Acoustic performance of covering systems with metallic roof tiles: effect of damping layers on rain noise

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Abstract

Weather events directly affect buildings, and despite buildings being composed of construction systems and elements with characteristics that determine the necessary structural safety, modifications can be made to meet other performance requirements. The degree of vulnerability of a building fundamentally depends on the characteristics of its envelope, and in the current context of climate change, alterations in rainfall patterns are one of the main consequences. Insulating rain noise from roofing systems is particularly important in buildings with large spans, as the greater distance between supports leads to less rigidity of the systems. This work aims to analyze the influence of damping layers on the acoustic performance of metallic tile covering systems during the action of artificial rain produced in a laboratory environment. The tests were carried out according to the parameters of ISO 10140, Parts 1, 3, and 5, in 12 different compositions of the roofing systems. For comparison purposes, 4 types of simple tiles were also tested. The results show that, in multilayer systems, filling with glass wool between two tiles is the most efficient, with results of $L_{IA} = 74$ dB for the simple trapezoidal tile TP-30 and $L_{IA} = 52$ dB for the system with glass wool and elastomeric tape.

Keywords: rain noise, sound insulation, covering systems.

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Desempenho acústico de sistemas de coberturas com telhas metálicas: efeito de camadas de amortecimento no ruído da chuva

Resumo

Os eventos meteorológicos afetam diretamente as edificações e, apesar das edificações serem compostas de sistemas e elementos construtivos com características que determinam a segurança estrutural necessária, podem ser realizadas alterações para qualificar os demais requisitos de desempenho. O grau de vulnerabilidade de uma edificação depende fundamentalmente das características de sua envoltória, sendo que, no atual contexto de mudanças climáticas, as alterações nos regimes de chuvas são uma das principais consequências. O isolamento ao ruído da chuva de sistemas de coberturas é particularmente importante em edificações de grandes vãos, por causa da maior distância entre apoios e consequentemente, menor rigidez dos sistemas. Neste trabalho, o objetivo é analisar a influência do uso de camadas para amortecimento no desempenho acústico de sistemas de coberturas com telhas metálicas sob a ação de chuva artificial produzida em ambiente de laboratório. Os ensaios foram realizados conforme parâmetros da norma ISO 10140, Partes 1, 3 e 5, em 12 diferentes composições de sistemas de cobertura. Para efeito de comparações, também foram testadas 4 tipos de telhas simples. Os resultados mostram que, nos sistemas multicamadas, o preenchimento com lã de vidro entre duas telhas é o mais eficiente, sendo obtidos resultados de $L_{IA} = 74$ dB para a telha trapezoidal simples TP-30 e $L_{IA} = 52$ dB para o sistema composto com lã de vidro e fita elastomérica.

Palavras-chave: ruído da chuva, isolamento acústico, sistemas de cobertura.

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1. INTRODUCTION

Roofing systems for buildings with large spans require structural solutions that enable the reduction of supports and/or greater spacing between supports. Systems using metal structures and roofing are constructive solutions that offer faster installation using lighter, standardized parts compared to concrete structures [1].

However, roofing systems composed of metal sheets demonstrate low acoustic performance on rainy days, due to certain characteristics of metallic materials, such as high sound propagation speed and reduced mass [2, 3].

In roofing systems that utilize a single sheet, the factors that most significantly impact noise production during rain include the thickness of the sheets, roof pitch, and roof tile geometry. Akarsh [4] suggests that reduced roof tile thickness and roof pitch result in higher sound pressure levels in single-sheet roofing systems. Furthermore, Sreerag *et al.* [5] indicate that flat metal roof tiles produce higher sound pressure levels than corrugated roof tiles for roof pitches between 10° and 20°.

The use of a damping material between metal elements, such as between two roof tiles, aims to create a mass-spring-mass system. In this system, the roof tiles act as the mass to increase system stiffness, and the core functions as a spring, damping and absorbing stationary sound waves between the roof tiles, thereby reducing noise transmission [3, 6]. In this regard, Lopes and Rigau [7] recommend the use of material with high density and low thickness to increase system mass without significantly increasing the overall roof thickness. Besides acoustic insulation efficiency, the authors also emphasize the need to consider installation complexity when selecting materials.

Noise caused by rain impact on metal roofs can be detrimental in indoor environments, amplified by structure radiation and subsequent airborne noise transmission. Additionally, the internal volume of spaces and their surface reflectivity can create multiple reflections, leading to prolonged sound presence in the environment [8]. Thus, in environments with large-span roofs and high people flow, such as airports, bus and train stations, gyms, etc., noise can be significantly amplified, affecting speech intelligibility and sound information comprehension.

The continuous noise generated by the vibration of elements in roofing systems, especially light roofing systems, can amplify sounds during rain events [2, 9]. Rain noise results from surface vibration of the roofing element caused by the impact of water droplets. Its sound spectrum is altered depending on the structure's mass, material damping, and resulting energy loss [10]. Despite understanding this propagation principle, estimating the behavior of rain energy is challenging due to seasonal variations in droplet size and the influence of the speed of rain fall [9, 11, 12].

Research on precipitation noise generation sources in roofing systems has compared natural and artificial rain [9], the impact of water droplets or solids [13], hail [14], as well as analyses of fall speed [15], intensity [16], and wind speed for driven rain [12]. Identifying droplet distribution and size, directly related to rain type and fall height; is an important aspect to understanding the noise generated. However, it complicates both measurement and laboratory simulation as well as estimation processes [9].

For artificial rain, Annex K of the ISO 10140-1:2021 standard [17] classifies rain according to intensity. Moderate rain is defined as having a flow rate greater than 4 mm/h, intense rain greater than 15 mm/h, heavy rain greater than 40 mm/h, and downpour greater than 100 mm/h. For laboratory studies, the intensity termed heavy rain is typically adopted, as indicated by Chéné *et al.* [18] and Rasa [19].

According to Hopkins and Yu [15], laboratory measurements with artificial rain can be used to compare individual construction elements. However, there is no established correlation with natural rain, as artificial rain in these tests is produced from a standardized source for the characterization of acoustic insulation.

Chéné *et al.* [18] state that since the 1990s, in Europe the approach to addressing rain noise in roofing systems significantly evolved with standards stipulating impact source standardizations for laboratory tests, ensuring experimental procedure reproducibility. As per Baruffa [20], some countries have already implemented requirements for rain noise insulation in buildings in regions with moderate rainfall, while in others the issue is considered relevant due to prolonged rainy seasons with torrential rains.

The general characteristics of efficient roofing systems for rain noise insulation, according to Jaramilo and Steel [21], include multi-layer synthetic membranes, with bituminous membranes providing adequate rain noise control even in rigid insulation panels. The authors note that metallic roofing systems using mineral fiber insulation materials tend to provide higher acoustic insulation levels compared to systems with rigid insulation panels. Additionally, Hopkins [2] suggests that damping layers applied to metal roofs increase the internal loss factor and therefore, the total loss factor.

Massaglia [22] highlights the use of materials such as fillers between roof tiles in roofing systems, typically mineral fibers, glass fibers, or rock fibers. The author concludes by indicating that these materials vary in density from 10 to 200 kg/m³ and that for high acoustic performance, systems should use materials with a density above 50 kg/m³.

Although it is a simple solution, the acoustic performance of multilayer construction systems can be reduced due to internal resonances if air cavities are present [3]. Therefore, the use of sound-absorbing material in multilayer systems can help reduce these resonances and consequently improve acoustic insulation [6].

In this context, this article aims to determine the influence of damping materials in layered configurations on the acoustic performance of metal roofing systems subjected to artificial rain in a laboratory environment.

2. METHOD

The method employed in this study involves characterizing the sound source, artificial rain, planning the tests, and defining the characteristics of the samples. The experimental procedure adhered to the recommendations of the ISO 10140-1:2021 standard [17], divided into two stages: tests with single roof tiles and tests with composite systems.

2.1 Production of artificial rain

This study used the type of artificial rain proposed in ISO 10140-5 [23], which consists of the constant precipitation of liquid water droplets with an intensity classified as "heavy", meeting the following parameters:

- Precipitation rate of 40 mm/h;
- Fall speed of 7.0 m/s; and
- Average droplet diameter of 5 mm.

The precipitation rate is the depth of the water layer created by the rain's distribution on a horizontal surface over a 1-hour interval.

Using the parameters established for volume, speed, droplet generation hole diameter, and water tank height, the dimensions of the water tanks were determined. For the perforated plate, 10 mm thick polycarbonate was used, and the hole pattern followed the drilling and division standard developed by Donohue and Pearse [10]. This adaptation was necessary because ISO 10140-5 does not specify a division standard and/or spacing for these holes, which defines the conditions of water entry and exit. The standard only specifies approximately 60 holes per m^2 with a diameter of 1 mm for the heavy artificial rain standard. Therefore, the perforated plate was manufactured as illustrated in Figure 1.

The chamber in which the tests were conducted consists of two overlapping rooms, separated by a 12 cm thick solid concrete slab, double brick masonry walls with a 2 cm mortar coating on both faces. A 2.35 m by 4.40 m space was arranged in the slab for sample installation, with a metal support structure for the samples. A 10 mm thick EVA layer was used to suppress

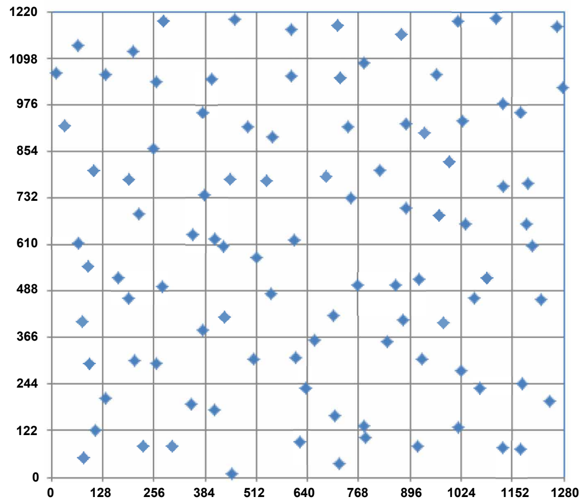

Figure 1: Drilling pattern adopted in the tests (adapted from Donohue and Pearse [10]).

flank transmission (Figure 2), and a PU-based sealant was applied around the perimeter of the sample to ensure the watertightness of the system during artificial rain production (Figure 3).

Figure 2: Space for sample installation.

Figure 3: Sealant applied at the joints between the roof tile and EVA.

The water tank characteristics and water drop mechanics conformed to the specifications of ISO 10140-5 [23], with the adoption of a closed-cycle system in the installations (Figure 4) for water supply, consisting of:

- Water Tank 1: production and distribution of droplets as water passes through the perforated plate (Figures 5 and 6);
- Water Tank 2: feeds Water Tank 1 with a constant volume and pressure;
- Water Tank 3: feeds Water Tank 2 and maintains a constant water volume in Water Tank 2 for up to 2 hours of testing; and
- Water Tank 4: stores water used during testing and supplies Water Tank 3 via a manually operated electric pump.

The water collection from precipitation, after flowing through the sample, is conducted by a metal gutter installed at the sample's front face. The water is then directed through a 100 mm diameter PVC pipe outside the chamber to Water Tank 4, and subsequently pumped to Water Tank 3.

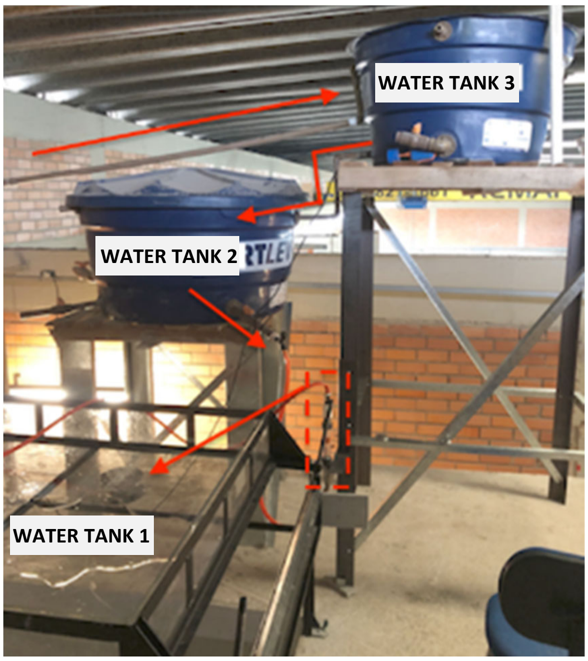

Figure 4: Water tank system.

2.2 Laboratory tests

The measurement procedure was conducted as proposed in ISO 10140:2021 [17], with sound intensity determined based on sound pressure level, the excitation area of the roof, and the

Figure 5: Internal view of Water Tank 1 with the perforated plate.

Figure 6: Structure for supporting the acrylic perforated plate of Water Tank 1.

reverberation time and volume of the chamber beneath the sample.

Measurements were taken at 12 points to obtain the sound pressure level in the receiving chamber, with four (4) microphone points and three (3) impact points. To change the rain impact points, Water Tank 1 was laterally moved on the rails of the metal structure.

Reverberation times were measured at 12 measurement points using the precision method proposed by ISO 3382-2 [24], with 3 decay rates at each point. The results were expressed using the T20 indicator.

The equipment used for the measurements included B&K's Type 2270 Sound Level Meter; omnidirectional Omnipower Sound Source Type 4292-L; Microphone Preamplifier model ZC-0032; ½-inch Free-Field Microphone Type 4189; Sound Calibrator Type 4231; and Power Amplifier Type 2734.

The sound intensity levels obtained in third-octave bands (L_I) and the A-weighted sound intensity level (L_{IA}, expressed as a single value) were used to evaluate the systems.

2.3 Sample characteristics

The first stage of the tests was single roof tiles without structural damping elements or glass wool filling, as presented in Table 1.

Upon single samples stage, the compositions of the multilayer roofing systems were defined in accordance with characteristics indicated by other authors [2, 7, 21, 22]. Therefore, upper and lower roof tiles with different profiles were used, along with combinations of glass wool and vibration damping elastomeric materials.

The composite samples were installed over the roof tile that showed the highest L_{IA}, with the following variations:

- Use of frame profiles with different heights of 30 mm and 100 mm;
- Utilization of 50 mm thick glass wool between the roof tiles; and
- Installation of elastomeric tape in contact with the frames and the upper roof tile.

Although some authors recommend the use of elastomeric material in the form of membranes across the entire roof area [7, 21], this study opted for the use of elastomeric tape applied only at the center of the longitudinal axis of the metal frame profile, to avoid altering the anticipated load on the structure. The compositions of the samples tested in the second stage are listed in Table 2.

The space between the upper and lower roof tiles varied according to the height of the frames. Therefore, in compositions using 100 mm frames and glass wool filling, there remained a void between the wool and the upper roof tile. In contrast, in compositions with the 30 mm frame, the glass wool was compressed, resulting in an increased density of the filling (Figure 7).

Table 1: Characteristics of Single Roof Tiles.

Identification	Type of Roof Tile
1	Zipper
2	Corrugated
3	Trapezoidal TP-40
4	Trapezoidal TP-30

Table 2: Characteristics of Composite Systems.

Identification	Space (mm)	Material
5	30	Elastomeric tape and glass wool
6	30	Elastomeric tape
7	30	Glass wool
8	30	—
9	100	Elastomeric tape and glass wool
10	100	Elastomeric tape
11	100	Glass wool
12	100	—

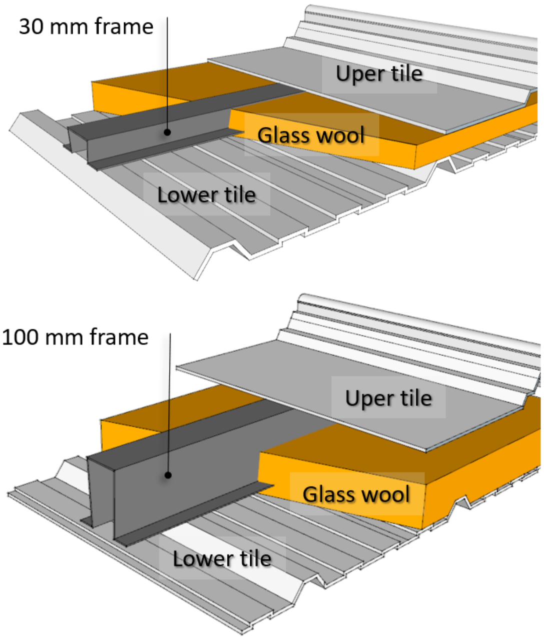

Figure 7: Composite systems with glass wool.

The installation of the frame and the glass wool in the system can be seen in Figure 8. Figures 9 to 11 illustrate, respectively, the elastomeric tape adhered to the 30 mm frame, the installation of the frame profile attached to the lower roof tile, the placement of the glass wool, and the installation of the upper zipper roof tile.

Figure 8: Installation of the roofing system in the chamber.

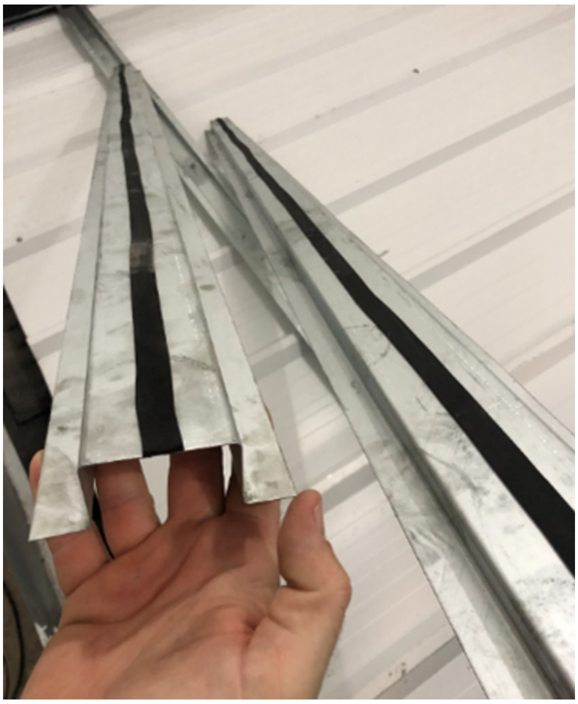

Figure 9: Damping tape on the frame profile.

Figure 10: Installation of the glass wool.

Figure 11: Installation of the upper zipper roof tile.

3. RESULTS AND DISCUSSION

Figure 12 presents the results from Stage 1, where the four simple samples were tested without additional layers.

In the results for the Roof Tile 1 test, the distinct curve behavior of a zippered roof tile with a trapezoidal stiffener is observed, showing higher values in the 630 Hz band. This can be attributed to the different fixing system between the roof tiles and the metal upright. The sample is suspended relative to the fixing structure, without direct contact with the purlin, and is connected through a clip with an expander. This type of fixing system allows the roof tile to operate independently of the structural system, enabling its flat surface to remain free in relation to the fixing structure. This roof tile type has the largest flat area, contributing to the impact of the droplet at nearly 90°.

When examining the results by third-octave bands, compared to other systems one perceives that Roof Tile 1 (zippered tile) presented a higher sound intensity level in 200 Hz to 800 Hz frequency bands. This may be due to the roof tile's low rigidity, having a larger flat area than the others, as also noted in the study by Sreerag *et al.* [5]. However, at mid and high frequencies Roof Tile 1 showed lower values than Roof Tiles 3 and 4, both with trapezoidal geometry.

Figure 13 allows for analysis of the results from tests with composite samples consisting of two roof tiles (lower TP-30 and upper zippered), with a 30 mm frame, with and without glass wool between roof tiles. Compositions 5 and

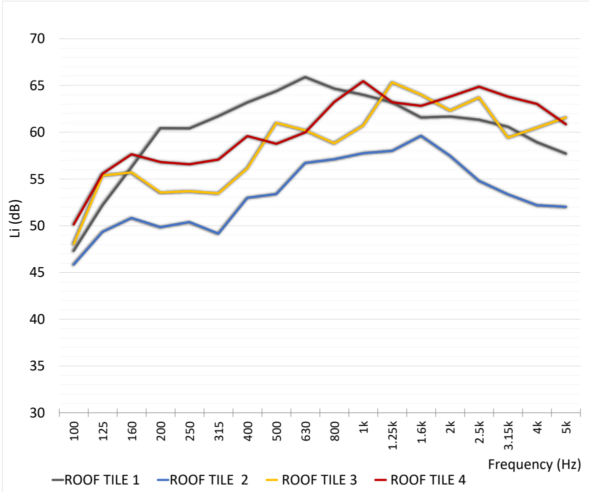

Figure 12: Results of samples with simple roof tiles.

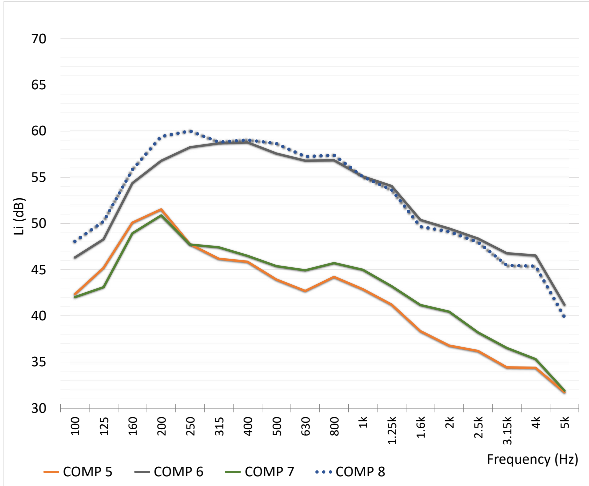

Figure 13: Results of compositions with a 30 mm frame.

7 include a glass wool core, with and without damping tape, respectively. It is observed that the behavior of the samples is similar at low frequencies, while at higher frequencies (above 500 Hz), differences increase, with Roof Tile 5 demonstrating better performance. In the results for Compositions 6 and 8, which do not contain glass wool, it is observed that installing elastomeric tape did not influence the results. The results of Compositions 5 and 7 demonstrate the efficiency of the glass wool core in composite roof tiles, with a significant reduction in (L_I) values from the 300 Hz band and above.

The results of compositions with a 100 mm frame can be seen in Figure 14. Compositions 9 and 10 include damping tape, Composition 11 has a glass wool, while Composition 12 has neither damping material nor tape. Comparing

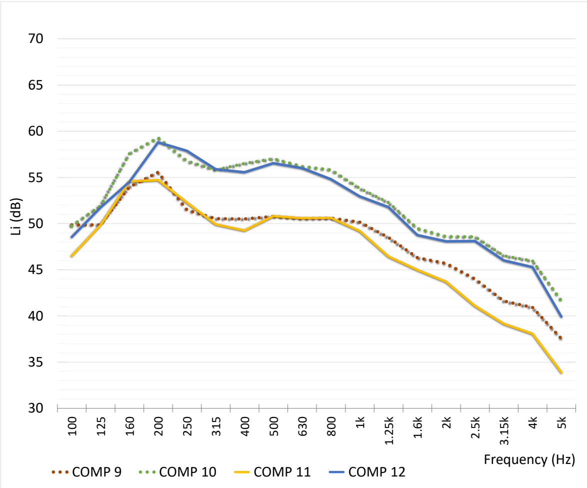

Figure 14: Results of compositions with a 100 mm frame.

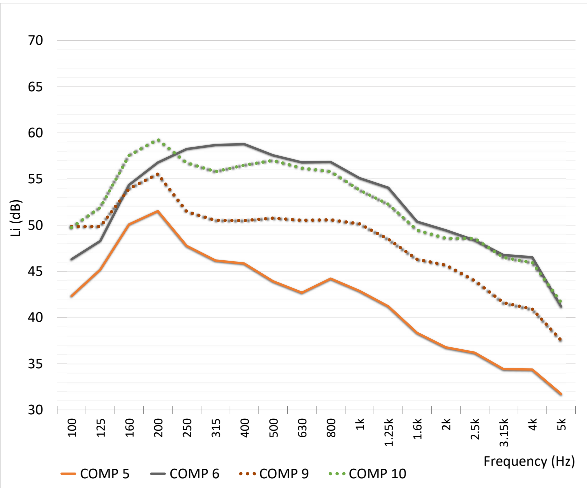

Figure 15: Results of compositions with damping tape.

the results of Compositions 9 to 12, a similarity in the graphic profile of third-octave bands is noted, with a decrease in sound intensity levels starting at the 200 Hz band. In Compositions 10 and 12, which do not contain glass wool, similar values are observed in all frequency bands analyzed.

In Figure 15, when comparing the results of compositions with tape, similarities can be observed in the results of Compositions 6 and 10, which lack filling, with 30 mm and 100 mm frames, respectively. In these samples, the increasing air chamber height did not significantly alter results across frequency bands.

Analyses regarding the influence of using glass wool to fill the space between roof tiles are extracted from the results of Compositions 7, 8, 11, and 12, compared to those with simple roof tile (Figure 16). The results of all the composite systems represented reductions from the 500 Hz band onwards compared to the simple roof tile. In samples without tape or wool, Compositions 8 and 12, the increase in frame height resulted in reductions in the 200 Hz to 1.5 kHz bands. Furthermore, compared to simple roof tile, there was a reduction in acoustic insulation in the 200 Hz to 315 Hz bands. In Figure 16, the influence of the glass wool density can also be observed by comparing Compositions 7 and 11. With a 30 mm frame in Composition 7, the wool was denser and produced lower results across all frequency bands.

The comparison between the A-weighted values can be seen in the graph in Figure 17, where gray bars represent the results for simple roof tile samples, blue bars for 30 mm frame samples, and green bars for samples with a 100 mm frame. The notable influence of the glass wool filling between roof tiles on standard rain noise reduction is evident, specifically for Compositions 5 and 7. The addition of glass wool between the roof tiles resulted in a reduction in artificial rain sound transmission by 12.2 dB. The tests for Compositions 7 and 8 show an 11 dB reduction in rain sound transmission.

The A-weighted results found in this study for compositions with simple roof tiles are consistent with laboratory studies by Chéné *et al.* [18] and Rasa [19], which indicate (L_{IA}) values above 70 dB for metal sheet roofing.

4. CONCLUSIONS

Defining solutions for adequate acoustic insulation in roofing systems for rainy scenarios can present a certain complexity, as the variables that influence the magnitude of precipitation are numerous and difficult to control. Therefore, there is still concern about identifying the most suitable source for experimental tests, comparing real rain situations to artificial rain produced in laboratories. However, producing standardized artificial rain involves controlling many variables, which is necessary to validate results

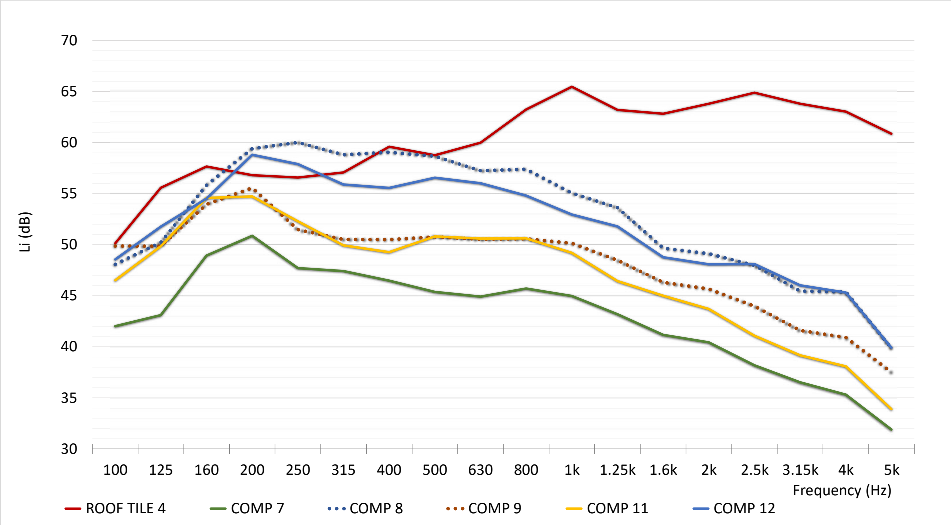

Figure 16: Comparison between compositions with and without glass wool.

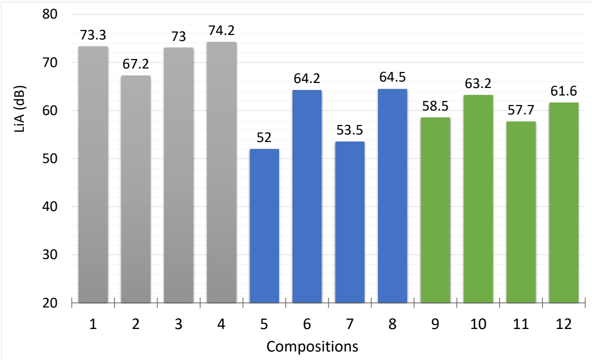

Figure 17: A-weighted results (L_{IA}).

from different laboratories for the characterization of construction systems.

This study addressed a specific situation of systems used in retrofitting roofing, by installing layers on top of existing roof tiles. Such installation allows for the uninterrupted continuation of internal activities within the building under renovation. Adopting these solutions that ensure greater increased sound transmission loss has shown high potential to reducing rain noise, as well.

Simple and double roofing systems have been analyzed in this study, with variations in the glass wool filling between the roof tiles and the use of elastomeric tapes at isolated points. Roofing systems with only one roof tile showed high sound levels, indicating their significant contribution to the degradation of acoustic conditions in the internal environments below them. This situation can be found in environments such as airports, bus stations, and event venues, which then require appropriate conditions in order to clearly understand face-to-face verbal communication.

This study concludes that damping with elastomeric material at isolated points of the roof tiles contributes to increasing rain sound insulation. However, the greatest efficiency to an increase in rain sound insulation is achieved by filling the voids between roof tiles with glass wool. It is noteworthy that increasing the height of the frame profile, and consequently the layer of air between the roof tiles, does not improve the roofing system's acoustic insulation.

The results presented through this study can not only serve as a basis for new architectural and engineering projects involving but not necessarily limited to buildings with large spans but can also provide qualified information for the development of research and practical projects seeking acoustic performance.

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