

## Article

# Determination of the Sound Absorption Area Inside an Elementary Classroom Using Three Acoustical Methods: Computer Modeling, 1/10-Scale Model Experiment, and Field Acoustic Measurement

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**Abstract:** Acoustic standards for classrooms around the world are still being studied, but the placement of sound-absorbing materials to meet these standards is still unclear. The present study examined an appropriate location for applying sound-absorbing materials inside an elementary classroom to ensure speech intelligibility while meeting the RT criterion using three scientific experimental methods, namely, computer modeling, a 1/10-scale model, and field acoustic measurement. A sound-absorbing material was applied to the rear wall or ceiling, and the ceiling was further divided into front, center, and rear sections. The acoustic performance was predicted using a 3D computer model of a standardized classroom based on the location of the sound-absorbing material. Subsequently, a 1/10-scale model following the law of similarity was used to compare the acoustic performances based on the location of the sound-absorbing material. Finally, field measurements were performed in an actual classroom to verify the acoustic performance based on the location of the sound-absorbing material. The findings revealed that the sound-absorbing material was most effective when applied to the rear wall, followed by application at the center, front, and rear of the ceiling.

**Keywords:** classroom; sound-absorption; computer modeling; 1/10-scale model experiment; field acoustic measurement



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## 1. Introduction

Elementary school children are less able to perceive speech than adults, owing to their underdeveloped hearing. Nilsson et al. [1] used the hearing-in-noise test (HINT) to demonstrate that hearing and speech-perception abilities change with age. Adolescents ( $\geq 14$  years in age) have the same hearing ability as adults, but children under 10 years old have considerably lower speech perception in a noisy environment. Because elementary school is the first stage of education, it considerably affects future learning. The hearing abilities of lower elementary students must be considered when designing classrooms to facilitate their education. The following acoustic standards for lower elementary students have been proposed in Korea to ensure speech intelligibility [2,3]: a reverberation time (RT) of  $<0.6$  s (unoccupied) and background noise level of  $<35$  A-weighted decibels (dB(A)) for a classroom volume of  $<185$  m<sup>3</sup>. Ensuring that the acoustic environment of lower elementary classrooms meets these standards will help to improve the learning efficiency of students. Decades of research on classroom acoustics and the effects of poor classroom acoustics on listening and learning have resulted in certain tenets concerning classroom acoustics [4]. RT and background noise are very important factors in indoor spaces, including classrooms. In particular, excessive background noise and reverberation have been found to exacerbate listening and learning problems [5–7]. For this reason, RT and background noise are

measured a scientific method. Therefore, many researchers worldwide have suggested RT and background noise criteria specific to each country's language.

However, merely applying RT and background noise criteria to classrooms is insufficient. In fact, various parameters (e.g., clarity within 50 ms ( $C_{50}$ ) and the speech transmission index (STI)) can be used to evaluate acoustic environments, some of which have already been reflected in national classroom acoustic standards. However, unlike the parameters that can be used to assess the clarity and quality of speech, discussions on the Deutlichkeit ( $D_{50}$ ) index, which can be used to evaluate definition, have been held but are not reflected in such standards. Classrooms, lecture halls, auditoriums, congress halls, and theaters must provide good speech intelligibility, which necessitates sufficient speaker loudness, unimpeded direct sound propagation, a high reflection energy within the first 50 ms (path difference of 17 m) after the arrival of direct sound, and a short RT [8]. Haas [9] found that early reflections with a delay of up to ~50 ms can improve speech intelligibility by reinforcing the direct sound energy. Accordingly, Thuele [10] proposed  $D_{50}$ , which is defined as the ratio of direct sound (first 50 ms) to total energy:

$$D_{50} = \frac{\int_0^{0.05 \text{ s}} p^2(t) dt}{\int_0^{\infty} p^2(t) dt} \times 100 (\%) \quad (1)$$

$$C_{50} = 10 \lg\left(\frac{D_{50}}{1 - D_{50}}\right) \text{dB} \quad (2)$$

$$STI = \sum_{K=1}^7 \alpha_k \times M_k - \sum_{K=1}^6 \beta_k \times \sqrt{M_k \times M_{k+1}} \quad (3)$$

In Equation (1),  $p(t)$  means the instantaneous sound pressure of the impulse response measured at the measurement point. The equation for  $C_{50}$ , which is frequently used in classrooms to assess speech clarity, is shown in Equation (2).  $C_{50}$  can also be calculated using  $D_{50}$ , as shown in ISO3382-1. If  $D_{50}$  is greater than 50%, a syllable intelligibility of >90% can be expected. Thus, in a classroom where speech transmission is important,  $D_{50}$ , RT and background noise are critical acoustic parameters. Ansay and Zannin [11] conducted an experimental study on the relation between RT and  $D_{50}$  and concluded that classrooms should have an evenly distributed  $D_{50}$  at every seat to ensure that all students can hear properly. Even if the acoustic standards for RT and background noise are met, applying sound-absorbing materials to the wrong locations in a classroom can disrupt the even distribution of  $D_{50}$ . Therefore, the present study investigates the optimal placement of sound-absorbing materials in classrooms based on the relation between RT and  $D_{50}$ , which can be used to create high-quality acoustic environments. The STI defined in IEC 60268-16 [12] can be calculated using Equation (3). STI is an acoustic factor that is so critical that some countries have set it as a standard.  $\alpha_k$  denotes gender-specific weight factor for octave band  $k$ ,  $M_k$  denotes the modulation transfer index for octave band  $k$ , and  $\beta_k$  denotes the gender-specific redundancy factor between octave band  $k$  and octave band  $k + 1$ . However, in the present study,  $D_{50}$  was used as a measurement factor to understand the level at which the teacher's direct voice is evenly transmitted to the students within 50 ms for clear speech transmission in a small space such as a classroom.

Many researchers have studied the effect of the placement and quantity of sound-absorbing materials on classroom acoustics. For example, Sala and Viljanen [13] determined the most effective acoustic treatment for classrooms by varying the amount of sound-absorbing material in different arrangements. Their results suggested that to realize acceptable acoustic conditions for speech intelligibility, the sound-absorbing material should be distributed across at least two surfaces (e.g., ceiling, and back wall) and cover approximately 30% of the combined surface area of the walls and ceiling. They found that increasing the quantity of the sound-absorbing material resulted in higher building material costs, a marginal improvement in speech intelligibility, and excessive sound-level attenuation. Bistafa and Bradley [14] comprehensively investigated various acoustic treat-

ments with varying amounts of a sound-absorbing material. They examined the efficacy of these materials by testing the same quantity in various configurations. They compared the predictability of the RT of a simulated rectangular classroom for different sound-absorbing material configurations using seven analytical expressions and two-room acoustic software (ODEON 2.6 and RAYNOISE 3.0). They found that none of the analytical expressions or acoustic software consistently predicted the RT within an accuracy of 10%. The amount and distribution of sound-absorbing material in the room affected the accuracy of the analytical expressions. Among the tested expressions, the Arau–Puchades formula [15] was the most accurate in predicting RTs, with the smallest average relative error. Notably, Bistafa and Bradley’s measurements for different sound-absorbing material configurations found variations in the average RT of up to 0.3 s. This observation was attributed to the increased efficiency of the sound-absorbing material when uniformly distributed throughout the room. Cucharero et al. [16] tested a sound-absorbing material placed on the walls and at the ceiling boundaries in a reverberation room and mockup classroom. Their results showed that sound-absorbing material was less effective for diffuse sound fields when mounted on the corners or at the edges between the walls and ceiling. If the room mode dominates the sound field, the most efficient location for the sound-absorbing material was one of the surfaces that caused the modes. Furthermore, an excessively short RT, caused by the overuse of sound-absorbing material, is undesirable because teachers are forced to speak louder so that students in the back rows can hear [17]. Thus, determining the appropriate location and amount of sound-absorbing material in a classroom to meet the RT standard is considerably important.

Three scientific experimental methods—prediction, comparison, and verification—were applied in the present study to more accurately determine the optimal placement of sound-absorbing materials in Korean elementary school classrooms. First, a computer modeling was used to predict where sound-absorbing materials should be placed in a classroom and the effects of sound-absorbing treatments on speech metrics. A 1/10-scale model was used to compare appropriate locations for the application of sound-absorbing materials in a classroom. Finally, field measurements were performed to verify the appropriate locations for applying sound-absorbing materials in a classroom. The goal was to find the best location for applying sound-absorbing material in an elementary classroom to ensure an even  $D_{50}$  distribution while meeting the Korean standard for the RT in a classroom.

The present study presents a scientific and robust method for determining the optimal RT and highly uniform distribution of  $D_{50}$  in Korean elementary school classrooms. Furthermore, it has two objectives: (1) to determine the location and area of sound-absorbing materials with a uniform distribution of  $D_{50}$  and an RT of 0.6 s, and (2) to identify the difference in RT and  $D_{50}$  when the same material area is applied to different locations.

## 2. Classroom Acoustic Standards by Country

### 2.1. Acoustic Standards in Classroom

Many countries have established acoustic standards to ensure their classroom environments are appropriate for their respective languages and learning cultures. The United States has established subject-specific and classroom-size-specific RT and background noise standards [18]: an RT of <0.6 s for classrooms with a volume of  $\leq 283 \text{ m}^3$  and of <0.7 s for classrooms with a volume of  $283\text{--}566 \text{ m}^3$ , as well as a background noise level of 35 dB(A) for all classroom sizes. These standards were established by considering a minimum signal-to-noise ratio (SNR) value of 15 dB(A) for speech recognition and a minimum sound pressure level from the teacher of 50 dB(A) [19]. The United Kingdom established standards for the RT and background noise based on the age and number of students and the size and type of classroom [20]: an RT of <0.6 s and a background noise of 35 dB(A) for elementary students. Germany established classroom-specific standards for the RT and background noise [21]: an RT of  $0.32 \log V - 0.17 \text{ s}$  (where  $V$  represents the volume) and background noise of 35 dB(A) for A3 classrooms. Italy based their acoustic standards on DIN 18041 and set the RT and background noise based on the classroom type [22]: an RT of  $0.32 \log V - 0.17 \text{ s}$  and a

background noise of 38 dB(A) for A3 classrooms of <math> <250 \text{ m}^3 </math> and 41 dB(A) for A3 classrooms of >math> >250 \text{ m}^3 </math>. New Zealand has different RT and background noise standards depending on whether the classroom is new or refurbished [23]: 0.4–0.5 s for elementary classrooms and 40 dB(A) for newly built classrooms and 45 dB(A) for refurbished classrooms. Table 1 shows the acoustic standards for each country.

**Table 1.** Classroom acoustic standards by country.

Country	Standard	Learning Space	Background Noise Level (Unoccupied)	Reverberation Time (Unoccupied)
USA	ANSI/ASA S 12.60 [18]	<math> <283 \text{ m}^3 </math> <math> 283\text{--}566 \text{ m}^3 </math>	35 dB(A)	<math> <0.6 \text{ s}</math> <math> <0.7 \text{ s}</math> (500, 1k, 2k Hz)
UK	Building Bulletin 93 [20]	Primary school	35 dB(A) (New build) 40 dB(A) (refurbishment)	<math> \leq 0.6 \text{ s}</math> (New build) <math> \leq 0.8 \text{ s}</math> (refurbishment) (500, 1k, 2k Hz)
Germany	DIN 18041:2016 [21]	A3	40 dB(A)	<math> 0.32 \log V - 0.17 \text{ s}</math> (125, 500, 1k, 2k, 4k Hz) (occupied)
Italy	UNI 11532-2 [22]	A3 <math> 30 \text{ m}^3 \leq V < 5000 \text{ m}^3 </math>	<math> \leq 38 \text{ dB(A)}</math> ( <math&gt; &lt;="" 250="" \text{="" math&gt;)<br="" m}^3="" v=""></math&gt;> <math> \leq 41 \text{ dB(A)}</math> ( <math&gt; &lt;="" 250="" \geq="" \text{="" math&gt;)<="" m}^3="" td="" v=""> <td>&lt;math&gt; 0.32 \log V - 0.17 \text{ s}&lt;/math&gt; (125, 500, 1k, 2k, 4k Hz) (occupied)</td> </math&gt;>	<math> 0.32 \log V - 0.17 \text{ s}</math> (125, 500, 1k, 2k, 4k Hz) (occupied)
New Zealand	AS/NZS 2107:2016 [23]	Elementary school <math> V < 300 \text{ m}^3 </math>	40 dB(A) (New build) 45 dB(A) (refurbishment)	0.4–0.5 s (500, 1k Hz)

## 2.2. Review of the Acoustic Criteria in Korean Classrooms

Korea has also researched classroom acoustic performance standards. Furthermore, acoustic performance standards have been suggested to create a listening environment that is suitable for learning in Korean middle- and high-school classrooms. The proposed standards are applicable to general classrooms of approximately  $\leq 220 \text{ m}^3$  when used by Korean middle- and high-school students with normal hearing [24]. In addition, acoustic standards for lower elementary school classrooms and learning spaces for the elderly have been proposed [25]. Table 2 shows the standards for background noise and RT in Korean middle- and high-school classrooms, lower elementary-school classrooms, and learning spaces for the elderly.

**Table 2.** Acoustic standards for classrooms in Korea.

Grade	Volume	Background Noise Level	Reverberation Time	Notes
Elementary school (lower grade) [2]	<math> <185 \text{ m}^3 </math>	35 dB(A)	0.6 s	Incomplete hearing
Elementary school (higher grade) [26]	<math> <185 \text{ m}^3 </math>	35 dB(A)	$\leq 0.8 \text{ s}$	-
Middle and high school [26]	<math> <220 \text{ m}^3 </math>	35 dB(A)	$\leq 0.8 \text{ s}$	-
Learning space for elderly people [27]	<math> <250 \text{ m}^3 </math>	30 dB(A)	$\leq 0.8 \text{ s}$	Incomplete hearing

The standards for middle- and high-school classrooms are established by assuming a minimum sound pressure level of 50 dB(A) for teachers and a minimum SNR value

of 15 dB(A) for adults to perceive speech. The standard RT is  $\leq 0.8$  s, the same as in the UK. Although the RT standard in the UK is not limited by classroom volume, the Korean standard is limited to general classrooms with a volume of approximately  $\leq 220$  m<sup>3</sup>. Moreover, the proposed RT standard for lower elementary classrooms is 0.6 s, which is the same as the standard for elementary classrooms with a volume of  $\leq 283$  m<sup>3</sup> in the UK and US. Furthermore, the Korean standard for lower elementary classrooms is applied to general classrooms with a volume of  $\leq 185$  m<sup>3</sup>.

### 3. Methods and Materials

Many methods are used for predicting room acoustics. Computer modeling is widely used to predict acoustics in various spaces, such as classrooms, offices, and performance venues. Another traditional method for predicting acoustic performance is the 1/10-scale model. Field measurements are the most reliable and necessary method of investigating acoustic performance. All three of the aforementioned methods were used in the present study to determine if the  $D_{50}$  performance varies depending on where the sound-absorbing materials are placed in the classroom. The results of the three experimental methods used in the present study are not intended to be compared. Based on a comparison of the similarities between the three results from each method, the appropriateness of the placement of sound-absorbing materials in the classroom can be determined. Figure 1 depicts the process of the present study.

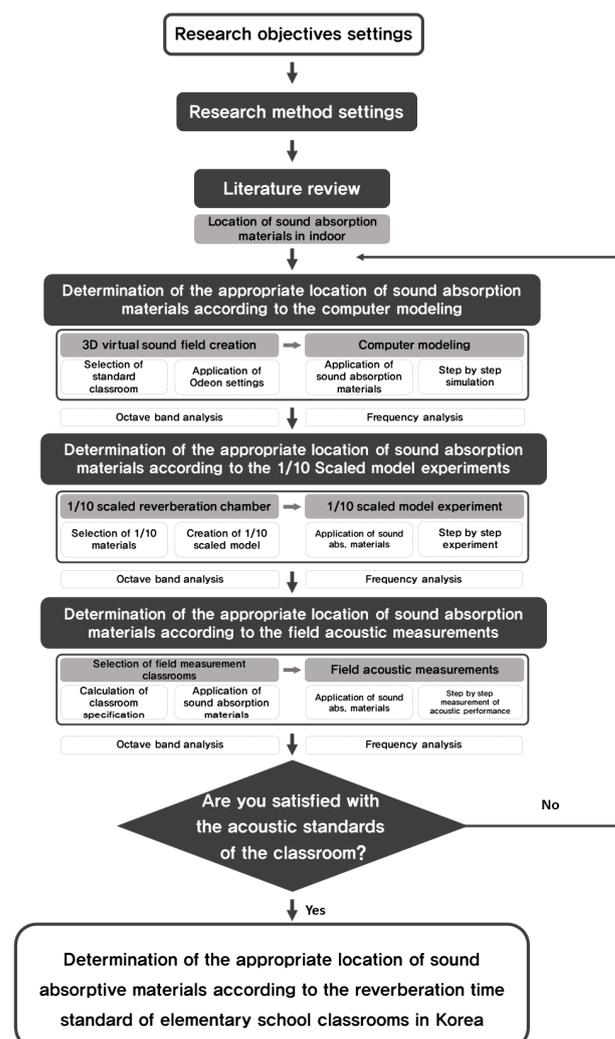
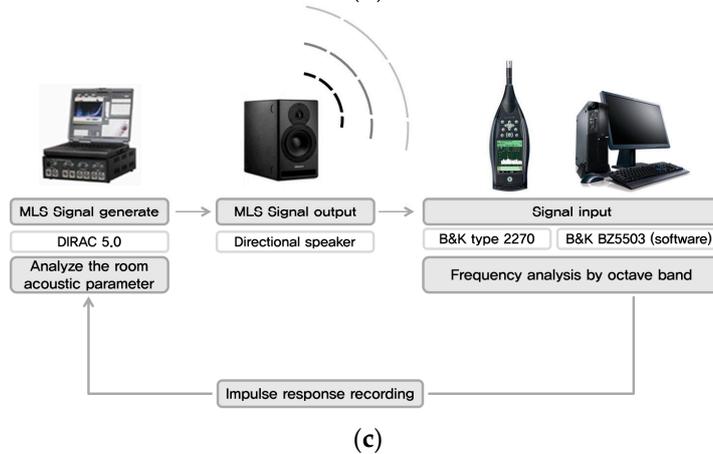
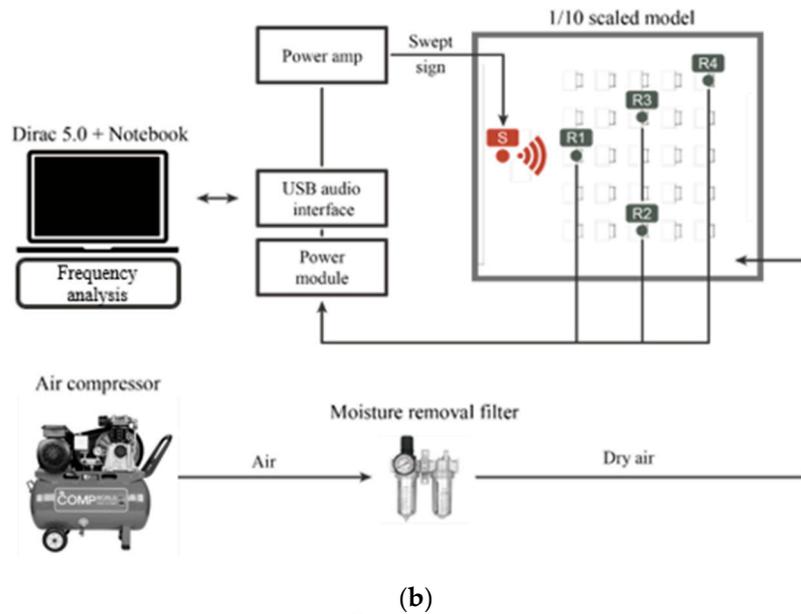
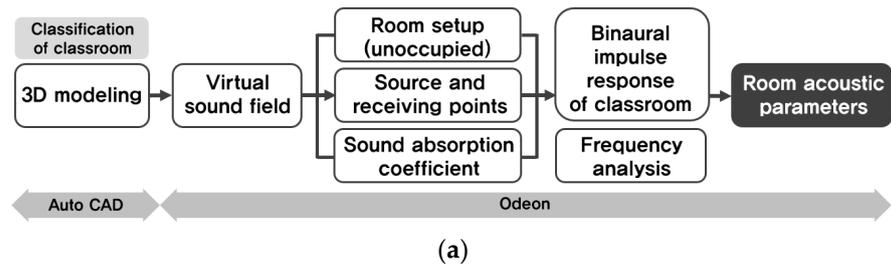


Figure 1. Research flowchart.

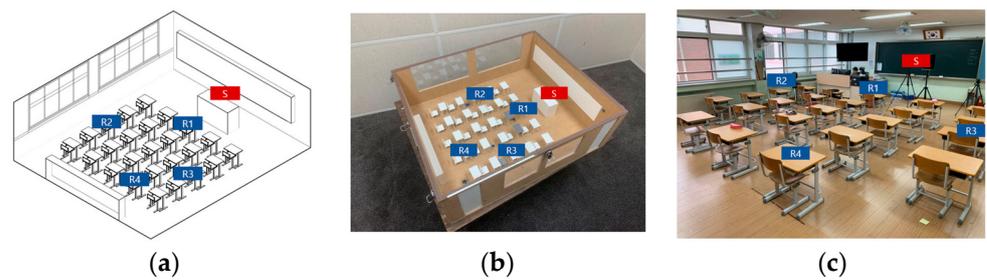
### 3.1. Methods

Computer modeling was used in the present study to predict the appropriate location for the application of a sound-absorbing material in an elementary classroom. In AutoCAD 2023, a 3D model of a standardized classroom was created and imported into the architectural acoustics software ODEON 12.10. Acoustic parameters were then calculated by varying acoustic parameters such as finishing material and location. The 3D model needed to be closed on all sides to prevent rays from escaping, and the modeling precision affects modeling results. Increasing the number of surfaces and rays increases the modeling precision [28]. In a scaled model, depending on the temperature and relative humidity, the air can absorb most of the high-frequency sound [29]. To account for this, the temperature and humidity in the present study were measured in real-time using a thermo-hygrometer (TESTO 605-H1, Testo SE & Co. KGaA, Titisee-Neustadt, Germany). To maintain the relative humidity at 15% and the temperature at 15 °C–20 °C, a moisture-removal filter (SMC IDG30V, SMC Corporation, Chiyoda, Japan) and an air-compressor (SWC S30-40-3, SEOWON COMPRESSOR CO., LTD., Yongin, Republic of Korea) were used to inject dry air into the scaled model. Acoustic performance was measured in one-third octave bands ranging from 800 to 40k Hz using acoustics measurement equipment and Dirac 5.0 analysis software. The average relative humidity was maintained at 50%, while the temperature was maintained at 26 °C, during the field acoustic measurement. In the unoccupied and off states of the HVAC systems, the background noise in the lower-grade classroom of Elementary School K was 29.6 dB(A). Furthermore, the room acoustics measurement equipment and Dirac 5.0 analysis software were used to measure the acoustic performance in the frequency range of 125–4k Hz. Figure 2 depicts the acoustic performance measurement method used for each experiment.

One sound source and four receiving points were assigned to the computer model. The sound source was placed at the front of the classroom, 1.5 m from the floor, to correspond to the height of the teacher's mouth. According to ISO 3382-1 Annex A.3.1, the source should be omnidirectional, but tests related to human conditions may use a source with a similar directivity to that of a human [30,31]. A directional speaker was used as the sound source to mimic the characteristics of human speech transmission. At 1 m, the sound pressure level was set to 72 dB. The value of the noise criterion (NC) was set to 30. The receiving points were evenly spaced throughout the classroom to capture the acoustic performance at a height of 1.0 m, corresponding to the ear height of seated elementary students. One sound source and four receiving points were included in the 1/10-scale model. A directional speaker was installed at the front of the classroom, 0.15 m above the floor. The sound source was a 1.26 s swept sine signal played through a directional speaker at a sound pressure level of 72 dB(A). At the four receiving points at a height of 0.10 m, the swept sine signal was picked up by 1/8-in microphones (B&K Type 4165, Brüel & Kjær, Nærum, Denmark), and the arithmetic mean of 15 measurements was taken to improve the accuracy. The locations and types of sound sources and receiving points were the same in each experiment. The sound source for the measurements was a directional speaker (HERCULES 2000W, APL Technology Corp., Atlanta, GA, USA) playing an ISO 3382-2 [31] maximum length sequence (MLS) signal with the sound pressure level set to 72 dB(A). The signals were measured using a sound-level meter (NTi XL2, Nti Audio, Schaan, Liechtenstein, B&K Type 2270, Brüel & Kjær, Nærum, Denmark) at four receiving points, and three measurements of 10 s each were arithmetically averaged for accuracy. Figure 3 shows the locations of the sound sources and receiving points in the experiments.



**Figure 2.** Measurement configuration: (a) computer modeling, (b) 1/10-scale model experiment, and (c) field acoustic measurement.



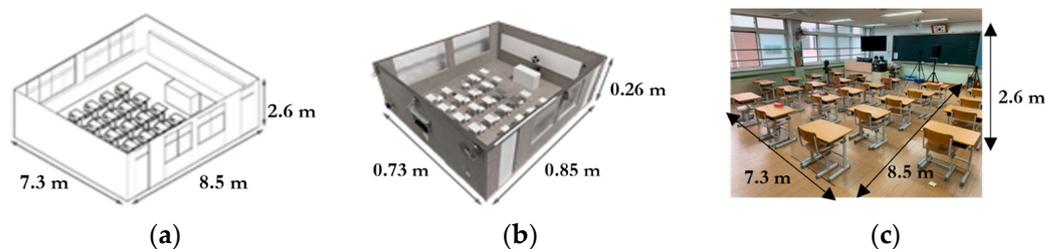
**Figure 3.** Locations of sound sources and receiving points in the experiments: (a) computer modeling, (b) 1/10-scale model experiment, and (c) field acoustic measurement.

### 3.2. Materials

#### 3.2.1. Classification of Classrooms

The geometry of the classroom considerably affects the reflection and diffusion of sound waves. Accordingly, the present study establishes a standard classroom, and special types of classrooms, such as creative convergence classrooms, are excluded from the study's scope. Although changes in teacher and student arrangements can improve speech intelligibility, changes in classroom layout (e.g., seating arrangement, furniture placement) do not directly affect the location of the sound-absorbing material.

Standardized classroom dimensions representing the architectural characteristics of elementary classrooms in Korea were calculated by averaging the architectural specifications of 10 classrooms in elementary schools in Cheongju [24]. The standardized classroom for computer modeling had dimensions of 7.3 (width)  $\times$  8.5 (length)  $\times$  2.6 m (height), corresponding to a width/length ratio of 1:1.16. This ratio created a 1/10-scale model measuring 0.73 (width)  $\times$  0.85 (length)  $\times$  0.26 m. Field measurements were performed in a classroom with dimensions of 7.3 (width)  $\times$  8.5 (length)  $\times$  2.6 m (height), resulting in a width/length ratio of 1:1.16. Figure 4 shows the dimensions of the classroom used in each experimental method.

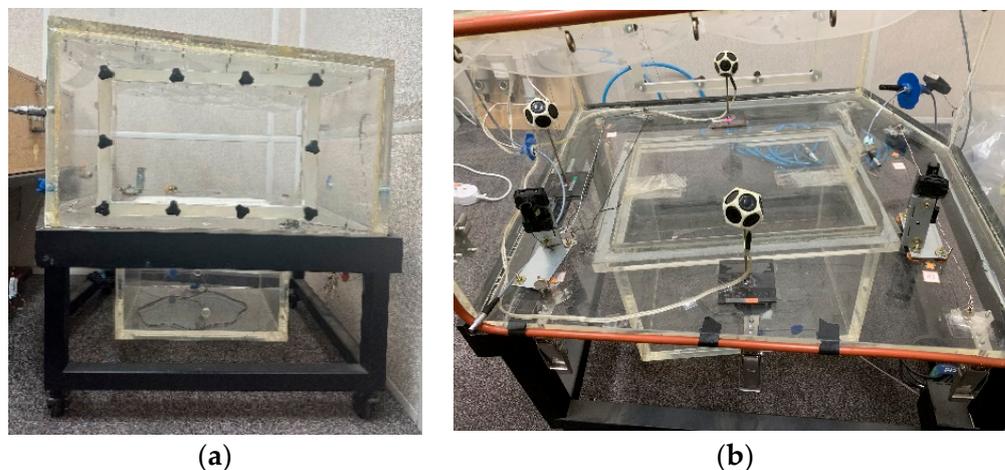


**Figure 4.** Dimensions of the standardized classroom used for (a) computer modeling, (b) the 1/10-scale model experiment, (c) and field acoustic measurements.

#### 3.2.2. Sound-Absorbing Coefficient of Materials

Because sound-absorbing materials are used as finishing materials in the classroom, there are only acoustic influences, and no psychological influences of students' or teachers' communication, concentration, and overall learning experience. The walls in a real classroom have different finishes on all four sides. The front wall is finished with painted concrete and has a blackboard; further, the exterior side walls have windows, while the side walls facing the corridor have windows and doors. Moreover, the rear wall (RW) has lockers. Therefore, the sound-absorbing material on the back wall was placed 1 m from the floor in the computer model. Furthermore, finishing materials similar to those used in a real classroom were used. Scaled model experiments should adhere to the law of similarity [32]. In the present study, the sound-absorbing coefficients of several materials in the 1/10-scale model were directly measured in a scaled reverberation chamber [33] using the interrupted-noise method and a type A installation method in one-third octave bands from 800 to 40k Hz, as shown in Figure 5. The arithmetic mean of 15 measurements was taken to improve measurement accuracy. High-voltage spark sources limit control, and impulse response sources are not properly represented in the scale model. Therefore, a 12-sided omnidirectional speaker, reduced to 1/10 size, was used to conduct an ISO 354 [33] experiment in the scaled reverberation chamber. The scaled omnidirectional speaker that was used was built by us, and methods for producing scaled omnidirectional speakers are detailed in B. Chojnacki's research results [34,35]. Furthermore, based on a study conducted by Baruch et al. [36], humidity was maintained at 10% because humidity absorption is high at high frequencies. The sound-absorbing coefficients of the finishing materials were determined for the field measurements based on the literature and empirical results provided by the manufacturers. The types of finishing materials and sound-absorbing coefficients used in the experiments are listed in Table 3. Using an appropriate sound-absorbing material is critical because its frequency-specific characteristics affect the indoor sound. Moreover,

different types of sound-absorbing materials have different sound-absorbing coefficients; hence, a considerable difference in what kind of sound-absorbing materials are used in a classroom is likely to exist. The present study, however, did not compare different types of sound-absorbing materials.



**Figure 5.** Scaled reverberation chamber for measuring the sound-absorbing coefficient of materials: (a) appearance of a scaled reverberation chamber; (b) experimental conditions.

**Table 3.** Finishing materials and noise reduction coefficients used in experiments.

Part	Computer Modeling		1/10-Scale Model Experiment		Field Acoustic Measurement	
	Material	NRC *	Material	10 × NRC **	Material	NRC *
Front wall	concrete	0.015	MDF panel	0.040	paint on concrete	0.015
Side wall	concrete	0.015	MDF panel	0.040	paint on concrete	0.015
Rear wall (absorptive)	polyester	0.480	polyester	0.490	10T polyester + 821 fabric	0.480
Ceiling (absorptive)	sound-absorbing tex	0.518	polyester	0.490	10T polyester + 821 fabric	0.480
Floor	linoleum tile	0.015	MDF panel 15	0.040	linoleum tile	0.015
Window	Glass	0.038	acrylic	0.070	glass	0.038
	metal frame	0.075	acrylic	0.070	metal frame	0.075
Door, blackboard, locker, desk, and chair	wood panel	0.085	extruded PVC foam sheet	0.070	wood panel	0.085

\* Noise reduction coefficient: average of the sound-absorbing coefficients at 250 Hz, 500 Hz, 1k Hz, and 2k Hz;

\*\* Noise reduction coefficient: average of the sound-absorbing coefficients at 2.5k Hz, 5k Hz, 10k Hz, and 20k Hz.

### 3.3. Application of Sound-Absorbing Material in Classrooms

When sound-absorbing materials are used in a classroom, the sound-absorbing power of the space increases, resulting in a decrease in the RT and an increase in speech intelligibility. To maintain the durability of the sound-absorbing materials, the sound-absorbing materials that are placed in a classroom should be semi-permanent and their long-term usability should be considered; for example, they should not be installed on the floor. Many studies have investigated the effect of the placement of sound-absorbing materials on classroom sound. Some fixed factors in the classroom can affect how the sound-absorbing material is arranged. Accordingly, the location of the blackboard and storage unit was considered in the present study.

Bradley [37] reported that the surfaces surrounding a speaker should reflect sound, and that the amount and location of a sound-absorbing material are important for effective speech transmission. T. Lokki and A. Kuusinen [38] reported that a sound-absorbing material should be placed close to the sound source to maximize clarity. Jeong et al. [39] addressed the requirement for a suitable reflective surface on the ceiling to enhance direct sound. Sala and Viljanen [13] suggested applying sound-absorbing material to the back wall and ceiling to improve acoustic performance. Ryu et al. [40] demonstrated that an appropriate RT could be achieved by sound-absorbing material covering only a portion of the ceiling. To avoid damage, Russo and Ruggiero [41] suggested that sound-absorbing material be evenly distributed over the surfaces of a classroom at an appropriate height from the floor. Park [42] found that adding a sound-absorbing material to the side walls can result in inter-aural-level differences, reducing speech intelligibility. According to Berg et al. [43], adding a sound-absorbing material or carpeting to classroom floors generally improves the acoustic performance by reducing distracting noises (e.g., books/pencils dropping and chair scraping). However, Seep et al. [44] and Knecht et al. [26] found that carpeting marginally affects sound absorption in classrooms, and is not used owing to its potential risks, such as difficulties maintaining its sound-absorbing performance and risks to student health.

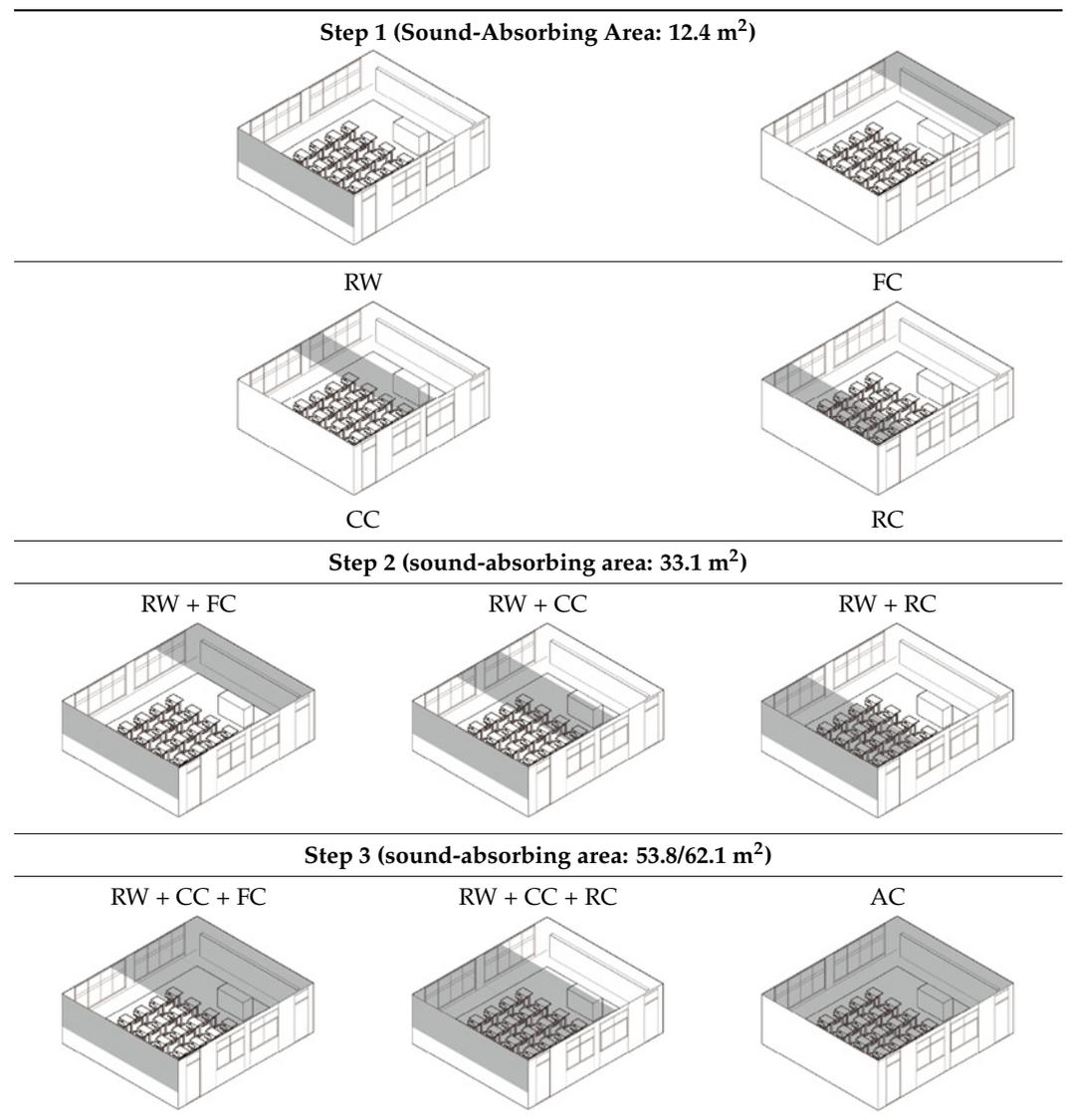
Based on the previous studies, the sound-absorbing material was not applied to the floor, front wall, or side walls of the classroom in the present study. Instead, only the RW and ceiling were considered as areas for the sound-absorbing material. Furthermore, the RW had a considerably smaller surface area than the ceiling. Therefore, the ceiling was divided into front, center, and back sections. Because of the reflection from the sidewalls, an even  $D_{50}$  distribution could not be obtained if the ceiling was divided lengthwise.

$$RT_{60} = \frac{0.161V}{A} \text{ (s)} \quad (4)$$

Based on the Sabine RT calculation formula shown in Equation (4), the required absorption area for the experimental space was determined to be 43.2 m<sup>2</sup>. Although this absorption area was not met, the primary goal was to demonstrate the difference in the acoustic performance when the sound-absorbing materials was applied to different placements with the same total area (see steps 1 and 2). The proposed placement method may be considerably simple for application in classrooms. Installing sound-absorbing materials in the front or center of a classroom ceiling can be challenging owing to practical issues, such as voice fatigue among teachers, and heating, ventilation, and air-conditioning (HVAC) systems. These cases, however, were critical for determining the difference in acoustic performance caused by the placement of sound-absorbing materials on the ceiling.

The sound-absorbing material was placed in a three-step procedure for all experiments, as shown in Table 4:

- The sound-absorbing material covering an area of 12.4 m<sup>2</sup> was applied individually to the rear wall (RW), front ceiling (FC), center ceiling (CC), and rear ceiling (RC), and the acoustic performances were compared.
- Based on the results of step 1, the sound-absorbing material was applied to the RW, and sound-absorbing material covering 20.7 m<sup>2</sup> was individually applied to the FC, CC, and RC for a total area of 33.1 m<sup>2</sup>. RW + FC, RW + CC, and RW + RC's acoustic performances were compared.
- The sound-absorbing material was applied to the RW and CC based on the results of step 2. Then, for a total area of 53.8 m<sup>2</sup>, sound-absorbing material covering an area of 20.7 m<sup>2</sup> was applied individually to the FC and RC. The acoustic performances of the RW + CC + FC, RW + CC + RC, and all parts of the ceiling (AC) were compared, with a total area of 62.1 m<sup>2</sup>.

**Table 4.** Experimental procedure for testing the acoustic performance of different sound-absorbing material configurations.

## 4. Results

### 4.1. Computer Modeling

The RT and  $D_{50}$  for various configurations were calculated by averaging the values measured at the four receiving points (R1–R4). In step 1, the shortest RT of 1.18 s and highest  $D_{50}$  of 51% were obtained at the RW. In step 2, the shortest RT of 0.75 s and highest  $D_{50}$  of 62% were obtained at the RW + CC. In step 3, the shortest RT of 0.55 s and highest  $D_{50}$  of 67% were obtained at the RW + CC + FC. In addition, for each step, values within the JND of the highest  $D_{50}$  were checked. The standard deviation for each receiving point was calculated using these values [27,45]. The smallest standard deviations (1%) were obtained for the RW in step 1, RW + CC in step 2, and RW + CC + FC in step 3. The standard deviation was calculated only from the location corresponding to the JND. The results of the computer modeling are shown in Figures 6 and 7.

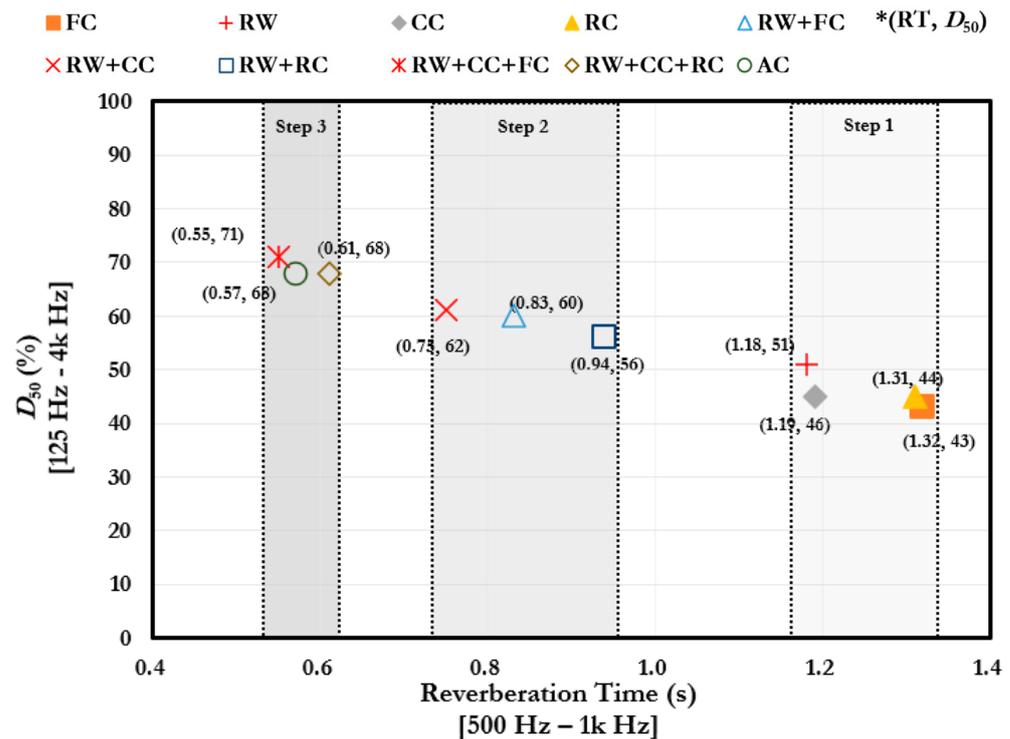


Figure 6.  $D_{50}$  and RT for each sound-absorbing material location in the computer modeling.

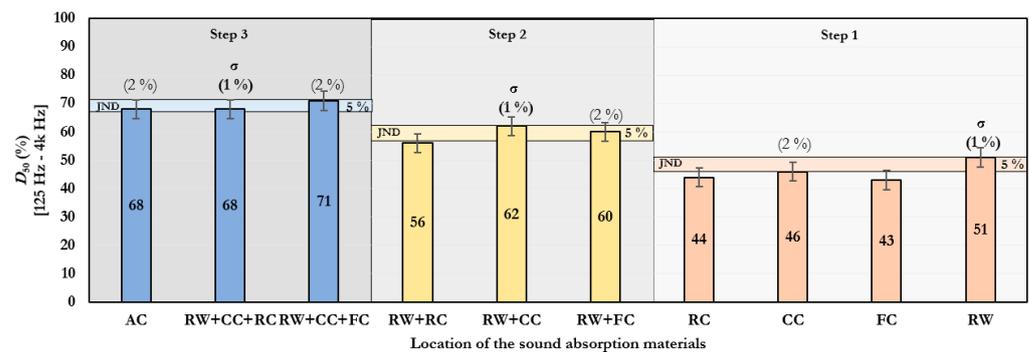


Figure 7.  $D_{50}$  for each sound-absorbing material location and the standard deviation among the receiving points within the JND in the computer modeling.

#### 4.2. 1/10-Scaled Model Experiment

The RT and  $D_{50}$  for various configurations were calculated by averaging the values measured at the four receiving points (R1–R4). In step 1, the shortest RT of 0.70 s and highest  $D_{50}$  of 46% were obtained at the RW. In step 2, the shortest RT of 0.60 s and highest  $D_{50}$  of 55% were obtained at the RW + CC. In step 3, the shortest RT of 0.52 s and highest  $D_{50}$  of 66% were obtained at the RW + CC + FC. Values within the highest JND of  $D_{50}$  were checked for each step, and these values were used to calculate the standard deviation for each sound-receiving point. The smallest standard deviations (1%) were obtained for the RW and RW + CC in step 1 and step 2, respectively. Step 3 was omitted because the standard deviation was calculated only where it corresponded to the JND. Figures 8 and 9 show the results of the 1/10-scale model.

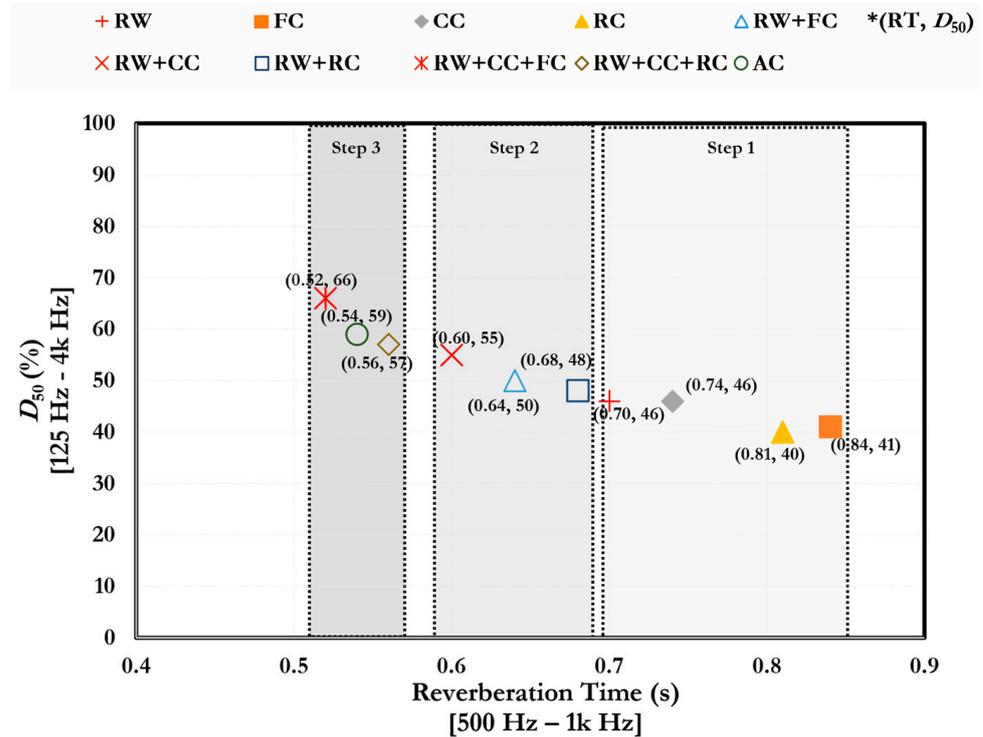


Figure 8.  $D_{50}$  and RT for each sound-absorbing material location in the 1/10-scale model.

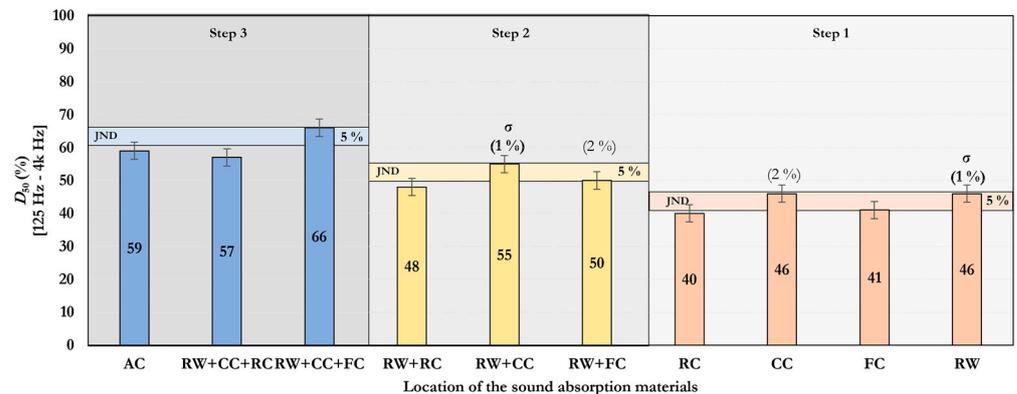


Figure 9.  $D_{50}$  for each sound-absorbing material location and the standard deviation among receiving points within the JND in the 1/10-scale model experiment.

### 4.3. Field Acoustic Measurement

The values measured at the four receiving points (R1–R4) were averaged to analyze the RT and  $D_{50}$  for various configurations. Unfortunately, owing to ceiling damage in the actual classroom, step 3 could not be completed. In step 1, the shortest RT of 0.81 s and highest  $D_{50}$  of 68% were obtained at the CC. In step 2, the shortest RT of 0.73 s was obtained at the RW + FC, while the highest  $D_{50}$  of 72% was obtained at the RW + CC. All measurements were within the JND range. Values within the highest JND of  $D_{50}$  were checked for each step, and these values were used to calculate the standard deviation for each receiving point. The smallest standard deviations (2%) were obtained for the RW and RW + CC in step 1 and step 2, respectively. Figures 10 and 11 depict the field measurement results.

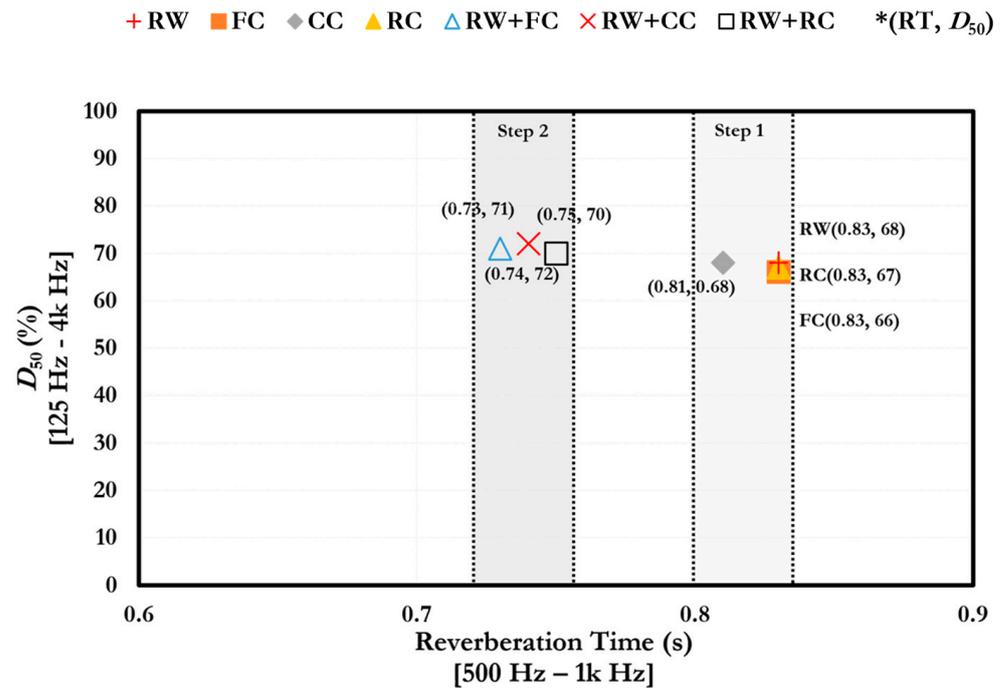


Figure 10.  $D_{50}$  and RT for each sound-absorbing material location in the field acoustic measurement.

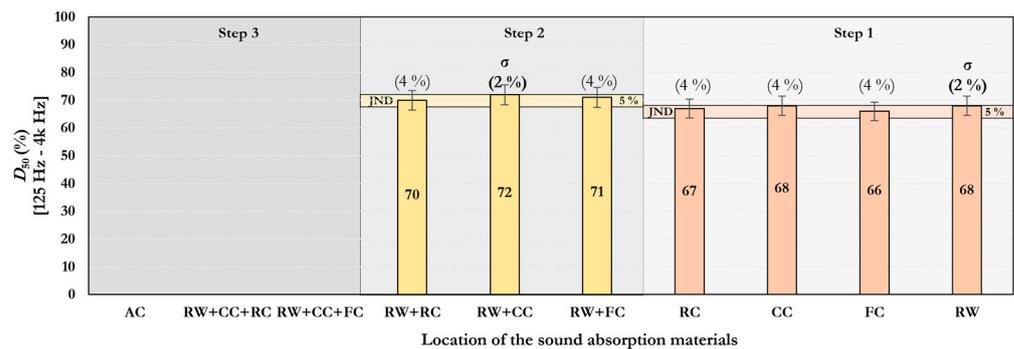


Figure 11.  $D_{50}$  for each sound-absorbing material location and the standard deviation among sound receiving points within the JND in the field acoustic measurement.

#### 4.4. Comparison among Three Experiments

For all experiments, the RW, RW + CC, and RW + CC + FC exhibited the lowest RT with a JND of 5%. Furthermore, for a JND of 5%, the RW, RW + CC, and RW + CC + FC exhibited the highest  $D_{50}$ . Figure 12 presents a comparison of the RT and  $D_{50}$  values, which indicates that the shortest RT and highest  $D_{50}$  with the most even distribution was obtained with RW, RW + CC, and RW + CC + FC in step 1, step 2, and step 3, respectively. Figure 13 presents a comparison of the RT and  $D_{50}$  values obtained from three experimental methods. The three experimental methods showed similar trends but differed in the actual values, which were attributed to unavoidable issues with diffraction and low-frequency calculations in the computer modeling and high-frequency sound absorption in the 1/10-scale model. Although Bistafa and Bradley [14] found that the difference between computer modeling and measurements is greater when the space has less sound absorption, this difference decreases significantly as the level of sound absorption increases. The similarity of the trends among the experimental methods was statistically validated using the Spearman correlation coefficient, which yielded  $p$ -values of less than 0.05 for all experimental methods. Consequently, because the correlation was significant at the 95% confidence level, the results of each experimental method were concluded to exhibit the same trend. The correlations for each experimental method are shown in Table 5. These findings are consistent with

those of Sala and Viljanen, as well as Ryu et al. [13,40], who concluded that applying a sound-absorbing material to the rear wall and a portion of the ceiling is effective. However, different results were obtained, due to differences in the research goals, from Lokki and Kusinen’s [38] research findings, which suggested that the absorption surface should be placed close to the sound source to maximize clarity. To achieve a rapid speech transmission index of 0.75, they suggested covering 30% of the total area with a sound-absorbing material on the ceiling and back wall. However, by covering 20% of the total area with the RW + CC configuration, the Korean standard of RT 0.6 s was met. The amount of sound-absorbing material required will vary depending on the acoustic standards of each country.

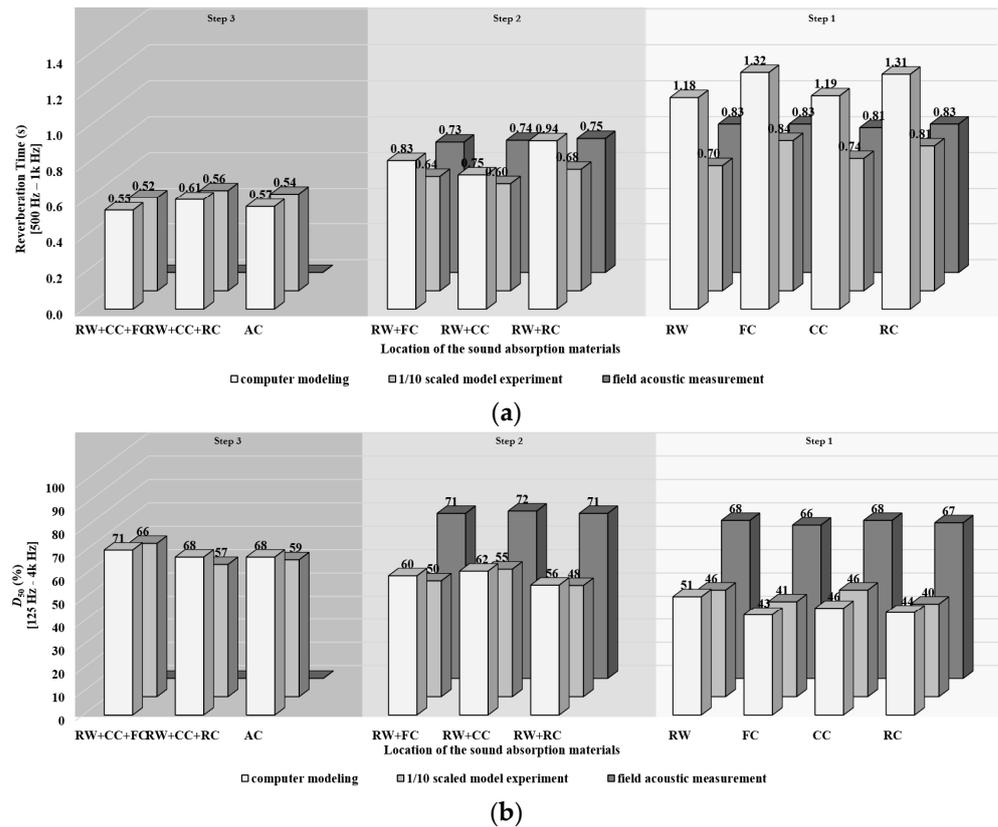


Figure 12. Comparison of (a) RT and (b)  $D_{50}$  for different steps.

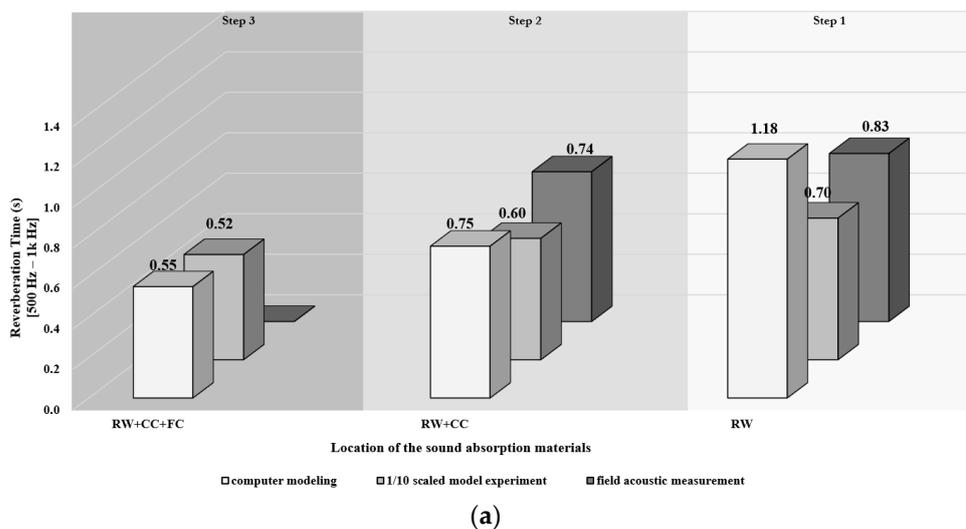


Figure 13. Cont.

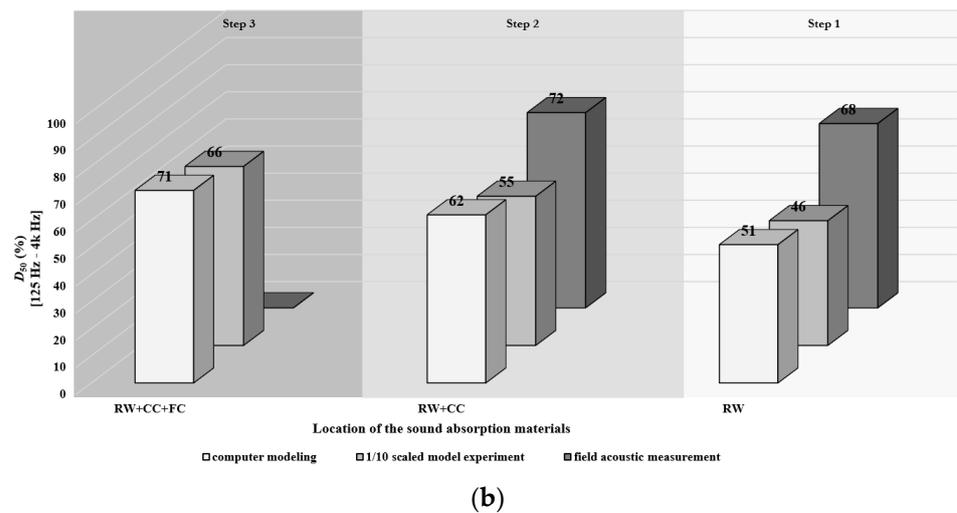


Figure 13. Comparison of (a) RT and (b)  $D_{50}$  according to the optimal location in experimental method.

Table 5. Spearman correlation coefficient analysis of RT and  $D_{50}$  for each experimental method.

Experiment Methods	Parameters	Computer Modeling	1/10-Scale Model Experiment	Field Acoustic Measurement
Computer modeling	RT	-	1.000 **	0.852 *
	$D_{50}$	-	0.982 **	0.982 **
1/10-scale model	RT	1.000 **	-	0.852 *
	$D_{50}$	0.982 **	-	0.954 **
Field measurement	RT	0.852 *	0.852 *	-
	$D_{50}$	0.982 **	0.954 **	-

\*  $p < 0.05$ , \*\*  $p < 0.001$ .

#### 4.4.1. Reverberation Time

Elementary classrooms in Korea should have an RT of  $<0.6$  s [2]. Table 6 shows the configurations that produced RTs of  $\leq 0.6$  s. The 1/10-scale model yielded a shorter RT than the other experimental methods. RW + CC produced an RT of  $\leq 0.6$  s in step 2. Step 3 yielded a suitable RT for all three configurations, implying that a sufficient area of the elementary classroom must be covered with a sound-absorbing material to achieve the required acoustic performance. However, the RT may differ among classrooms. Therefore, the acoustic performance of existing classrooms should be investigated, and a sound-absorbing material should be gradually applied until the appropriate RT is achieved.

Table 6. Comparison of RT among configurations and experimental methods.

	Computer Modeling	1/10-Scale Model Experiment	Field Acoustic Measurement
RW (7% of total area)	1.18 s	0.70 s	0.83 s
RW + CC (20% of total area)	0.75 s	0.60 s	0.74 s
RW + CC + FC (32% of total area)	0.55 s	0.52 s	-

#### 4.4.2. $D_{50}$

A  $D_{50}$  of  $>50\%$  is required for speech intelligibility at all frequencies [46–48]. Table 7 shows that the measured values of  $D_{50}$  are greater than 50%. The  $D_{50}$  for the field measurement was higher than for the other experimental methods. The  $D_{50}$  standard was met

at the RW in step 1. The  $D_{50}$  standard was also met in step 3 at the RW + CC. The field measurement results were not available in step 3, but the other two experimental methods indicated that the RW + CC + FC produced a  $D_{50}$  of ~70%, which would ensure a high level of speech intelligibility.

**Table 7.** Comparison of  $D_{50}$  among configurations and experimental methods.

	Computer Modeling	1/10-Scale Model Experiment	Field Acoustic Measurement
RW (7% of total area)	51%	46%	68%
RW + CC (20% of total area)	61%	55%	72%
RW + CC + FC (32% of total area)	71%	66%	-

## 5. Discussion and Conclusions

The appropriate locations for sound-absorbing material inside an elementary classroom were determined in the present study to achieve an even  $D_{50}$  distribution while meeting the RT standard. Three different experimental methods were used to measure and compare the RT and  $D_{50}$  results for various configurations (Table 4). A summary of the findings is presented as follows:

- The RW produced the shortest RT and the highest and most even  $D_{50}$  in step 1, while the RW + CC produced the shortest RT and the highest and most even  $D_{50}$  in step 2. Further, the RW + CC + FC produced the shortest RT and highest  $D_{50}$  in step 3, despite using less sound-absorbing material than the AC. Thus, the RW + CC + FC is more economical and acoustically sound than the AC, despite the latter's widespread use in Korean classrooms.
- The RW + CC + FC met the RT standard of <0.6 s suggested for elementary classrooms. Furthermore, the RW + CC met the requirement of  $D_{50} > 50\%$ . The best configuration to ensure a high-quality acoustic environment for learning in a classroom appears to be RW + CC + FC.
- Even when side walls are excluded from the interaural level difference, the uniformity of  $D_{50}$  can vary depending on where the sound-absorbing materials are located within an area. The back walls of many Korean elementary school classrooms are frequently used as bulletin boards, but this should be improved to block late-reflected sound in small spaces like classrooms.
- In comparison to an RT of 0.6 s, speech intelligibility for  $D_{50}$  can be achieved with a smaller area of sound-absorbing materials. However, sufficient intelligibility values can be obtained if an RT of 0.6 s is achieved in Korean elementary school classrooms by strategically placing sound-absorbing materials.
- The current study examined the best location for sound-absorbing materials in Korean elementary school classrooms based on  $D_{50}$  and RT, the two important parameters in evaluating classroom acoustics. The findings reveal that the  $D_{50}$  can vary depending on the sound-absorbing materials' locations. This can lead to improved teacher–student communication and an increase in satisfaction with the overall educational experience. However, several limitations should be mentioned. First, step 3 could not be performed in the field acoustic measurement due to damage to the classroom ceiling. Although this value can be predicted using scientific statistical methods, comparing it to actual experimental data would be inappropriate. Hence, it was regarded as a missing value in the present study. Furthermore, numerical simulations and scale modeling are suitable for acoustic design. Obtaining a full-scale object to derive some design principles is unnecessary. Second, the location of the sound-absorbing materials was only investigated with a small group of students, excluding teachers,

and assuming that the classroom was mostly empty. When researching classroom acoustics, future researchers must consider the occupied/unoccupied states of classrooms and teacher fatigue. Finally, the present study compared the level of acoustic performance by dividing the ceiling into three equal parts based on the area of the rear wall. However, this method may have limitations in other classrooms due to factors such as HVAC systems and lighting. Overall, the findings of the present study and those of future studies based on these limitations can hopefully be used as guidelines for the development of national standards for classroom acoustic environments.

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