Indicative Assessment of Classroom Acoustics in Schools Built in Reinforced Concrete Technology on The Example of a School Building in Zabrze

Marcelina Olechowska¹, Artur Nowoświat¹, Michał Marchacz¹, Karolina Kupczyńska¹

¹ Silesian University of Technology, Faculty of Civil Engineering, Akademicka 5, 44-100 Gliwice, Poland
marcelina.olechowska@polsl.pl

Abstract. In view of room acoustics in schools, not only noise level is extremely important, but also the reverberation conditions in a given room. Such conditions affect the intelligibility of speech, which determines the acquisition level of knowledge conveyed by the teacher. The article presents problems of school classroom acoustics for a building made in reinforced concrete technology on the example of a school building in Zabrze. For the research, we selected one of schools established in 1970s as a memorial of the Millennium Jubilee of the Republic of Poland. The obtained results of the reverberation time indicate poor acoustic conditions, which, regrettably, is quite common in Polish schools. For low frequencies, the reverberation time of a classroom for teaching mathematics was over 2 seconds, and for medium frequencies it was almost 2 seconds. The article presents the acoustics of the studied classrooms without proposals of acoustic adaptation.

1. Introduction
The most important parameters influencing the perception of verbal sound in classrooms include reverberation time [1], [2] and Speech Transmission Index [3], [4]. The issue of reverberation time in classrooms was already described in 2000 by Bistafa and Bradley [5], who, using theoretical and numerical models, simulated reverberation conditions in school classrooms. In Poland, Leśna and Skrodzka [6] conducted research on the acoustic subjective feelings of students of various school age, and Mikulski Radosz [7] examined 110 school classrooms in five primary schools, indicating a large variety of reverberation conditions and speech intelligibility in those rooms. The common technology applied for the erection of educational buildings in Poland was the technology of traditional construction or traditional industrialized construction. As an example of reverberation research in such schools, we can refer to the results presented by Nowoświat and Olechowska [8].

A common group of school buildings in Poland are memorial schools commemorating the Millennium the Republic of Poland. Such buildings are currently being insulated or renovated. Therefore, the authors of the article selected one of such buildings to examine the acoustics of school classrooms. It is the first work of the research cycle being currently developed on the acoustics of school buildings with different construction technologies.
2. Methodology

2.1. Description of the building
The examined building was erected on the mining damage area of the 3rd category. The school consists of thirteen segments with a total cubature of 35,287.03 m$^3$. The view of the school from the street is presented in Figure 1.

![Photo on the left presents the view of the school (before thermo-modernization) from the street, and photo on the right shows the investigated maths classroom with equipment](image)

The ceilings between the storeys are made of hollow-core prefabricated slabs 120 cm or 150 cm wide, with a DZ3 ceiling above the basement. The flat roof is made of prefabricated hollow-core slabs. The walls and ceilings in the rooms are covered with cement-lime plaster. The walls of the rooms above ground level are covered with glue paint. In the classrooms, the floor is covered with rubber flooring. The acoustically assessed classroom has a volume of 154.75 m$^3$ and a total area of 190.86 m$^2$. There are 15 benches and 28 chairs inside. Each table top measures 1.4 × 0.55 m and is 2 cm thick. The seats measure 0.38 × 0.38 m and are 1 cm thick. The interior of the classroom with its equipment is presented in Fig. 1.

2.2. Measurement
The measurement of the reverberation time was performed using the intermittent noise method, as in other studies by Nowoświat et al. [9]. The method is based on controlling the drop in sound pressure in a room. The interior was excited with broadband noise shaped to ensure an approximately pink steady state reverberation spectrum for the range spanning the 1/3 octave bands with center frequencies of 50 - 5000 Hz. The noise generator produced a sound pressure level sufficient for the decay curve to start at least 35 dB above the background noise in an appropriate frequency range. The measurements were made with two different setups of the speaker column. Six measuring points were placed at a height of 1.2 m from the floor surface and at least 1 m from the wall surface, while the omnidirectional sound source at a height of 1.5 m. In order to obtain high accuracy of the results and to minimize the influence of randomness of the excitation signal, the measurement was repeated 6 times at each point.

3. Indicators and parameters of acoustic assessment of the interiors
Let us define three basic concepts of the acoustic assessment of interiors.

**Definition 1**
Reverberation – is referred to as the phenomenon of gradual loss of sound energy after turning off the source.

**Definition 2**
Reverberation time (T) - is referred to as the time measured from the moment the source has been turned off, after which the sound pressure level in the room decreases by 60 dB.

**Definition 3**
Speech Transmission Index (STI) - is a measure ranging from 0 to 1, representing the quality of speech transmission in terms of intelligibility through a speech transmission channel.
In the paper, reverberation time is determined by means of measurements, while the speech transmission index is determined through calculations. For the existing objects, there is no definite calculation method for the speech transmission index STI. The only method is to measure the relevant parameters. Many acousticians studying this issue try to develop equations that characterize the STI index in the most objective way. In this study, the STI was determined using the model published by Nowoświat and Olechowska [3]:

\[
\text{STI} = A \ln T + B \tag{1}
\]

where: \(A = -0.2078\), \(B = 0.6488\).

In the model (1), reverberation time is the average of the following frequencies: 500, 1000 and 2000 Hz.

**Assessment in terms of Optimal Reverberation Time**

One of the options for the assessment of classroom acoustics can be the application of optimal reverberation time \(T_{\text{opt}}\) calculated using the formula (2) [10]:

\[
T_{\text{opt}} = 0.32 \log V - 0.17 \tag{2}
\]

where: \(V\) is the volume of the room in the range from 30 to 1000 m\(^3\).

\(T_{\text{opt}}\) should meet the following conditions:

\[
0.65 \cdot T_{\text{opt}} < T < 1.2 \cdot T_{\text{opt}} \quad \text{for 125 and 4000 Hz bands}
\]

\[
0.8 \cdot T_{\text{opt}} < T < 1.2 \cdot T_{\text{opt}} \quad \text{for 250, 500, 1000 and 2000 Hz bands}
\]

**Assessment in terms of Global Index**

Both \(T_{\text{opt}}\) and STI are referenced to the measurement of reverberation time. A more detailed analysis of the acoustic quality of school classrooms can be obtained by means of the Global Index published by Radosz [11]. The global index method enables to comprehensively assess didactic rooms, because it takes into account several important factors that affect the acoustic quality. Based on the measured acoustic parameters, the value of the global index can be defined using the formula:

\[
QI_G = \frac{\sum_{i=1}^{n} QI_i \eta_i}{\sum_{i=1}^{n} \eta_i} = \frac{QI_{RT} \eta_{RT} + QI_{SI} \eta_{SI} + QI_{SE} \eta_{SE} + QI_{SD} \eta_{SD} + QI_{RN} \eta_{RN} + QI_{SNR} \eta_{SNR}}{\eta_{RT} + \eta_{SI} + \eta_{SE} + \eta_{SD} + \eta_{RN} + \eta_{SNR}} \tag{3}
\]

where: \(QI_i\) is the \(i\)-th partial index, \(\eta_i\) is the weight of the \(i\)-th partial index, and \(n\) is the total number of partial index.

The parameters used to determine the global index of acoustic quality of rooms and their weights are presented in Table 1.

The weights \(\eta_i\) applied in Table 1 were described by Radosz [11] and they have been adopted on the basis of the analysis of the factors affecting the acoustic quality of classrooms and based on the results of experimental tests conducted in selected rooms.
The global index has the value from 0 to 1. The higher the index value, the better the acoustic quality in the room. For the values from 0 to 0.5 it is bad quality, then to 0.75 it is poor, to 0.9 good and above 0.9 to 1 excellent.

The following subsections present the methods used to determine the partial indicators described in Table 1.

**Table 1. Indicators of partial indices and their weights**

| Parameter indicator - QI<sub>i</sub> | weight - η<sub>i</sub> |
|------------------------------------|------------------------|
| QI<sub>RT</sub> – reverberation index | η<sub>RT</sub> = 0.8 |
| QI<sub>SI</sub> – speech intelligibility index | η<sub>SI</sub> = 1.0 |
| QI<sub>SE</sub> – speech effort index | η<sub>SE</sub> = 0.3 |
| QI<sub>SD</sub> – sound strength distribution index | η<sub>SD</sub> = 0.5 |
| QI<sub>BN</sub> – background noise index | η<sub>BN</sub> = 1.0 |
| QI<sub>SNR</sub> – signal-to-noise ratio index | η<sub>SNR</sub> = 0.5 |

**Reverberation Index**

Reverberation time is one of the most important criteria for the assessment of acoustic quality of rooms. Reverberation is perceived as an extension of sound associated with the occurrence of waves reflected from the surface of the room. Reverberation occurs principally in large, empty rooms that reflect sound well, which is why it is a common problem in classrooms.

The reverberation index QI<sub>RT</sub> can be calculated using the formula (4) [11]:

\[ QI_{RT} = -0.48(T_{2kHz})^4 + 2.55(T_{2kHz})^3 - 4.77(T_{2kHz})^2 + 3.13(T_{2kHz}) + 0.34 \]  

where: \( T_{2kHz} \) is the reverberation time for the frequency of 2kHz.

**Speech intelligibility index**

Based on the research by Bradley [12], the formula [10] was determined:

\[ QI_{SI} = -0.55 \cdot STI + 0.44 \cdot CI \]  

where: STI is speech transmission index.

CI is an auxiliary index that is calculated by formula [11], modified in such a way that instead of clarity C<sub>50</sub> the definition D<sub>50</sub> is in the formula:

\[ CI = 0.00616 \left( D_{50} \right)^2 + 0.0615 \left( D_{50} \right) + 0.85 \]  

with D<sub>50</sub> adopted as in [13], [14]:

\[ D_{50} = 1 - e^{-\frac{0.69}{T}} \]  

**Speech effort index**

Speech sound pressure level is an inert parameter that defines speech. Normal sound is equivalent to the level of weighted sound pressure, which is 60 dB at a distance of 1 meter from the sound source. Speech effort index can be calculated from the formula [11]:
where: $L_{Aeq,1m}$ is the numerical value of the sound pressure level $A$ of the teacher's voice at a distance of 1 m. $L_{Aeq,1m}$ takes the following values:
- 78 dB - very loud speech,
- 72 dB - loud speech,
- 66 dB - raised voice,
- 60 dB - normal speech.

To estimate the value of speech effort index, the following scale of speech effort in terms of reverberation time was adopted:
- normal speech - if the room meets the standard specific conditions for reverberation time,
- raised voice - reverberation time values are exceeded by a maximum of 20%,
- loud speech - reverberation time values are exceeded by 20% to 65%,
- very loud speech - reverberation time values are exceeded by more than 65%.

**Sound strength distribution index**

With respect to $QI_{SD}$, the frequency bands of 1 kHz, 2 kHz and 4 kHz are examined, and this relation is expressed by the formula [11]:

$$QI_{SD} = 0.296 \cdot QI_{SD,1kHz} + 0.37 \cdot QI_{SD,2kHz} + 0.333 \cdot QI_{SD,4kHz}$$  \hspace{1cm} (9)

The values of $QI_{SD}$ for a given frequency can be calculated by the formula:

$$QI_{SD,f} = -0.08 \cdot (\Delta G_{rel,f}) + 1$$  \hspace{1cm} (10)

where: $\Delta G_{rel,f}$ is the numerical value of the difference between extreme values of the relative sound strength $\Delta G_{rel}$ for the frequency band $f$. The value of $\Delta G_{rel}$ is defined as the volume of reverberation sound, which depends on sound power, reverberation time and room volume. The measure of loudness is expressed as the ratio of reverberation time in the range from 500 to 1000 Hz to the volume of the room.

**Background noise index**

Background noise index has a significant impact on the reception of messages in the process of speech comprehension. It can be calculated on the basis of [11]:

$$QI_{BN} = 0.002 \cdot (L_{Aeq})^2 - 0.246 \cdot (L_{Aeq}) + 7.64$$  \hspace{1cm} (11)

where: $L_{Aeq}$ is the numeric value of the background noise level in the empty classroom. $L_{Aeq}$ should not exceed the following values:
- 40 dB - total noise from all sources,
- 35 dB - noise from the building and from other facilities in the building or outside.

**Signal-to-noise ratio index**

The signal-to-noise ratio affects the quality of the delivered speech content. This parameter defines the distance of speech signal from the background noise level at the recipient's location. The signal-to-noise ratio index is calculated from the formula [11]:

$$QI_{SNR} = 0.058 \cdot e^{0.18(SNR)+0.14}$$  \hspace{1cm} (12)
where: SNR is the numerical value of the signal-to-noise ratio in the real teaching / learning environment.

SNR was approximated as the value 0.5 from the weighted histogram $A$ of sound pressure level in the classroom during the lecture.

4. Results and discussions
The requirements involving reverberation conditions in classrooms vary in different countries. The requirements for selected European countries are presented in Table 2.

| Country   | Document               | Reverberation time [s] | ST I |
|-----------|------------------------|------------------------|------|
| France    | Decree 1995            | 0.4-0.8                | -    |
| Netherlands | Guidelines NEN 5077   | 0.8                    | -    |
| Sweden    | Standard SS 025268     | 0.5-0.6                | -    |
| Norway    | Standard NS 8175       | 0.6                    | -    |
|           |                        | 0.6-0.8                |      |
| Portugal  | NBR 12179, 1992        | (250-4000Hz)           | 1    |
|           |                        | (125-250Hz)            |      |
|           |                        | 0.6-0.8                |      |
| Finland   | Standard SFS 5907: en  | (250-4000Hz)           | 1    |
|           |                        | 50% higher for 125Hz   |      |
|           |                        | <=0.6                  |      |
|           |                        | (V<=250m$^3$)          |      |
|           |                        | <=0.8                  |      |
|           |                        | (V<=500 m$^3$)         |      |
|           |                        | =>                     |      |
|           |                        | (V=>500 m$^3$)         |      |
| Poland    | PN-B-02151-4           | (250 m$^3$<V<=500 m$^3$)| 0.6  |
|           |                        | 1                      |      |

The results obtained for the tested classroom are presented in Figure 2.

![Figure 2. Diagram of reverberation time depending on sound frequency.](image-url)
Based on Figure 2, we can conclude that the classroom does not meet the requirements involving the duration of reverberation time.

The STI value calculated from the model (1) is 0.52, which also does not meet Polish requirements with STI at the level of $= 0.6$.

The optimal reverberation time calculated from the formula (2) is: $T_{\text{opt}} = 0.53 \text{ [s]}$

We verify whether the reverberation time is within the optimal limits:

$$T \notin \left( \frac{0.34, 0.64}{0.65T_{\text{opt}}, 1.2T_{\text{opt}}} \right) \text{ for 125 and 4000 Hz bands} \quad (13)$$

$$T \notin \left( \frac{0.42, 0.64}{0.8T_{\text{opt}}, 1.2T_{\text{opt}}} \right) \text{ for 250, 500, 1000 and 2000 Hz bands} \quad (14)$$

It can be observed that the reverberation time $T$ (Fig. 2) does not meet the requirements for the optimal reverberation time, as presented in Figure 3.

Figure 3 presents the recommended range of the obtained reverberation time to the optimal reverberation time.

![Fig. 3. Ratio of reverberation time of the room to the optimal reverberation time.](image)

The calculations made for the Global Index and summarized in Table 3 also demonstrate unsatisfactory acoustic conditions in the tested maths classroom.

| Name of indicator                              | Value for classroom with equipment | Weight of indicator |
|-----------------------------------------------|-----------------------------------|---------------------|
| Reverberation Index                           | 0.415                             | 0.8                 |
| Speech Intelligibility Index                  | 0.577                             | 1.0                 |
| Speech Effort Index                           | 0.270                             | 0.3                 |
| Sound Strength Distribution Index             | 0.576                             | 0.5                 |
| Background Noise Index                        | -                                 | 1.0                 |
| Signal-to-noise Ratio Index                   | -0.080                            | 0.5                 |
| **Global Index** $QI_g$                       | **0.399**                         | -                   |
The result of 0.399 is contained in the range of poor acoustic quality of the room. Since all classrooms in this school have a similar structure, finishing and equipment, the tested classroom can be considered as reference. This means that in the school built in prefabricated reinforced concrete technology erected as the memorial of the 1000th anniversary of the Republic of Poland, the conditions for conducting classes are not appropriate.

5. Conclusions

Based on the analysis, we can observe that the classroom has bad reverberation conditions. The minimum values of speech transmission index STI have not been reached. The Global Index indicates that the examined classroom has not the best acoustic climate. There is a need to adapt the existing classroom (but probably also other ones in this school and other schools built as memorials of the millennium of the Republic of Poland) to reduce noise nuisance and improve speech clarity. In summary, we can also recommend improving the acoustic properties of classrooms by using, e.g. floor coverings, room equipment or sound-absorbing ceilings. The cubature of the investigated classroom is the size of typical school classrooms in this type of reinforced concrete construction technology. This work is an introduction to a larger venture of researching schools with different construction technologies. It seems particularly interesting to study schools made in wooden technology and modern schools in the technology of passive energy building construction.

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