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ORIGINAL RESEARCH PAPER

An approach to estimating sound absorption increment via equivalent substitution

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ABSTRACT

Excessive reverberation time in classrooms can impair speech intelligibility, reduce lecture quality, and hinder students' listening efficiency. Implementing precise and scientifically rigorous acoustic modifications is crucial for these classrooms. Calculations and simulations based on Sabine's equation or acoustic modeling software require precise absorption coefficients of the finishing materials, making it challenging to determine the required sound absorption increment. This paper proposes a method of equivalent substitution measurement: A non-destructive control group is established for acoustic experimentation, allowing for the precise calculation of the sound absorption increment required to achieve the target reverberation time. This approach provides scientific, rigorous, and customized reverberation time recommendations particularly for complexly shaped spaces from small to medium size to optimize the acoustic environment.

KEYWORDS

equivalent substitution measurement, reverberation control, sound absorption increment, classroom acoustics, Sabine's formula

1. INTRODUCTION

1.1. Research background

With the continuous development of modern architecture, Leadership in Energy and Environmental Design (LEED) [1], WELL Building Standard (WELL) [2], Assessment standard for green building, GB/T 50378:2019 [3], and other standards advocating the concept of green, healthy, and sustainable have been constantly introduced. Research [4] compares these three evaluation standards and finds that users are most dissatisfied with the acoustic aspect. The acoustic environment, as a medium of close contact between humans and buildings, demands increased attention and reassessment. Universities, as highly populated spaces with cyclical gatherings, have increasingly emphasized acoustic conditions in their building development strategies. Research in building acoustics has primarily focused on noise control, while acoustic renovations for older buildings [5] have largely remained at the sound insulation level. However, in educational spaces, the design and enhancement of indoor sound quality remain key research areas. Research [6] indicates that university students spend up to 71.5% of their school time listening and speaking in the classroom, and a good acoustic environment is crucial for students in the classroom. The findings of [7] highlight that reverberation time and speech intelligibility are the most important acoustic aspects of educational space. Poor speech intelligibility extremely reduces learning efficiency, while excessive reverberation time can lead to psychological issues, including depression and anxiety. A well-designed acoustic environment plays a pivotal role in learning efficiency, fostering interaction and communication, and promoting the psychological well-being and overall satisfaction of both students and staff.

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1.2. Acoustics and minimalism

Modern style buildings [8] remain the predominant architectural style in schools, playing an important role in shaping the contemporary trend of minimalism [9]. The concept of minimalistic design has been inherited by the new generation of architects in their design practices [10]. However, an excessive emphasis on simplicity, flat surfaces, and uniform finishing materials may lead to considerable acoustic deficiencies. The Faculty of Engineering and Information Technology, University of Pécs (FEIT UP), characterized by geometric architectural forms and a minimalistic interior design concept tailored for engineering education [11], faces particularly challenging acoustic conditions. A comprehensive review of 67 papers [12] indicates that excessive reverberation time affects students' learning efficiency and further demonstrates that poor speech intelligibility can lead to a decline in comprehension abilities [13].

In this paper, a study of acoustic environment satisfaction through questionnaires and interviews was conducted among students and teachers from FEIT UP: The result in paragraph 4.1 indicated that the majority of the students and part of the teachers believe that the teaching spaces in the faculty suffer from significant acoustic defects and hope that improvements can be made in the future to improve the quality of learning and teaching.

1.3. Traditional reverberation time measurements and disadvantages

Reference [14] explains that the acoustic environment of university classrooms is mostly evaluated in terms of reverberation time and speech intelligibility. In Nordic classrooms [15], standard reverberation times are typically classified into four levels, A, B, C, and D, according to the function of the space, with a comprehensive reverberation time range of 0.4 s to 0.8 s. The calculation of reverberation time is mostly based on Sabine's equation [16] and its modified formulas. For geometrically complex space, computer software: Odeon [17] and Ease [18] are usually used for acoustic simulation. However, these simulation methods must be based on obtaining the exact absorption coefficient of the original finishing materials before calculation, but the real conditions are often variable with missing or inaccurate information. As a result, acoustic design proposals frequently rely on estimations or experiential recommendations rather than precise calculations.

1.4. The equivalent substitution measurement

In this paper, the method of the Equivalent Substitution Measurement (ESM) is proposed for calculating the required sound absorption increment, effectively passing reliance on Sabine's equation and the absorption coefficients of room finishing materials. This approach provides more realistic results of the necessary usage of absorption for optimizing room reverberation, offering greater accuracy compared to theoretical calculations and computer simulations.

2. MATERIALS AND METHODS

The study of the acoustic environment in university classrooms is an interdisciplinary field that integrates architecture, physics (acoustics), engineering, psychology, humanities, and education. This paper uses a hybrid research approach, combining qualitative and quantitative analyses. The ESM is not limited to the educational acoustic environment at FEIT, UP but can also generally be applied to the precise determination of the required absorption increment for optimizing the reverberation time of small-to medium-sized rooms.

2.1. Sabine's equation and reverberation time

Sabine introduced the concept of reverberation and published the famous reverberation time formula: Sabine's equation [19] in 1922. Since then, various modifications to this foundational equation including Eyring's equation [20] have emerged. However, there is no doubt that Sabine's equation, represented by Eqs (1) and (2), remains the most fundamental and widely recognized formula for reverberation time calculation:

$$T_{60} = \frac{0.161V}{A} = \frac{0.161V}{S\overline{\alpha}}, \tag{1}$$

$$A = S\overline{\alpha} = S\cdot\frac{\sum_{i=1}^{n} S_i\alpha_i}{\sum_{i=1}^{n} S_i} = S\cdot\frac{S_1\alpha_1 + S_2\alpha_2 + S_3\alpha_3 + \ldots + S_n\alpha_n}{S_1 + S_2 + S_3 + \ldots + S_n}, \tag{2}$$

where T_{60} (s) is the time in seconds required for a sound to decay 60 dB; V (m^3) is the volume of the room; A is the total room absorption; S (m^2) is the boundary surface area; $\overline{\alpha}$ is the average absorption coefficient of the room.

The uncertainty of Sabine's equation: for university educational spaces, the room volume V (m^3) and surface area S (m^2) can be accurately measured. However, the sound absorption coefficients α of all finishing layers cannot be precisely obtained. Due to the uncertainty of α, the calculated results would be significantly different from actual conditions. If the reliance of uncertain sound absorption coefficients α can be eliminated in the calculation process, the reverberation time and the required sound absorption increment can be calculated with greater accuracy.

2.2. Theory of equivalence substitution measurement

The theoretical derivation of the ESM will be conducted by the rooms and conditions as following steps outlined below.

At a room temperature of 20 °C, the volume of the room V (m^3), the surface area S (m^2), and the original reverberation time of the room, $T_{60origin}$, can be measured by an instrument. According to [16], the room parameters and the reverberation time $T60_{origin}$ are represented by Eq. (3). The original room absorption A_{origin}, is given by Eq. (4):

$$T_{60origin} = \frac{0.161V}{A_{origin}}, \tag{3}$$

$$A_{origin} = S\frac{\sum_{i=1}^{n} S_i\alpha_i}{\sum_{i=1}^{n} S_i} = S\overline{\alpha}. \tag{4}$$

By manipulating the equation, the overall average sound absorption coefficient $\overline{\alpha}$ of the original room can be calculated, as it is shown in Eq. (5):

$$\overline{\alpha} = \frac{0.161V}{T_{60origin} \cdot S}. \tag{5}$$

Control group for the ESM method: A sound-absorbing material x which can be conveniently mounted on the walls or ceiling is used as the "equivalent substitution" with the absorption coefficient of α_x. This material is gradually installed on the classroom walls, with sequential reverberation time measurements taken after each installation. The process continues until the room's reverberation time, Eq. (6), falls below the target. At this point, the area of the material used is recorded as S_x (m^2). The target absorption of the room can be determined as Eq. (7):

$$T_{60control\ group} = \frac{0.161V}{A_{control\ group}}, \tag{6}$$

$$A_{control\ group} = (S - S_x)\overline{\alpha} + S_x\alpha_x = S\overline{\alpha} - S_x\overline{\alpha} + S_x\alpha_x. \tag{7}$$

Sound absorption increment equation: The increment of sound absorption (ΔA) required to achieve the target reverberation time, can be calculated as Eq. (8):

$$\begin{aligned}\Delta A &= \text{Eq. (7)} - \text{Eq. (4)} = S\overline{\alpha} - S_x\overline{\alpha} + S_x\alpha_x - S\overline{\alpha} \\ &= -S_x\overline{\alpha} + S_x\alpha_x.\end{aligned} \tag{8}$$

Sound Absorber increment equation: If the sound-absorbing material specified by designers has an average absorption coefficient of $\alpha_{product}$, the required area ($S_{product}$) of the product to achieve the target reverberation time in the room can be determined as it is shown in Eq. (9):

$$S_{product} = \frac{-S_x\overline{\alpha} + S_x\alpha_x}{\alpha_{product}} = \frac{\Delta A}{\alpha_{product}}. \tag{9}$$

Extension of the sound absorber increment equation: If n types of sound-absorbing products are specified by the designers, with corresponding absorption coefficients $\alpha_1, \alpha_2 \ldots\ldots \alpha_n$. The area of these materials, $S_1, S_2 \ldots\ldots S_n$ (m^2), satisfies the Eq. (10):

$$\Delta A = -S_x\overline{\alpha} + S_x\alpha_x = \sum_{i=1}^{n} S_i\alpha_i = S_1\alpha_1 + S_2\alpha_2 + \ldots + S_n\alpha_n. \tag{10}$$

3. EXPERIMENT AT FEIT UP

3.1. Selection of appropriate experimental subjects

To enhance the feasibility of the experiment and the generalizability of the results in the educational buildings, it is very important to select the experimental subjects appropriately. In this paper, the selection is usually carried out according to the following steps:

- Conduct objective statistical analysis on the size, type, number, frequency of use, content, and language of instruction of the classrooms commonly used in schools;
- Distribute questionnaires to assess how the end users: students, professors and lecturers evaluate the acoustic environment of the classrooms at FEIT UP, and to identify which type of classrooms are the most disturbing in terms of acoustic environment;
- Determine the performance limitations of the test equipment, the experimental budget, consumables, whether it affects others and other feasible factors to define the experimental subjects.

3.2. Determination of the target reverberation time

The acoustic environment of a classroom is typically categorized into four classifications: A, B, C and D based on the function, size, and acoustic characteristics of the room. The reverberation time has a range between 0.4 and 0.8 s. To prevent the formation of frighteningly silent spaces by overusing acoustic materials, and from the perspective of budget, cost, mental health, and sustainability, it is essential to determine the desired reverberation time prior to conducting an experiment.

Acoustic consultants and designers do not always perfectly align with practical conditions. However, the calculation of acoustic material usage ultimately informs and advises the design, establishing an upper limit of the appropriate reverberation time of the room is the best way for suggesting designer from the acoustic aspects. The final recommendation would be: the application of a specific sound-absorbing material in the room should not be less than the calculated area.

3.3. Room physical information measurement

According to the survey and questionnaire result in paragraph 4, the experiment subject will be based on classroom A215 at FEIT UP. As essential data and conditions for calculating the experimental results, various information about the classroom must be collected prior to conducting the acoustic experiments. The experiment subject will be based on:

- The dimensions of the room, including its length, width, and height, were accurately measured using a laser meter and a tape measure. The size and location of windows, beams and columns were also measured;
- Room finishing material types: determine the material properties of the walls, floors, ceilings, and special components of the room based on field observations or construction drawings;
- Room temperature: Sabine's equation is usually calculated using 20 °C as the ambient temperature, but if the temperature of the test room is much lower or higher than

20 °C, then according to [19], the constant K of the equation needs to be modified based on the speed of sound corresponding to the temperature of the room ($K = 0.161$ at 20 °C):

$$K = \frac{24 \cdot \ln 10}{C_{room}}, \tag{11}$$

where C_{room} is the speed of the sound in the room and $K = 0.161$ (s m^{-1}) at the room temperature of 20 °C. Based on the measured data, room model should be performed. The detail drawings with surface area (m^2) and volume (m^3) of the space can be calculated and finalized. These values will facilitate subsequent testing, calculations, and the development of acoustic proposals.

3.4. Acoustic measurement

Test platform construction (Fig. 1): This study utilizes the "XL2 Measurement Kit" (Model Identification Numbers: A2A-18509-E0, M2230: 9469) from the manufacturer of "NTi Audio" as the test platform to measure the Reverberation Time (RT60) and speech intelligibility Speech Transmission Index (STI) in the experimental room. In this study, speech intelligibility is assessed by reproducing the test signal called Speech Transmission Index for Public Address (STIPA) systems and measuring the quality of that signal as it reaches each of the measurement positions.

The temperature and humidity conditions during the tests were recorded by a thermo-hydrometer from the manufacturer of DYWSJ. The microphone and sound level meter were calibrated to a standard value of 94.1 dB using the 4,230 Sound Level Calibrator from the manufacturer of Bruel and Kjaer.

Placement of test platform components: Since the function of the classroom is mainly teaching, the test platform must be configured closely to the actual lecture environment. The speaker needs to simulate the sound source of lecturers or professors as accurately as possible. In this study, the speaker is placed 1 m away from the blackboard, centered horizontally, and set at a height of 1.8 m. The microphone placement is designed to represent the listening positions of students. Three positions (A, B, and C) are designated to represent students sitting in the front, middle, and back rows. The microphone height is uniformly set at 1.2 m, centered horizontally. The three test positions are located at distances of 1.7 m, 3.8 m, and 5 m from the back wall (Figs 2 and 3).

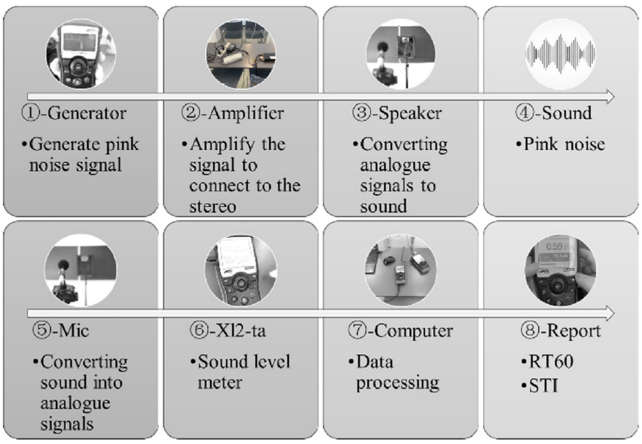

Fig. 1. Test principle and equipment platform construction flow chart (*Source*: photos and drawings by the Authors)

Original room acoustic environment test (Fig. 4): After calibrating and debugging the equipment, the acoustic environment testing of classroom A215 at FEIT UP is formally initiated. The measurement is divided into room RT60 and STI. To enhance the reliability of the experiments, two sets of ten tests are conducted for reverberation time and speech intelligibility in the positions of A, B, and C.

Mid-frequency reverberation time (500–1,000 Hz): According to the international standard ISO 3382-2:2008 [21] and American standard ANSI/ASA S12.60/Part1:2010 = R2020) [22], T_{mf} is the reverberation time of

Fig. 2. Position of speaker and microphone (*Source*: photo by the Authors)

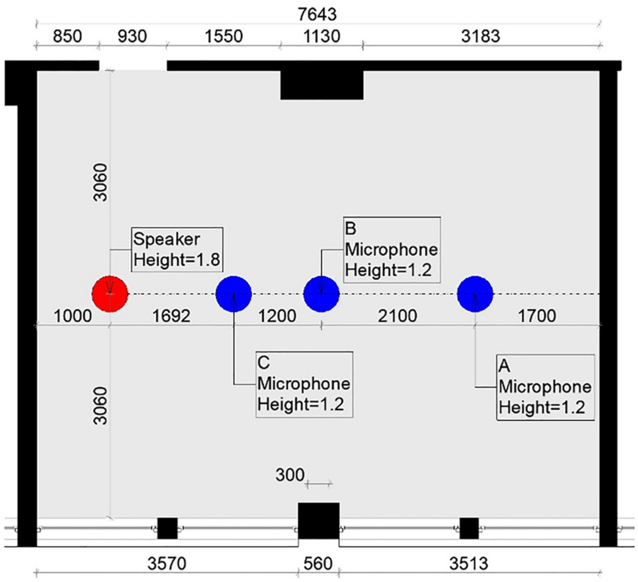

Fig. 3. Testing position, A, B and C (*Source*: Authors' drawings)

Fig. 4. Original form of A215 (*Source*: photo by the Authors)

the frequency range where the human ear is most sensitive and where normal speech typically occurs in classrooms. In this study, all the reverberation time (RT60 results are produced and calculated based on mid-frequency reverberation time: T_{mf}.

Calculate the average sound absorption coefficient: By obtaining the volume V (m^3), surface area S (m^2), and original reverberation time $T_{60origin}$ of the classroom are obtained, and the average sound absorption coefficient of the room $\overline{\alpha}$, can be calculated by the Eq. (5).

3.5. Setup for non-destructive control group

The construction of a non-destructive experimental control group is one of the most critical steps of the ESM method. The success of the experiment largely depends on selecting a sound absorber that is portable, environmentally friendly, cost-effective, and offers moderate sound absorption performance.

In the experiment, acoustic curtains were suspended evenly using hooks on the interior finishes to achieve a more homogeneous acoustic performance throughout the room. As it is shown in Fig. 5, the locations of the substitute acoustic were distributed across the left window, the right wall, and the blackboard side of the classroom.

Fig. 5. The control group (*Source:* photo by the Authors)

In this study, the acoustic curtains were used as an equivalent substitution to build a control group. The absorption coefficient of the acoustic curtain is 0.52 and its dimension is around 1.3 × 1.8 m per piece. According to paragraph 3.2, the upper limit of the target room reverberation time for this experiment was set to $T_{60tagret} = 0.8$ s.

The experiment involved gradually increasing the number of acoustic curtains installed and testing the reverberation time until the target reverberation time was reached. The number of curtains used was recorded. Additionally, the speech intelligibility of the room was assessed, and the STI was obtained.

3.6. Acoustic design proposals

According to the sound absorber increment Eq. (9) and its extension Eq. (10), the minimum required usage (m^2) of single or multiple acoustic products selected by designers can be precisely calculated. These recommendations offer significant support to designers in enhancing room acoustic performance for building renovation projects.

4. RESULTS AND DISCUSSION

4.1. Research subject and the target

The experimental subject: Classroom A215 at FEIT UP, serves as a representative example of small teaching spaces within the institution. Many of the smaller classrooms share similar dimensions and layout with A215. As one of the most frequently used classrooms, A215 hosts a variety of courses, including those in architecture, civil engineering, and computer science. Additionally, the classroom accommodates instruction in multiple languages, including Hungarian, English, and German. This diversity in usage further highlights the importance of optimizing the acoustic environment in A215, ensuring it meets the needs of both instructors and students across different disciplines and languages. This experiment did not consider larger classrooms (e.g., A007) having a capacity of 200 students. The decision was driven by practical considerations, including budget limitations, the availability of experimental materials, and the number of participants involved in the experiment.

Acoustic survey of A215: To evaluate the acoustic environment of classroom A215 at FEIT UP, a total of 50 questionnaires were distributed with a method of "filling and explaining" to get direct feedback from the end users of the room. The participants included 10 teachers and 40 students, all of whom regularly use classroom A215 for academic activities. The results indicate that only 22% of participants found the classroom conducive to efficient learning or work, and 10% thought they could hear lectures clearly. Noise disturbances were a significant issue, with 74% of participants hearing noise from ventilation and mechanical devices, and 36% hearing sounds from the corridor outside. Echo-related issues were the fundamental factors: as 92% of respondents reported being disturbed by echoes, and 74% considered the reverberation excessive. For the comparison in and out of the room: 92% of participants felt a sense of relief from ear discomfort after leaving the classroom. Rating of the experience: participants reported an average of 2.5 out of 5 (standard deviation 0.6), indicating the medium possibility of maintaining concentration. The study and working experiences were rated 2.8 points (standard deviation 0.6), and the acoustic clarity of the room received the lowest score at 2.0 points (standard deviation 0.4), reflecting poor satisfaction with sound quality. Ear stress after lectures was rated 3.2 points (standard deviation 0.6). Furthermore, the necessity for improving the acoustic environment received the highest rating of 4.7 points (standard deviation 0.5), showing strong agreement among participants about the need for acoustic improvements. In conclusion, classroom A215 has acoustic environment issues from users' side, and it is suitable to be the research subject.

Determination of target RT60: According to the function outlined in [13] and the study conducted in [15], classroom A215 is classified as category D, with the target upper limit for reverberation time set at 0.8 seconds.

4.2. Measurement of the room's physical characteristics

Figure 6 shows the drawing of classroom A215 at FEIT UP, based on the on-site measurements. The calculations reveal that the floor area of the classroom is $A = 46.5\ \text{m}^2$, the total surface area is $S = 182.9\ \text{m}^2$, the total volume is $V = 136.4\ \text{m}^3$, and the temperature on the experiment day was 21 °C with 34% humidity.

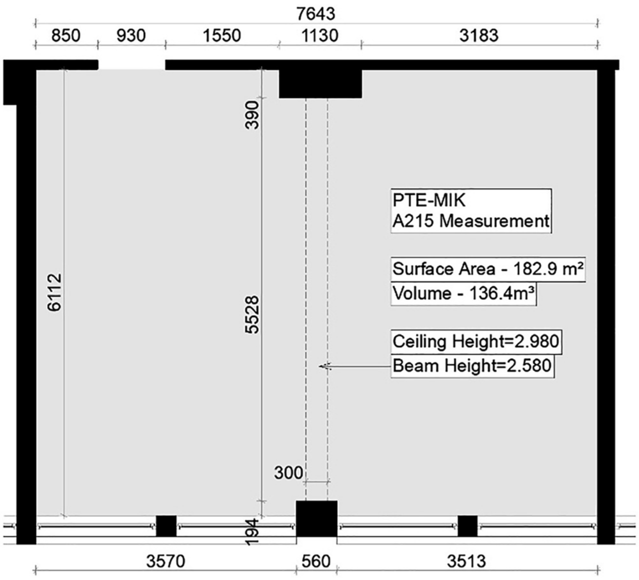

Fig. 6. Measurements of A215 (*Source*: Authors' drawings)

4.3. Acoustic measurements of the original room

Table 1 shows the measured reverberation time at the positions of A, B, and C; Fig. 7 shows the overall average reverberation time curve in octave band of the room. The calculated mid-frequency reverberation time is $T_{mf-origin} = 1.08$ s; According to the average sound absorption coefficient Eq. (5), the calculated average absorption coefficient of the original room is $\overline{\alpha} = 0.11$.

Table 2 shows the measured STI values and the noise condition reference (measured in LZeq) of the original room at the positions of A, B, and C. According to the standard evaluation system *IEC 60268-16:2020* [23], the average speech intelligibility of the classroom is between Fair and Good.

4.4. Acoustic measurements of the control group

The acoustic curtains with a sound absorption coefficient of $\alpha_x = 0.52$ were gradually installed until the mid-frequency reverberation time fell below 0.8 s. The total area of the installed curtains was $S_x = 19.04\ \text{m}^2$ (Table 3). shows the measured reverberation time values of the control group at the positions of A, B, and C (Fig. 8) shows the overall average reverberation time curve in octave band of the room. The calculated mid-frequency reverberation time is $T_{mf-controlgroup} = 0.78$ seconds.

4.5. Calculations and proposals

Calculation of sound absorption increment: According to Eq. (8), the increment of absorption can be calculated as $7.82\ \text{m}^2$.

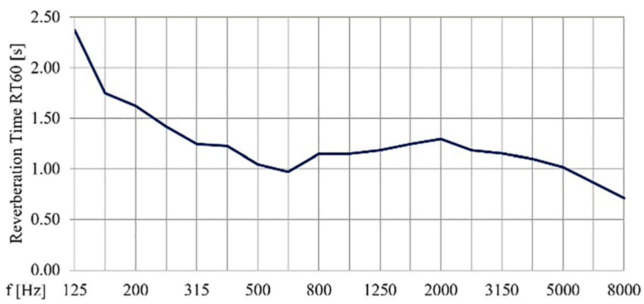

Fig. 7. Average reverberation time of the original room

Table 1. Reverberation time in octave band at positions A, B and C of the original room

Frequency (Hz)	125	250	500	1,000	2,000	4,000	8,000
				RT60			
Average	2.37	1.42	1.05	1.15	1.30	1.10	0.71
A	2.47	1.54	1.06	1.18	1.28	1.09	0.69
B	2.42	1.40	1.06	1.15	1.30	1.11	0.72
C	2.21	1.31	1.02	1.12	1.31	1.10	0.73

Table 2. STI and LZeq in octave band at positions A, B and C of the original room

	Frequency (Hz) STI	125	250	500	1,000	2,000	4,000	8,000
					LZeq in octave band			
Average	0.63	77.9	75.0	71.3	63.7	56.8	53.5	43.8
A	0.59	76.3	73.0	70.8	63.0	55.4	52.7	41.3
B	0.63	76.6	75.8	69.7	63.2	56.4	53.6	44.4
C	0.67	80.9	76.3	73.3	64.8	58.6	54.2	45.8

Table 3. Reverberation time in octave band of position A, B and C of the control group

Frequency (Hz)	125	250	500	1,000	2,000	4,000	8,000
				RT60			
Average	2.04	1.22	0.87	0.68	0.69	0.67	0.50
A	1.80	1.14	0.86	0.68	0.71	0.65	0.51
B	1.97	1.26	0.84	0.71	0.70	0.69	0.50
C	2.36	1.25	0.91	0.66	0.67	0.66	0.49

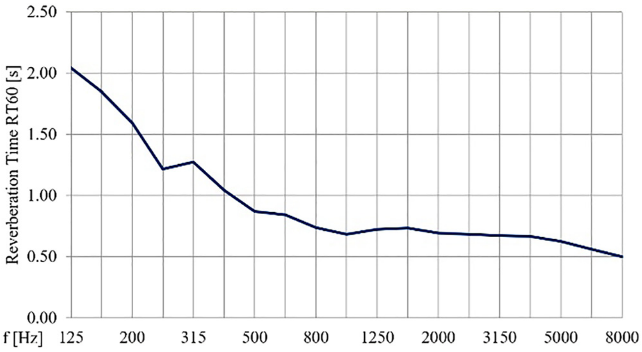

Fig. 8. Average reverberation time of the control group

Speech intelligibility: (Table 4) shows the STI values and the noise condition reference (LZeq of the control group at the positions of A, B and C. According to the standard evaluation system *IEC 60268-16:2020* [23], the average speech intelligibility of the classroom is between Good and Excellent. Compared to the original room, it is objectively demonstrated that the speech intelligibility of the control group has improved by one grade, which has a positive impact on the educational experience in classroom A215 at FEIT UP.

Market Product Proposals: The calculation results indicate that a minimum absorption increment of 7.82 m^2 is required to reduce the mid-frequency reverberation time of the classroom to below 0.8 seconds (the experimental actual value is 0.78 s). In this case, the classroom meets the acoustic requirements for Category D [12]. Based on common acoustic products in the market, the authors propose the following acoustic solution for the A215 classroom at FEIT UP. Based on the common acoustic products available in the market, the authors propose the following possible solutions for the classroom: Kvadrat acoustic's Alu Tracks wall-mounted acoustic panels (NRC 0.75) [24], requiring at least 10.43 m^2; Softcells acoustic panel (NRC 0.95) [24], requiring at least 8.23 m^2; Knauf's micro-perforated ceiling panels (NRC 0.5) [25], requiring at least 15.64 m^2; Gabriel's fabric-wrapped rock wool composite wall panels (NRC 0.8) [26], requiring at least 9.77 m^2

5. CONCLUSION

The classroom acoustic environment is closely linked with learning efficiency and the overall quality of education. Controlling reverberation time and enhancing speech intelligibility are key objectives in optimizing acoustic environment. Although theoretical calculations and computer simulations provide valuable insights, their practical application remains crucial. This study introduces the ESM method to precisely determine the required absorption increment. Experimental results show that the ESM method effectively identifies potential acoustic solution for classroom A215 at FEIT UP. In contrast to theoretical calculations or computer simulations, the ESM method is particularly suited for optimizing reverberation time in small to medium-sized complex shaped spaces. Additionally, it offers advantages in terms of accuracy, cost-effectiveness, and design prioritization.

Table 4. STIPA and LZeq of the control group in the octave band at positions A, B and C

	Frequency (Hz) STI	125	250	500	1,000	2,000	4,000	8,000
					LZeq in octave band			
Average	0.72	77.8	74.9	71.3	63.0	56.1	53.0	43.6
A	0.68	77.0	72.8	70.7	62.0	53.9	51.8	40.9
B	0.70	75.5	75.4	69.8	62.1	55.9	53.3	44.0
C	0.78	81.0	76.4	73.3	64.8	58.5	53.8	45.9

6. LIMITATIONS AND FUTURE DIRECTIONS

The ESM method introduced in this study is based on mid-frequency ranges for acoustic proposals in room acoustics. This method offers general applicability for most building spaces with common functions. However, for rooms that having specialized acoustic requirements (used in high or low frequencies), special consideration must be given to the equivalent substitution absorbers during the process of the ESM. The theory can be expanded to accommodate specific frequency bands, enabling accurate and tailored recommendations for suitable products and quantities for rooms with unconventional functions.

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