Airborne sound insulation of single-leaf partitions under hygric load

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Abstract. In buildings of all types the use of single-leaf partitions are recommended, not least for reasons of cost efficiency and possible resource optimisation. In addition to the familiar building physics topics they play also a particularly important role in noise protection. Numerous factors influence the acoustic properties of single-leaf, plate-shaped and dry partitions. These include the mass, the bending stiffness, the position of the critical frequency and the total loss factor of the partition as well as the stimulating frequency of the airborne sound, the sound incidence angle or the characteristic impedance of the air. Each mineral wall-building material has its own product-specific pore structure. In the usual calculation of the airborne sound insulation of single-leaf, airtight and dry partitions, this has so far not been taken into account. It is precisely in these building material pores that a hygrothermal, continuous adjustment of the moisture content takes place in addition to the production-related water quantities. This changes the mass of the building component and thus the airborne sound insulation of the wall. In addition to this well-known mass effect, a further mechanism, which has not yet been considered, increases airborne sound insulation: the smaller the pore sizes in the building material, the greater the mechanical forces caused by stored pore water. The existing equations for airborne sound insulation do not take these effective forces into account and must therefore be extended. The wall building material is considered as a porous medium with solid and fluid components. The new calculation approach allows the calculation of the airborne sound reduction index for single-leaf partitions under hygric load for saturated and partially saturated moisture conditions with high accuracy. The calculation results provide valuable information for the planning and product development of new building materials.

1. Introduction
In this paper, an equation is presented that allows the calculation of the airborne sound insulation index of single-leaf partitions in wet condition. The effects and parameters that essentially influence the airborne sound insulation of wet single-leaf walls and to what extent they change it are named. With the newly developed calculation method, wall examples are calculated and the results compared with the measurement results. For this purpose, plate-shaped test specimens are subjected to a series of measurements in the dry and wet condition of the building material.

2. Basics
Given is a single-leaf partition wall. Airborne sound hits this wall from one side. Depending on how well the wall insulates the sound energy, more or less sound is transmitted through the wall. Typical for single-shell partitions is the well-known coincidence effect. This
divides the airborne sound insulation values into a range below the critical frequency $f_c$ and one above it.

2.1. Sound reduction index below the critical frequency
For the airborne sound reduction index $R$, the famous mass law applies for this area below the critical frequency \[1\][2][3]:

$$R = 20 \log_{10} \left( \frac{m' \omega}{2Z_0} \right) - 3 \text{ [dB]} \quad (1)$$

The specific mass (mass per m²) is $m'$, $Z_0$ means the characteristic impedance of the air and $\omega$ the angular frequency. Equation (1) states that the increase in airborne sound insulation with a doubling of the mass is 6 decibels. Even with a doubling of the frequency, and thus with each octave jump, an increase in airborne sound insulation of 6 dB is achieved in the range below the critical frequency.

2.2. Sound reduction index above the critical frequency
For the range above the critical frequency $f_c$, the following relationship applies for the airborne sound reduction index $R$ \[4\][5]:

$$R = 10 \log_{10} \left( \frac{m' \omega}{2Z_0} \right)^2 + 5 \log_{10} \left( \frac{f}{f_c} \right) + 10 \log_{10} \left( 2\eta \right) \text{ [dB]} \quad (2)$$

with $f$ for the frequency of the impinging sound wave. This equation (2), often briefly referred to as the "Heckl equation", states that the increase in airborne sound insulation of single-leaf partitions at frequencies above the critical frequency $f_c$ now depends not only on the mass and the frequency but also on the loss factor $\eta$. The increase above the critical frequency is steeper than below the critical frequency at 7.5 decibels per octave.

2.3. Poroelastic Plates
In the context of this paper, poroelastic plates are understood as Kirchhoff plates made of mineral building materials with a building material-specific pore structure. The pore spaces are gas-filled when the building material is dry. As the moisture content of the building material increases, gas and water are present in the pores in the proportions corresponding to the moisture content. In saturated building materials, the pore spaces are finally filled with water. The stored water increases the mass of the single-leaf partition, which can be expected to increase the airborne sound insulation compared to the dry partition.

However, a mass-related increase in airborne sound insulation caused by an increased moisture content turns out to be downright moderate. For example, the achievable increase with a water-related mass increase of 10% to 60% is between 0.4 decibels and 2.0 decibels according to equations (1) and (2). Therefore, no effective improvements in airborne sound insulation can be expected from the mere increase in mass due to water storage in the pores using the equations known to date. However, this is in contradiction to the experimental investigations carried out on partitions in dry, wet and water-saturated condition with the building materials aerated concrete and lime sandstone.

3. Experimental Investigations
Acoustic and hygric measurements and measurements to determine the pore size distribution and pore shape are carried out to obtain measured values. Transportable, 115 mm thick single-leaf partitions made of mineral building materials measuring just under two square metres form the core of the experimental investigations. Starting from the water-saturated state of the building material, each of the single-leaf partitions are dried step by step. At
several moisture levels, the airborne sound insulation, the structure-borne sound reverberation time and the impulse response are measured in succession. The focus is on the building materials lime sandstone and aerated concrete. Investigations of these two materials with the aid of the scanning electron microscope, computer tomography and the helium pycnometer open up essential insights into the respective pore structure.

3.1. Sound reduction index lime sandstone

The measurement results of the airborne sound insulation for the lime sandstone wall are shown by thirds in Figure 1. There are two curves that are close together in the lower frequency range up to about 500 Hz. They differ on average only by up to 2 dB and at most by up to 4 dB in the corresponding thirds. Above 500 Hz, a clear fanning out of the curves takes place. The wall in dry condition has the lowest sound insulation values, the saturated partition achieves above 500 Hz on average 5 dB and in some third octaves between 6 dB and 7 dB higher values of the airborne sound reduction index.

3.2. Sound reduction index aerated concrete

Figure 2 shows the results of the measurement of the airborne sound reduction index of the dry and the wet partition made of aerated concrete. In contrast to the curve of the wet lime sandstone in Figure 1, the curve of the wet aerated concrete in Figure 2 is clearly above that of the dry aerated concrete even at lower frequencies. The dry wall condition has the lowest sound insulation values, the saturated wall achieves above the critical frequency around 315 Hz on average 4.2 dB higher airborne sound reduction indices. In contrast to the lime sandstone results, the impinging airborne sound in the range of the critical frequency around 315 Hz produces the highest differences between the dry and the moist to saturated building material conditions. This is due to the high water absorption capacity of aerated concrete. The wall therefore experiences a high increase in mass.

3.3. Pore Sizes and Porosity

In the lime sandstone used, 55% of the pore volume is in the range of up to 100 nanometres. These belong to the micropores. In aerated concrete, on the other hand, only 27% of the pore volume belongs to this pore size range. 73% thus belong to the macropores. The
porosity measured with the helium pycnometer method is 27.9% for the lime sandstone used here and 75.8% for aerated concrete [3].

3.4. Evaluation of the experimental results
The measurement results document a clear increase in the airborne sound reduction index with increasing water content in the pores. Especially in the case of the partition made of lime sandstone, the increase in the sound insulation values cannot be explained with the previous formulas by the mere increase in mass due to the water storage in the pore spaces. Depending on the frequency range of the airborne sound wave impinging the component, the increase in the airborne sound reduction index is up to seven decibels. In the literature reviewed in [3], there is neither an explanation for this phenomenon nor a calculation method for predicting the airborne sound insulation of such hygrically loaded single-leaf partitions.

4. New calculation approach
In order to derive an extended calculation method for the calculation of the airborne sound reduction index, the mineral wall building material is considered as a porous medium according to [6] and [7].

This model approach divides the wet partition into two components: a solid and a fluid part. The solid component hides the elastic structural framework of the solid, while the fluid component hides the pore spaces, which are mainly filled with water. The adhesion of the embedded pore water to the pore walls creates a mechanical coupling of the two components. As a result, the vibrations of the solid structure generated by the impinging airborne sound are transmitted directly to the water stored in the pore spaces. The vibrating pore water in turn immediately acts on the vibrating solid structure. In this interplay, viscous friction effects and, with increasing frequencies, also increasingly the inertia effects of the pore water mass cause damping of the vibration in the partition. This hygric-induced additional damping effect contributes to an increase in the loss factor in the wall-building material [3].

4.1. Solid and fluid fraction
The separate consideration of solid and fluid content leads with the solid density \( \rho_s \) and the fluid density \( \rho_f \) under consideration of the porosity \( \sigma \) to the total bulk density of the porous material [6]:

\[
\rho = (1-\sigma) \rho_s + \sigma \rho_f \quad \text{[kg/m}^3\text{]} \quad (3)
\]

This results in the specific mass \( m_h \) (mass per m²) of the wet component with thickness \( h \):

\[
m_h = \left((1-\sigma) \rho_s + \sigma \rho_f \right) h \quad \text{[kg/m}^2\text{]} \quad (4)
\]

4.2. Poroelastic moduli
In addition, in the theory according to [6], the two poroelastic moduli \( Q_B \) and \( R_B \) according to equations (5) and (6) occur as fundamental influencing variables. They serve to quantify the pressure conditions that occur in the pore spaces under an external load. For the solids-related modulus \( Q_B \), the following applies in the context of this investigation, depending on the porosity \( \sigma \) [3]:

\[
Q_B = \frac{\sigma \left(0.08533 - \sigma\right)}{2.0127 \cdot 10^{-10}} \quad \text{[N/m}^2\text{]} \quad (5)
\]
The fluid-related modulus $R_B$ is calculated according to [3] to:

$$R_B = \frac{\sigma^2}{2.0127 \cdot 10^{-10}} \quad [\text{N/m}^2] \quad (6)$$

With increasing porosity, the modulus $R_B$, for example, approaches the value for the Young's modulus $Y$ of aerated concrete, thus underlining that the poroelastic moduli in the theory according to [6] are not to be neglected.

4.3. Extended equation

An approach available in [8] for low-frequency vibrations of a floor slab lying in the ground provides a coupled system of two equations of motion to describe the flexural vibrations triggered in it. This system of equations from [8] forms the starting point for the derivation of a bending wave equation extended by the hygric effects in [3]. Finally, a new equation for the airborne sound reduction index of single-leaf, porous and wet partitions is developed from this. It applies [3]:

$$R = 10 \log_{10} \left( \frac{m' \omega}{2Z_0} \right)^2 + 5 \log_{10} \left( \frac{f}{f_0} \right) + 10 \log_{10} (2\eta) + 10 \log_{10} \left( 1 + C_h \lambda_{bh}^2 \right) \quad \text{[dB]} \quad (7)$$

The additional term on the right side in equation (7) compared to equation (2) formulates the moisture-related increase of the loss factor. In addition to the squared bending wavelength $\lambda_{bh}$ of the wet partition, it also contains the new "pore fluid number $C_h$". It is made up of components that affect both the solid structure and the water stored in the pore space. The following applies to $C_h$ in the simplified form with only real-valued terms [3]:

$$C_h = \frac{\nu}{R_B} \left[ \frac{1}{\lambda} \left( \frac{Q_B + R_B}{R_B} - 1 \right) \omega^2 \frac{Q_B \sigma \rho_f}{(2\mu + \lambda)} \right]$$

$$+ \frac{\sigma \rho_f}{R_B} \left( \frac{Q_B \sigma \rho_f (Q_B + R_B)}{(2\mu + \lambda)R_B} \right) \quad [1/\text{m}^2] \quad (8)$$

In equation (8) $\lambda$ and $\mu$ represent the well-known Lamé constants from mechanics, $\nu$ means the Poisson’s ratio. In total, the pore fluid number $C_h$ is influenced by more than a dozen factors [3]. The following five basic variables have the greatest effect:

- frequency
- porosity
- pore structure (including pore size distribution)
- fluid density
- fluid viscosity

5. Comparison and interpretation

5.1. Experimental and numerical results

The calculated values of the wet single-leaf partition are based on the measured values of the dry wall. This means that the numerical result from the hygric term from equation (7) is added to the sound insulation values of the dry partitions. Thus it can be checked directly
whether an approximation to the measured values of the wet partition can be achieved with the hygric influence term 
\[ +10 \log_{10} \left( 1 + C_h \frac{\rho_w}{\rho_{ Bh}} \right) \].

![Figure 3. Numerical prediction of the airborne sound reduction index of the lime sandstone partition based on the dry measured values.](image1)

![Figure 4. Numerical prediction of the airborne sound reduction index of the aerated concrete partition based on the dry measured values.](image2)

The comparisons in Figure 3 and Figure 4 confirm a high level of agreement between the calculated airborne sound insulation values and the results actually measured for the wet components. This analysis includes the pore structure factor described in [3] from the theory of [6] [7]. The factor can lead to a correction at higher frequencies and lower the curve slightly there, especially for materials with a high proportion of micropores.

5.2. Classical and extended equation

In addition, the airborne sound reduction indices of the two single-leaf partitions made of lime sandstone and aerated concrete are determined according to equation (7) without taking into account the course of the measured sound reduction indices of the dry partitions.

Figure 5 shows the change in the airborne sound reduction index of the aerated concrete partition as a function of the moisture content \( \psi \) in the building material between 0 vol.% and 36 vol.% in the left diagram already clearly even without taking into account the additional hygric term from equation (7). The clear increase results from the mass increase of the water mass stored in the macropores of the aerated concrete. The moisture-dependent maximum values for the airborne sound insulation index therefore reach around 52 dB to 59 dB with a frequency quotient \( f/f_c = 12 \). In the right-hand diagram in Figure 5, the effect of the pore fluid number is also taken into account. It can be seen that the airborne sound reduction index increases again slightly at high moisture contents in the building material above around 25 vol.% compared to the left-hand diagram, thus increasing the maximum value to around 62 dB. This value is reached at 36 vol-%, which corresponds to the water-saturated state of the single-leaf partition made of aerated concrete.

Finally, Figure 6 provides the corresponding diagrams for the single-leaf partition made of lime sandstone. The diagram on the left again shows the change in the airborne sound reduction index as a function of the moisture content \( \psi \) and the frequency \( f/f_c \) only due to the increase in mass caused by the water trapped in the pores.
Since the increase in mass of lime sandstone is only 13%, the increase in the maximum values at f/fc = 12 is hardly noticeable, from a good 58 dB to around 60 dB. However, if the additional hygric effect of the water stored in the pores is taken into account via the pore fluid number C_h, according to equation (8). The right-hand diagram of Figure 6 shows a clear increase in airborne sound insulation at the higher moisture contents of the wall made of lime sandstone. Due to the special pore structure of lime sandstone, in which more than half of the total pore volume is composed of micropores, higher internal forces prevail, which are taken into account via the pore fluid number C_h in the right-hand diagram of Figure 6. It thus clearly shows that the increase in airborne sound insulation of single-leaf partition walls made of building materials with a high proportion of micropores does not occur via the increase in mass, but ultimately via the internal forces acting in water-filled capillaries with radii below 100 nanometres.
5.3. Sound insulation curves

The principle course of the airborne sound reduction index for single-leaf partitions with the known influencing factors for dry partitions is shown in Figure 7. In Figure 8, the additional influences for wet partitions are shown for comparison.

![Figure 7](image1.png)  ![Figure 8](image2.png)

**Figure 7.** Principle curve of the airborne sound reduction index (so far)  
**Figure 8.** Principle curve of the airborne sound reduction index (extended concerning hygric loads)

6. Conclusion

The main result of the investigations is that the increase in the airborne sound reduction index due to water storage cannot be attributed to the mechanism of mass increase alone, but to the effect of mechanical forces due to stored water in the pore spaces. The smaller the pore sizes, the greater the mechanical forces. Building materials with a similar micro/nanopore ratio as in the case of the lime sandstone are likely to behave similarly with regard to the change in airborne sound insulation when water is stored. This assumption leads to a number of possible approaches for future investigations and developments in the most diverse product areas.

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