IMPACT NOISE ISOLATION OF FLOOR SYSTEMS USING PLASTERBOARD CEILING WITH AND WITHOUT PET WOOL

ISOLAMENTO AO RUÍDO DE IMPACTO DE SISTEMAS DE PISOS UTILIZANDO FORRO DE GESSO COM E SEM LÃ DE PET

AISLAMIENTO AL RUIDO DE IMPACTO DE SISTEMAS DE PISOS UTILIZANDO TECHO DE YESO CON Y SIN LANA DE PET

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ABSTRACT

The acoustic insulation against impact noise of two floor systems was evaluated, using plasterboard lining installed under a prefabricated ribbed slab with prestressed joists, combined with PET wool in the lining. The tests followed the requirements of the ISO 16283-2 standard (ISO, 2020), and the data in accordance with the ISO 717-2 standard (ISO, 2020). Performance was classified by the values of the $L'_{nT,w}$ results established in the Brazilian standard NBR 15575-3 (ABNT, 2021). The flooring systems were composed of ceramic floors, vinyl floors, laminated wood floors and mechanical decoupling of the subfloor with glass wool and recycled rubber. Two situations were tested, with plasterboard lining (150 mm gap), and the second with filling the gap with 50 mm PET wool. From the experiments it was possible to conclude that the placement of 50 mm of PET wool blanket in the gap improved impact noise isolation by up to 3 dB, only in systems where there is no mechanical decoupling. Note that the better the impact noise insulation of the flooring system without PET wool in the lining, the less efficient the placement of this fibrous material will be.

KEYWORDS

Architectural acoustics. Sound insulation. Building performance.

RESUMO

Avaliou-se o isolamento acústico ao ruído de impacto de dois sistemas de piso, usando forro de gesso cartonado instalados sob uma laje pré-fabricada nervurada com vigotas protendidas, combinados com lã PET no entreforro. Os testes seguiram os requisitos da norma ISO 16283-2 (ISO, 2020), e os dados de acordo com a norma ISO 717-2 (ISO, 2020). O desempenho foi classificado pelos valores dos resultados de $L'_{nT,w}$ *estabelecidos na norma brasileira NBR 15575-3 (ABNT, 2021). Os sistemas de piso eram compostos por pisos cerâmicos, pisos vinílicos, pisos laminados de madeira e com desacoplamento mecânico do contrapiso com lã de vidro e borracha reciclada. Foram testadas duas situações, com forro de gesso acartonado (entreforro 150 mm), e a segunda com preenchimento do entreforro com lã PET 50 mm. A partir dos experimentos foi possível concluir que a colocação de 50 mm de manta de lã PET no entreforro melhorou em até 3 dB no isolamento de ruído de impacto, apenas em sistemas onde não há desacoplamento mecânico. Nota-se que quanto melhor for o isolamento de ruído de impacto do sistema de piso sem lã PET no entreforro, menos eficiente será a colocação desse material fibroso.*

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PALAVRAS-CHAVE
Acústica arquitetônica. Isolamento sonoro. Desempenho de edificações.

RESUMEN
Se evaluó el aislamiento acústico al ruido de impacto de dos sistemas de piso, utilizando techo de yeso cartón instalado debajo de una losa prefabricada nervada con viguetas postensadas, combinados con lana PET en el entretecho. Las pruebas siguieron los requisitos de la norma ISO 16283-2 (ISO, 2020), y los datos de acuerdo con la norma ISO 717-2 (ISO, 2020). El rendimiento fue clasificado según los valores de los resultados de $L'_{nT,w}$ establecidos en la norma brasileña NBR 15575-3 (ABNT, 2021). Los sistemas de piso estaban compuestos por pisos cerámicos, pisos vinílicos, pisos laminados de madera y con desacoplamiento mecánico del contrapiso con lana de vidrio y goma reciclada. Se probaron dos situaciones, con techo de yeso cartón (entretecho de 150 mm), y la segunda con el llenado del entretecho con lana PET de 50 mm. A partir de los experimentos, se pudo concluir que la colocación de 50 mm de manta de lana PET en el entretecho mejoró hasta 3 dB en el aislamiento del ruido de impacto, solo en sistemas donde no hay desacoplamiento mecánico. Se observa que cuanto mejor sea el aislamiento acústico al ruido de impacto del sistema de piso sin lana PET en el entretecho, menos eficiente será la colocación de este material fibroso.

PALABRAS CLAVE
Acústica arquitectónica; Aislamiento acústico; Desempeño de edificaciones.

1. INTRODUCTION

The growing verticalization of cities has driven a search for new technologies that allow for lower costs and greater agility in construction times. Furthermore, the use of increasingly larger spans in projects has brought a demand for construction techniques that meet this need, such as, for example, the use of slab prestressing systems. Thus, it became imperative that this search for optimizing construction processes did not compromise the quality of the products delivered to users (PEREYRON; SANTOS, 2007).

In view of the improvement in Brazilian housing, the Brazilian performance standard, NBR 15.575 (ABNT, 2021a), came into force in Brazil in July 2013, which determined the requirements regarding safety, habitability and sustainability in residential housing, relating them to the construction systems that make up these buildings. In 2021, this regulation was updated.

Therefore, among the requirements set out in NBR 15,575 (ABNT, 2021a), it is essential that a reflection be carried out on the acoustic performance of the materials that make up the flooring systems, even in the design, execution and use phases of residential buildings.

This research aimed to evaluate the acoustic insulation behavior against impact noise of two different flooring systems, using a plasterboard lining installed under a prefabricated slab of prestressed joists and ceramic tiles, combined or not, with PET wool in the interior of the gap. Furthermore, it classifies the acoustic performance of the tests according to the requirements established by the Brazilian standard ABNT NBR 15.575-3 (ABNT, 2021).

2. LITERATURE REVIEW

The Brazilian standard NBR 15.575 (ABNT, 2021) established requirements for the safety, habitability, and sustainability of residential buildings to improve the performance of dwellings. Thus, it is important to evaluate the impact of sound insulation performance on different floor systems. A few studies were found in the literature. For instance, Lee et al. (2016) stated that designers must evaluate the sound insulation conditions between apartments, whether by a wall or slab. Oliveira and Mitidieri Filho (2012) emphasized the significance of acoustic performance in the design process, considering various types of noise generated by activities such as walking, moving furniture, or objects falling (MORENO; SOUZA; PENTEADO, 2017). Post-occupancy studies conducted on dwellings indicated that the main complaint of users was related to the annoyance produced by impact noise caused by neighbors (ANDARGIE; TOUCHIE; O'BRIEN, 2021.; FRESCURA and LEE, 2021.; SANTANA; MAUÉS; SOEIRO, 2017).

Additionally, an on-site assessment carried out in four different apartments complexes with one hundred (100) residents from each location, totaling four hundred people (400), found that the answers were significantly affected by impact noise sensitivity and the properties of the floor system used (PARK and LEE, 2019). An example of a solution to noise insulation for floor systems was the execution of a suspended ceiling in the noise reception area for airborne and impact noise (SANTOS, 2012).

Impact noise is propagated through structural links, so mechanical decoupling of rigid structures is the best solution (SANTOS, 2012). Studies like this one are necessary to investigate potential solutions, such as ceiling systems, which are normally used for airborne noise isolation when decoupling is not possible.

Some studies indicated the inefficiency of ceilings for homogeneous floor systems like reinforced concrete slabs (MEDEIROS, 2003.; RYU; SONG; KIM, 2018.; MAXIMILIAN; PAUL; THOMAS, 2021). Unlike what was found (in computer simulations) when it was compared to slabs composed of hollow clay blocks with more complex materials to impact sound propagation (OLIVEIRA; PATRÍCIO. 2017.; SOUZA; PACHECO; OLIVEIRA, 2020).

Although the execution of a suspended ceiling can be inefficient for the sound insulation of homogeneous slabs like reinforced concrete, this technique could be efficient for heterogeneous slabs since there are layers of materials and, consequently, change the impedance due to the vibrational responses of the systems (MAXIMILIAN; PAUL; THOMAS, 2021). Alonso, Patrício and Suárez (2019) evaluated the impact of sound insulation and concluded that the acoustic behavior of floors differs significantly, whether homogeneous or not.

Thus, it is important to determine the efficiency of installing ceiling systems to mitigate the impact noise of heterogeneous flooring systems like hollow clay floor slab blocks. As mentioned by the authors (NOWOTNY and NURZYNSKI. 2020), the effect of floor coating on decreasing impact sound pressure level needed to be corrected because the acoustic properties of the coating depend on the number of layers over the slab (NOWOTNY and NURZYNSKI. 2020).

Light wooden ceilings and floors had the potential to provide superior insulation compared to systems based only on concrete slabs, if mechanically decoupled from external elements (CHUNG et al., 2010). This type of ceiling needs to include systems components such as tie rods with damping, fiberglass wool, and layers of sawdust mixture to avoid vibration (CHUNG et al., 2010).

The studies that used wall-to-wall ceilings (without connections to the slab) were compared with the performance of suspended ceilings under the slab. Differences of 2 to 7 dB and 2 to 8 dB were found for tests done with a standard impact machine and rubber ball, respectively (KIM; CHO; KIM, 2021). For floating floors, a low resonant frequency of mass-spring-mass systems and the high damping in the resilient layer material allow frequency-dependent improvements of up to 10 dB (MAXIMILIAN; PAUL; THOMAS, 2021).

This can be achieved by a low rigidity of the support system and the choice of a ceiling with high mass (MAXIMILIAN; PAUL; THOMAS, 2021). From the point of view of the two possibilities of acoustic conditioning (insulation and sound absorption), ceilings with microperforated panels using glass wool in the interlining performed a reduction of 6 dB for the weighted impact sound pressure level. Also, they presented a coefficient of absorption of 0.6 in the 100 Hz band (RYU; SONG; KIM, 2018).

Furthermore, among the variety of options for ceiling systems found on the market, there is the possibility of using a plasterboard ceiling with sound-absorbing material in the ceiling to improve the insulation against impact noise. One material that could be used for this purpose is fibrous, such as those composed of polymeric waste like polyethylene terephthalate (PET), widely used in the packaging industry and mainly in producing plastic bottles (KLIPPEL FILHO; LABRES; PACHECHO, 2017).

In Brazil, fibrous materials such as glass or rock wool are commonly used in civil construction. These materials have specific conditions such as thermal conductivity, bulk density, chloride, fluoride, silicate, sodium content, and moisture absorption (ABNT, 2014.; ABNT, 2013).

For example, Medeiros (2003) tested several compositions of plasterboard ceilings executed under a solid slab, some of which contained rock wool. In these tests, the rock wool placed in the ceiling had a minor influence on the impact noise insulation provided by the floor system, although it improved the performance for low frequencies. Also, it is important to note that the materials used as sound absorbers comply with the technical standards and current fire safety legislation (TORMOS; FERNÁNDEZ; RAMIS-SORIANO, 2011).

3. MATERIALS AND METHODS

The Brazilian Standard ABNT NBR 15.575-1 (ABNT, 2021) established the minimum building performance requirements. Different aspects are mentioned, such as acoustics, thermal, lighting, structural, fire safety, and water impermeability. For impact noise, the required performance criteria are divided into three categories: minimum (M), intermediate (I), and superior (S) (ABNT, 2021). Furthermore, the methodology of measurements must be carried out according to the ISO 16.283-2 standard (ISO, 2020). Finally, the values provided in NBR 15.575-3 (ABNT, 2021) were used to classify the performance of floor systems in terms of impact noise, for cases of separation of autonomous housing units, as presented in Table 1.

Separating element	$L'_{NT,w}$ (dB)	Performance
The floor system of autonomous housing units over dormitory.	66 to 80	Mínimum (M)
	56 to 65	Intermediate (I)
	≤ 55	Superior (S)
Flooring systems areas for collective use (leisure and sportsactivities, such as home theater, gym, party room, games room, collective bathrooms and changing rooms, kitchens, collective laundries, and circulations) over dormitory of autonomous housing units.	51 to 55	Mínimum (M)
	46 to 50	Intermediate (I)
	≤ 45	Superior (S)

Table 1: Weighted standardized impact sound pressure level classification ($L'_{nT,w}$)
Source: ABNT, 2021.

3.1. TESTS SETUPS

The acoustic tests were carried out at the building and material laboratory of the Federal University of Santa Maria in a chamber built specifically for impact noise tests, according to standard ISO 16283-2 (ISO, 2020). The chamber walls were made of solid concrete block masonry with nineteen centimeters (19) of thickness and coated with three (3) centimeters of roughcast and plaster on both sides of the walls.

Above these walls, a prefabricated slab was built with prestressed slab joists with clay elements and a total

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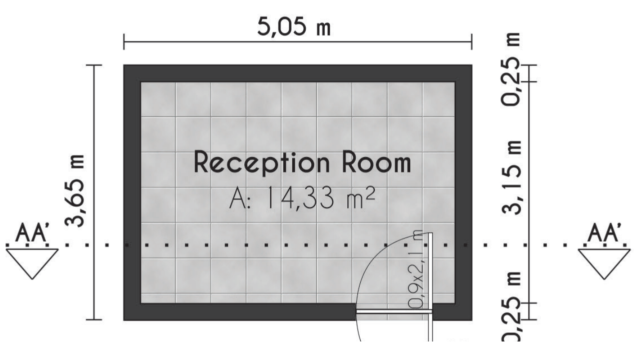
thickness of 13.5 cm. The prestressed joists had dimensions of 10 cm in width, a height of 8.5 cm, and 4 longitudinal steel bars with a diameter of 5 mm. The clay tiles had dimensions of 37 cm, 8 cm, and 20 cm for width, height, and depth, respectively. The distance between the axis of the joists was 47 cm. The thickness of the concrete above the slab was five (5) centimeters and was made with characteristic compressive strength of 25 MPa and a steel mesh of 4.2 mm, spaced every 15 to 15 cm. Also, it was positioned electrical conduits of 0.75 inches in diameter embedded in the concrete.

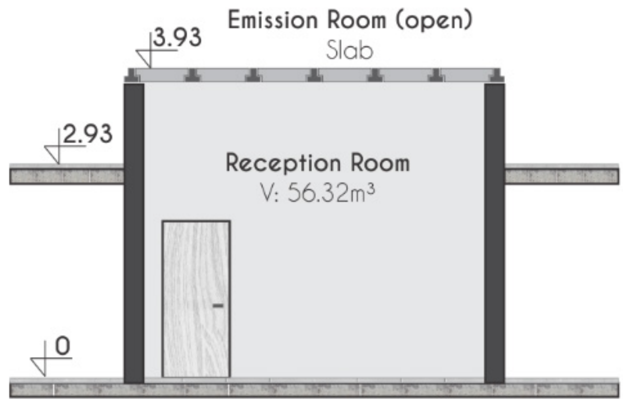
Figure 1 shows an image of the tested prestressed slab joists with clay elements. Figures 2 (a) and (b) present the dimensions of the concrete chamber, showing the floor plan of the chamber and the section with the details of the emission and reception room and the support of the slab.

Figure 1: Slab assembled in the test site
Source: The authors.



(a)

Figure 2: Details of test: (a) floor plan and (b) section AA'
Source: The authors.



(b)

3.2. MATERIALS USED IN THE TESTS

An accredited PET wool blanket supplier was chosen, whose material was classified as Classes II-A or higher, according to IT nº 10 of CBPMESP (OLIVEIRA and MITIDIERI FILHO, 2012). PET wool was composed of polyester fiber without any addition of resin, with a surface density of 0.350 kg/m^2, a thickness of 50 mm, and an apparent specific mass of 7 kg/m^3.

To make it possible to conduct tests with different coatings and resilient materials, a subfloor plate was positioned superimposed on the slab, together with different types of coatings. This research simulates, in a laboratory, the field situation, using elements of structural connections and electrical installations on the slab to represent an evaluation of the finished construction situation. Thus, according to what is prescribed in the ISO 10140-3 and ISO 10140-4 standard (ISO, 2021), the subfloor size used had dimensions of 1 per 1 m. In addition, the minimum dimensions established must exceed 0.35 per 0.35 m.

The subfloor plates were produced with mortar, and cement and sand proportions in volume were 1:4, reaching a mean compressive strength of 20 MPa. Figure 3 presents an example of the subfloor used in tests. The coating materials used in this research are shown in Table 2 and illustrated in Figures 4 (a), (b), and (c).

Figure 3: Tested subfloor sample.
Source: The authors.

Coating	Characte-ristics	Dimensions	Density (kg/m³)
Ceramic Figure 4 (a)	Porcelain	500 x 500 x 9	2200
Vinyl Figure 4 (b)	Plate	200 x 1220 x 4	600
Wood laminate Figure 4 (c)	Clicked ruler	445 x 1357 x 8	800

Table 2: Coating materials used in measurements.
Source: The authors.

(a)

Figure 4: Coatings used in the tests: (a) ceramic, (b) vinyl and (c) wood laminate
Source: The authors.

(b)

(c)

A glass wool blanket with a density of 60 kg/m³ (thickness of 15 mm) and a recycled rubber pad with a density of 600 kg/m³ (thickness of 5 mm) were used as resilient materials, used to improve system performance, and evaluate the ceiling's ability to improve this sound insulation for impact noise further. Figure 5 demonstrates an example of the presentation of glass wool (a) and recycled rubber (b) tested in this study.

(a)

Figure 5: Resilient materials for floating floor: (a) 15 mm glass wool, (b) 5 mm recycled rubber
Source: The authors.

(b)

The metal structures were fixed along the chamber's perimeter at 150 mm below the slab for ceiling mounting, as depicted in Figure 6. For each metal bar, five supports were used to fix the metal structures to the joists.

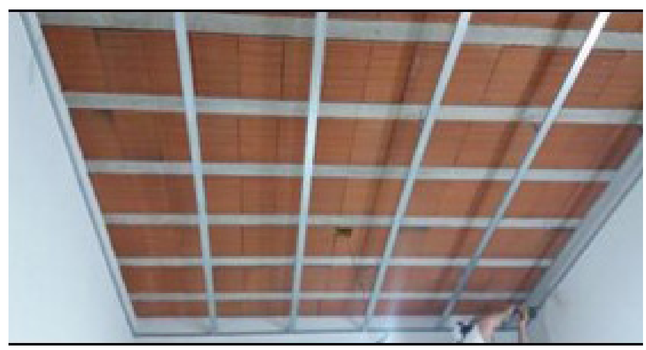


Figure 6: Metal bars for the plasterboard ceiling system
Source: The authors.

The plasterboard plates were fixed to the metallic bars using a combination of two systems of materials compositions to test the impact noise insulation as follows, the first one was called the reference or "PB", and was composed of a plasterboard ceiling and a plenum of 150 mm gap; the second one was called "PB+PW", and was composed of 50 mm of PET wool blanket to the reference component of the lining. Thus, after the first tests, the PET wool blanket was positioned on the plasterboard with a laser level and a metallic beacon. In both cases, the detail of the execution of the lining at the encounter with the wall was done respecting the angle and joint treatment. Figure 7 shows the PET wool in the lining and the metal structure fixed to the joist.

Figure 7: PET wool positioned in the lining
Source: The authors.

Finally, a treatment was done between gypsum boards with a plaster-based putty coat and micro-perforated tape, ending with another putty coat. Gypsum-based putty was also applied in the spots where the plates were perforated. Figure 8 presents the final appearance of the ceiling under the slab.

3.3. INSTRUMENTS OF TEST

Figure 8: Executed plasterboard ceiling
Source: The authors.

The material and building construction laboratory provided the equipment for the tests listed in Table 3.

Equipment	Manufacturer	Model
Amplifier	01 dB	AMPLI 12
Sound level calibrator	01 dB	4230, classe 1
Dodecahedral acoustic source	01 dB	OMNI 12
Standard impact machine	01 dB	CALPEST-one
Sound pressure level meter	01 dB	Black Solo, classe 1
Capacitive microphone	GRAS	MCE 212
Microphone preamp	Metravib	PRE 21 S
Digital thermo--hygrobarometer	Instruterm	THB 100

Table 3: Instruments of test
Source: The authors.

The 01dB sound level meter black solo is a class 1 accuracy equipment according to specifications provided by the manufacturer. The calibrator used is by the procedure of CETAC-LCA-PC06 "sound pressure level meter calibration" and CETAC-LCA-PC-03 "sound pressure level meter calibration" found in IEC 61672-3:2013 (IEC, 2013) and IEC 60942:2017 (IEC, 2017) requirements for the calibration of sound pressure level meter and sound level calibrator, and the equipment was calibrated before its use by an accredited institute.

The methodological procedures for the test field followed the recommendations of ISO 16.283-2 (ISO, 2020). The test simulation of different field situations was carried out at the acoustic laboratory. The ISO standard 16.283-2 (ISO, 2020) establishes the test procedure to obtain the impact noise insulation measurements for standardized impact sources obtained in a room with a volume between 10 m³ and 250 m³, for 1/3 octave frequency bands of 50 Hz and 3150 Hz. A free field fixed microphone was used, although the sound level meter used had the inside correction for diffuse field measurement. Table 4 explains the number of impact source points and mic positions in the ISO standard 16283-2 (ISO, 2020).

Reception room area (m²)	Equipment	Number of positions
< 20 m²	Standard impact machine	4
	Fixed microphone	4

Table 4: Instruments of test
Source: (ISO, 2020).

3.4. MEASUREMENTS PROCEDURES AND DATA ANALYSIS

The Brazilian standard ABNT NBR 15.575-3 (ABNT, 2021) indicates that impact noise tests for floor systems must be carried out in accordance with ISO standard 16.283-2 (ISO, 2020). Therefore, the reverberation time, background noise level, and standardized impact sound pressure level were determined at the experimental tests.

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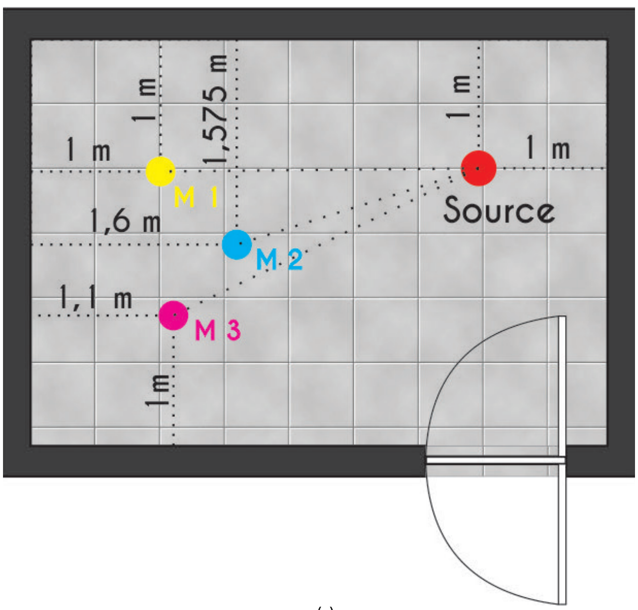
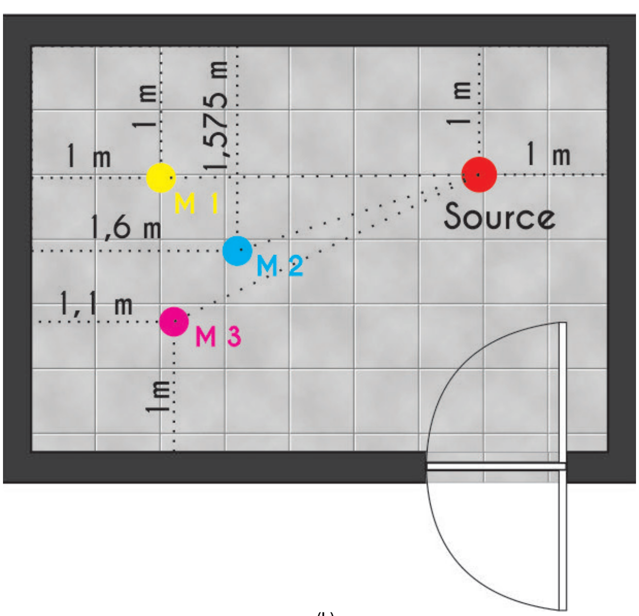
The reverberation time was measured using the interrupted noise method described by NBR ISO 3382-2 (ABNT, 2017). Three microphone positions were used for the measurements for each sound source position. Two measurements were done for each microphone position to determine the reverberation time, totaling 12. The microphone height used in tests was 1.30 m; 1.90 m, and 2.3 m for microphones M1 and M6; M2 and M5, and M3 and M4, respectively. The microphone and sound source distance used in reverberation time measurement are depicted in Figures 9 (a) and (b).



(a)

Figure 9: Positions of sound sources and microphones (M) for reverberation time measurement
Source: The authors.



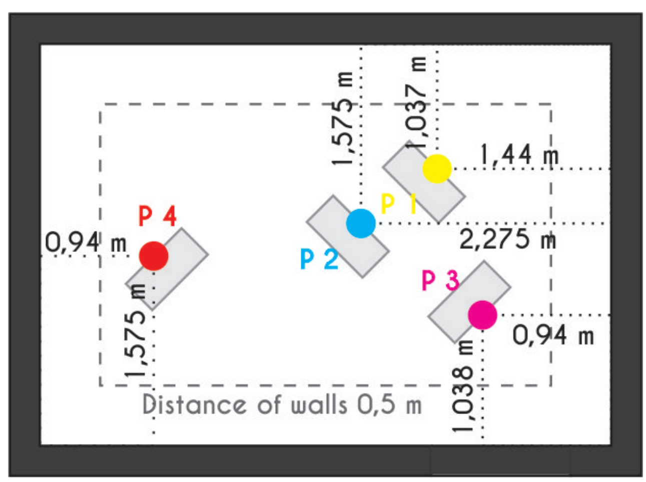
(b).

Background noise level and the standardized impact sound pressure level (L'_{nT}) measurements were carried out for ranges of 100 Hz to 3150 Hz for third-octave bands, according to the procedure described in ISO standard 16.283-2 (ISO, 2020). Four positions were used to measure the standardized impact sound pressure level (mic and tapping machine), distributed respecting the distance of 0.50 m from the edges of the floor.

The impact test machine used five hammers with 500 grams each, falling freely and repetitively from a height of 40 mm. Invariably, the hammer's positions were over the slab joists and at a direction angle of 450 degrees. Also, four microphones were positioned for each impact machine position.

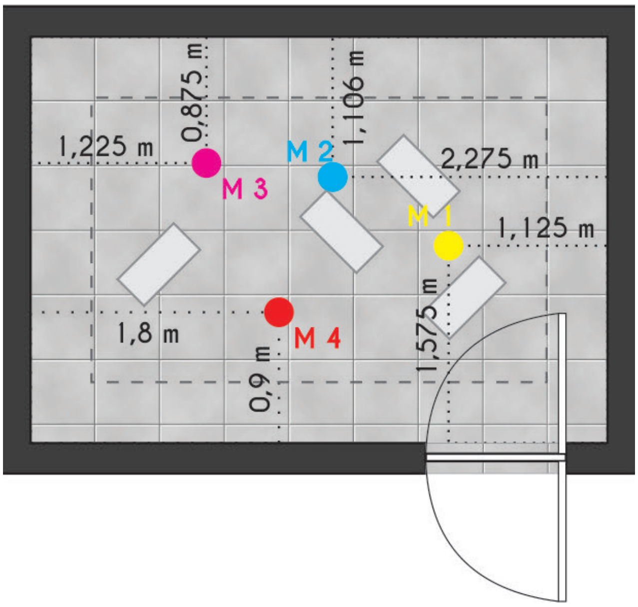
The microphone distribution followed the minimum distances of 0.70 m between the positions of the fixed microphones; 0.50 m between the microphone and the room reception limit; and 1.0 m between any microphone and the excited slab by the impact machine. Two measurements were taken for each microphone position, totaling a number of thirty-two (32) for background noise level and 32 measurements for standardized impact sound pressure level. For each microphone position, the following heights were used: M1 (1.20 m); M2 (1.60 m); M3 (2.10), and M4 (1.50 m). Figures 10 (a) and (b) depict the position of the impact machines and microphones distributed in a measurement room.

The L'_{nT} and $L'_{nT,w}$ calculations were performed according to the standards ISO 16283-2 (ISO, 2020) and ISO 717-2 (ISO, 2020), respectively.



(a)

Figure 10: Positions of sources (P) and microphones (M) for impact sound measurement.
Source: The authors.



(b).

Sample	Material
CF	Ceramic Floor
PB	Plasterboard
RR5	Recycled rubber pad of 5mm
GW15	Glass wool of 15 mm
VF	Vinyl Floor
LW	Laminated wood floor
S	Prefabricated slab with prestressed joists and ceramic tiles
SUB	The subfloor of 40 mm
PW	PET wool of 50 mm

Table 5: Material designations

Source: The authors.

	Composition of the floor system	$L'_{nT,w}$ (dB) Without PET wool	$L'_{nT,w}$ (dB) With PET wool
References	S: Prefabricated slab of 135 mm (HAAS et al., 2022)	91	-
	S+SUB: Prefabricated slab (135 mm) + Subfloor (40 mm) (HAAS et al., 2022)	84	-
	PB (reference): Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	74	71
	PB+SUB: Subfloor (40 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	67	66
Ceramic floor	CF+PB: Ceramic floor (9 mm) + Subfloor (40 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	68	65
	CF+RR5+PB: Ceramic Floor (9 mm) + Subfloor (40 mm) + Recycled Rubber (5 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	54	54
	CF+GW15+PB: Ceramic Floor (9 mm) + Subfloor (40 mm) + Glass Wool (15 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	50	50
Vinyl floor	VF+PB: Vinyl floor (4 mm) + Subfloor (40 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	62	60
	VF+RR5+PB: Vinyl Floor (4 mm) + Subfloor (40 mm) + Recycled rubber (5 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	52	51
	VF+GW15+PB: Vinyl Floor (4 mm) + Subfloor (40 mm) + Glass Wool (15 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	46	46
Laminated wood floor	LW+PB: Laminated wood floor (8 mm) + Expanded Polypropylene (2 mm) + Subfloor (40 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	57	55
	LW+RR5+PB: Laminated wood floor (8 mm) + Expanded Polypropylene (2 mm) + Subfloor (40 mm) + Recycled rubber (5 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	53	50
	LW+GW15+PB: Laminated wood floor (8 mm) + Expanded Polypropylene (2 mm) + Subfloor (40 mm) + Glass Wool (5 mm) + Prefabricated slab (135 mm) + Plenum (150 mm) + Plasterboard (12,5 mm)	47	46

Table 6: $L'_{nT,w}$ resume of flooring system compositions with and without PET wool.

Source: The authors.

Comparing the results of Table 6, it was possible to identify the slab type's influence and the suspended ceilings' presence as a solution for impact noise isolation without floor covering. Impact noise is structural, system stiffness and mass can significantly change the values. In this case, adding a subfloor improved the results by 7 dB.

For PB floor system composition, the $L'_{nT,w}$ was 74 dB, showing an improvement in the impact sound isolation of about 17 dB in relation to the slab without plasterboard ceiling ("S") and 10 dB in relation to the slab and subfloor ("S+SUB") (HAAS et al., 2022). Plasterboard is a strategy generally used for airborne noise insulation, but for the slab under test, the results show an improvement when there are no floor coverings.

Also, Medeiros (2003) and Oliveira et al. (2021) found a similar reduction in direct impact noise transmission with ceilings for slabs types T, massive and hollow. The authors concluded that adding layers to the slab could provide lower values of $L'_{nT,w}$.

Adding 50 mm of PET wool blanket in the interlining improved the impact noise insulation of the PB floor composition by 3 dB (Figure 11). The same direction was found in the studies of Pagnoncelli and Morales (2016). The authors improved the impact noise insulation to 5 dB with rock wool over the ceiling. Just as PET wool improved impact noise by 3 dB, when there is no mechanical decoupling of the upper floor, there is more high-frequency energy in the lower floor and, therefore, a sound-absorbing material improves the results. Thus, to improve the acoustic performance, using a PET wool blanket was a helpful solution only when it was impossible to mechanically decouple the upper floor with rubber or glass wool.

Different floor coverings were tested herein, as presented in Table 6. Among the compositions that used PET wool in the plenum, the systems with laminate floors such as LW+PB, LW+RR5+PB and LW+GW+PB obtained the best $L'_{nT,w}$ compared to those systems like vinyl or ceramic floors. For example, when the ceramic floor was changed by laminate, in the exact composition of the construction system, there was an improvement in $L'_{nT,w}$ from 65 dB (CF+PB) to 55 dB (LW+PB). Without PET wool in the plenum, the differences in $L'_{nT,w}$ were from 68 dB (CF+PB) to 57 dB (LW+PB), respectively. The same was identified in the study of Pagnoncelli and Morales (2016), who tested different combinations of floor systems. The authors got that the wooden floor reduced by 3 dB the impact noise by when compared to the ceramic floor for the same slab typology. The wool aided in the absorption of a high-frequency band, possibly improving the weighted result.

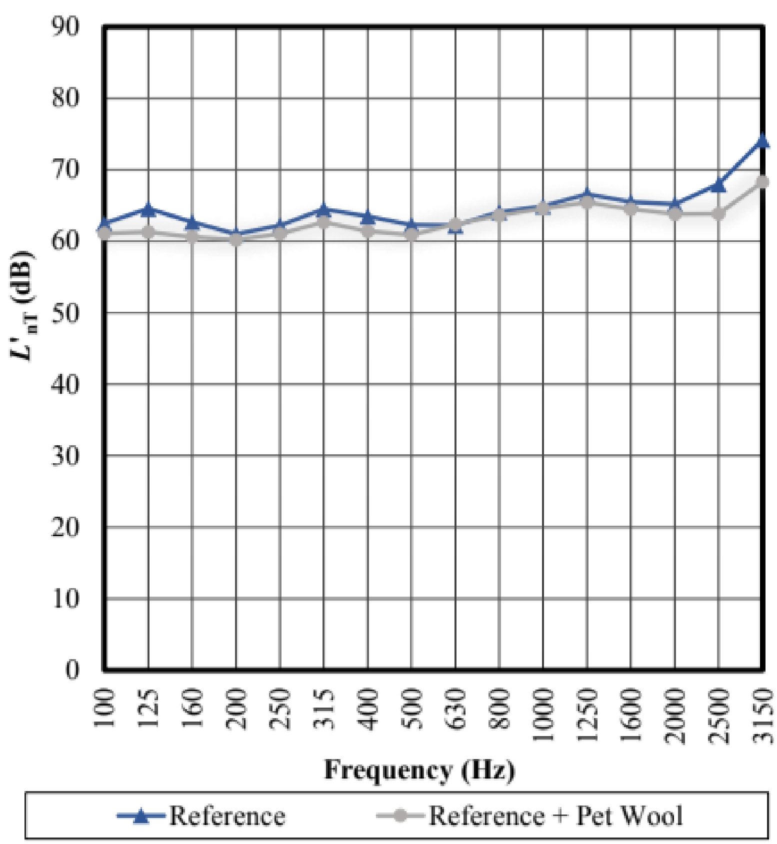


Figure 11: L'_{nT} values per third-octave frequency band in the tests for the "PB" reference samples with and without PET wool
Source: The authors.

The analyses show that adding the subfloor improved the system's performance in impact noise isolation. Initially, adding 40 mm of subfloor over the slab provided an insulation of 7 dB, the same value found by Haas et al. (2022). The results are presented in Figure 12.

It is identified that adding a subfloor adds mass to a slab typology filled with ceramic tiles. (LOURENÇO et al., 2022.; PARK; YOON; CHO, 2020). The impact noise insulation improvement of 50 mm of PET wool in the plenum was only 1 dB, which has negligible influence on the experimental results.

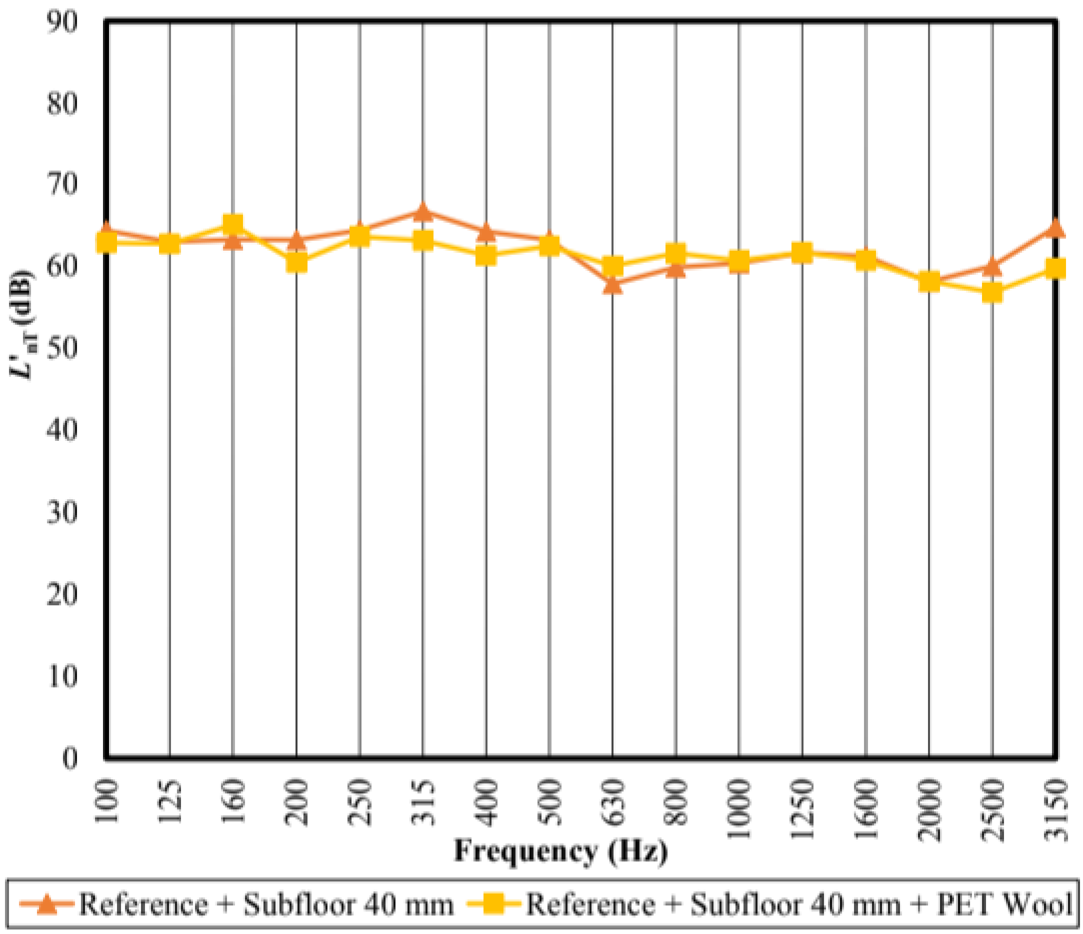


Figure 12: Test results for reference flooring systems with the subfloor
Source: The authors.

It was noticed that the use of 50 mm of thickness PET wool like CF+PB in the ceiling improved up to 3 dB (with PET wool in the plenum) in the impact noise insulation, because it mainly absorbs noise in the high-frequency bands. When the floor covering was mechanically decoupled, the PET wool absorbed the high frequencies but did not change the final performance value. Figure 13 presents the experimental results for different compositions, according to the designation of Table 6. The graphs contain the L'_{nT} values by third-octave frequency band.

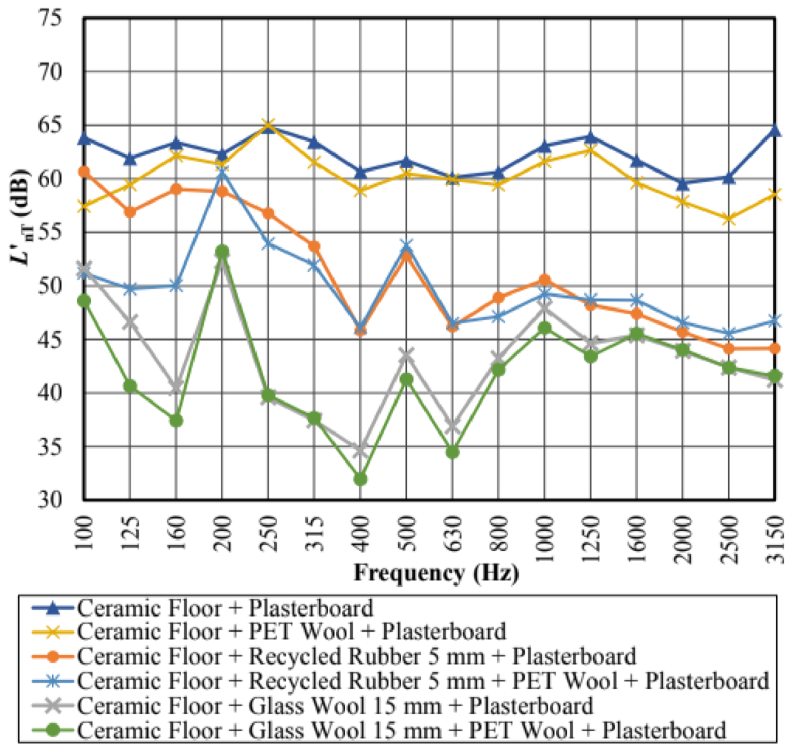


Figure 13: L'_{nT} values by third-octave frequency band in tests for ceramic floor systems
Source: The authors.

Installing resilient material among the linings modified the spectrum of the L'_{nT} values measured for the floor system without resilient material (CF+PW+PB), changing the system's behavior considerably. This occurred, especially for band frequencies below 250 Hz and above 1250 Hz.

On the other hand, for systems that are mechanically decoupled like those as CF+RR5+PW+PB and CF+GW15+PW+PB, the installation of PET wool in the plenum provided greater sound insulation for band frequencies of below 160 Hz and, also, 400 Hz e 630 Hz. Another important observation is that decoupling with rubber generated the most significant differences with and without PET wool, although the final weighted result did not change.

Despite the PET wool in the plenum modifying the frequency spectrum, significant changes in impact noise insulation are perceived with the improvement in the mechanical decoupling system, and not with the addition of plasterboard ceiling. Figure 14 presents the impact noise performance rating of the ceramic tile flooring systems studied in this research.

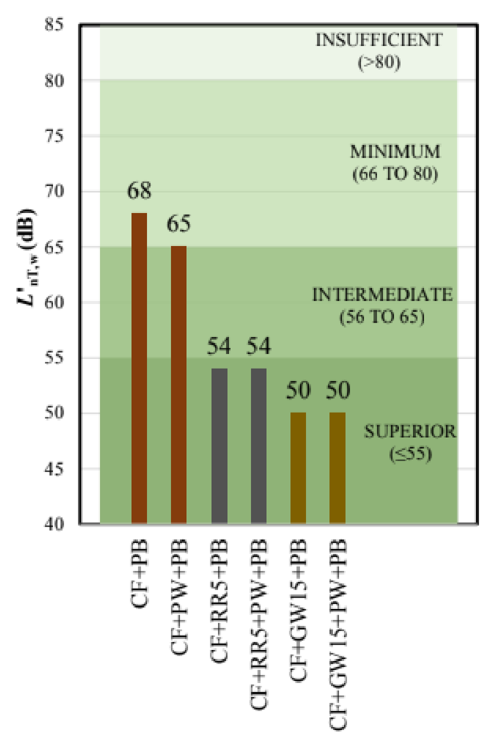


Figure 14: Performance of ceramic floor and ceiling systems as separating elements of autonomous housing units over bedrooms
Source: The authors.

In the first case (CF+PB), the addition of plasterboard lining brought the flooring system from minimum to intermediate (CF+PW+PB). These combinations of materials that promote mechanical decoupling from the floor can be classified as a superior level of performance according to NBR 15.575-3 (ABNT, 2021).

When it was inserted as a resilient material into the compositions of the floor system, the installation of PET wool in the plenum did not improve impact noise performance, as seen in $L'_{nT,w}$ values. For the CF+RR5+PB and the CF+GW15+PB systems, when adding PET wool, the $L'_{nT,w}$ results kept the same performance at 54 and 50 dB, respectively.

Installing sound-absorbing material in the ceiling modified the curve of L'_{nT} values measured for the floor system without resilient material (VF+PW+PB). Except for the 200 Hz frequency, the addition of PET wool to the system attenuated the noise in the sound spectrum. Figure 15 demonstrates the L'_{nT} values for samples using vinyl floors.

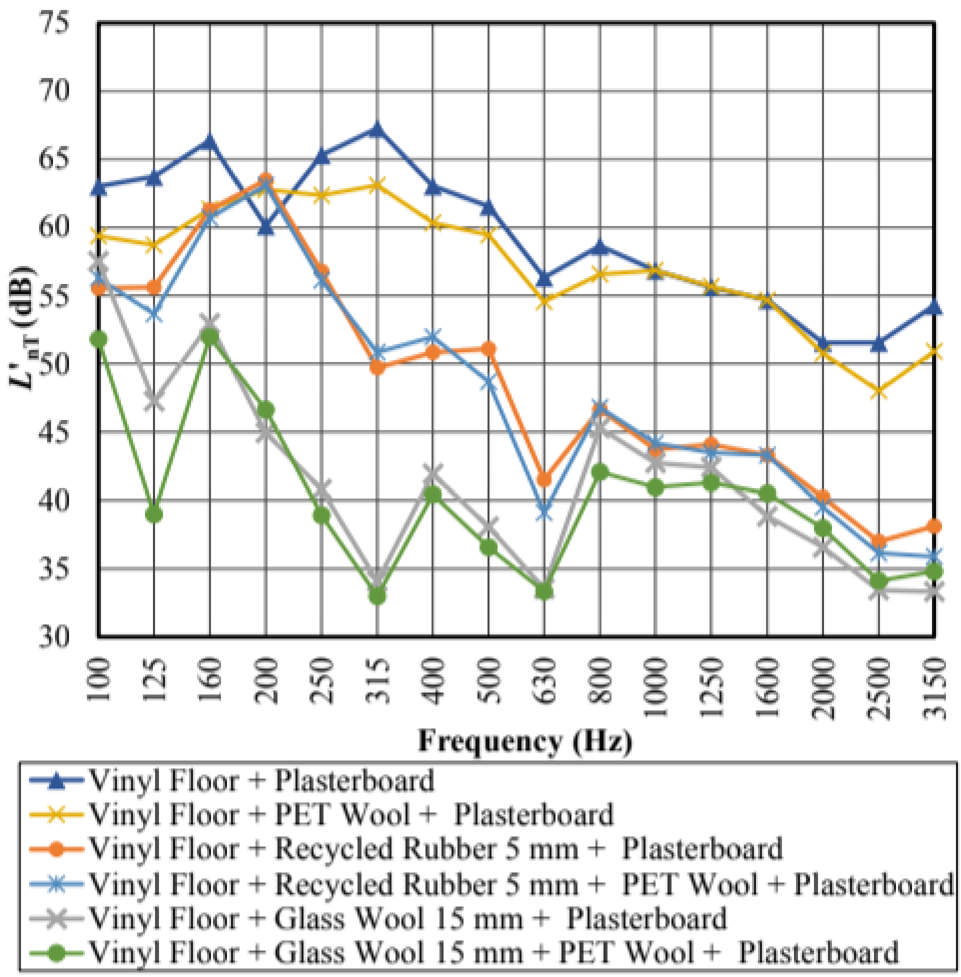


Figure 15: L'_{nT} values by third-octave frequency band in tests for vinyl flooring systems
Source: The authors.

With the mechanical decoupling of the subfloor with a recycled rubber pad (VF+RR5+PW+PB), it was noted that the installation of PET wool in the ceiling provided greater sound insulation for a frequency of 125 Hz (attenuation of 2 dB) and 630 Hz (attenuation of 3 dB). However, for compositions with recycled rubber pads (VF+GW15+PB and VF+GW15+PW+PB), the installation of PET wool in the interlining did not show significant differences in impact sound insulation. That is, the values of the L'_{nT} spectrum were close to each other. Figure 16 shows the impact noise performance classification of vinyl floor systems as separating elements of autonomous housing units over bedrooms.

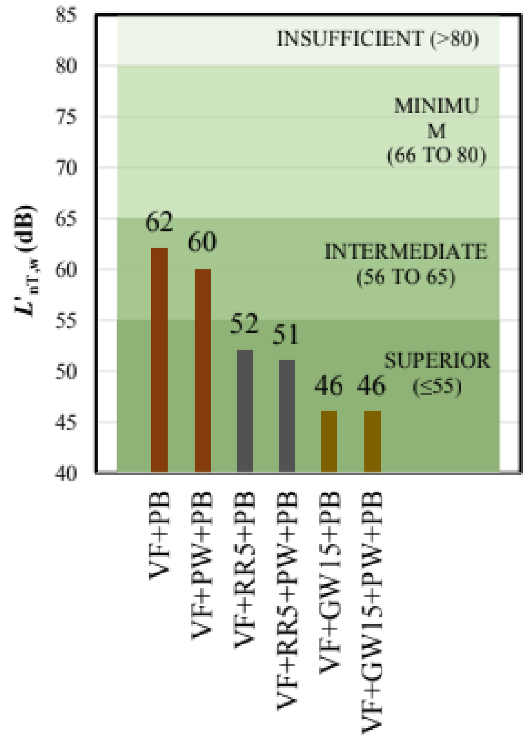


Figure 16: Performance of vinyl flooring and ceiling systems as separating elements of autonomous housing units over bedrooms
Source: The authors.

The same performance level of floor systems remained for vinyl floor compositions with PET wool in the plenum. Although the placement of PET wool in the system's interlining resulted in a 2 dB improvement in the impact noise insulation of the flooring system without resilient materials (VF+PW+PB), the system's performance level was maintained (intermediate). The VF+RR5+PB system resulted in a performance of $L'_{nT,w}$ = 52 dB, and the addition of PET wool improved the impact noise insulation by 1 dB. However, both systems rank in the NBR as superior.

Regarding laminated wood floor, the results show that the application of PET wool in the ceiling caused a different behavior to the other types of coating, showing greater sound insulation in the frequency bands below 2000 Hz, as can be visualized in Figure 17. In addition to changes in the surface density of floor coverings, laminated wood floors have a polypropylene layer for laying, corroborating different behaviors in the frequency spectrum for sound insulation. Also, the system that had the most significant influence on the application of PET wool was LW+RR5+PB. There was an improvement of 9 dB in L'_{nT} for the 100 Hz frequency band and 5 dB for 500 Hz.

Thus, the PET wool improved the insulation regarding impact noise, mainly at low and medium frequencies. The results of the tests of the compositions with laminated wood cladding in the interlining are shown in Figure 17, whose graph contains the L'_{nT} values per third-octave frequency band.

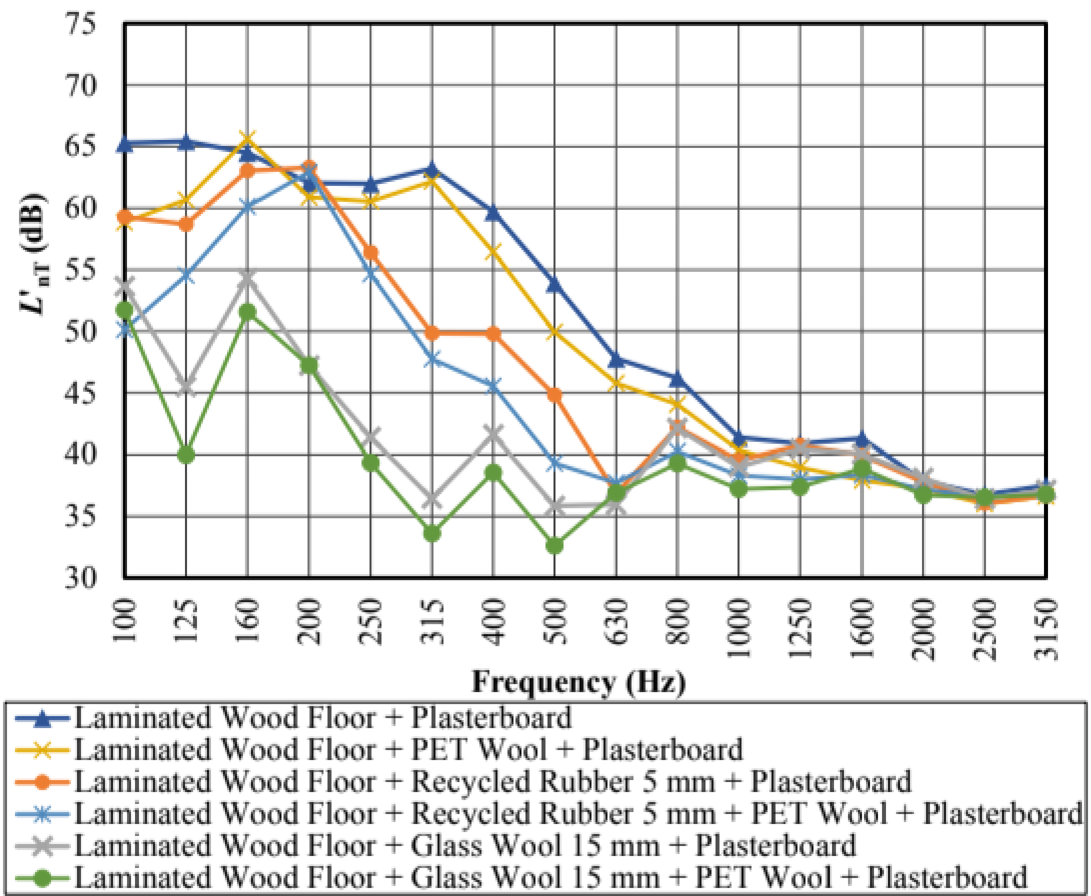


Figure 17: L'_{nT} values by third-octave frequency band in tests for wood laminate flooring systems
Source: The authors.

Figure 18 presents the impact noise performance rating of wood laminate floor systems. PET wool in the plenum and wood laminate flooring proved the most efficient ($L'_{nT,w}$ = 46 dB). In addition, the placement of PET wool in the interlining of the flooring system without resilient material (LW+PW+PB) allowed it to reach a higher level of performance, improving $L'_{nT,w}$ by 2 dB.

In this case, without the pet wool, the performance was intermediate ($L'_{nT,w}$ = 57 dB), and with the addition, the system reached superior performance ($L'_{nT,w}$ = 55 dB). Thus, the superior level of performance provided for in NBR 15.575-3 (ABNT, 2021) was reached.

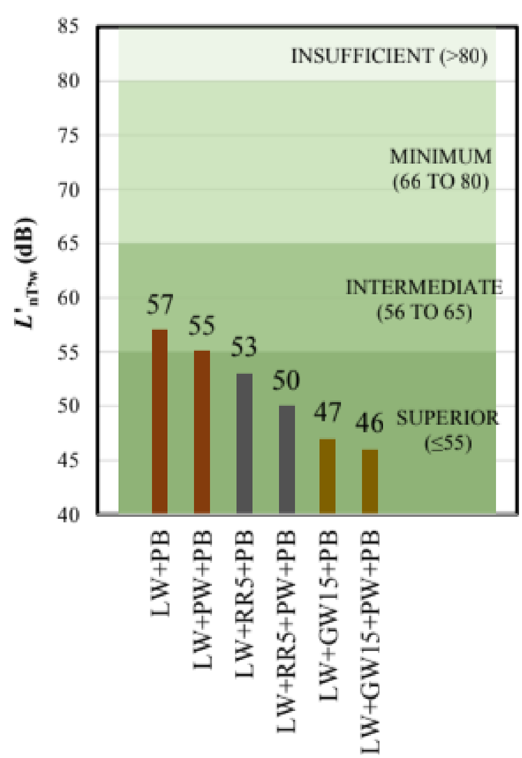


Figure 18: Performance of wood laminate flooring and ceiling systems as separating elements of autonomous housing units over bedrooms
Source: The authors.

Therefore, adopting wood laminate flooring in conjunction with the plaster lining with PET wool in the interlining results in higher performance ($L'_{nT,w}$ = 46 dB). However, the results with PET wool did not test the performance of the samples. Thus, it is important to make the structural system compatible with techniques aiming for good acoustic performance.

From the above, the performances were better when the lining had an additional insulation layer. The use of PET wool evidences an absorption at high frequencies, which suggests its applicability in cases of insulation for airborne noise, and not for impact noise, as tested in this research. Furthermore, it is confirmed that other studies indicate that different strategies can be used to improve acoustic performance regarding impact noise. For example, the adoption of resilient materials in floating screeds, the use of suspended ceilings, and other alternatives that promote the discontinuity of the structure to attenuate the acoustic bridges (HAAS et al., 2022.; OLIVEIRA et al., 2021.; PARK; YOON; CHO, 2020).

The results indicate that placing absorbent material in the ceiling improves the impact noise insulation performance of flooring systems at low frequencies, as was concluded in different flooring systems (MEDEIROS, 2003.; RYU; SONG; KIM, 2018). However, Medeiros (2003) concluded that the rock wool placed in the ceiling had little influence on the impact noise insulation of a massive reinforced concrete slab.

5. CONCLUSIONS

The placement of a 50 mm thick PET wool in the plenum of the plasterboard ceiling system, installed under the prefabricated slab of prestressed joists and ceramic tiles analyzed, improved up to 3 dB in the noise insulation of impact. Two situations reached a higher performance level, considering the performance levels provided for in Brazilian standard NBR 15.575-3 (ABNT 2021), but which are linked to the mechanical decoupling of the subfloor, and not due to the addition of PET wool in the plenum. Notably, the acoustic performance of floor systems varies according to the geometry, volumes, execution details, and the unions between the building systems.

The results showed that PET wool significantly influenced the reduction of L'_{nT} at low frequencies in some mechanical decoupling systems, as in samples of laminated wood and vinyl flooring. In the reference samples, PET wool in the plenum resulted in up to a 3 dB improvement in impact noise insulation. In the samples of ceramic flooring, the use does not show improvement, in the case of vinyl floors, this increase in sound insulation is in the order of 2 dB, as well as in laminated wood floors. The improvement of the PET wool occurs only when there is no mechanical decoupling, and there is no influence on the wool when the subfloor is uncoupled.

It is noted that the better the impact noise insulation of the flooring system without PET wool in the plenum, the less efficient the placement of this fibrous material. Also, the use of PET wool in the interlining is more efficient when combined with the use of laminated wood cladding. Using a resilient blanket on the slab and a 50 mm thick PET wool in the plenum proved ineffective in insulating impact noise for the systems with vinyl and ceramic coatings tested.

In future research, computer simulations will be used to compare the simulation with that obtained in the laboratory to encourage the use of these constructive systems in projects. In addition, new insulation materials will be tested in the ceiling and other ceiling systems to optimize this system's acoustic performance.

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WML: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, supervision, validation, visualization, writing - original draft and writing - review & editing.

GM: conceptualization, data curation, formal analysis, investigation, methodology, validation and writing - review & editing.

EHLS: conceptualization, data curation, formal analysis, investigation, methodology, validation and writing - review & editing.

CTR: conceptualization, investigation, methodology, validation and writing - review & editing.

GIM: conceptualization, funding acquisition, methodology, project administration, supervision and writing - review & editing.

Conflict declaration: nothing to declare.