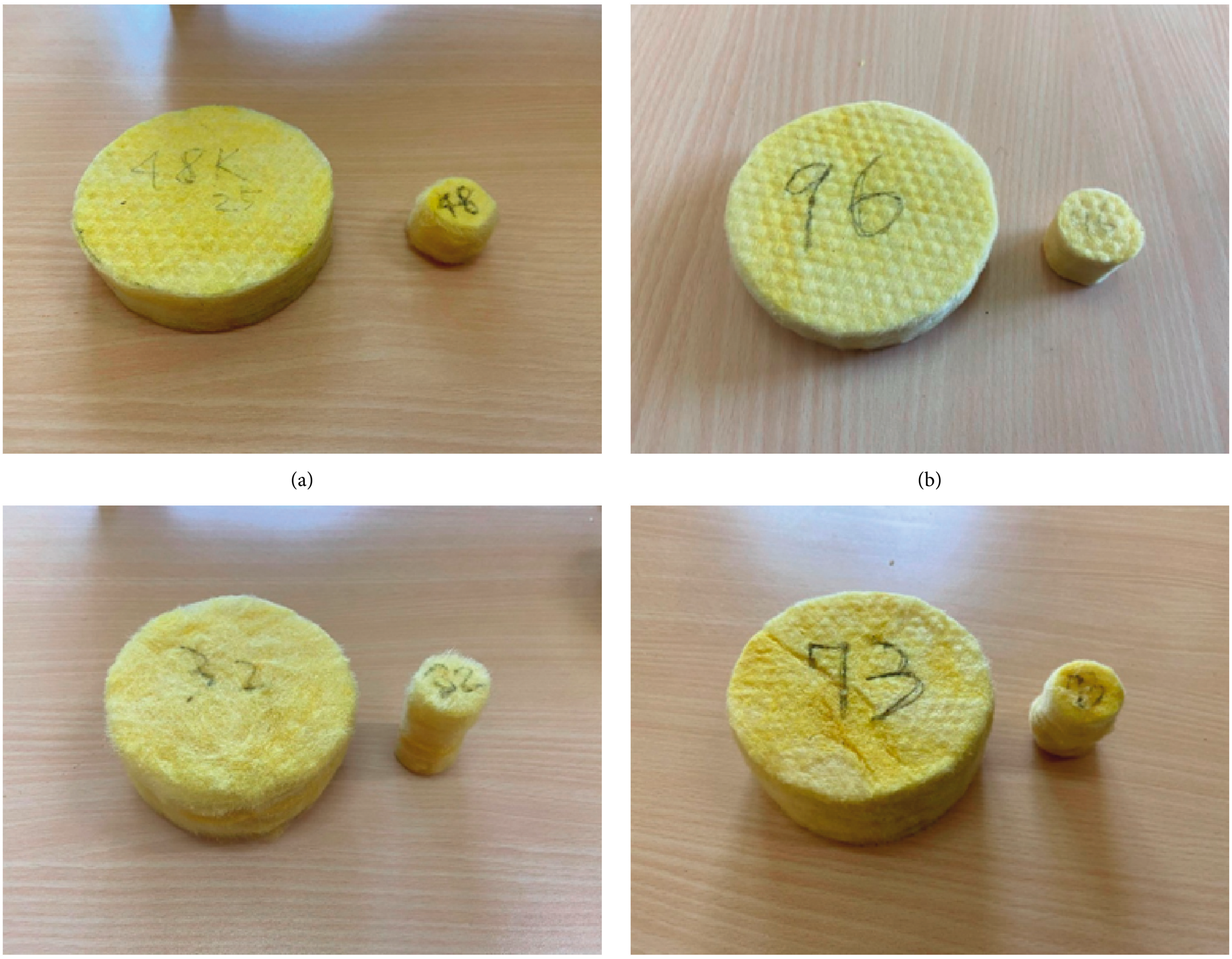
reverberation room method, the product test time and cost could be greatly reduced.

5. Estimation Model Building and Result Discussion

5.1. Building of Dual Model. The frequency range measured by a large tube of the impedance tube is 50–1.6 kHz, whereas the frequency range measured by a small tube of the impedance tube is 500–6.3 kHz. Therefore, the modeling was divided into two groups. Group 1 used the data measured by a large tube of the impedance tube on 100–500 Hz to build the first model. On the other hand, Group 2 used the data measured by a small tube of the impedance tube on 630 Hz–5 kHz to build another regression model. Further, the two regression models are the measured data on frequency 100 Hz–5 kHz.

After data measurement, the weights of frequency, density, and thickness were adjusted, where the maximum value was 1, as shown in Table 4. The accuracy of the prediction value depended on the selection and weight distribution of an independent variable. Therefore, the value was controlled within 0-1 by adjusting the weights without influencing the influence of weights: the closer the value was to 1, the greater the influence was, whereas the closer the value was to 0, the slighter the influence was.

The calculated regression coefficient was substituted in the multiple regression equation to obtain the dual prediction model of the large tube and small tube of impedance tubes. The coefficients are compiled in Table 5.



(a) (b) (c) (d)

Figure 6: (a) 48K25, (b) 96K25, (c) 32K50, and (d) 73K50 impedance tube large tube and small tube samples.

5.2. Estimated Result Comparison and Discussion. Finally, the estimated value of the SAC of the reverberation room method was obtained by the dual prediction model using the large and small tubes of impedance tubes. Then, the estimated value was compared with the SAC measured in the reverberation room to calculate the absolute error (the reverberation room measured value − the estimated reverberation room value). This result is shown in Figure 9. It was observed that the absolute error of the SAC between the prediction values and measured values of four samples obtained by the dual model was mostly below 0.1, and the maximum value did not exceed 0.16, implying the dual prediction model's high accuracy and feasibility.

In addition, the 45° oblique line in Figure 10 means that the calculated value of the estimation model is equal to the measured value. Thus, the estimated SACs of four samples were employed as the X-coordinate and the measured SACs were adopted as the Y-coordinate to draw a scatter diagram, as shown in Figure 10. The more concentrated the scatter points are on the 45° oblique line, the more accurate the estimation model is. As these scatter points mostly gather along the 45° oblique line, the model accuracy can be observed.

The most important purpose of this study is to obtain an estimation model for SACs by the reverberation room method. As the impedance method is fast and economical, the SAC data measured by the impedance tube method were substituted in the dual prediction model to obtain accurate estimated SAC values by the reverberation room method. Therefore, as shown in Figures 9 and 10, the absolute values of the error of SACs between the prediction value and measured value mostly fell below 0.1, and the maximum value did not exceed 0.16. The dispersal points of the prediction and measured values were distributed on the straight line at a slope of 1. This means that the prediction value was quite close to the experimental value. Therefore, the two figures show that the estimation model had very high accuracy and feasibility.

6. Validation of Estimation Model and Discussion

To further prove the accuracy of the dual prediction model, the SAC of 64K25 glass fiber specimen was measured by the impedance tube method and the reverberation room

Table 3: SAC measurement results of the impedance tube method and reverberation room method.

Frequency	48K25 Impedance tube method	48K25 Reverberation room method	96K25 Impedance tube method	96K25 Reverberation room method	32K50 Impedance tube method	32K50 Reverberation room method	73K50 Impedance tube method	73K50 Reverberation room method
100	0.00	0.04	0.01	0.04	0.05	0.11	0.07	0.10
125	0.03	0.11	0.05	0.10	0.09	0.23	0.11	0.21
160	0.04	0.11	0.05	0.09	0.10	0.30	0.16	0.32
200	0.05	0.17	0.07	0.18	0.14	0.40	0.22	0.45
250	0.08	0.24	0.11	0.26	0.19	0.53	0.30	0.62
315	0.09	0.30	0.15	0.35	0.22	0.74	0.39	0.82
400	0.13	0.37	0.22	0.48	0.35	0.92	0.44	1.04
500	0.19	0.50	0.25	0.67	0.47	0.96	0.65	1.08
630	0.25	0.60	0.42	0.85	0.64	1.00	0.81	1.06
800	0.33	0.82	0.57	0.94	0.78	1.04	0.86	1.01
1000	0.42	0.84	0.68	0.91	0.88	0.96	0.85	0.96
1250	0.53	0.80	0.77	0.90	0.90	0.96	0.82	0.92
1600	0.67	0.81	0.89	0.95	0.88	0.93	0.74	0.92
2000	0.77	0.83	0.94	0.96	0.89	0.83	0.75	0.87
2500	0.90	0.78	0.98	0.95	0.93	0.85	0.81	0.89
3150	0.97	0.84	0.98	0.87	0.98	0.84	0.90	0.88
4000	1.00	0.81	0.96	0.86	0.98	0.86	0.92	0.84
5000	0.97	0.77	0.94	0.86	0.85	0.84	0.68	0.84

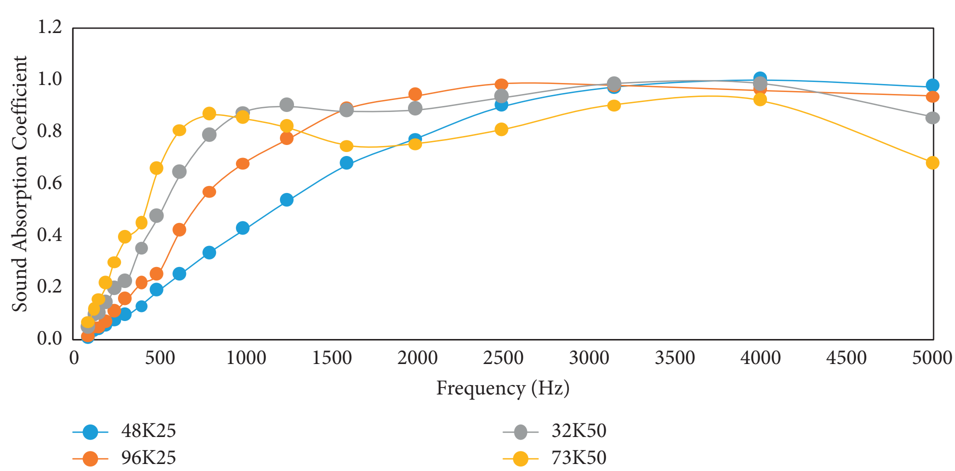


Figure 7: SAC of the impedance rube method.

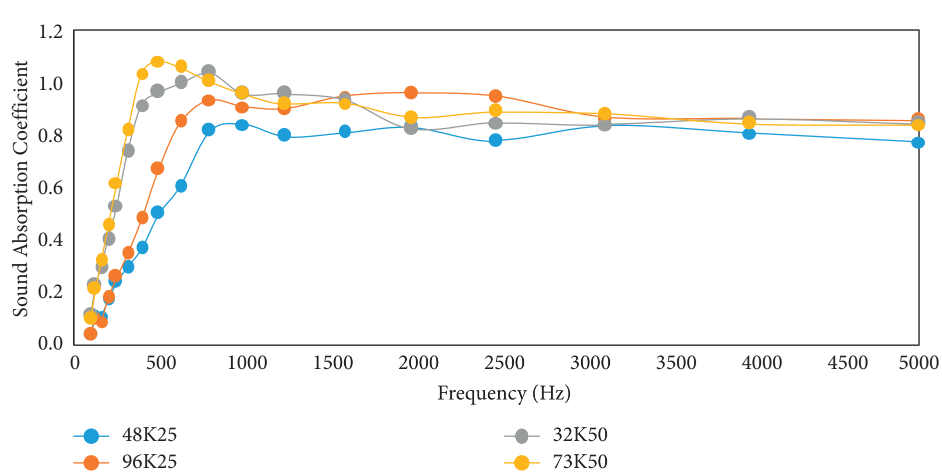


Figure 8: SAC of the reverberation room method.

Table 4: Variable weight adjustment.

Frequency	100	125	160	200	250	315	400	500	630
Weight	0.20	0.25	0.32	0.40	0.50	0.63	0.80	1.00	0.126
Frequency	800	1k	1.25k	1.6k	2k	2.5k	3.15k	4k	5k
Weight	0.160	0.200	0.250	0.320	0.400	0.500	0.630	0.800	1.000
Thickness	25	50							
Weight	0.5	1.0							
Density	32	48	73	96					
Weight	0.33	0.50	0.76	1.00					

Table 5: Regression coefficients.

Tube	Frequency range	Model	(x_1)	(x_2)	(x_3)	(x_4)	Constant
Large	100~500 Hz	First model coefficient	0.416	−0.054	0.213	1.206	-0.142
Small	630~5000 Hz	Second model coefficient	−0.194	0.117	0.137	0.244	0.594

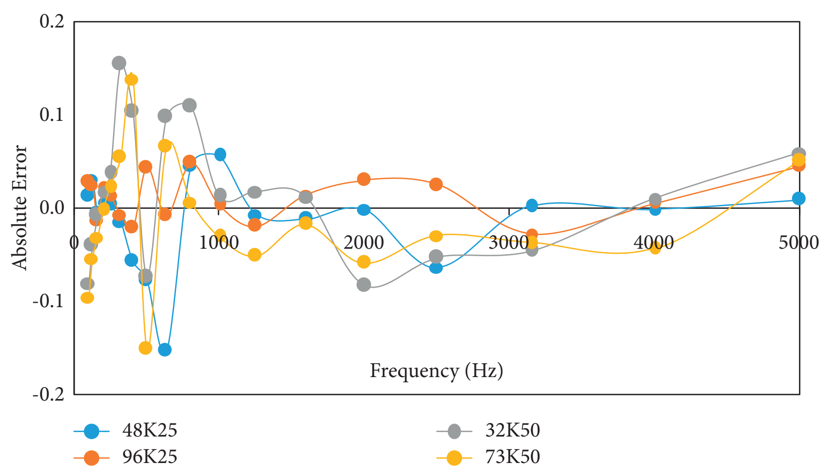


Figure 9: Absolute errors between the estimated results and true values of four samples.

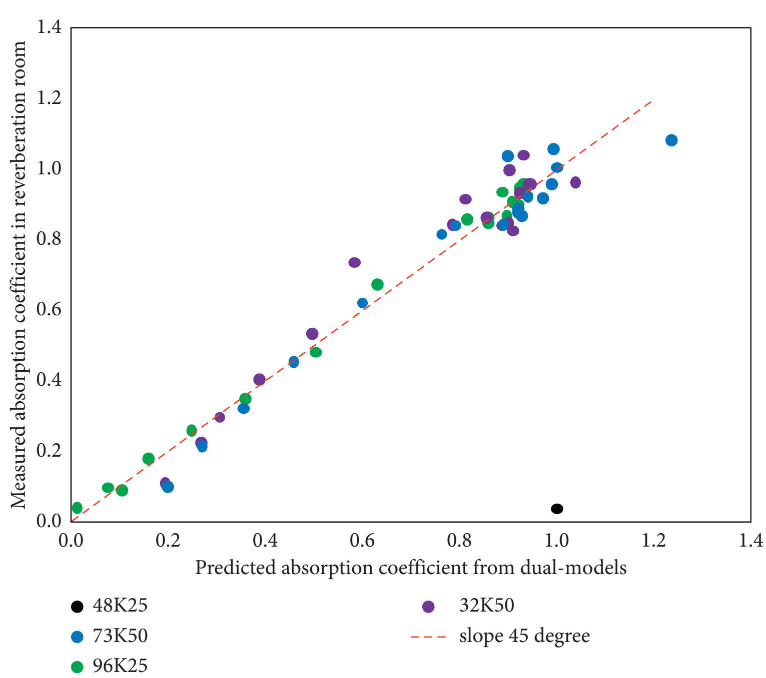


Figure 10: Scatter diagram of the estimated and measured sound absorption coefficients of four samples.

Table 6: Absolute error of the 64K25 estimation model.

Frequency	Estimated SAC of reverberation room method	SAC measured by reverberation room method	Absolute error
100	0.05	0.04	−0.01
125	0.08	0.08	−0.01
160	0.11	0.11	−0.01
200	0.16	0.17	0.00
250	0.24	0.24	−0.01
315	0.33	0.31	−0.03
400	0.43	0.39	−0.03
500	0.64	0.54	−0.10
630	0.80	0.64	−0.16
800	0.81	0.73	−0.08
1000	0.82	0.82	0.00
1250	0.83	0.89	0.05
1600	0.84	0.90	0.06
2000	0.86	0.91	0.06
2500	0.86	0.91	0.05
3150	0.85	0.84	−0.01
4000	0.83	0.82	0.00
5000	0.78	0.82	0.04

method. The measurement result of the specimen was not the data in the estimation model but the experimental result of the prepared test specimen. The measured value was substituted in the dual prediction model to calculate the absolute error between the estimated and actual values, and the result is shown in Table 6. It was observed that the maximum absolute value of all errors did not exceed 0.16, and most absolute errors were below 0.1. Thus, the accuracy of the estimation model is validated again.

After validation, for the dual prediction model of the SAC of the glass fiber material by the reverberation room method, the final mathematical model is expressed as follows.

First model (range: 100 Hz–500 Hz) is as follows:

$$y_i = 0.416 \times X_1 - 0.054 \times X_2 + 0.213 \times X_3 + 1.206 \times X_4 - 0.142. \tag{15}$$

Second model (range: 630 Hz–5000 Hz) is as follows:

$$y_i = -0.194 \times X_1 + 0.117 \times X_2 + 0.137 \times X_3 + 0.244 \times X_4 + 0.594, \tag{16}$$

where y_i is the prediction value by the reverberation room method; X_1 is the weights of frequency; X_2 is the weights of density; X_3 is the weights of thickness; and X_4 is measured by the impedance tube method.

7. Conclusions

Experimental measurements of SACs are generally obtained by the reverberation room method or the impedance tube method. In this study, the SAC of glass fiber material measured by the reverberation room method can be predicted using the SAC obtained by the impedance tube method. This prediction was made possible only after adjusting the weights of frequency, thickness, and material density. The maximum absolute error between the estimated value and measured value of SACs did not exceed 0.15. This study used multiple regression to obtain an estimation model for SACs by the reverberation room method. As the frequency measuring range of impedance tubes is limited, the large tube has better performance at 100–500 Hz while a small tube has a better performance at 630–5000 Hz. Therefore, this study proposed the dual prediction model to estimate SACs of the reverberation room method. The frequency, thickness, and material density after weight adjustment were combined with the SAC measured by the impedance tube method as variables for estimation. The advantage of this estimation model is that the independent variables are simple. The dual prediction model was built on a simple impedance tube measurement. The accuracy of estimation was enhanced when compared with the single mathematical model. This study used glass fiber material 64K25 to validate the estimation model and further validate the accuracy of the dual model. The result shows that the maximum absolute error of the SAC is 0.16. This proved the accuracy and feasibility of this dual prediction model. This method can be provided to the industry and academic circles in the future as it is convenient to evaluate SACs measured in a reverberation room. Thus, the new specimen development schedule can be shortened efficiently, and the related development costs can be reduced.

Data Availability

All data included in this study are available upon request by contacting the corresponding author.

Conflicts of Interest

The authors declare that there are no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

[1] S. Yan, J. Wu, J. Chen, Q. Mao, and X. Zhang, "Design of honeycomb microperforated structure with adjustable sound absorption performance," *Shock and Vibration*, vol. 2021, pp. 1–12, Article ID 6613701, 2021.

[2] N. Hiremath, V. Kumar, N. Motahari, and D. Shukla, "An overview of acoustic impedance measurement techniques and future prospects," *Metro*, vol. 1, no. 1, pp. 17–38, 2021.

[3] M. Abd-Elbasseer and H. Kh Mohamed, "Performance evaluation and effectiveness of the reverberation room," *Sound and Vibration*, vol. 55, no. 1, pp. 43–55, 2021.

[4] C. W. Kang, E. S. Jang, S. S. Jang, and H. Y. Kang, "Comparison of transfer function method and reverberation room method in measuring the sound absorption coefficient of rice straw particle mat," *Journal of the Korean Wood Science and Technology*, vol. 46, no. 4, pp. 362–367, 2018.

[5] S. S. Bhattacharya and D. V. Bihola, "Development of impedance tube to measure sound absorption coefficient," *International Journal of Engineering and Advanced Technology*, vol. 8, no. Issue 6, pp. 3218–3222, 2019.

[6] E. Taban, A. Khavanin, A. J. Jafari, M. Faridan, and A. K. Tabrizi, "Experimental and mathematical survey of sound absorption performance of date palm fibers," *Heliyon*, vol. 5, no. 6, Article ID e01977, 2019.

[7] M. Chelidze, "A new simple method for determining the sound absorption coefficient," *MATEC Web of Conferences*, vol. 211, p. 04003, Article ID 04003, 2018.

[8] A. Nandanwar, M. C. Kiran, and K. C. Varadarajulu, "Influence of density on sound absorption coefficient of fibre board," *Open Journal of Acoustics*, vol. 07, no. 01, pp. 1–9, 2017.

[9] J. Niresh, S. Neelakrishna, S. Subharan, and R. Prabhakaran, "Performance testing for sound absorption coefficient by using impedance tube," *Research Journal of Applied Sciences, Engineering and Technology*, vol. 11, no. 2, pp. 185–189, 2015.

[10] M. Kimura, J. Kunio, A. Schuhmacher, and Y. Ryu, *A New High-Frequency Impedance Tube for Measuring Sound Absorption Coefficient and Sound Transmission Loss*, Inter-noise, vol. 16, 19 pages, Melbourne Australia, November, 2014.

[11] M. McGrory, D. C. Cirac, O. Gaussen, and D. Cabrera, *Sound Absorption Coefficient Measurement: Re-examining the Relationship between Impedance Tube and Reverberant Room Methods*, Australian Acoustical Society, Fremantle, Australia, 2012.

[12] H. Tsai, *Interior of Sound Field Simulation and Design Variable Appraisal Acoustics Impedance Tube*, Feng Chia University/Master's Program of Electro-acoustics, Taichung, Taiwan, 2009.

[13] Astm C384-95, *Standard Test Method for Impedance and Absorption of Acoustical Materials by the Impedance Tube Method*, American Society for Testing Materials, West Conshohocken, PA, 1995.

[14] Astm E1050-90, *Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System*, American Society for Testing Materials, West Conshohocken, PA, 1990.

[15] Cns 9056, *Acoustics – Measurement Of Sound Absorption in a Reverberation Room*, Chinese National Standards, Taiwan, 2008.

[16] Astm C423-17, *Standard test method for sound absorption and sound absorption coefficients by the reverberation room method*, American Society for Testing and Materials, West Conshohocken, PA, USA, 2017.

[17] Iso 354, *Acoustics — Measurement Of Sound Absorption in a Reverberation Room*, International Organization for Standardization, Switzerland, 2003.

[18] Iso 10534-2, *Acoustics Impedance in Impedance Tubes -Transfer-Function Method*, International Organization for Standardization, Switzerland, 1998.

[19] Astm E1050-98, *Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System*, American Society for Testing and Materials, West Conshohocken, PA, USA, 2006.

[20] J. Y. Chung and D. A. Blaser, "Transfer function method of measuring in-duct acoustic properties. I. Theory," *Journal of the Acoustical Society of America*, vol. 68, no. 3, pp. 907–913, 1980.