On the efficiency of impact sound insulation systems on prefabricated lightweight floor and on standard homogeneous base-floor

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Abstract

Considering the impact noise as a major social issue in many countries, extensive work have been developed aimed at reducing the noise level in dwellings. Laboratory tests were carried out to investigate the acoustic performance of same constructive proposals, arranged to reduce the impact sound transmission. According to this study, acoustic performance of both types of floors differs significantly, with a difference of up to four times that of the effect of floating floor system on a homogeneous floor in some cases. The conclusions can help to determine the proposal of best suitable constructive solutions in accordance with legal regulations.

Keywords: impact sound insulation, acoustic regulations, homogeneous floors, lightweight floors, floating floors, dynamic stiffness.

1. INTRODUCTION

Several studies have identified noise as a major social issue in European countries. Efforts are increasingly being made in order to reduce noise levels, also in relation to human health. In residential buildings, the constructive elements that divide adjacent spaces, such as floors and walls, make these structures crucial to noise transmission. Various recent studies show that some degree of neighbouring noise had adverse effects on sleep, quality of life, and health issues [1,2]. In this regard, an increasing demand for noise comfort from dwelling occupants in recent decades has promoted the development of extensive research in the field of noise reduction, in order to reach the maximum degree of wellbeing for the users. Therefore, the investigation of suitable constructive solutions for new and retrofitted buildings has become a major concern for architects and builders to comply fully with national regulation requirements [3,4]

Given that this work focuses on the transmission of impact noise, the acoustic performance of floors is analysed. From the acoustic point of view, the main objective of these elements is to avoid the propagation of airborne and impact noise. As regards impact noise, compliance with national regulations cannot generally be achieved just with bare floors, regardless of whether they are homogeneous or not. Therefore, it will be interesting to analyse the variations of the acoustic behaviour of different homogeneous and non-homogeneous floors in order to ascertain whether the same constructive solutions, arranged as floor coverings or floating floor systems, can provide the same efficiency on different types of floors.

For the purpose of helping to reach the values set by the acoustic regulations, research is required into the behaviour of various materials resilient to impact noise in correlation with the base floor. In turn, this should provide solutions to efficiently reduce the impact sound transmission.

Although the provisions of the standards are taken into account in this study, it should be noted that the characterizations based on standards do not always correspond to real cases found in buildings. For this reason, this study aims to develop a more practical approach, with comparative experiments carried out on the effect of different materials laid out directly on the base floors (i.e. floor coverings) or between the floating panel and the two types of base floors, homogeneous and prefabricated lightweight floor with a rectangular aluminium beam structure (i.e. floating floor systems). Based on structural properties, it can be assumed that the acoustic behaviour of both types of floors differs significantly. However, laboratory tests of impact sound insulation and stiffness properties were carried out to analyse the acoustic performance of these materials when placed on both floors. Research into the acoustic characteristics of these materials allows their efficiency to be compared, considering two types of floors and four types of resilient materials in this study.

2. IMPACT SOUND INSULATION OF BASE FLOORS AND SYSTEMS

Impact noise is generated by blows on the floor, such as falling objects, furniture dragging or people walking. The vibrations generated on the surface struck can be transmitted to the other building elements (partitions), resulting in new sound emission sources. A doubt arises in relation to this: does the impact sound transmission change when the same resilient materials are placed on different types of floors?

2.1 Insulation of base floors: homogeneous and non-homogeneous

A homogeneous floor can be defined as a single-layer floor with uniform thickness, as it is the case of concrete slabs. In contrast, a non-homogenous floor is considered to have a more complex geometry and is generally composed of several solid components which come in numerous solutions with a wide variety of design possibilities. Regardless of the weight of the slab, the three basic component elements of non-homogeneous slabs are beams, plates and the spaces between the beams. In this regard, some examples of heavyweight non-homogeneous floors are ceramic blocks and unidirectional reinforced concrete slabs, whereas wooden and timber floors are considered lightweight solutions. The diversity of components and variables to be predicted by theoretical models for non-homogeneous floor systems [5] determines the more complex means of propagation in homogeneous systems.

The use of lightweight non-homogeneous floors is very common in buildings located in historic centres of many European cities. Some authors focused their analysis on demonstrating variations in noise behaviour in this type of floors. For example, Johanson showed that the increase in the floor stiffness did not significantly affect its impact sound insulation at low frequencies in wooden floors [6], while Ljunggren and Agren, concluded that extra board layers, or the use of elastic glue between floor boards, could improve the acoustic performance of lightweight floors [7]. Other researchers assessing lightweight solutions such as timber floors concluded that there was an increase in acoustic behaviour when adopting either composite solutions or suspended ceilings, since the performance of the timber floor solution is really poor [8,9]. This aspect was also investigated by Emms et a. [10], when developing and evaluating solutions to improve the insulation effect of timber floors by increasing mass or damping layers such as the addition of ceiling panels - two layers of 13 mm plaster-board, or a composite system, whose performance relies on the different connecting devices: screws, reinforcement bars, steel plates or even adhesives [11].

2.2 Insulation systems

Regarding the acoustic performance of the insulation systems, floating floor is an important concept to be taken into account. Its acoustic behaviour can be characterized as a mass-spring-dampener system, where the rigid plate is the mass, and the spring is the resilient layer in the middle of the system. Due to the elastic and damping properties of the resilient layer, floating floors are considered to be a very efficient solution to reduce the transmission of impact noise.

Several authors propose various analytical models to evaluate the improvement of the impact sound insulation and to compare the acoustic behaviour of different types of floor. Neves e Sousa and Gibbs developed an analytical model, which was experimentally validated, in order to investigate the effect on impact sound transmission at low frequencies through various types of floors [12]. In addition, research conducted by Schiavi confirms that resilient layers applied on the top of the reference floor effectively reduce impact noise [13] and establish a method with the aim to evaluate the real acoustic behaviour of a floating floor, as a function of frequency, using a single analytical function [14].

The calculation of floor noise insulation indices was studied by varying the finishing coverings (PVC, foliated cork) both in laboratory and on-site assessments, identifying discrepancies in the values obtained for the characterization of each floor covering, probably due to the type of index used [15]. Based on the tests performed and on the results obtained, it appears that the dB(A) metric is the best suited to characterizing the efficiency of floor coverings. The effectiveness of different types of heterogeneous floors is also analysed, for example, by estimating the rating indices for the case of a double-leaf wooden floor [16]. This research demonstrates that in the bare slab condition, A-weighting floor impact sound level can be calculated from the measured floor impact sound levels; however, it is not possible in the case of a double-leaf wooden floor installed as the floor substrate.

Compression conditions are also analysed in other studies to evaluate the acoustic performance of resilient layers of floors [17], with the conclusion that a greater decrease in the sound reduction performance over time is found when considering soft resilient materials in floating floor systems [18].

3 THEORETICAL CONCEPTS

3.1 Reduction of impact noise

- Floating floors

The reduction of the impact sound level of a floating floor can be defined as the difference between the sound pressure level produced in the receiving room due to the impacts exerted on the supporting bare floor (L_{n0}), and the corresponding sound pressure level when these impacts are exerted on the floating floor (L_n), following Eq. (1).

$$\Delta L = L_{n0} - L_n \quad (1)$$

Equations of the empirical model for predicting improvement in impact sound insulation are defined in ISO 12354-2 Standard [19]. Calculations of this model were developed by Cremer, whose method is based on the theory of parallel plates coupled to a resilient layer [20].

Cremer established that, for frequencies above the (mass-spring) resonance frequency, it was possible to determine the reduction of impact noise level (ΔL) of a floating floor on a base structural floor by specifying the mechanical properties of the resilient layer and the mass of the floating panel. In this regard, it was not necessary to know the acoustic properties of the receiving room and the mechanical properties (such as flexural stiffness and mass), of the base floor.

In the case of frequencies below the resonance frequency, the spatial distribution of the displacements of the floating panel and the base floor are the same, and the resilient layer acts as an infinite stiff element.

After various experimental tests, Cremer's model was further investigated, refined and updated, particularly by Vér [21].

Thus, it was determined that reduction of impact sound insulation of a floating floor (ΔL) placed on a heavyweight base floor is provided by Eq. (2):

$$\Delta L = 30 log \frac{f}{f_0} \text{ dB} \quad (2)$$

where the slab is highly damped and infinite, f is the third-octave band centre frequency (Hz) and (f_0), the resonance frequency of the floating floor only depends on the elastic properties of the floating panel and resilient layer, as is shown in Eq. (3):

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{s'}{m'}} \text{ Hz} \quad (3)$$

in which s' (N/m^3) is the dynamic stiffness of the resilient layer and m' (kg/m^2) is the mass per unit area of the floating panel. It should be noted that, in some cases, simplified models developed for floating floors, such as the model presented in Eq. (3), are not always valid for lightweight base floors, so that limitations of theoretical models should also be taken into account.

- Floor coverings

Insulation systems as floor coverings provides an improvement of the impact noise isolation by an elastic surface disposed on the base floor and it can be expressed as a function of dynamic stiffness, as follows in Eq. (4), where α and β are expressed as a function of resonant frequency [28]. Therefore, the improvement in impact noise isolation ΔL_n, achieved by the addition of the soft surface layer (floor covering), which reduces the force acting on the slab, is defined in terms of the logarithmic ratio:

$$\Delta L_n = 20\log\left(\frac{\frac{4}{\pi}}{\frac{1}{\alpha}\sin\alpha + \frac{1}{\beta}\sin\beta}\right) \quad (4)$$

3.1 Dynamic stiffness

The fundamental frequency f_0 of the mass-spring system, whose scheme is shown in Figure 1a), can be determined from the theoretical analysis of the vertical vibration of the system. Eq. (5) determines a simple mathematical model of a system with mass *m*, elasticity *k*, and damping *c*, whose movement can be described by *x*, considering only the homogeneous differential equation in whith f(t)=0, and it is obtained by decreasing the excitation force on the system. Analysing the free vibration of systems allows us to identify the parameters of the system, such as the quotient of two consecutive maximums of oscillation (x_{M1} and x_{M2}), where T is the period of oscillation, as can be seen in Figure 1b).

$$\mathrm{m}\ddot{x} + \mathrm{c}\dot{x} + \mathrm{kx} = 0 \quad (5)$$

Once these parameters have been obtained, ωo^2 (rad/s) the square of the natural frequency of the mass-spring system can be obtained from Eq. (6), where m' (kg/m²) is the mass per unit area of the loading mass and δ is defined as the decrease of the function (Figure 1b) which can be obtained using the quotient of the Naperian logarithm of the amplitude ratio and the period (T) between peaks.

$$\frac{\mathrm{c}}{2\mathrm{m}} = \eth = \ln\left(\frac{\mathrm{x_{m1}}}{\mathrm{x_{m2}}}\right)/\mathrm{T} \quad (6)$$

Then, once imposed the vertical motion as a damped harmonical, it can be expressed as Eq. (7) or Eq. (8):

$$\omega_d = \sqrt{\frac{k}{m} - \frac{c^2}{4m^2}} \quad (7)$$

$$\omega_d = \omega_0\sqrt{1-\zeta^2} \quad (8)$$

where ζ is the damping factor, defined as Eq. (9), and in turn it can be determined from the logarithmic decrement δ,as shown in Eq. (10):

$$\zeta = \frac{c}{2\sqrt{km}} \quad (9)$$

$$\zeta = \frac{\delta}{\sqrt{4\pi^2+\delta^2}} \quad (10)$$

Finally, Eq. (11) will determine the direct influence between the peak values and the vibration velocity. Therefore, it can be concluded it is possible to write that the actual solution is *k/m*= *s'/m'*, since *s'*= *k/A* and *m'*=*m/A* (where A is the surface area in m2 on which the mass m is applied)..

$$\omega o^2 = \omega^2 + ð^2 = (2\pi/T)^2 + ð^2 = \frac{s'}{m'} \quad (11)$$

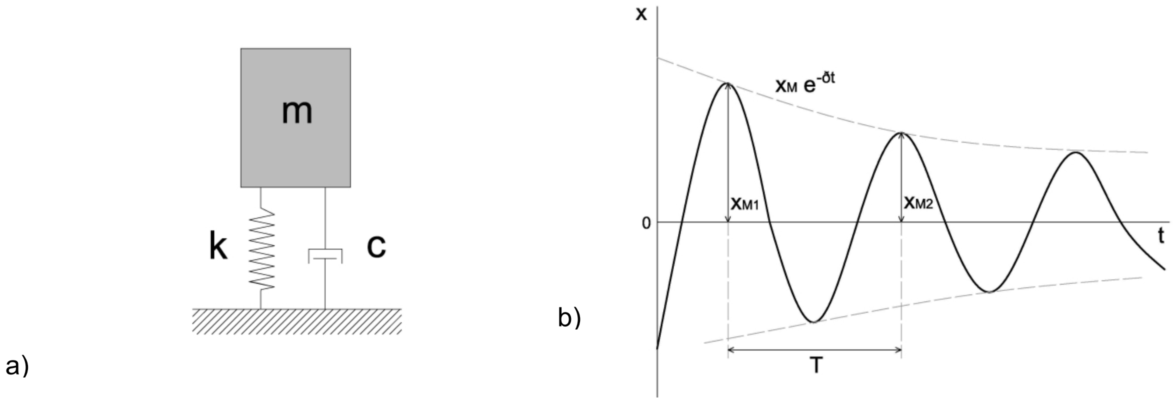


Figure 1. a) Scheme of mass-spring system; b) Free vibration of the system with one degree of freedom

4 METHODOLOGY

For this study, experimental tests were performed in the National Laboratory of Civil Engineering (LNEC), in Lisbon (Portugal), aiming to compare the acoustic behaviour of the same resilient materials when placed on homogeneous and heterogeneous floors.

The measurement procedure was divided into two parts. Firstly, impact sound insulation of diverse constructive solutions was obtained; and secondly, results of dynamic properties of selected materials were analysed to compare their efficiency and to evaluate the weighted reduction of the impact sound transmission. Likewise, impact sound reduction of the floating system was calculated based on dynamic stiffness values following Annex C of ISO 12354-2 [19]

To this end, four resilient materials were considered and installed on both structural floors as coverings or floating floor systems.

Table 1. Main properties of the materials (see Figure 2).

Properties	**Flexible and low- density panels**		**Low porosity compacted grain sheets**	
	S1	**S4**	**S2 - cork**	**S3 – cork+rubber**

Surface mass density (kg/m²)	0.36	0.38	1.3	4
Thickness (mm)	9	9	5	7

This work starts from the premise of a series of theoretical concepts and physical insights attempting to explain the behaviour and the results obtained. However, as indicated above, although there is always an approximation it is important to note that although theoretical concepts are always approximate and not always capable of justifying what happens in all case studies.

4.1 Specimen of resilient materials

The four selected specimens of resilient materials, commonly used in floating floors, are commercially available in Spain and Portugal. All samples of materials with different properties, listed from S1 to S4, are shown in Figure 2 and their description and main characteristics are included in Table 1. On the one hand, S1 and S4 were flexible low-density samples made up of highly porous fibrous material coupled with protective plastic sheets. On the other hand, S2 and S3 were low-porosity compacted grain sheets made of cork (S2) and cork mixed with rubber (S3).

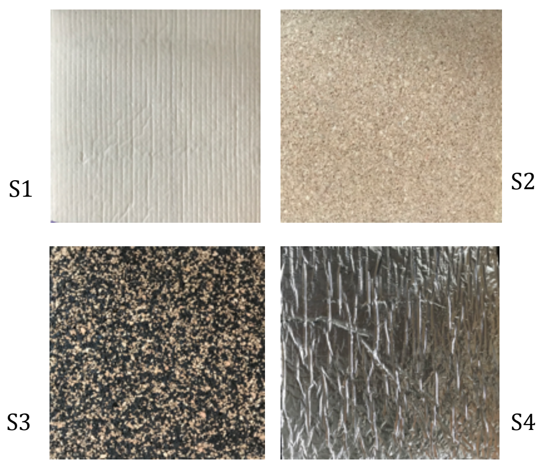
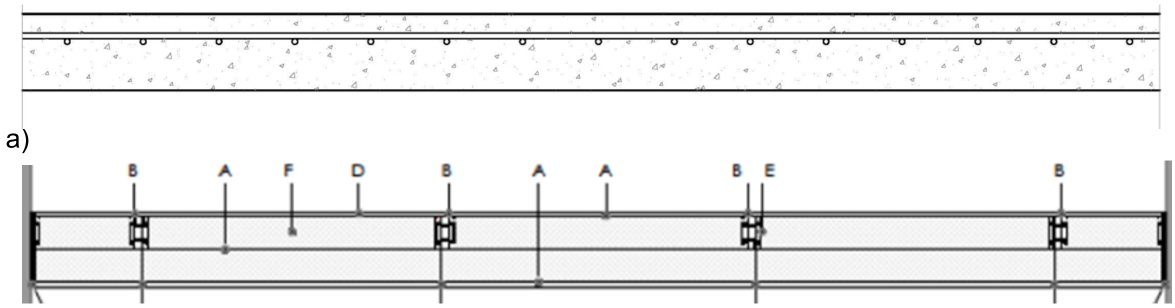


Figure 2. Materials used in the study (S1 to S4, see Table 1).



A – Polyurethane adhesive B- Silicone C – Polyurethane insulation
D – Recycled materials bonded with thermosetting resins (Coretech) panel (15 mm)
E – Aluminium profile F – Extruded plystyrene (XPS) panel (20 cm)

b)

Figure 3. Cross-section of: a) concrete slab homogeneous floor (14 cm); b) prefabricated lightweight non-homogeneous floor.

4.2 Description of floors selected for the study

The two types of floors selected for the tests were:

- Homogeneous floor: a 14-cm-thick heavyweight uniform concrete slab. Estimated mass: 336 kg/m^2.
- Non-homogeneous floor: a prefabricated lightweight floor with a rectangular aluminium beam structure, which is mainly responsible of the structural operation of the floor. It is composed of two 15-mm-thick panels in recycled materials bonded with thermosetting resins (Coretech board) with a rigidity of 9kNcm^2 and a flexural strength of 11.5 N/mm^2. Between both panels there is a 200 mm chamber filled with two extruded polystyrene (XPS) as water resistant and lightweight board of thermal insulation panels (100mm + 100mm) inside the cavity, making contact with both the upper and lower panel. Estimated mass: 30 kg/m^2. The floor is built from the composition of different prefabricated panels, where the perimeter of the metal beams is machined together.

A cross-section of both floor types is shown in Figure 3. Figure 4 shows the three-dimensional scheme of the different lightweight prefabricated panels assembled together, which would rest directly on the structural perimeter.

4.3 Laboratory tests

4.3.1 Impact noise measurements

Impact noise measurements were conducted between the emission-receiving chambers of the LNEC following ISO standard 10140-3 [22], and the equipment used in the tests were in agreement with ISO standard 10140-1 [23].

For this test, a sample of 10 m^2 of floor is located in the laboratory, being the constructive element existing between the emitting room and the receiving room. In relation to the lateral connections and junctions, the floor is located in a hole of the same dimensions as the test sample, with a metallic profile along the perimeter. Once the sample has been placed (thanks to the use of a crane), the perimeter joint is sealed with polymeric foam in order to avoid marginal transmissions, which are not evaluated in this study (being the subject of future research).

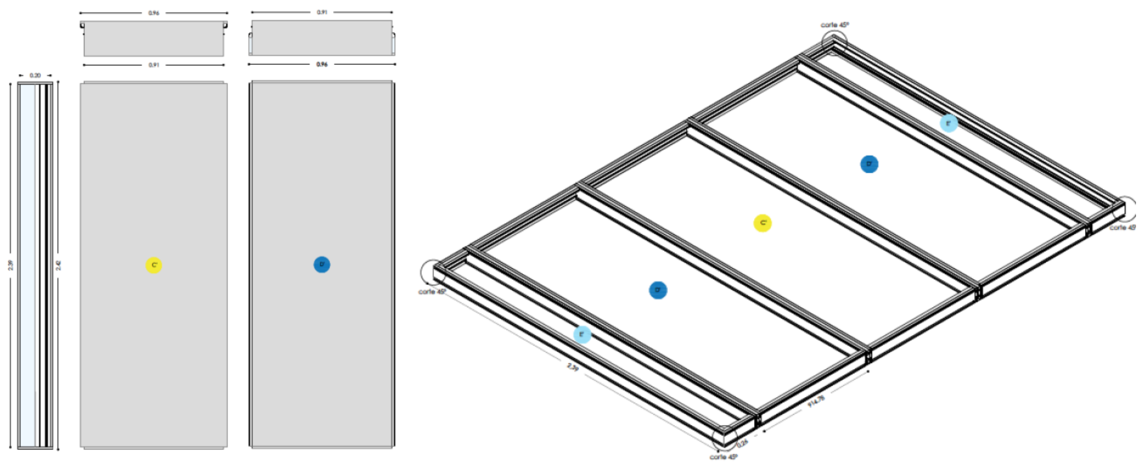


Figure 4. Three-dimensional scheme of the different lightweight prefabricated panels assembled together and aluminum beam framework.

The impact noise was generated in the emission room with a standard 3207 Bruel & Kjaer tapping machine located at six different positions on the floors. The volume of the receiving room is 120 m^3, and results were obtained at one-third octave frequency bands in the frequency range from 100 Hz to 3150 Hz. The received signals were processed using an eight-channel Pulse TM Bruel & Kjaer multi-analyser.

Phases of the measurement procedure aimed at comparing the acoustic performance of floors in which different resilient materials were arranged. The processes are shown in Figure 5 a-c) (homogeneous floor - H) and Figure 5 d)-f) (prefabricated lightweight floor - NH) and took the following form:

- Firstly, the two uncoated floors selected for the study were tested and non-normalized impact sound pressure levels (Li) were obtained. Although normalized values are recommended, this is not significant in this study, since only a comparison is needed (Figures 5a) and d)).

- Subsequently, in order to assess the impact sound reduction level of different floating floor systems, a specimen of one square metre of each material was placed between the base floors and a 1 m^2 mortar panel, 4 cms thick, with a mass of 100 kg/m² per unit area. In relation to the size of the mortar panel and these test specimens, Miškinis et al. [24] carried out a study concluding that the size of the test sample has significant influence on the test results. However, as mentioned before, this aspect is not relevant for this analysis since only the differences were analysed (Figures 5b) and e)).
- Finally, the four samples of materials were tested as floor coverings (Figures 5c) and f)) and d)), using a sample size just large enough to support the whole tapping machine, following ISO 10140-1 [16].

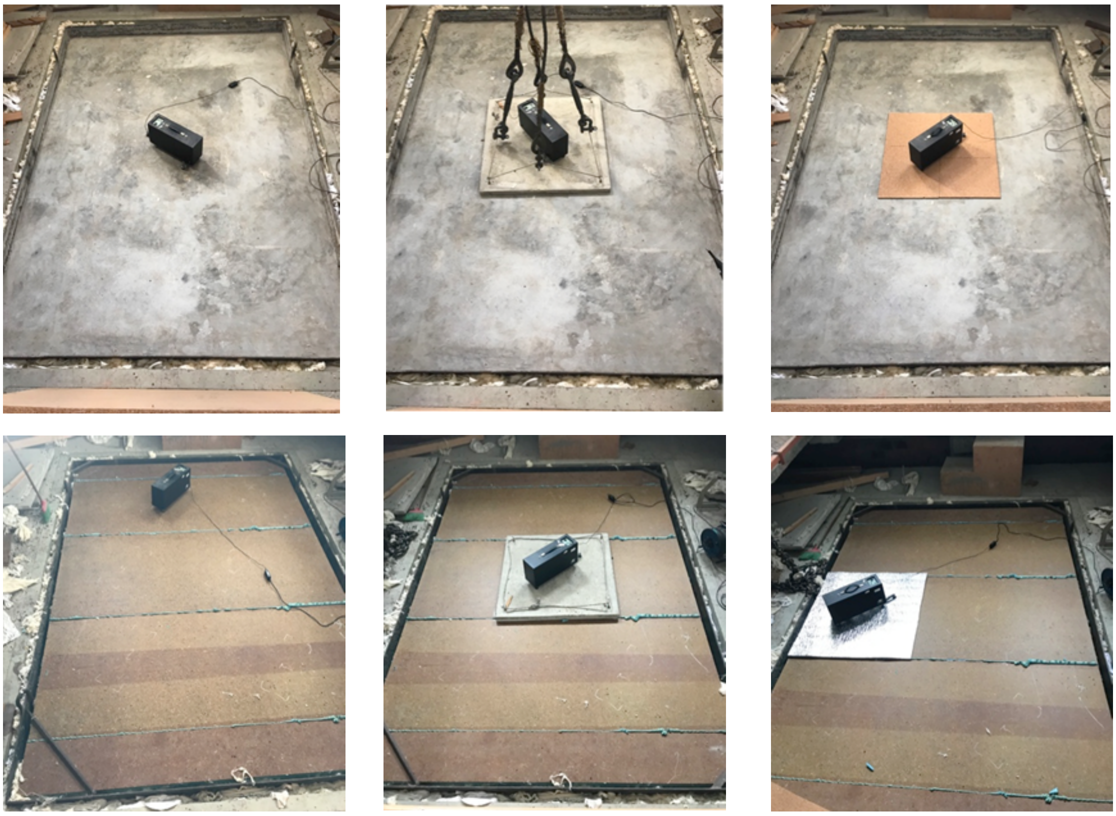


Figure 5. Impact noise measurements (emission room) of homogeneous (H) and non-homogeneous lightweight floor (NH): a)-d) uncoated base floor, b)-e) floating floor systems, c)-f) material placed as floor coverinas.

Values of impact noise insulation (L_i) were obtained in third octave-frequency bands. This was followed by a comparison of values of uncoated floors together with values of reference floors, both homogeneous and lightweight, and obtained from ISO 717-2 [25].

4.3.2 Dynamic stiffness measurements

The dynamic stiffness of the resilient materials was characterized in order to evaluate the efficiency of floating floor systems, and to compare the accuracy between calculations and measurements of impact sound reduction, following ISO 12354-2. In this study, the calculation of dynamic stiffness of samples allows to determine the damping behaviour of the four materials tested. The measurements were performed following the procedure of ISO 9052-1 [26] which explains the calculation of the apparent dynamic stiffness per unit area (s') by measuring the resonant frequency (f_0).

The procedure was theoretically based on the study of vertical vibration of the mass-spring system. In the tests, the 200 kg/m^2 load plate represents the mass of the method, while each material represents the spring of the damping system. Samples were placed between inertial bases, and both the loading mass and the specimen measurements were 20 cm long by 20 cm wide. Thanks to the use of two Bruel & Kjaer 4383 accelerometers located at opposite corners of the load plate, it was possible to obtain an average of the vertical vibration generated by the impact of a hammer at the geometric centre of the load plate. Figure 6) shows the dynamic stiffness measurement set-up described. In each measurement, three overlapped samples of the same material were used to facilitate experimental data collection, therefore it should be taken into account that results turned out to be a third of the total value of s'. This procedure led to a response with lower frequency, lasting longer (≈1 s) and giving more accurate results from the processing of the signal. Moreover, the one-sample setting and three-sample setting were compared in order to verify that they did not influence the results.

The resonance frequency f_0 using the Fast Fourier Transform (FFT) to process the signals was determined thanks to the data obtained by the accelerometers. Once FFT resonance frequency f_0 was calculated, the dynamic stiffness of tested materials was obtained using relation Eq. (3), in which m' (kg/m^2) is the mass per unit area of the loading mass used in the tests.

Figure 6. Dynamic stiffness measurement set-up.

5 RESULTS

A group of comparisons between various constructive solutions of floors were analysed in this paper in order to better understand the acoustic performance and the improvement in terms of impact sound reduction for different base floors. The results obtained contributed to the proposals for future constructive solutions of floors to meet the requirements of acoustic regulations. To carry out the research, four resilient materials (S1-S4, Figure 1) were added as floor coverings and as floating floor systems over homogeneous and lightweight base floors.

5.1 Variability of impact sound tests

Firstly, it was studied whether there was a significant correspondence between the measurements carried out and the type of base floor, or the type of resilient material arranged between the floating panel and the base floor. It is therefore necessary to analyse the variability of the measurements, by assessing the standard deviation values.

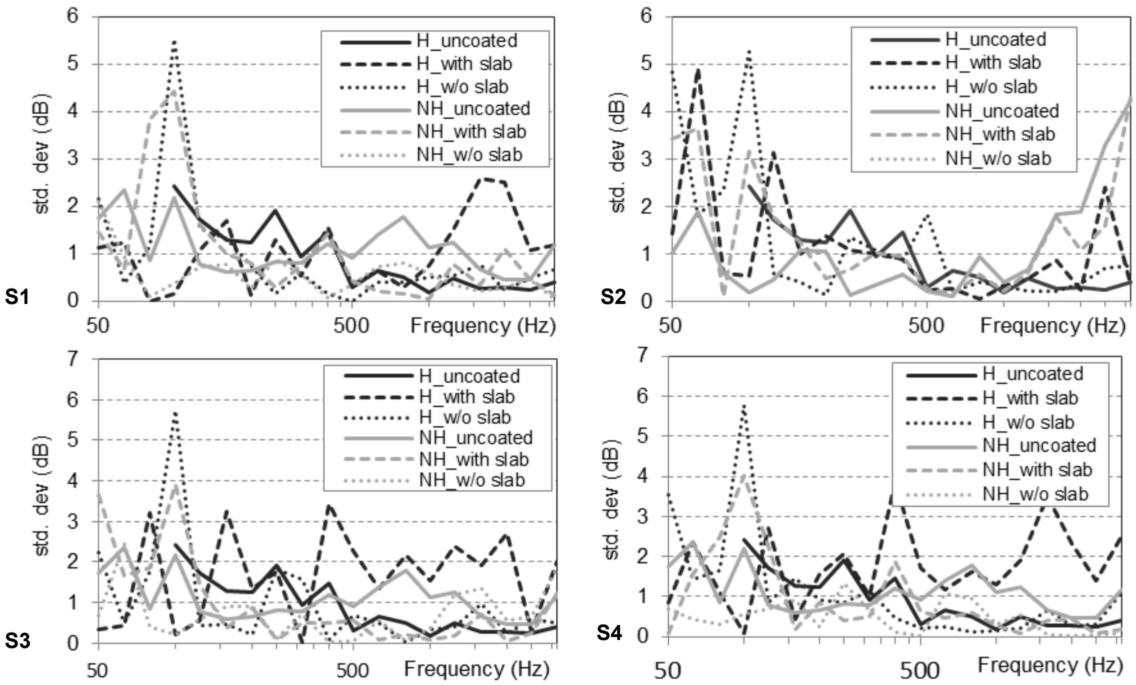


Figure 7. Comparison of standard deviation values of impact sound measurements of all specimens (S1 a), S2 b), S3 c) and S4 d), see Figure 1). W/o panel = without panel

All standard deviation values obtained for each resilient material are shown in Figure 7 (S1 to S4, Figure 1). On the one hand, measurements of uncoated floors provide higher variability than those with floor covering, in high frequency ranges. On the other hand, the highest values of standard deviations are generally obtained in the lower frequency ranges, while a decrease is observed as frequency increases. In light of the results, it can be determined that the type of floor has a direct relationship with the variability of measured results since measurements with a floating floor panel give the highest uncertainties for the homogeneous base floor. Moreover, as can be seen in Figure 7 a)-d), the type of material may also have a significant effect since the spectral curve shows an increase in high frequency values in the case of cork sample material (S2), when it is tested on top of a prefabricated lightweight base floor.

As a concluding remark to this subsection, it could be determined that, in frequency ranges higher than 100 Hz, the standard deviation of the impact noise measurements is less than 2 dB, with the exception of floating system on homogeneous base floor, where in certain frequency ranges amount to 3 dB. In this regard, variability of test is low and the reliability of the results of the measurements can be confirmed for both types of floors and materials, in the frequency bands considered in the procedure of the standard to evaluate global magnitudes for the insulation to the impact noise.

5.2 Measured values of impact sound transmission

5.2.1 Impact sound insulation of uncoated floors and reference floors

It is important to analyse the relation between efficiency and impact noise of the floors tested for this study and the reference floors, both heavyweight and lightweight, specified in Annex C of ISO 10140-5 [26]. In order to determine the relationship, Figure 8 shows both values of impact noise insulation (L_i) in third octave-frequency bands of uncoated floors together with curves of values of reference floors, both homogeneous and lightweight, obtained from ISO 717-2 [25].

Firstly, it can be confirmed that homogeneous floor values have a close relationship with the values of the homogeneous reference floor, with the exception of a peak in 250 Hz. However, all values of the reference floor are slightly lower than those of the homogeneous tested floor, especially in high frequency bands. This could be due to the non-normalization of values and the damping of the floor. Secondly, it is observed that the trend of lightweight floor values is comparable to that of the lightweight-reference-floor curve. However, major variations are observed between both curves for values at mid-frequencies.

It will be useful to consider the correspondence of both floors when assessing the differences between the values of impact sound insulation previously discussed.

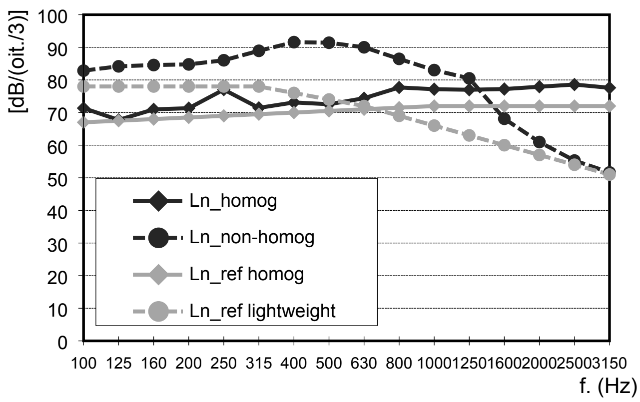


Figure 8. Values of impact noise insulation (Li) obtained from measurements for uncoated homogeneous floor, uncoated non-homogeneous lightweight floor, and values of impact noise insulation of reference floors as stated in Annex C of ISO 10140-5 [26] according to the method established in ISO 717-2 [24].

Table 2. Resume of impact sound level values (L_{iw}, $L_{iwr,1}$ and $L_{iwr,2}$) and impact sound reduction values (ΔL_{iw}, ΔL_{ir1}, ΔL_{ir2}) of each sample (S1-S4).

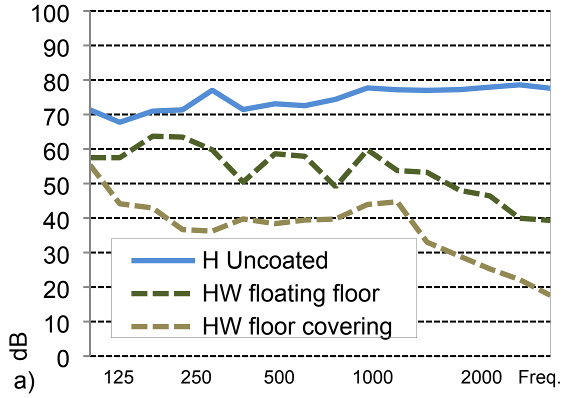
Comparison	L_{iw} (dB)		ΔL_{iw}		$L_{iwr,1}$ (dB)		ΔL_{ir1} LW		$L_{iwr,2}$ (dB)		ΔL_{ir2} HW	
	NH	H	NH	H	NH	H	NH	H	NH	H	NH	H
With slab – floating floor system												
S1	78	61	7	23	65	-	7	-	-	56	-	22
S2	79	62	6	22	68	-	4	-	-	59	-	19
S3	78	60	7	23	66	-	6	-	-	56	-	22
S4	78	62	7	22	65	-	7	-	-	57	-	21
W/o slab – floor coverings												
S1	56	44	29	40	47	-	25	-	-	40	-	38
S2	78	63	7	21	70	-	2	-	-	59	-	19
S3	73	60	12	24	66	-	6	-	-	56	-	22
S4	57	45	28	39	48	-	24	-	-	41	-	37

H = Homogeneous floor; NH = Non-homogeneous floor; HW = Reference homogeneous heavyweight floor; LW = Reference non-homogeneous lightweight floor

As mentioned above, despite the fact that the acoustic behaviour of homogeneous and non-homogeneous lightweight floors varies significantly, it was not known whether the efficiency of impact sound reduction (ΔLw) analysed individually for each case would differ. It should be noted that impact sound reduction values were obtained as the difference between the sound pressure level produced due to the impacts exerted on the supporting bare floor, and when these impacts are exerted on the insulation system (Eq. 1). It is therefore necessary to assess the influence in the results when the materials are placed over homogenous and prefabricated lightweight floors.

It should be noted that single number improvements were calculated on the heavyweight reference floor of the standard using measured ΔLw-spectra on a homogeneous base floor and vice versa, improvements on the lightweight reference floor of the standard were obtained using measured ΔLw-spectra on a non-homogeneous lightweight base floor.

Table 2 shows important data to be taken into account in rehabilitation intervention in historic centres, a solution that is especially common in Spain and Portugal, and summarizes all the results obtained from the lab tests between the values of impact sound reduction, and the three main types of comparisons between the two type of floors are shown: i) differences between uncoated floors and floors with covering (ΔL_{iw} w/o); ii) differences between single number improvements of a floating floor/covering on the non-homogeneous lightweight floor ($\Delta L_{iwr,1}$ LW, type 1 of ISO 717-2); and iii) differences between single number improvements of a floating floor/covering on the homogeneous heavyweight floors ($\Delta L_{iwr,2}$ HW).



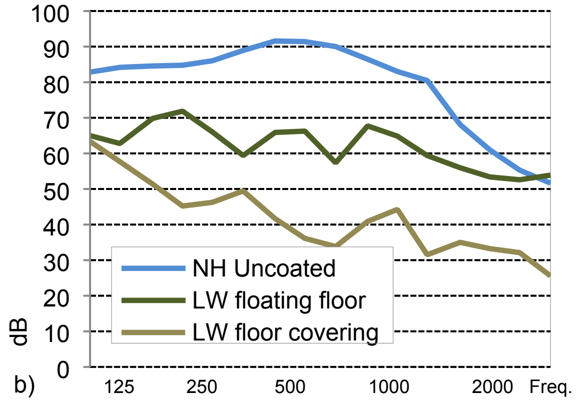


Figure 9. Measured sound level curves spectra when the floating floor or floor covering is placed on floors following ISO 10140-5 [26] using sample S1: a) the reference homogeneous floor; and b) non-homogeneous lightweight floor.

Measured sound level curves spectra are analysed in order to determine whether or not there is a shift of results when the floating floor or floor covering is applied to the different types of floors. Figure 9 a-b) shows the improvement spectra when the floating floor or floor covering is placed on the reference heavyweight and lightweight floors of ISO 10140-5 [26]. It can be seen that although the spectral trend is similar in both cases, the values differ by almost 10 dB when referring to floating floor/covering placed on different types of floor.

- Energy sum and spectral adaptation term for impact noise (C_{tr}).

Table 3 and Table 4 summarizes all the results of energy sum of the impact noise insulation values together with values of spectral adaptation term for impact noise. Without taking into account uncoated floors, the highest values of the spectral adaptation term (C_{tr}) are obtained in comparison ii), when it the floating floor/covering placed on the homogeneous lightweight floor is analysed, specifically in the case of materials with higher mass-air-mass frequency.

Table 3. Energy sum of impact noise insulation values.

	Uncoated		Coated		~~R~~LW		~~R~~HW	
	NH	H	NH	H	NH	H	NH	H
With panel – floating floor system								

S1	98	87	90	73	77	-	-	69
S2			91	76	77	-	-	72
S3			90	73	77	-	-	69
S4			91	75	78	-	-	71
W/o panel – floor covering								
S1	98	87	72	61	65	-	-	57
S2			92	79	85	-	-	74
S3			89	76	82	-	-	72
S4			72	62	66	-	-	58

LW= Reference lightweight floor. HW= reference heavyweight floor

Table 4. Values of spectral adaptation term (C_{tr}) of impact noise level.

	Uncoated		Coated		~~R~~LW		~~R~~HW	
	NH	H	NH	H	NH	H	NH	H
With panel – floating floor system								
S1	-2	-12	-3	-3	-3	-	-	-2
S2			-3	-1	-6	-	-	-2
S3			-3	-2	-4	-	-	-2
S4			-2	-2	-2	-	-	-1
W/o panel – floor covering								
S1	-2	-12	1	2	3	-	-	2
S2			0	1	0	-	-	0
S3			1	1	1	-	-	1
S4			0	2	3	-	-	2

LW= Reference lightweight floor. HW= reference heavyweight floor

5.2.2 Measured values of impact sound insulation.

In this section, the procedure followed for the calculation of results is remembered, and the obtained values are shown. Then, comparison of both measured and calculated results will be discussed in Section 6.

As regards measurements, it should be noted that when characterizing the stiffness of a material, variable stiffness results are obtained depending on the time interval of application of the load on the material [27].

Table 5. Resonance frequency, dynamic stiffness of the tested materials. Impact sound reduction of floating floors and floor coverings according to ISO 12354-2 [25]

Material	*Dynamic stiffness tests*			
	s'	f_0	*ΔLw* *floating floor*	*ΔLw* *floor covering*
S1	17.8	67.5	29.8	44.58
S2	34.4	93.8	25.3	23.08
S3	36.0	96.0	25.1	22.03
S4	15.0	61.9	30.1	53.02

Table 5 summarizes all calculated results of dynamic stiffness (s') values of resilient materials used in the study, from the resonance frequencies (f_0) obtained from measurements (see theoretical analysis of the vertical vibration of the system, Eq. 5 to Eq.11). Likewise, impact sound reduction of the floating system (Eq. 1, 2 and 3) and floor coverings (Eq. 4) were calculated based on dynamic stiffness and resonance frequency values following Annex C of ISO 12354-2 [22] and Vér calculations [28].

6 DISCUSSION

6.1 Analysis of different impact sound reduction values obtained from measurements

All results showed in Table 2 are compared between the tests of floating floors and of floor coverings. Due to the similarities found, it is assumed that single number values of impact sound reduction with floating floor/floor covering are the same between the floors measured in the study and the reference floors established in ISO 10140-5 (Fig 7).

- Floating floor system: From the results, major variations are observed between both type of base floors, mainly for case i) and iii). In addition, when comparing both types of base floors, with and without floating systems (ΔL_{iw} w/o), impact sound reduction on homogeneous slab are more than three times higher than the values for the non-homogeneous prefabricated floor.
- Floor covering system: This fact is repeated in the case of the other insulation system analysed, when coverings are disposed on the base floor. In this case, the results obtained are also better and the reduction to the impact sound is greater when the base floor is homogeneous.

In fact, in all three cases the difference obtained when considering the homogeneous floor as the base floor of the system provides higher results. However, more significant differences are observed when the comparison is made in relation to the reference floor ($\Delta L_{iwr,2}$ HW.)

Therefore, it is showed that the same materials, and therefore, the same constructive solutions of floating floors behave differently from the acoustic point of view, depending on whether the base floor is homogeneous or prefabricated lightweight floor.

6.2 Comparison of measured and calculated results

In order to determine the efficiency of insulation systems and to compare the accuracy of calculations and measurements in terms of impact sound reduction, it is of interest to analyse the impact sound reduction values obtained from stiffness properties, and to compare the reduction values of both insulation systems: floating floors and floor coverings.

Firstly, in both insulation systems, a close direct relationship is observed between the results Impact sound reduction of materials S2 an S3, which corresponds to cork materials. Secondly, as could be expected and can be stated in Table 5, stiffness values exhibit a direct relationship with the characteristics of materials, including material and mass with respect to the size of the specimen. In this regard, S1 and S4 display lower density, and therefore lower stiffness. As it can also be seen in Table 5, in the case of floor coverings there is a correspondence between the values provided and the results of Table 2, since the impact isolation achieved by materials S1 and S4 increases significantly with respect to S2 and S3. In addition, the differences of impact sound insulation vary by up to ~~9~~ 10-11 dB with respect to the comparisons with homogeneous reference floor values with the same coating S1 and S4 (ΔL_{iw}-NH and ~~RHF~~ ΔL_{iw}-H, Table 2), or 8-9 dB (ΔL_{iw}-NH and ΔL_{ir2} HW-H). This fact may be influenced by the size of the floating panel and of the specimen (1 m^2), since the energy transmitted to the receiver room can be propagated differently.

In the case of floating floors, tencendy of values is similar, however, there is a slight increase in the values when obtained from dynamic stiffness values. It is therefore observed that estimated efficiency of the floating system is more significant ~~when obtained from~~based on ~~dynamic~~ stiffness values of 25-30 dB (Table 5), than when the results are provided by lab tests, with values of 22-23 dB (Table 2).

7 CONCLUSIONS

The acoustic behaviour of the same materials was analysed in this work when placed over homogeneous and prefabricated lightweight floors. A total of four resilient materials was selected to help to understand the influence of coatings and floating system behaviour in relation to different types of base floor. Based on the work completed following acoustic regulations the conclusions can help to determine the most suitable constructive solutions and to assess the efficiency of impact sound reduction systems.

Generally, the efficiency of floor coverings and floating floors is calculated in laboratory conditions, considering a homogeneous floor as the base floor of the system. The values obtained from tests are used directly as market results in order to save time. However, the development of this study has shown that the acoustic performance of homogeneous slab and non-homogeneous lightweight floors differ significantly when assessing the impact sound reduction, where the difference in some cases is almost four times higher than the effect of floating floor system on an homogeneous floor. In other words, the arrangement of a resilient material on top of a lightweight non-homogeneous floor will probably provide a different efficiency of the system compared to a homogeneous base floor.

Taking into account the results obtained in the study, which can be considered in rehabilitation intervention in historic centres, it can be stated that:

- Acoustic measurements must be carried out in the laboratory to avoid possible design errors. Special attention must be paid to the type of base floor used for the floor system, since this can significantly influence the impact noise reduction results. In a floating floor system, when the base floor is homogeneous, efficiency can be improved by up to four times in comparison with that of a lightweight floor.

- In the case of prefabricated lightweight base floors, it would be advisable to use materials of lower dynamic stiffness as floor coverings to obtain similar results as in the case of homogeneous floors.

- When comparing calculations and measurements of stiffness properties, it is observed that the estimated efficiency of the floating floor in relation to the dynamic stiffness of the material is slightly higher than the efficiency obtained from laboratory tests. This factor may be influenced by the damping of the floor. However, in any case, it is advisable to check the results by performing laboratory tests.

From this study it is clear that implementing projects based solely on efficiency values obtained in laboratory conditions does not guarantee compliance with legal requirements. In fact, the simple characterization of floor coverings, whether floating or otherwise, using the standardized base floors, is important for comparison purposes but the values obtained should not be assumed to be representative of a foolproof performance for all uses, especially when the base floor greatly differs from ISO standards.

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- Research on floor constructive solutions that comply with regulations was developed
- The acoustic behaviour of resilient materials disposed on floors was analysed
- The efficiency of floor coverings and floating floors were obtained in lab conditions
- Dynamic and static stiffness properties of selected materials were analysed