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RAINFALL SOUND INSULATION OF (LIGHTWEIGHT) WOODEN ROOF CONSTRUCTIONS

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ABSTRACT

Rain can lead to increased noise levels in the building, especially in lightweight structures with metal roofs. To evaluate the rainfall sound insulation of roofs in the laboratory, the heavy rain simulation method according to EN ISO 10140-5:2021 Annex H is used. In this study, the rainfall sound insulation of timber roofs was determined, optimised and compared with the corresponding airborne sound insulation. The paper first presents the development of the test stand to measure both airborne and rainfall sound insulation on the same test element. The results of the measurements on different types of timber roofs are then discussed. In addition to the substructure of the roofs (exposed rafters, cross-laminated timber) and the roofing itself (concrete tiles, sheet metal, FPO membrane), the type of insulation placed on the substructure (PUR/EPS/mineral wool/wood fibre) was varied. The article shows that the roof covering has the most significant influence on the rainfall sound insulation and that there is only a limited correlation between the airborne sound insulation and the rainfall sound insulation of the roofs studied.

Keywords: *artificial rain, laboratory measurements, lightweight roof, rain noise, rain sound intensity*

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1. INTRODUCTION

In general, timber roofs can be divided into a) structures insulated between rafters and b) structures insulated on top of the roof. Roofs with the insulation on top are robust constructions in terms of thermal and moisture insulation, as the supporting structure is always in the warm zone and is therefore protected from condensation. From the building acoustics point of view, however, insulated roofs have disadvantages, especially around rain noise protection.

For this reason, Holzforschung Austria (HFA), together with the Technologisches Gewerbemuseum (TGM) and partners from industry, carried out the research project "Schutz.aufs.Dach", in which the airborne sound insulation as well as the rainfall sound insulation of roofs with insulation mounted on top was investigated [1]. The test setup for achieving this research objective was integrated into the large-scale test stand of the Akustik Center Austria (ACA) [2] and is presented in the following. Furthermore, the validation of the airborne sound measurements of the new implemented test stand configuration is presented. In the main part of the paper, individual constructive influences on the airborne and rainfall sound insulation of roofs are discussed.

1.1 Sound insulation requirements

The minimum requirements for the airborne sound insulation of roofs (in Austria) essentially correspond to those for external walls, although also installations such as roof windows must be considered. This means that the weighted sound reduction index of $R_w \geq 48$ dB must be achieved for opaque building elements and $R'_{res,w} \geq 43$ dB must be achieved for all external building elements including windows [3].

Similarly to the weighted sound reduction index R_w, there is also a normatively defined Single-Number Quantity (SNQ) for rainfall sound insulation, the A-weighted sound intensity level L_{IA}, which can currently only be used to compare components. In contrast to airborne noise, there are no minimum requirements for the rain sound insulation of building components. Rather, the purpose of the rain sound measurements is (according to EN ISO 10140-1:2021 Annex H) a) to assess the noise in the room under the test object, b) to design components for adequate rainfall sound insulation, c) to compare the rainfall sound insulation of components. Due to the increased use of attics as living space, as well as the increase in storm events with heavy rainfall [4], special requirements for bedrooms could be useful. The World Health Organization (WHO) itself states that a sound level of less than 30 dB(A) should prevail in bedrooms for healthy, restful sleep [5]. This is often significantly exceeded by many roof constructions during rain events.

2. MATERIALS

In the course of the work, exposed rafter roofs and cross-laminated timber (CLT) roofs are discussed. The focus of the project was the variation of the roof insulation materials, whereby the influence of the roofing was also investigated. Table 1 shows the construction details presented in this paper. In addition to the load-bearing structure (roof type), the various design influences are illustrated either for the CLT or the exposed rafter roof.

Table 1. Variations of the different layers of the discussed roofs. (s'...dynamic stiffness in MN/m³)

Layer	Variation
Roof type	CLT (120 mm) Esposed rafters
Insulation (on top)	MW: Mineral wool (s‘ = 1 MN/m³) WF: Wood fibre (s‘ = 16 MN/m³) PUR: Polyurethan (s‘ = 18 MN/m³) EPS: expanded polystyrol (s‘ = 46 MN/m³)
Roof covering	Sheet metal (Aluminium) Concrete tiles
Other	Influence of screwing Additional weight Structural mat

Underhead or double-thread screws were always used to screw the counter-battening in place. As a result of the reduced pressure of the counter-battening on the roof deck, significantly better sound insulation values can be achieved compared to a screw connection using part-threaded screw [6, 7]. Further details of the designs can be found in the final report [1].

3. METHODS

The building acoustics measurements were all performed at the ACA, with both airborne sound and rain noise measurements performed in the larger (XL) of the two test benches. The test opening for roof measurements in the XL-test stand has a surface area of 10.3 m² with an inclination of 5°. The volume underneath is approximately 150 m³. To achieve the highest possible maximum sound insulation of the test stand, the test component mask was made of reinforced concrete and acoustically equipped with additional facing layers. The performance of the airborne and rain sound measurements on the same test specimen is described below.

3.1 Airborne sound reduction

In order to validate the airborne sound measurements in the newly established XL-test stand, similar roof constructions were tested for their airborne sound insulation in the standard test stand (M-test stand, test opening: 19.8 m², volume of the receiving room: 54 m³, see also [8]) and in the ventilation test rig of the ACA (XL-test stand, test opening: 10.3 m², volume of the receiving room: 153 m³). The sound insulation values of two constructions, their deviations and the standard uncertainty according to EN ISO 12999-1:2021 are shown and discussed in section 4.1.

3.2 Sound intensity level of artificial rainfall noise

A test facility for determining rainfall noise has been installed in the source room of the XL-test stand. The 5° inclined test surface ensures that water can drain off. The test facility for generating artificial rainfall consists of the above-mentioned component mask, the irrigation system itself including a water supply system and a positioning system. The development as well as a detailed description of the artificial irrigation is to be found in [9]. To produce artificial rain drops, a tank with a perforated bottom according to EN ISO 10140-5:2021 Annex H was used. Figure 1 shows the tank placed in the positioning system described. This allows the test specimen to be easily moved to three different positions as required in EN ISO 10140-1:2021 Annex K.

Figure 1. Water tank with perforated bottom to produce artificial rain in a positioning system with guide rails.

Prior to each measurement, the system was calibrated to ensure that the precipitation rate of 40 mm/h (heavy rain) was maintained over the measurement period (see [9]. The sound intensity levels L_I in the receiving area are to be used for the evaluation of the rainfall sound insulation. The A-weighted intensity sum level L_{IA} from 100 Hz to 5000 Hz is the SNQ and must be specified to one decimal place.

4. RESULTS & DISCUSSION

The following graphs show the frequency-dependent results of the airborne sound measurements (R) and the rain sound measurements (L_I). In addition, for the airborne sound measurements, the insertion values R_w including the spectrum adaption terms for the extended frequency range $R_w + C_{50\text{-}5000}$ and $R_w + C_{tr,50\text{-}5000}$ are given in dB in the legend (according to EN ISO 717-1). For rain measurements, the SNQs L_{IA} in dB(A) are rounded to one decimal place in the legend (according to EN ISO 10140-1:2021 Annex K).

4.1 Validation of the airborne sound reduction index

As mentioned above, the first step was to carry out comparative measurements on the M- and XL-test stands. Figure 2 compares the sound reduction indices of a 120 mm CLT-roof (left) and a flat roof element (OSB – rafters, insulated - OSB) (right) in the two test stands. From a constructional point of view, the components in the test benches differ not only in area (M: 4230 mm × 5240 mm; XL: 4705 mm × 2350 mm), but also only minimally in the arrangement of the elements (CLT-roof) and in the spacing between the rafters (flat roof).

In addition to the sound reduction index of the components, the maximum airborne sound insulation of the XL-test stand is also given. As it is much higher for these two elements, the influence of it can be ruled out. The deviations lie mostly within the normative standard uncertainty, as can be seen in the lower part of the figure. However, in individual one-third octave bands, especially in the low and medium frequencies, this is also clearly exceeded. In the case of the flat roof element, the sound insulation value is shifted by one one-third octave band.

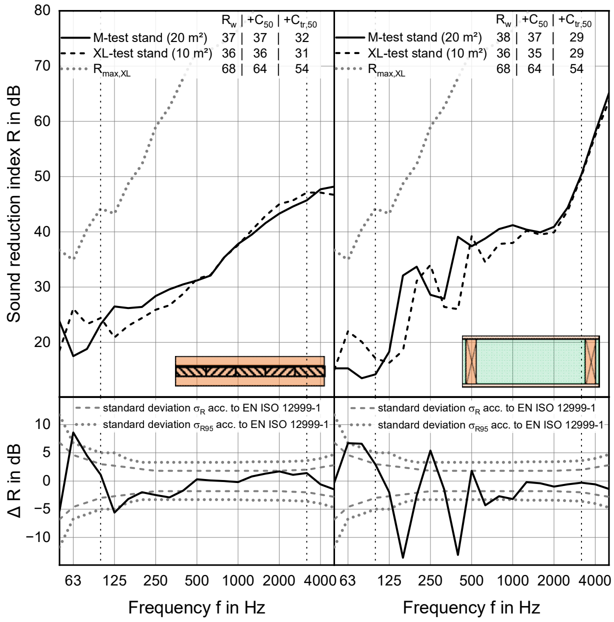

Figure 2. Comparison of the sound reduction index of a CLT element (left) and a flat roof element (right) in the two test stands at the ACA with different test openings. The differences and the standard uncertainty according to EN ISO 12999-1:2021 are shown in the lower part of the figure.

One reason for the deviations is to be found in the eigenfrequencies of the structures, as shown by the simulated velocity levels for point excitation in Figure 3. The FEM-simulations of the eigenmodes were performed using the software COMSOL 6.3. For the two flat roof elements, the eigenfrequencies are shifted to the same extent as the sound reduction indices. Due to the clear differences in the eigenfrequencies and its dependence on the element size, the different sound reduction indices in these one-third octave bands can be explained.

Only the frequency range below 100 Hz cannot be explained by the simulation, as no eigenmodes for the flat roofs occur below 125 Hz. In the authors' opinion, the size of the test opening, which is only 2350 mm in one direction in the XL-test stand, also plays a role here, as sound transmission for low frequencies below 100 Hz is only possible to a limited extent.

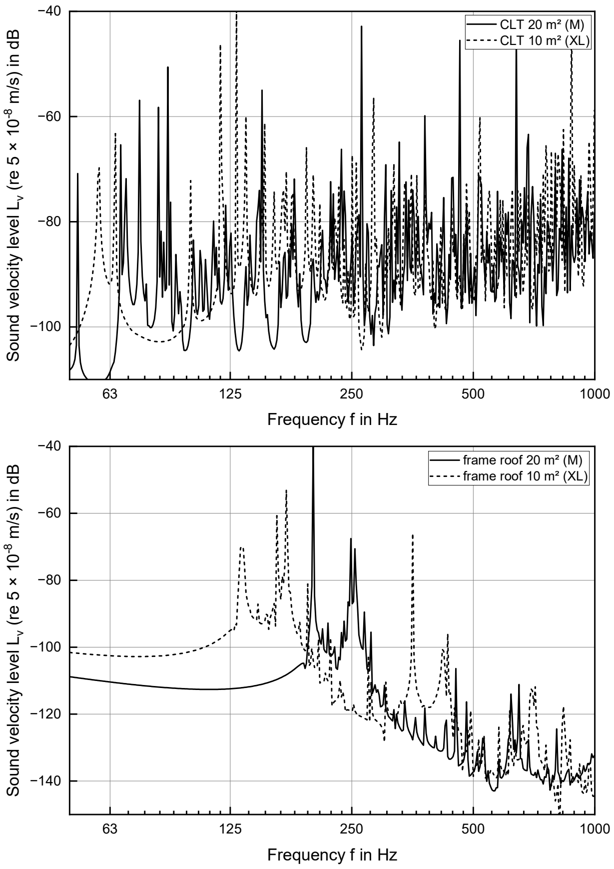

Figure 3. Comparison of the sound velocity levels of CLT elements (top) and flat roof elements (bottom) in the two test stands at the ACA with different test openings.

The large deviations beyond the standard deviation according to EN ISO 12999-1:2021 are no longer detectable in the case of practical roof constructions including roofing as well as insulation. With the explainable differences in the eigenfrequencies, as well as the approximation of the sound insulation values of structures including roofing (see project report [1]), the suitability of the XL-test stand could be ensured. However, the dependence on the test size should be considered as the simulations and comparative measurements have shown.

4.2 Influence of construction details

4.2.1 Influence of the structural roof

Figure 4 illustrates the influence of the structural roof on the airborne and rainfall sound insulation of a roof with WF or PUR insulation and sheet metal covering. As can be seen, the use of a CLT- instead of an exposed rafter roof results in a higher airborne and rainfall sound insulation over almost the entire frequency range. For the roofs with rigid foam insulation, the differences in airborne sound attenuation are even more pronounced than for the fibre insulation.
The sound intensity levels in the graph on the right also show the more favourable influence of the CLT-roof on rainfall sound insulation. The intensity levels in individual one-third octave bands differ much more from each other than the sound reduction indices in the left graph. A continuous parallel shift can be seen. This is also reflected in the SNQs in the legends. After the choice of roof covering (see section 4.2.3), the supporting structure has the greatest influence on the rain attenuation of the roof.

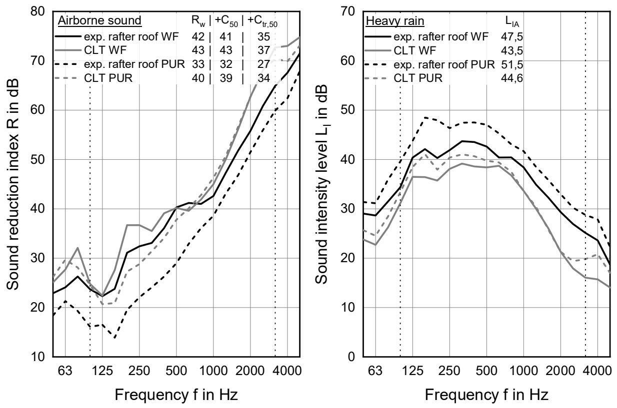

Figure 4. Influence of the load-bearing structure (exposed rafters/CLT) with roof insulation (PUR/WF) and sheet metal covering on the airborne sound insulation (left) and the rainfall sound insulation (right).

4.2.2 Influence of the insulation material type

Figure 5 shows the influence of the type of insulation on the airborne sound reduction index (left) and the rainfall sound insulation (right) of an exposed rafter roof with sheet metal covering. As can be seen, the rigid foam (PUR/EPS) and fibrous (MW/WF) insulation materials behave very differently in terms of airborne sound reduction. However, the differences within these groups of insulation materials are small, with the WF achieving slightly higher sound insulation values in the frequency range below 160 Hz than the MW. Similarly, with EPS slightly higher sound insulation values are achieved than with PUR.

Looking at the rainfall sound insulation (right), we can see that the groups of insulation materials do not differ as clearly as in the case of airborne sound insulation. In any case, the highest levels are achieved with PUR, followed by EPS, MW and finally WF with the lowest levels due to higher mass. A similar picture can be seen for insulation layers with a thickness of 260 mm instead of 200 mm (data not shown), where the advantage of the wood fibre insulation is even clearer. Below 125 Hz, unexpectedly MW, PUR and EPS produce almost the same rain noise levels.

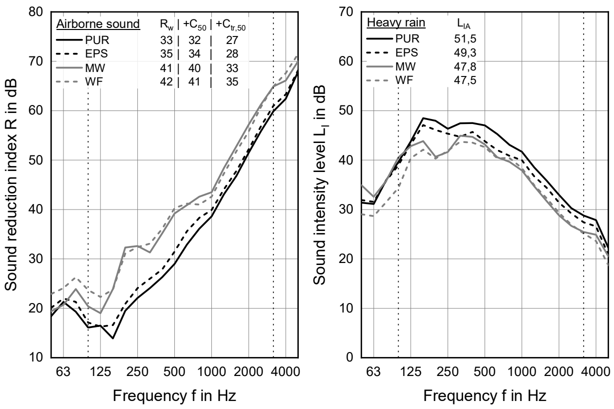

Figure 5. Influence of the insulation material (PUR/EPS/MW/WF) on the airborne sound insulation (left) and the rainfall sound insulation (right) of an exposed rafter roof with sheet metal covering.

If we look only at the SNQs L_{IA} from the rain noise measurement, we see a slightly different picture to that of the R_w-values. The L_{IA}-values of the roofs with fibre insulation materials are very close to each other, whereas the roof with EPS insulation material tends to be closer to the fibre-insulated roofs than the PUR roof as for the airborne sound insulation.

4.2.3 Influence of the roof covering

Figure 6 shows the difference in the roof covering by means of a CLT-roof with MW insulation. The roofing options are concrete tiles, a sheet metal (aluminium), and an FPO roofing membrane. As can be seen, in the mid-frequency range, a higher airborne sound insulation is achieved with a concrete roof than with sheet metal covering. However, in the frequency range below 100 Hz, the roofs with sheet metal covering have higher sound insulation values than those with concrete tiles. This was also observed in [9].

Calculated, the mass-spring-mass-resonance frequency of the concrete tiles on the MW at a CLT-roof (without consideration of the screws) is $f_0 = 31$ Hz, which may explain the lower sound insulation compared to the sheet metal covering. In the higher frequency range, the sound insulation values of the concrete tiles and sheet metal covering approach each other. With FPO a clearly different behaviour can be observed. Due to reduced mass, the airborne sound insulation is very low at low frequencies but rises very steeply due to the absorption properties of the MW underneath and the low stiffness of the FPO itself. Above 250 Hz, this element has the highest sound insulation.

The same variation was also carried out with PUR insulation (data not shown), where the FPO roofing showed the lowest sound insulation above the resonance frequency of the concrete tiles on PUR due to the low absorption properties of the foam insulation. In the case of the PUR insulation, the sheet metal covering also exceeded the sound insulation values of the concrete tiles variant in the frequency range above 1250 Hz, which can be attributed to the higher airtightness of the sheet metal covering.

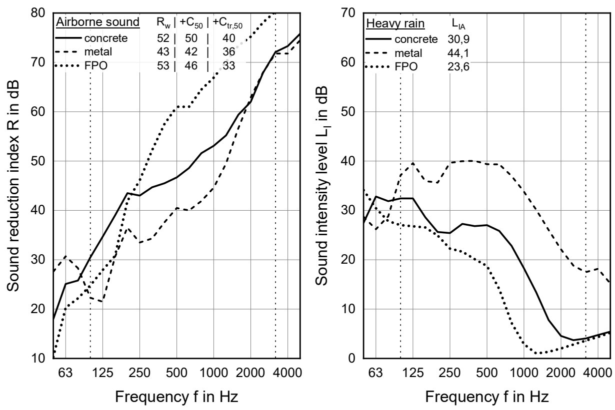

Figure 6. Influence of the covering (aluminium sheet, concrete block, FPO) on the airborne sound insulation (left) and the rainfall sound insulation (right) of a BSP roof with mineral wool roof insulation.

The rainfall sound insulation values in the graph on the right show that the concrete tiles produce significantly lower sound intensity levels than the sheet metal covering over almost the entire frequency range. The FPO variants again behave differently depending on the insulation material. While the lowest sound intensity levels are achieved with a soft MW insulation with a FPO membrane, a much stiffer PUR insulation with a FPO membrane produces the highest rain sound intensity levels, as the variant with a sheet metal covering (data not shown).

The significant differences in the air and rainfall sound insulation provided by the different roof coverings are also illustrated by the SNQs in the legends. The choice of roof covering in combination with the insulation material has the greatest influence on the rain attenuation of the roof.

4.2.4 Influence of screwing of the counter-battening

To investigate the influence of the acoustical bridge caused by the underhead or double-thread screws on the air and rainfall sound insulation, the counter-battening was not screwed to the supporting structure during a comparative measurement but was simply laid loose on the insulation material.

Figure 7 shows the influence of the screw connection on the air and rainfall sound insulation of a CLT-roof with 200 mm WF insulation and concrete tiles. As can be seen, the screwing does not influence the airborne sound insulation up to 400 Hz, but it clearly does above 400 Hz. The drop in the slope of the sound reduction index due to the acoustical bridge is clearly visible. However, these differences do not show up in the SNQs of the airborne sound insulation.

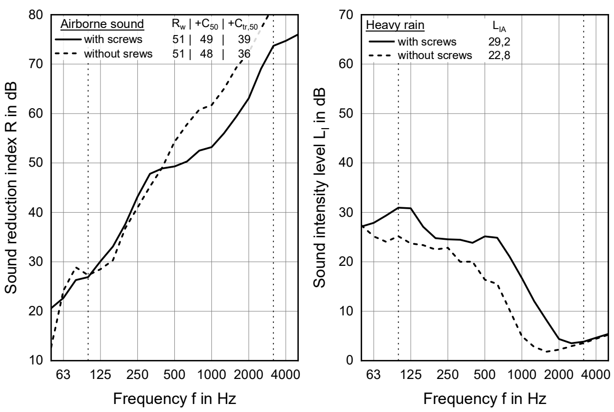

Figure 7. Influence of the screwing of the counter-battening on the airborne sound insulation (left) and the rainfall sound insulation (right) of a CLT-roof with WF insulation and concrete tiles.

Looking at the sound intensity levels in the right-hand graph; the bolted joint has a very significant effect on the rainfall sound insulation over the entire frequency range. This can also be seen from the significant difference in the L_{IA}-values in the legend.

4.2.5 Structural mat / additional weighting

Figure 8 (left) shows the effect of a structured mat underneath the sheet metal covering on the rainfall sound insulation of an exposed rafter roof with a 200 mm EPS insulation. As can be seen, the mat has a positive effect on the rainfall sound insulation above 1000 Hz. The same applies to the airborne sound insulation, which is not shown here, although the structural mat has no effect on sound insulation in the more relevant frequency range below 1000 Hz. The SNQs in the legends therefore hardly differ.

A variant to effectively reduce the rain sound intensity levels is shown in Figure 8 on the right-hand side. Two layers of gypsum board (12.5 mm) have been placed on top of the structural exposed rafter roof to increase its mass. This not only increases the rainfall sound insulation shown, but also the airborne sound insulation, which is not shown here.

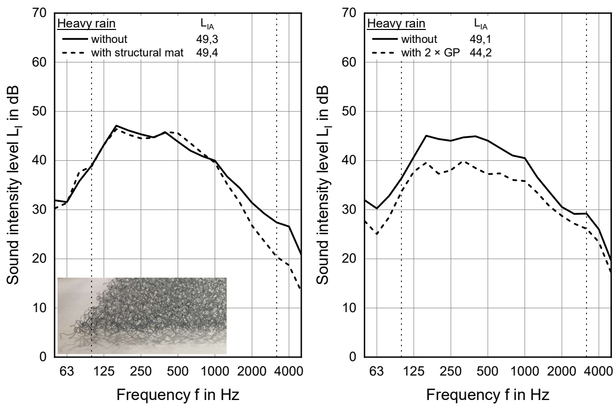

Figure 8. Effect of a structural mat beneath the roofing (left) and additional weight (2 × 12.5 mm Gypsum board) (right) on an exposed rafter roof with EPS insulation and sheet metal covering.

4.3 Correlation of Single-Number Quantities

Figure 9 shows the relationship between the SNQs R_w and L_{IA} of the air and rainfall sound insulation measurements of the investigated roof constructions with sheet metal covering and concrete tiles. As can be seen, the L_{IA}-values of the roofs differ significantly depending on the roofing,

even though their R_w-values are very similar. From the R_w-value of a roof, therefore, it is not possible to conclude on its L_{IA}-value. At the very least, a distinction must be made between the different types of roofing, with only a weak correlation between the R_w- and L_{IA}-values for roofing with concrete tiles. For sheet metal covering, the relationship between air and rainfall sound insulation shown in [10] is more likely to be present. In addition to the regression lines, the graph also shows the standard errors of the regression SER and the coefficients of determination R^2 for both roofing types. The given coefficient of determination for the sheet metal covering indicates a strong correlation between the R_w- and L_{IA}-values. In contrast, the R^2 for the (very few) concrete-covered roofs illustrates the rather low correlation between the R_w- and L_{IA}- values.
Also shown in the graph are the prediction bands, which have a 95 % probability of containing new measured values for the same roofing. Due to the relatively wide prediction bands, a practical prediction of the L_{IA}-value based on the R_w-value is only possible to a limited extent, also for the variants with sheet metal covering.

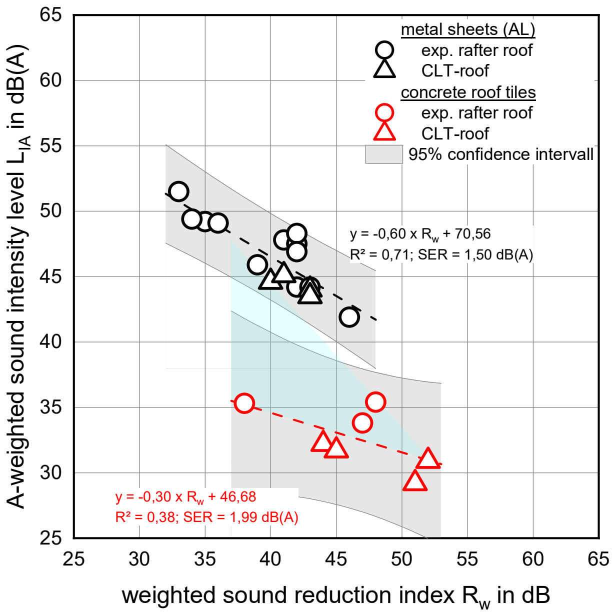

Figure 9. Relationship between the airborne sound insulation (R_w) and the rainfall sound insulation (L_{IA}) of the investigated roofs with concrete tiles and sheet metal coverings. The graphs include linear regressions lines, the standard errors of the regressions SER and the coefficients of determination R^2 for the different coverings.

5. SUMMARY & OUTLOOK

5.1 Airborne and rain noise measurements

As shown, the results of the airborne sound measurements on CLT-roofs in the developed test stand (test opening 10.3 m²) are comparable with those in the standard test stand (test opening 19.8 m²). The deviations found are mostly within the standard deviation according to EN ISO 12999-1:2021, but in some cases they are higher. The reasons for this are mainly due to the different component sizes and the resulting different natural frequencies, what was shown by FEM-simulations. The test openings for frequencies below 100 Hz are also not to be underestimated. In any case, the largest differences can be explained; the suitability of the XL-test stand for airborne sound measurements was shown.
In [9] it was shown that heavy rain according to EN ISO 10140-1:2021 Appendix K can be well realised with a water tank with a perforated bottom according to EN ISO 10140-5:2021 Appendix H. It is important to accurately calibrate the rainwater system and to continuously check the precipitation rate.

5.2 Influence of construction details

The investigations carried out have provided an in-depth look at the air and rainfall sound insulation of lightweight roof constructions. As can be seen, there is only a limited correlation between the SNQs of air and rainfall sound insulation.
It has been shown that the rain sound intensity levels are mainly determined by the covering, although factors such as the roof insulation and the supporting structure can also play a decisive role, especially in combination with the covering. High A-weighted sound intensity sum levels up to 50 dB(A) are achieved, particularly with sheet metal covering. The maximum sound pressure level of 30 dB(A) at night recommended by the WHO [5] will be exceeded by such roofs with heavy rain and may be perceived as annoying by occupants [11].
At present, it is not known to what extent the L_{IA}-values correlates with the subjective perception of rainfall sound insulation, or to what extent roof installations and "ancillary areas" (e.g. the surrounds of roof installations or attics) influence the rainfall sound insulation of roofs. These issues must be addressed in a further research project.

6. ACKNOWLEDGEMENTS

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