Sound insulation performance of aerated concrete walls

Barbara Szudrowicz[1], Genowefa Zapotoczna Sytek[2], Piotr Gębarowski[2]

[1] Building Research Institute in Warsaw
[2] The Institute of Ceramics and Building Materials - Concrete Research Center CEBET in Warsaw

Abstract: Autoclaved aerated concrete (AAC) has been universally applicable in the construction of internal and external walls. In order to be able to correctly use AAC in new buildings, the properties of this construction material need to be analysed in order to safeguard compliance with resistance and functional requirements laid down in the Construction Products Directive 89/106/EEC. Aerated concrete has been commonly known to exhibit favourable thermal properties, high fire resistance and high compressive resistance at relatively low density. However, little attention has been devoted to the sound insulation performance of aerated concrete partitions.

This paper presents the results of studies on acoustic properties of AAC partitions aimed at identifying the effect of specific factors on AAC sound insulation performance. The following AAC properties have been taken into account in the studies: concrete density, resistance, humidity, and structural factors, i.e.: wall thickness, type of connections between wall elements (mortar, etc.), and surface finish. Single-leaf walls have been mainly examined. The tests have been carried out in close cooperation with acousticians, aerated concrete production engineers and design engineers in order to account for the latest achievements in concrete production and construction methods along with the most common structural solutions.

A variety of acoustic problems with AAC partitions still remain unsolved, in particular, flanking sound transmission, which may be of importance in estimating sound insulation performance in buildings on the basis of the properties of AAC elements. Selected study outcomes referring to flanking sound transmission have been also summarized in this paper.

Keywords: sound insulation, mass law, flanking sound transmission, autoclaved aerated concrete.

1. INTRODUCTION

Autoclaved aerated concrete AAC offers specific favourable properties in the context of sustainable development in the construction industry. AAC production technologies are energy-efficient and consume low quantities of raw materials as compared to the production of other construction materials, which can be attributed to low density and a special waste-free and environmental friendly production formula of AAC. [1]. Typical AAC density is between 300 and 1,000 kg/m^3 (in a dry condition) [2].

In addition, AAC exhibits favourable thermal properties, which is important from the viewpoint of energy balance of AAC buildings.

AAC has the potential to become even more popular and universally used in the construction industry provided that AAC solutions meet all 6 basic requirements, including the requirements for sound insulation performance in buildings.

The positive acoustic properties of autoclaved aerated concrete as such can be attributed to its internal structure, however, its density is relatively low, which is why the sound insulation performance of AAC partitions can be worse than that of walls of the same thickness made of other materials (e.g. normal concrete, etc.).

Sound insulation requirements for internal and external walls differ considerably and depend on the location and intended use of the buildings and of the building interiors [3]. Therefore, these diverse requirements must be taken into consideration in the evaluation of sound insulation performance of AAC walls. Sound insulation performance of single-leaf walls made of aerated concrete can be considered sufficient in a number of applications. In exceptional circumstances, when special requirements on sound insulation performance, special materials and structural solutions need to be applied which exhibit better acoustic properties. This problem can be only solved by conducting suitable tests.

In Poland, acoustic properties of AAC walls have been initially tested to identify the basic sound insulation properties of various thickness walls, made of concrete representing different surface densities and coming from different producers. In the period 1990-2010, the studies on the development of improved acoustic properties have been considerably intensified. Laboratory and in-field studies have been conducted by the Acoustic Department of the Building Research Institute in Warsaw, in cooperation with the Central Research and Development Centre of Concrete CEBET (from 1st January 2011 – the Institute of Ceramics and Construction Materials ICiMB, Concrete Research Center – CEBET) and several producers of aerated concrete.

2. EVALUATION PARAMETERS OF SOUND INSULATION PERFORMANCE OF WALLS

Sound reduction index R for walls is defined by means of weighted sound reduction index in 1/3 octave or 1/1 octave bands at min. 100-3150 Hz or 125-4000 Hz frequency, respectively. Sound insulation performance of walls at minimum frequency interval is defined by 16 sound reduction values R (for 1/3 octave bandwidths) or by 5 sound reduction values R (for 1/1 octave bandwidths).

In practice, instead of several (or several dozen) values defining sound insulation performance of a single wall, other ratings have been in use, according to the international ISO standard EN 717-1:1996 [4]:

- weighted sound reduction index R_w
- two spectrum adaptation terms C and C_{tr}.

These ratings are defined as $R_w(C, C_{tr})$. The weighted sound reduction index R_w is based on sound insulation performance at 100-3150 Hz interval or in octave bands between 125 and 2000 Hz. C and C_{tr} refer to sound insulation performance within the same frequency interval. Whenever a wider frequency interval is taken into consideration, it is defined as a subscript, e.g. $C_{100\text{-}5000}$, $C_{tr50\text{-}5000}$.

Depending on the noise spectrum that a specific wall is exposed to, its sound insulation performance is defined as:

- R_w+C (mainly for internal walls), or
- R_w+C_{tr} (mainly for external walls).

Sound insulation performance tests of aerated concrete walls have been performed in accordance with the ISO measurement standards (currently ISO EN or EN), within one-third octave band at 100-3150 Hz frequency interval.

3. SOUND INSULATION PERFORMANCE OF SINGLE-LEAF AAC WALLS IN LABORATORY CONDITIONS

3.1. Relationship between acoustic properties of AAC walls and technical parameters of concrete, brickwork technology and wall surface finish

In order to be able to improve acoustic properties of AAC walls, it is essential to identify the correlations between sound insulation performance of aerated concrete walls and technical parameters of concrete, structural solutions and surface finish of walls.

The Acoustic Department of the Building Research Institute in Warsaw has been examining walls made of small-size elements coming from different manufacturers in Poland and abroad. They were found to differ in numerous technical parameters, i.e.: density, strength, element type, wall construction method, type of wall surface finish, etc. A considerable number of walls (over 60) have been used in the tests in order to be able to produce universal test results and to draw conclusions on the general effect of specific factors on sound insulation performance of walls [5].

a) Aerated concrete density and wall thickness.

From the viewpoint of acoustic properties, the density of aerated concrete should be revised along with wall thickness. Alterations in aerated concrete density between 400 and 700 kg/m^3 were found to affect sound reduction indices of walls of specific thickness only if the surface density (mass per unit area) of the wall has changed as a result (wall thickness between 120 mm and 300 mm). The same correlations have been identified between changes in the thickness of aerated concrete walls of specific density. The thicker the wall, the higher the surface density (mass per unit area) and the better the sound reduction indices. These relationships are a perfect example of the mass law of sound insulation.

As a result, the sound insulation performance of aerated concrete walls of lower and higher density had to be examined. This time, the tests involved aerated concrete walls of approx. 300 kg/m^3 and between 900 to 1,000 kg/m^3 density. It was shown that the sound insulation performance could be expected to be slightly higher for densities below 400 kg/m^3, and slightly lower for over 400 kg/m^3 densities than what would be implied by the surface density (mass per unit area) of the wall. However, the differences were not higher than ± 1,5 dB.

b) Strength

The correlations between aerated concrete strength and its acoustic parameters have not been tested. Instead, concrete strength typical for a specific concrete density has been taken into consideration.

c) Humidity

In the majority of studies of sound insulation performance of aerated concrete walls, the wall humidity has not been considered as one of the variables. The tests have been conducted in about 10 days after plasterwork, at a test stand in air-conditioned chambers.

The first tests on the effect of humidity on sound reduction indices referred to aerated concrete walls of increased density (up to over 950 kg/m^3). In parallel to sound insulation properties of walls tested in laboratory acoustic chambers, the humidity of aerated concrete has been measured at several day intervals. The humidity has been examined on specimens collected at specific time intervals from the wall built directly at a laboratory test stand.

When the results of sound insulation tests and aerated concrete humidity tests have been compared, it was concluded that the values of (R_w + C) and (R_w + C_{tr}) indices remained unaffected by humidity fluctuations within the range of 18 %, ≤ 6%.

It can be therefore concluded the sound reduction index remained virtually unaffected by higher humidity values and the resulting higher surface density (mass per unit area) of the wall.

d) Types of small-size elements – brickwork technology

In general, the wall structure depends on the side surface profile of small-size elements made of aerated concrete. With smoothed-surface small-size elements, the wall is built in a traditional manner with horizontal and vertical joints. When the elements are profiled into tongue and groove joints, horizontal joints remain present, but the vertical joints are mortar-free and resemble a "labyrinth". Vertical joints reduce the sound insulation performance of the walls as they let the sound pass through. Surface insulation applied under the plasterwork can eliminate this undesirable phenomenon, which is typical for all walls with tongue and groove joints, e.g. with ceramic or silicate elements. However, walls made of aerated concrete blocks typically have relatively high sound insulation performance in tongue and groove joints, which can be attributed to the porosity of AAC.

e) Type of mortar in the joints

The influence of mortar on sound insulation properties of walls made of small-size aerated concrete elements has been compared to the results of sound insulation tests of walls with elements joined by means of an adhesive cement mortar. Walls with cement-lime mortar and walls with adhesive cement mortar were shown to have a comparable sound reduction indices (R_w, (R_w + C) and (R_w + C_{tr})). The sound insulating properties of walls with thermal insulating mortar were shown to deteriorate to a specific extent, mainly within the middle and upper frequency interval, and the sound reduction indices values were lower by 2-3 dB (R_w and (R_w + C)). This tendency cannot be properly quantified because of insufficient data.

f) Plaster type and density

As indicated in subparagraph d), the plaster on aerated concrete walls with tongue and groove joints has specific sound insulating properties. Aerated concrete was also confirmed to transmit sound, even at higher densities, which means that the sound insulation performance of plaster-free walls is lower than that of plastered brickwork, even when the joints are filled with mortar. The difference in the values of sound reduction indices is considerably higher than what would be implied by the increased surface density (mass per unit area) of the plastered wall.

3.2. Relationship between sound reduction indices and surface density (mass per unit area) of AAC walls

The relationship between the surface density (mass per unit area) of a single-leaf wall [kg/m^2], and the values of sound reduction indices [dB] is stated in the mass law. EN 12354-1 [6] standard defines the mass law calculated for walls made of normal concrete, light-weight aggregate concrete, small-size AAC elements and lime-sand brick construction elements. There have been only minor differences identified in the sound reduction index curves based on theoretical models for different types of materials listed above, mainly for surface density (mass per unit area) between 60÷200 kg/m^2.

EN 12354-1 [6] standard also lists examples of empirical relationships adopted as average values for specific material types specified in Table 1.

Table 1. Empirical mass law for single-leaf walls in different countries (according to EN 12354-1 [6])

Country	Surface density (mass per unit area)	"Mass law" formula
Germany (A)	$m' \geq 100$ kg/m^2	$R_w = 32.4 \lg m' - 26.0$ dB
France (F)	$m' \geq 150$ kg/m^2	$R_w = 40.0 \lg m' - 45.0$ dB; C = -1 dB
Great Britain (GB)	$m' \geq 50$ kg/m^2	$R_w = 21.65 \lg m' - 2.3 \pm 1$ dB

In the tests of single-leaf walls performed at the Acoustic Department of the Building Research Institute, the differences in sound reduction properties of walls made of different materials representing the same surface density (mass per unit area) were shown to be significant.

The tests of acoustic insulation performance of aerated concrete walls have produced a considerable pool of data, which was sufficient to determine the 'mass law' relationships for this type of walls. The impact of specific structural solutions used in AAC walls on sound reduction properties was proved to be negligible, and the final results could be therefore generalized to be able to formulate mass law relationships for a variety of solutions used in practice.

The mass law relationships [7] developed at the Acoustic Department of the Building Research Institute includes 3 sound reduction indices: R_w, $R_{A1} = R_w + C$ and $R_{A2} = R_w + C_{tr}$ and refers to AAC walls with density between 400÷700 kg/m^3, made of elements joined with an adhesive cement mortar or cement-lime mortar; the construction elements are assumed to be smooth or profiled (forming mortar-free tongue and groove joints). Aerated concrete was confirmed to transmit sound, and all test results, including the mass law relationship, refers to walls covered with a 6 mm layer of cement-lime mortar, whereas the mortar has not been included in the total mass per unit area of the wall. The mass law relationships are shown in Table 2.

Table 2. Mass law referring to laboratory-determined values of sound reduction indices for aerated concrete walls, with concrete density between 400 ÷ 700 kg/m^3, and a 6 mm surface layer of mortar (mortar has not been included in the total mass per unit area of the wall) according to the tests conducted by the Building Research Institute [7].

Mass per unit area	Laboratory-determined sound reduction indices
40 kg/m^2 < M ≤ 70 kg/m^2	R_w = 17.9 lg(m') + 7.9 (± 2.0) dB
	R_{A1} = 17.9 lg(m') + 6.4 (± 2.0) dB
40 kg/m^2 < M ≤ 80 kg/m^2	R_{A2} = 10.5 lg(m') + 17.0 (± 2.0) dB
70 kg/m^2 < M ≤ 250 kg/m^2	R_w = 25.5 lg(m') - 6.1(± 1.5) dB
	R_{A1} = 25.5 lg(m') - 7.6 (± 1.5) dB
80 kg/m^2< M ≤ 250 kg/m^2	R_{A2} = 25.5 lg(m') - 11.1(± 1.5) dB)

Figure 1 compares the average mass law relationship for specific materials according to EN 12354-1 standard (Table 1), and the mass law relationship for AAC walls calculated on the basis of the tests (Table 2). The comparison refers to weighted indices R_w.

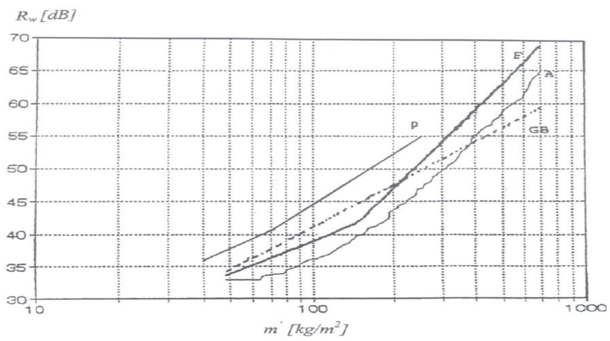

Fig. 1. Comparison of different mass law relationships in Germany -A, France - F, Great Britain – GB – according to Table 1 and in Poland - P – according to Table 2.

The comparison indicates a significantly better sound insulation performance of walls made of small-size AAC elements as compared to other construction materials representing a specific surface density (mass per unit area). However, when the sound insulation performance of walls made of different materials, but of the same thickness is compared, the sound insulation performance of AAC walls was found to be inferior due to lower density of aerated concrete.

In Poland, the mass law relationship taken into account in building designs is typically lower by 2.0 dB (for mass per unit area between 40 ÷ 70 (80) kg/m^2) and by 1.5 dB (for mass per unit area between 70 (80) ÷ 250 kg/m^2) against the laboratory-determined values listed in Table 2, which is compliant with PN-B-02151-3:1999 standard [3]. Index values used in designs are denoted as R_{wR}, R_{A1R} and R_{A2R}. The discussed relationships are shown in Figure 2.

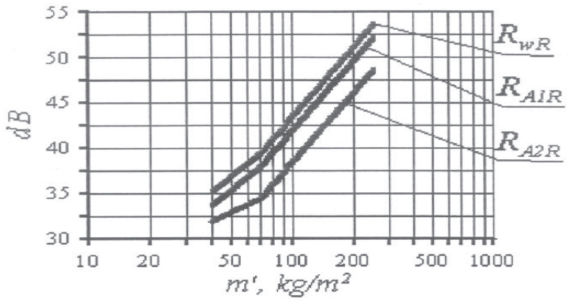

Fig. 2. Mass law relationship for AAC walls at 400÷700 kg/m^3 density referring to the calculation values of sound reduction indices R_{wR}, R_{A1R} and R_{A2R} (technical parameters of the walls are listed in Table 2).

4. SOUND REDUCTION PERFORMANCE OF AERATED CONCRETE WALLS IN BUILDINGS

4.1. General data

There are differences between sound insulation performance of walls in in-situ tests and of the same walls under laboratory conditions. Sound insulation can be affected by the quality of workmanship, and by the so-called flanking sound transmission illustrated in Figure 3, along with the path of direct transmission Dd, and the paths of flanking transmission Ff, Fd and Df.

Sound insulation performance of the paths of flanking transmission shown in Figure 3 depends on the sound insulation performance of partitions that are involved in the flanking transmission, and on the vibration reduction index.

The calculation methods of sound reduction indices of partitions inside buildings in consideration of the flanking transmission are laid down in EN 12354-1 standard [6], which also defines calculation formulas of vibration reduction index for different types of junctions (rigid cross-junctions, rigid T-junctions, junction with flexible interlayers) and mass per unit area of junction partitions. However, there are no formulas which would account for specific materials that the partitions are made of.

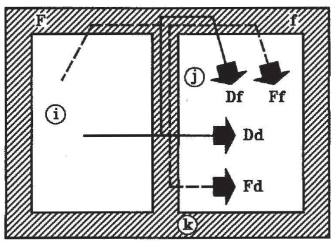

Fig. 3. Layout of sound transmission paths between dwellings for massive structures (as per [6]): **Dd** – direct path, **Ff, Fd, Df** – side paths; **i** – sending room; **j** – receiving room, **k** – vibration reduction at the junction.

The model for flanking sound transmission in buildings according to EN 12354-1 standard [6] indicates that the internal partitions and external walls interact acoustically, which is why it is essential to analyse the systems as a whole and to consider the way the system elements are interconnected.

4.2. Internal partitions made of small-size AAC elements

Estimated sound reduction index of internal AAC partitions in in-situ studies was shown to be lower by 1 to 3 dB on average from the laboratory-based calculations, depending on the inter-room partition thickness and on the type of side partitions (external walls, ceilings, partition walls). Deterioration of the sound reduction index was shown to be lower in thinner walls (of inferior sound insulation performance) and higher in thicker walls (e.g. 24 cm).

It can be deducted from the calculations that the major acoustic problems in terms of compliance with the statutory sound reduction index (laid down in PN-B-02151-3:1999 standard [3]) can be expected for interdwelling partition walls in multi-family (R'_{A1}≥50dB) and single-family semi-detached and terraced houses (R'_{A1}≥52 ÷55dB). However, single-leaf walls of specific thickness can comply with lower requirements for walls in a variety of public buildings (schools, office buildings), as well as partition walls in residential buildings.

It was confirmed in acoustic in-situ studies that 24 cm thick interdwelling AAC walls (with a typical density of 600 kg/m^3) fail to comply with the standard requirements. Sound reduction deficiency is significant and is estimated at 3÷4 dB. The only method to improve sound insulation between dwellings is to apply an insulating system made of mineral wool and gypsum-cardboard panels on one side of the interdwelling wall. Under laboratory conditions, the sound reduction index of the additional insulation was estimated at R_w (C, C_{tr}) = 61(-5, -12) up to R_w (C, C_{tr}) = 62 (-3, -10), depending on technical details [5]. In in-situ conditions, the average values were found to be slightly lower: R_w (C, C_{tr}) = 57(-3, -8).

In new buildings, the application of additional insulating systems cannot be considered the most desirable solution. In order to improve sound reduction properties of interdwelling walls, some other solutions need to be applied, i.e. by increasing the wall thickness and aerated concrete density, or by introducing double walls. However, laboratory tests in this respect have so far failed to produce any reliable data. Sound reduction index for 30cm thick walls of 1005kg/m^3 density covered with gypsum plaster on both sides is by 1 dB lower for interdwelling walls in multi-family residential buildings (under the assumption that the flanking sound transmission adjustment equals 3dB). If the impact of the flanking transmission was below 2 dB, the sound reduction standards would be complied with.

Expansion joints applied in-between the walls produce highly advantageous sound reduction properties of double walls, but can be used mainly in single-family terraced houses.

4.3. External walls made of small-size aac elements

Sound insulating performance of all types of external walls can be evaluated on the basis of sound insulation performance of the wall against outdoor noise, and of the impact of the external wall on flanking sound transmission, i.e. on the sound reduction index of internal walls (interdwelling walls, etc.) and ceilings.

(R_w + C_{tr}) indices are typically taken into consideration in evaluating the direct sound insulating performance of external walls.

In analyses conducted at the Acoustic Department of the Building Research Institute, the flanking transmission was shown to have a negligible impact on the sound insulating performance of massive external walls [3], and it can be therefore assumed that the calculations based on the mass law relationship can be used in assessing direct sound insulating performance of aerated concrete walls (see Fig. 2, R_{A2R} curve). R_{A2R} indices for aerated concrete walls compliant with thermal insulation requirements for buildings are typically sufficient in terms of building protection against outdoor noise. This applies particularly to walls with windows.

Moreover, (R_w + C) sound reduction indices are also taken into account in determining the effect of external walls on sound insulating performance of partitions inside building.

The tests have been conducted in buildings with external walls made of aerated concrete and internal walls made of a variety of construction materials (aerated concrete of various thickness, or lime and sand small-size elements), and ceilings made of ferroconcrete slabs or beam and block ceilings with concrete hollow bricks and AAC hollow bricks.

The measurement data [5, 8, 9] on the sound insulation performance of flanking transmissions paths Ff and Df (rys.3) have been later compared to the results of calculations according to EN 12354-1 in order to check the extent to which the forecasting methods of sound insulating performance of building partitions according to the applicable EN standard prove useful in designing sound insulating performance in buildings with external walls made of aerated concrete.

Considerable differences have been identified between the measured and calculated values (± 5 dB), which can be attributed to insufficient data on the technical solutions in junctures between external walls and internal partitions, and the resulting incorrect calculation assumptions. It is therefore necessary to continue to investigate the acoustic properties of aerated concrete in order to further promote its application in the construction industry.

5. FINAL REMARKS

On the basis on mass law relationships identified in the course of laboratory tests, sound reduction indices R_{A1}, R_{A2} and R_W have been determined for single-leaf walls made of aerated concrete elements, of 400-700 kg/m^3 density, joined with thin layer mortar or cement-lime mortar. Walls made of aerated concrete with density below 400kg/m^3 and above 700kg/m^3 have shown specific deviations from the mass law relationship – the sound insulating performance was found to be slightly higher at 300kg/m^3 density and slightly lower at 700kg/m^3 density from the values calculated from the mass-law relationship.

In evaluating the test results for aerated concrete walls in terms of compliance with the sound reduction requirements, the following conclusions can be drawn:

- sound insulating performance of external AAC walls of appropriate thickness in accordance with the thermal requirements (e.g. 240 mm thick single-leaf AAC wall with up to 340 kg/m^3 density) were found to be compliant with acoustic requirements for the majority of building locations;
- AAC walls comply with the recommended requirements for partition walls in multi-family and single-family basic-standard residential buildings (at 75 mm and 100 mm thickness, respectively, and 600 kg/m^3 density);

- compliance with the acoustic requirements can be problematic for interdwelling walls in multi-family residential buildings and for walls between semi-detached and terraced residential buildings. Therefore, from the viewpoint of acoustics, it would be desirable to use double walls with complete expansion joints between single-family semi-detached and terraced residential buildings. In multi-family residential buildings, it would be recommended to use single AAC walls of approx. 1000 kg/m^3 density (following appropriate tests).

The results of laboratory tests can be only used in preliminary assessment of sound reduction performance of walls made of aerated concrete in relation to acoustic requirements for partitions. Sound insulating performance to a large extent depends on structural solutions used in the construction of internal and external walls, in consideration of sound propagation principles within buildings. Moreover, the workmanship quality of structural solutions is equally important from the viewpoint of sound reduction properties. It would be also advisable to continue to investigate the sound reduction properties of innovative structural solutions which have the potential to improve the insulating properties of AAC walls.

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