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CICLO XXVI

TITOLO TESI

ENERGY, ACOUSTICS AND ENVIRONMENTAL SUSTAINABILITY ANALYSIS OF BUILDING SYSTEMS BASED ON WOOD WOOL MINERALIZED WITH PORTLAND CEMENT

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SUMMARY

In the present work various aspects of the energetic, thermal and acoustic properties of porous materials with wood wool mineralized Portland cement have been analyzed, in cooperation with the company Celenit Srl, a manufacturer of panels for building insulation.
These products are also recognized interesting and desirable for their environmental sustainability through specific certifications. Remind that sustainability means "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", as formulated in 1987 by the United Nations Assembly Gro H. Brundtland. It is for these reasons that in periods of strong research in renewable energy and environmental crisis such as the current one is important to ensure the sustainability of materials, elements, components, and building processes.
During the Ph.D. school some software for the evaluation of the thermal performance of the products were subjected to analysis and validation. As input data were chosen experimental values obtained in the laboratories of the Department of Industrial Engineering (DII).
Sound absorption, sound reduction and impact noise tests were done in laboratory for what concern the acoustic part. These analyses have led to the development of dynamic databases for data collection and usage.
The dynamic databases, processed in Excel, are collecting all the data of the acoustic tests performed in the lab at the University of Padua. In particular they have been processed two separate databases: one collecting data of airborne sound insulation and one collecting data of test acoustic absorption of materials.

RIASSUNTO

Nel presente lavoro sono stati analizzati diversi aspetti relativi alle proprietà energetiche, termiche ed acustiche di materiali porosi in lana di legno mineralizzata con cemento Portland, in collaborazione con la ditta Celenit S.r.l., produttrice di pannelli per l'isolamento edilizio .
Questi prodotti si rivelano interessanti e attualmente desiderabili anche per la loro sostenibilità ambientale riconosciuta tramite certificazioni specifiche. Ricordiamo che, in ambito edilizio, costruire sostenibile significa sviluppare progetti e realizzare edifici che soddisfino a pieno le esigenze degli utenti di oggi garantendo alle generazioni future di poter fare altrettanto, così come formulato nel 1987 all'Assemblea delle Nazioni Unite da Gro H. Brundtland. È per questi motivi che in periodi di forte ricerca di fonti energetiche e crisi ambientale quali quello attuale è importante garantire la sostenibilità dei materiali, degli elementi, dei componenti e dei processi edilizi.
Nel corso del dottorato sono stati sottoposti ad analisi e validazione alcuni software di valutazione delle prestazioni termiche dei prodotti. Come dati di input sono stati scelti i valori sperimentali ottenuti presso i laboratori del Dipartimento di Ingegneria Industriale (DII).
Sono state condotte, per quanto riguarda la parte acustica, prove di fonoisolamento, fonoassorbimento e calpestio in laboratorio. Tali analisi hanno consentito l'elaborazione di database dinamici per la raccolta dei dati e il loro utilizzo.
I database dinamici, elaborati in Excel, sono la raccolta di tutti i dati dei test acustici effettuati nel laboratorio universitario di Padova. In particolare sono stati elaborati due database distinti: uno che raccoglie i dati di potere fonoisolante per via aerea ed uno che raccoglie invece i dati di test sull'assorbimento acustico dei materiali.

PREFACE

This work was done in collaboration with Celenit S.p.A., the company that has financed the PhD in 2011-2014. The paper collects the experimental activities carried out in two different laboratories building acoustics (Labacus, University of Padova and Isolgomma Srl) and at the CNR-ITC in Milan. It also presented some software tests and analysis of data.

The aim of the research was the characterization of the material produced by the company, woodwool Portland cement board for insulation, in many of its aspects: energetic, acoustic and environmental sustainability. So the main issues dealt with the study are the thermal, acoustic properties and environmental compatibility of the product.

The chapter 1 explains the product properties, starting from the manufacturing process, the wood wool production, and its characteristics, as fire resistance, wet and dry rot resistance, thermal insulation, acoustic performances, mechanical strength, sustainability control.

The second section deals with the verification and validation of softwares for the thermohygrometric calculation, the interstitial condensation, thermal bridges and the evaluation of the reverberation time of rooms. In the structures involved it is assumed the use of wood wool panels to achieve a sufficient thermal and acoustic comfort in the respect of ambience.

The third chapter explains the acoustic measurements doing during the doctoral course. In particular the results of tests of sound insulation index on roofs are shown, as the impact noise results on floors and the proofs of dynamic stiffness.

The tests in laboratory of airborne sound insulation were characterized by partial reconstruction of structures used or to be used in building construction, which were then tested by evaluating the acoustic performance according to the methods suggested by the existing rules. The tests in question were carried out in the laboratory of acoustics LABACUS at University of Padua and at the ITC -CNR in Milan. In particular, the procedures described in the UNI EN ISO 10140 (part 2, 4 and 5) and UNI EN ISO 717 were followed.

A series of tests for the evaluation of the dynamic stiffness and acoustic properties of construction systems for slab which involve the use of insulating panels in wood wool mineralized with Portland cement combined with recycled rubber, were carried out. For these tests were followed the methodology proposed by the UNI EN 29052-1. Then tests of impact noise insulation were carried out from the solutions selected by performance evaluation of dynamic stiffness according to the UNI EN ISO 10140 Part 3 and UNI EN ISO 717. The measurements in question were done at the laboratory Isolgomma Ltd. This laboratory consists of two rooms connected vertically with an opening in the floor where the common element is installed to test. The performance is evaluated by measuring the sound pressure level in the underlying room while a machine generating normalized impact noise is tapping on the floor. The laboratory measurements provide two types of tests: one for complete ceiling and one for floor coverings which can be installed on standard ceiling as in the case in question. The magnitude which describes the acoustic behavior of the coatings of the floor base is the attenuation of the impact noise. In this case solutions were tested from a concrete base floor and the same starting from a beam and hollow block floor. The results of this work are interesting and have allowed to make some assessment estimates for other types of floors such as the wood floor.

Chapter 4 deals with materials for sound absorption and the evaluation of the reverberation time. In particular, the various types of absorbing materials were presented to evaluate, in specific, the acoustic reverberation time corrections of large halls through the application of wood wool panels.

The fifth part is devoted to the statistical analysis of the dynamic databases developed from the results of acoustic tests carried out in about fifteen years at the Laboratory of Padova. Statistical evaluations were carried out from airborne sound insulation tests on various types of wall. These proofs take into account various parameters in mathematical and constructive character. Therefore, these structures have been divided into macrogroups at different levels of typology and for each of them the performances were evaluated and compared each others. From this work we have obtained the bands of common use which may therefore be taken into account by the designers for the definition of a construction project.

Finally, the sixth part is about the possibility of correlation between the improvement of the thermal insulation performances of the building vertical structures and the improvement of sound insulation of the same structures.

CHAPTER 1

CELENIT INSULATION PANELS: THE PRODUCT AND THE PRODUCTION PROCESS

INTRODUCTION

The company Celenit that produces materials for the acoustic and thermal insulation made of wood wool mineralized with Portland cement. Wood wool slabs are good insulation material that can be made locally and due to their versatility, they are easy to integrate with most construction techniques. The standard dimensions panels are made of high porosity material and that guarantees good acoustic absorption and thermo-acoustic insulation. It could be utilized to improve the acoustic of closed environments reducing the reverberation time.

Figure 1: The wood wool panel.

MANIFACTURING PROCESS

The components needed for wood wool slabs are wood wool, binder (Portland cement) and water. Normally a small amount of binder additive is added to speed up setting. The productive cycle starts from the cut of logs, then it continues with the milling and obtaining of wood chips to which is added the mixture of mineral binder. The mixture is then processed, distributed on molds and sent on pressing.

So the process of manufacture of Celenit thermal and acoustic insulation panels can be divided into two major sections:

- Production of wood wool;
- Production of panels.

Then the panel can be subjected to further processing (finishing, painting, etc…) called “secondary processing”.

Wood wool production

The most commonly used wood for wood wool slabs comes from conifers, mainly pines and firs. Usually the tree trunks are air-dried before cutting into logs and shredding to wood wool. This reduces the amount of sugar and other compounds in the wood that inhibit setting of the slabs, and lowers the moisture content. The wood logs debarked (all certified PEFC) are sectioned using a wood logging saw; then two automatic machines reduce the wood into wool. The wood wool is sent to the next work area by air. To make wood wool, a half meter long log is placed in a shredding machine fitted with scoring knives perpendicular to the planing knives. The thickness of the wood wool can vary between 0.2 – 0.5 mm, and the width between 1.5 – 5 mm depending on how the slab will be used. The amount of wood wool in a slab varies between about 75 – 200 kg depending on the density of the slab.

Figure 2: Different size of wood wool thickness.

Binder

The most commonly used binder in wood wool slabs is Portland cement normally of ordinary type (OPC), although rapid-hardening cement can be used to make the setting faster. Sometimes white cement is used for aesthetic reasons. The amount of binder depends on the density of the wood wool slab, and varies between about 150 and 400 kg/m^3.

Cement is delivered to the plant in bags. The bags are emptied into a container and the cement is transferred to the mixers. The correct amount of cement for a batch is controlled by a cement dosing unit next to the mixer. The water should not contain anything that would inhibit the setting of the slabs. The amount of water required is about 50% of the cement by weight.

Mixing and moulding

Before the wood wool is mixed with the binder, it is soaked in a water bath containing a salt solution. The wet wood wool is transferred to a mixer, where dry binder is added generally in the ratio of about 2:1. Wet wood wool and dry cement are mixed continuously in a mixer. The homogenous mix is then spread in moulds that are pushed into place under the mixer on a line of rollers. The amount of material in the moulds depends on the density of slab to be produced. The moulds are stacking on top each other and put under pressure so that the mixture in each mould is compressed. After the slabs have hardened, usually in 24 hours, they are demoulded and transferred to a dryer. Then the panels are subjecting to trimming of the edge and then packed.

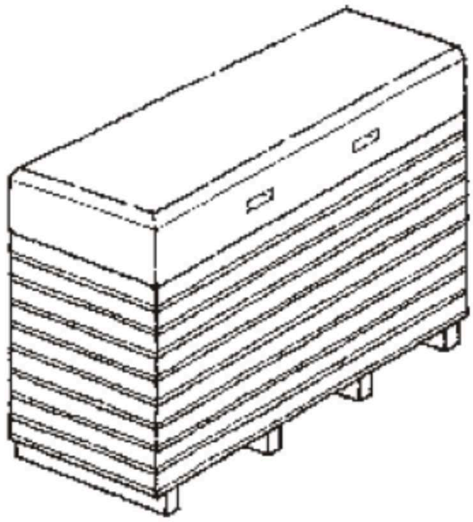


Figure 3: The slabs set under pressure for 24 hours. The required pressure is maintained by a concrete slab weighing about a ton.

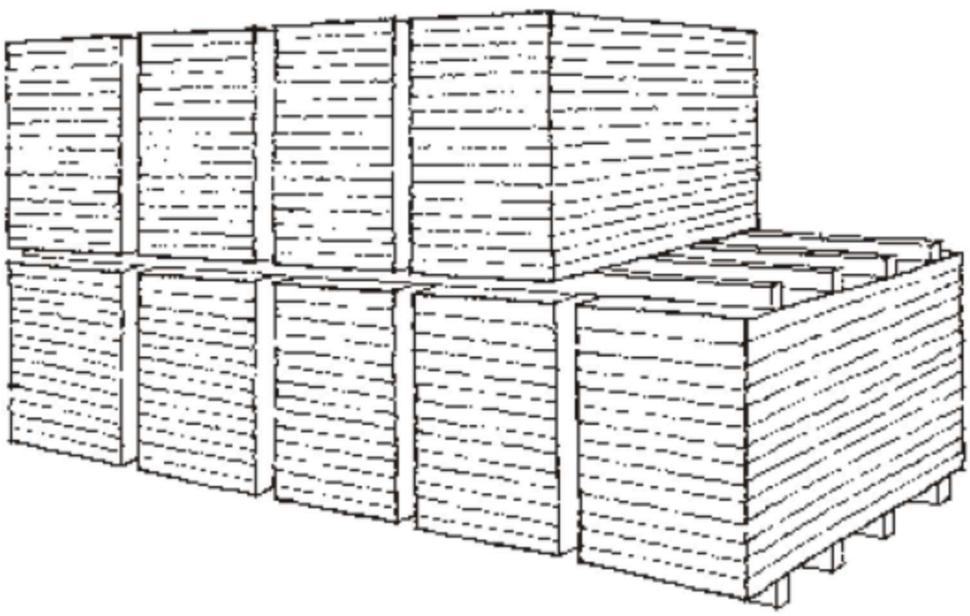


Figure 4: Storing of slabs stacked on top of each other.

The semi-finished panels can undergo a series of subsequent working consisting of: battening of two or four sides, chamfering of two or more sides, calibration (steps in thickness), painting. In Figure 4 are shown some profiles required.

Since their multi-use the wood wool panels are also used as formwork, and it's certified that there is an improvement up to 30% of the compressive strength and the elastic modulus of concrete matured in formwork consisting by Celenit.

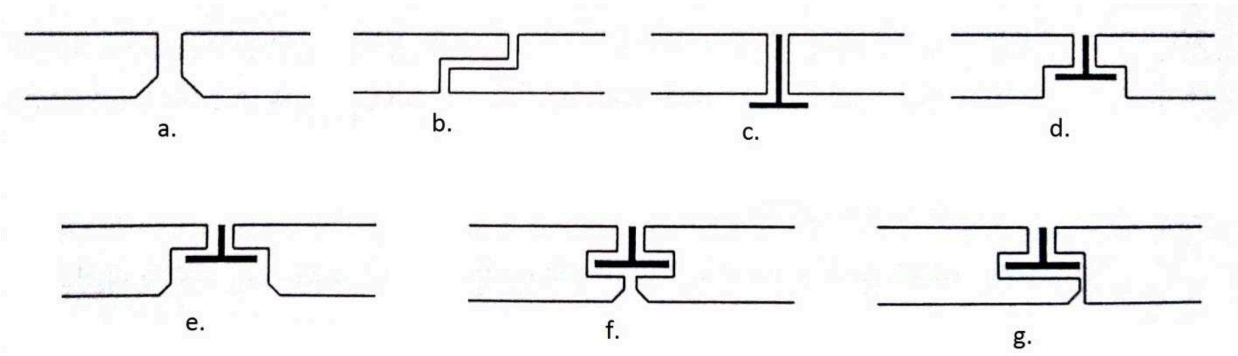


Figure 5: Secondary working on panels: profiles. In sequence: a)beveled edges; b)rabbeted edges; c)sharp edges with visible profile; d)lowered edges with visible profile; e)beleved lowered edges with visible profile; f)beleved edges with retractable profiles; g)profiles retractable and mobile panels.

CHARACTERISTICS

The main characteristics of the wood wool panels are:

- Fire resistance
- Wet and dry rot resistance
- Thermal insulation
- Acoustic performance – sound absorption
- Bending strength
- Acceptance of a wide range of finishes

FIRE RESISTANCE

In spite of the wood content, wood wool slabs have good resistance to fire. The material is classed as hard to ignite, and is therefore approved for indoor surfaces according to international standards. The good fire performance of the material is related to the fact that the wood strands are protected by the binder, as well as its thermal insulating capacity and coarse structure. If the material is covered with a layer of cement or gypsum plaster, fire resistance increases further. The panels have been tested and classified B1 (non-readily ignitable) according to UNI EN 13501-1.

In case of fire the panel does not cause dripping, no toxic fumes and no propagation of flame. According to DIN 4102-4 products of wood wool and cement are suitable for fire protection of building elements: in fact they work as a heat shield increasing the fire resistance of these elements. This is due to the insulating properties of the material determined by a honeycomb open structure, that is not subject to outbursts or chipping and its ability to remain unchanged for a long time thanks to the protective effect of the mineral component. The combustion of the panel is slow and without flame, with formation of a mass of ash that protects the underlying part of the panel, reducing the speed of combustion until it ends.

WET AND DRY ROT RESISTANCE

Because the wood wool has been mineralized by the cement, moisture loses its effect on the board. The boards can even be applied in moist conditions like ceilings in indoor swimming pools. The wood wool slabs have the ability to absorb large amounts of moisture and for this reason they are suitable where the relative humidity is occasionally very high, for example in sports halls. The slabs attenuate the variations in the indoor air humidity, by absorbing moisture rapidly when there is a moisture input (when the relative humidity rises) and releasing this moisture when the relative humidity decreases. The ability of the panels to absorb moisture is from 2 to 3.5 l/m^2. The resistance to the fungal attack is total. The diffusivity resistance of vapor of the panels (at 20°C) is about 5.

Because the wood strands are covered by binder, also the resistance to insects and termites increases significantly. However the risk of termites must be considered, if the slabs have an active function in the loadbearing construction. Plastering the slabs will further reduce the risk of termite attack.

Furthermore this type of panels behave as hygrometric regulators: they absorb moisture in excess and yield it when the normal conditions are restored, without undergoing deformations.

Thanks to the cement the panel is insensitive to water and frost. There is no swelling nor crumbling in presence of moisture. These properties are verified by tests repeated 20 times.

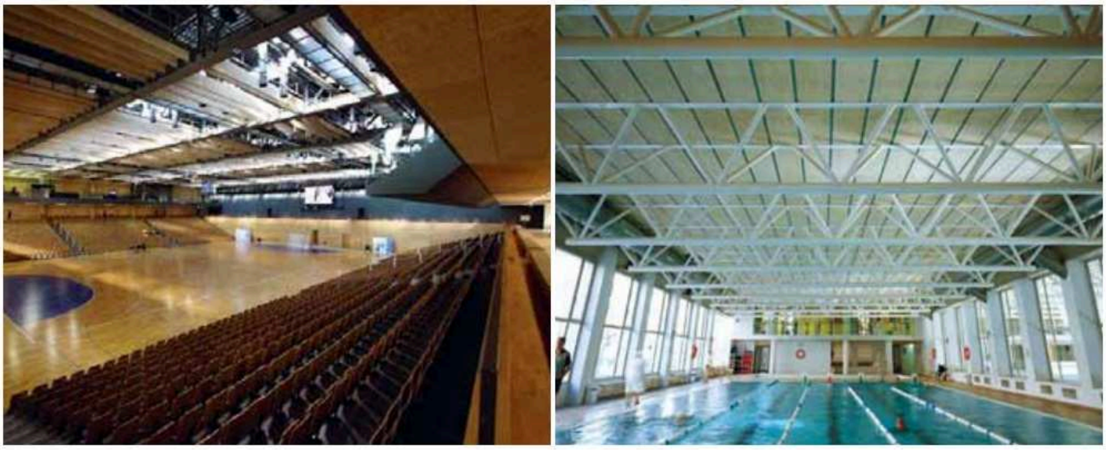


Figure 6: Applications in a sport hall and in a swimming pool.

THERMAL INSULATION

Wood wool slabs give good thermal insulation. Thermal conductivity is, however, relative to their density and moisture content; it increases as density and/or moisture content increases. The thermal resistance goes from about 0.20 m^2K/W for the standard panels of 15 mm thickness to 1.15 m^2K/W for the panels of 75 mm thickness. The panels used for thermal insulation, and are normally not visible but rendered/plastered. Wood wool slabs allow air to pass easily, which could increase the thermal conductivity by forced convection when the material is left unplastered (acoustic applications). The relatively high thermal capacity of roofs and walls constructed with wood wool slabs can significantly improve indoor comfort, since indoor temperature changes are attenuated, when there are large diurnal variations in outdoor temperature.

The slabs can be 1.2 – 2.4 m long, 600 mm wide and 15 – 150 mm thick. Their density ranges from 340 – 530 kg/m^3 depending on use. If thermal insulation, capacity is important, they are made with low density; if strength is important, they are made with high density. The wood wool slabs are often used for elimination of thermal bridges and coating of walls.

Acoustic performance

Wood wool slabs have very good acoustic properties since the open surface structure allows for a high level of acoustic absorption and they are often used, for example, in factories, public gathering places, sports and concert halls. The panels are used also for sound insulation of walls, impact noise insulation for floors, insulation of flat and sloping roofs.

The good sound absorption of the panels makes them suitable for all kinds of public gathering places, industries, etc. The sound absorption normally increases somewhat with increased thickness, especially for low frequencies. Sound absorption is also affected by proximity to other materials, while painting the slabs has only slight effect.

A wood wool slab itself gives moderate sound insulation (sound reduction of about 22 dB for a panel 25 mm thick), but the sound insulation properties are very good if the slab is interposed in a wall with other materials. Good sound insulation can also be achieved with a wall made of two plastered wood wool slabs with an air cavity (sound reduction of about 50 dB).

Figure 7: Celenit applications.

Bending strength

The bending strength of a slab is high relative to its weight, because the two components (wood wool and binder) are complementary: the wood strands take the tensile stress, while the hardened cement paste takes most of the compressive stress. The tensile strength of the wood strands is crucial to the slab’s bending strength. Bending strength increases with density. Normally thin slabs are made with higher density than thick slabs to give adequate bending strength.

SUSTAINABILITY

It is essential to have clear information about the sustainability characteristics of construction products. This allows you to better respond to user requests to design in accordance with the new regulations and to obtain certification of sustainable buildings, possible incentives and tax reduction that can be obtained using sustainable materials manufacturing.

There are some rules that define sustainability requirements that ensure the realization of high performance buildings. Some of these rules are defined by the regions, other from countries, and others are drawn up at international level.

The mineralized wood wool panels with Portland cement described above are certified as sustainable by the PEFC international brand, a series of environmental statements of type II (ISO 14021) and studies ANAB-ICEA of type III (ISO 14025).

In particular, these panels are certified as components comply with the following guidelines:

- use of local materials, sourced from areas close to the construction site. By limiting the distance between the place of sourcing of raw materials and the production site the pollution related to the transport of materials is limited;
- materials from sources certified as sustainable. It must be ensured that the proper management and use of forests and forest lands in the manner and quantity, maintaining their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social life at the local, national and global levels, without affecting other ecosystems;
- recycled materials;
- non-polluting materials to the indoor environment, guaranteeing the absence of emissions of volatile organic compounds (VOC) or radiation that pollute the environment within the building;
- materials are not harmful to the climate, which have low global warming potential (GWP). This evaluation analyzes the greenhouse gases emitted during the production phases, including construction materials and measuring the way in which they contribute to global warming;
- materials with low embodied energy.

CHAPTER 2

APPLICATIONS FOR ENERGY SAVING

Energy efficiency is "using less energy to provide the same service and to obtain the same comfort conditions". There are many motivations to improve energy efficiency. Using less energy means save energy cost, investing in energy efficiency technologies has interesting values of return of investment. Reducing energy use is also seen as a solution to the problem of reducing carbon dioxide emissions. Energy saving is reducing and using less energy. Both efficiency and conservation can reduce greenhouse gas emissions.

A building's location and surroundings play a key role in regulating its temperature and illumination. The building design, including additional thermal insulation of walls, can reduce significantly the energy consumption.

With the increasing emphasis on energy-conscious design and the broader environmental impact of buildings, greater attention is necessarily being focused upon the appropriate use of thermal and sound insulation materials.

Insulation is a passive product; once installed, it works efficiently, usually out of sight, enclosed within a structure or a casing or under cladding. It comes to the fore when new design of buildings, plant, equipment, or production processes is being considered. There are many reasons why professional engineers and architects use insulation: to comply with mandatory legislation, to reduce heat loss/heat gain, to reduce running costs, to control process temperatures.

CALCULATION CODES

To help the knowing of energy dispersion in a building the company Celenit has a platform to spread hardware and software for thermal and acoustic insulation. These tools include:

JVap: a software that allows the study and analysis of temperature and humidity conditions of insulating structures, such as walls, roofs or floors. It describes in a simple and intuitive way the properties of the structure and its stratigraphic composition. It verifies the conditions of temperature, the calculation of the interstitial condensation in the interfaces and the accumulation of condensation during the year.

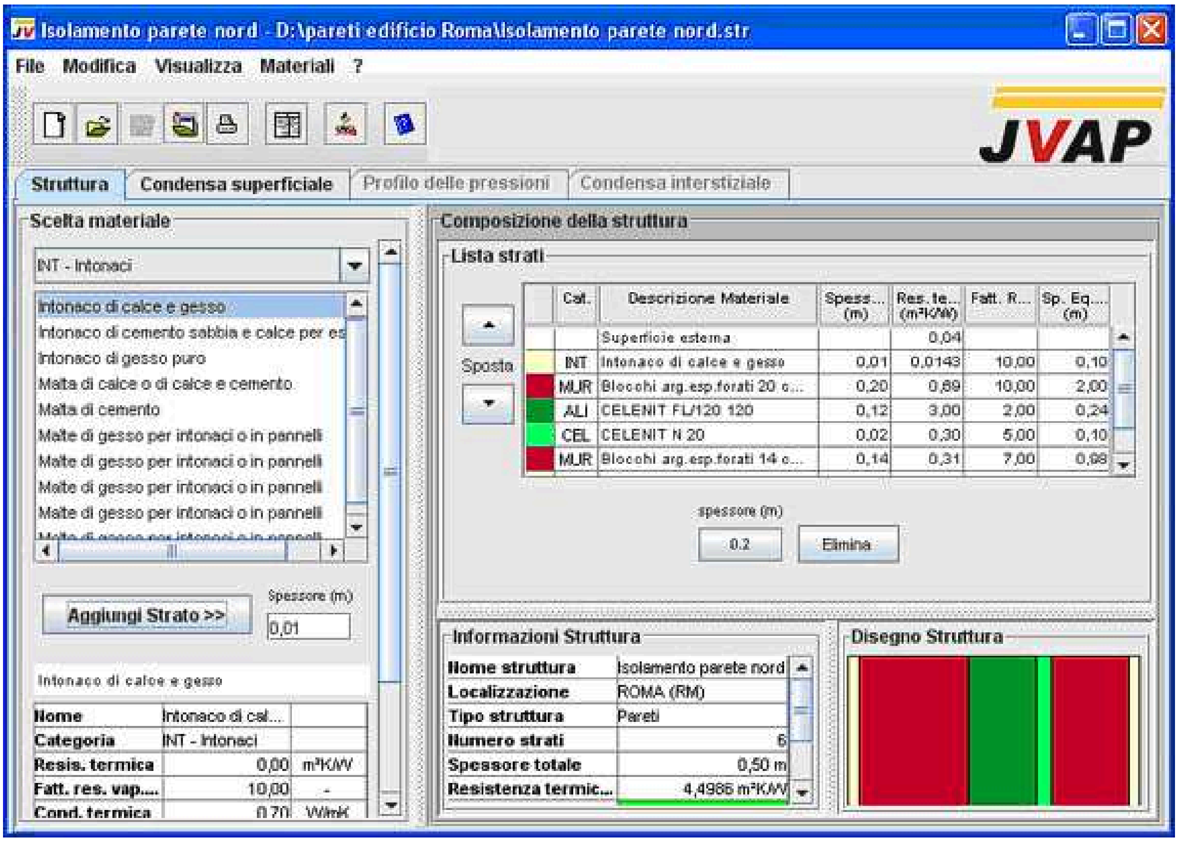


Figure 8: JVap interface.

JTempEst: it is the application for the calculation of the phase shift of the thermal wave and the summer temperature of the internal surface of isolated structures, such as walls, roofs or floors. This software guides the user in the composition of the various layers of the isolated structure, allowing the choice of materials by a rich integrated archive. The user can choose between the materials in the archive or enrich the archive itself with new materials. It follows the guidelines of the standards UNI 10375, UNI EN 13792, UNI 10349, UNI 10351, UNI 10355.

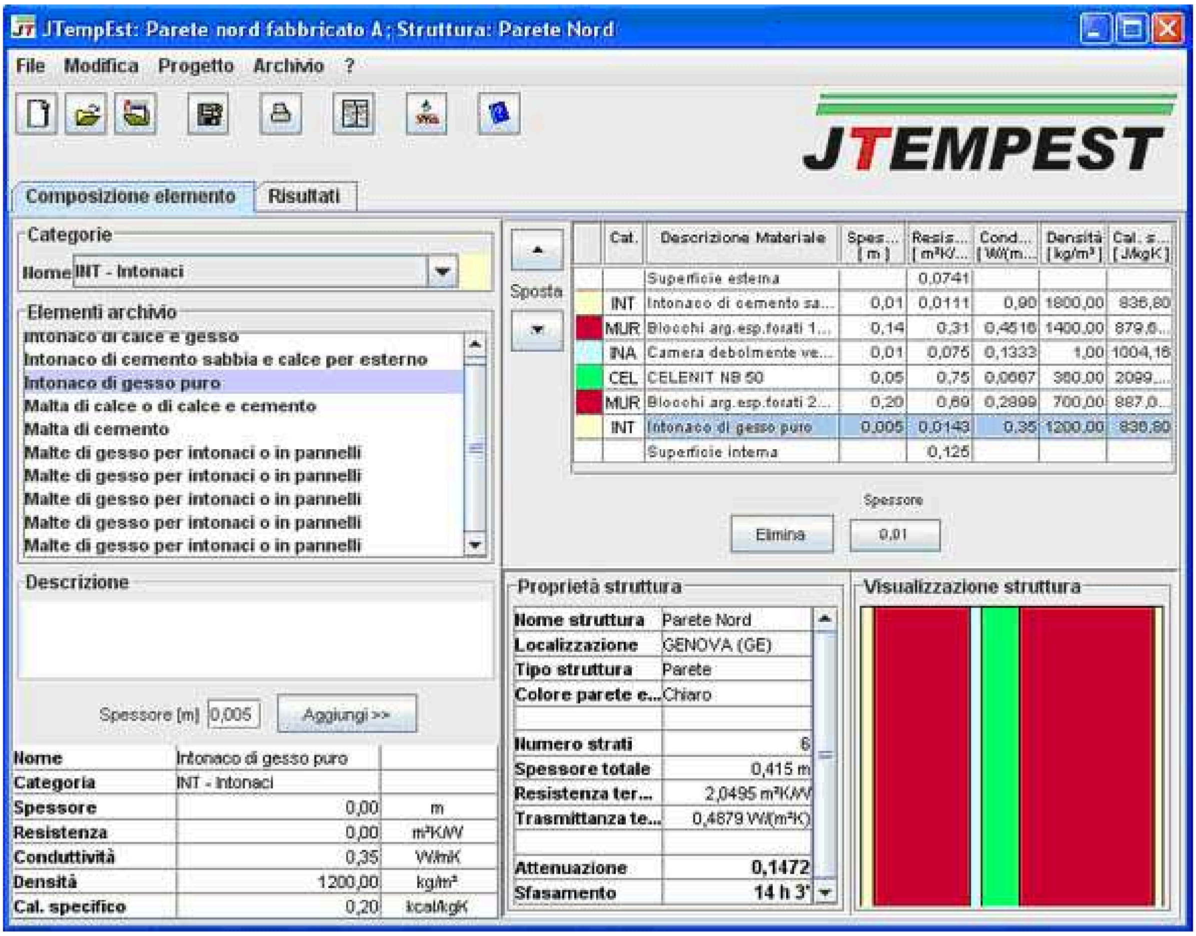


Figure 9: JTempEst interface.

JEcho: a software that estimates the acoustic performance that the internal partitions and the external elements will be in place, starting from the acoustic values determined in the laboratory according to the calculation methods described in the standard UNI EN 12354 (part 1-2-3). It performs calculations according to the simplified method stated in the standard, determining the single number. It calculates an additional parameter for the evaluation of the acoustic quality within the environment: the reverberation time. JEcho is divided into these types of calculations:

1. R'_w calculation : calculation and verification of the sound reduction index of the partition;
2. Calculation $D_{2m,nT,w}$: index calculation and verification of standardized sound insulation of a facade;
3. Calculation $L'_{n,w}$: calculation and verification of normalized sound absorption;
4. T60 calculation: calculation of the reverberation time.

It follows the guidelines of the standards 447/1995, UNI EN 12354-1/2/3, UNI EN 12758, UNI EN 29052-1, UNI EN 29053.

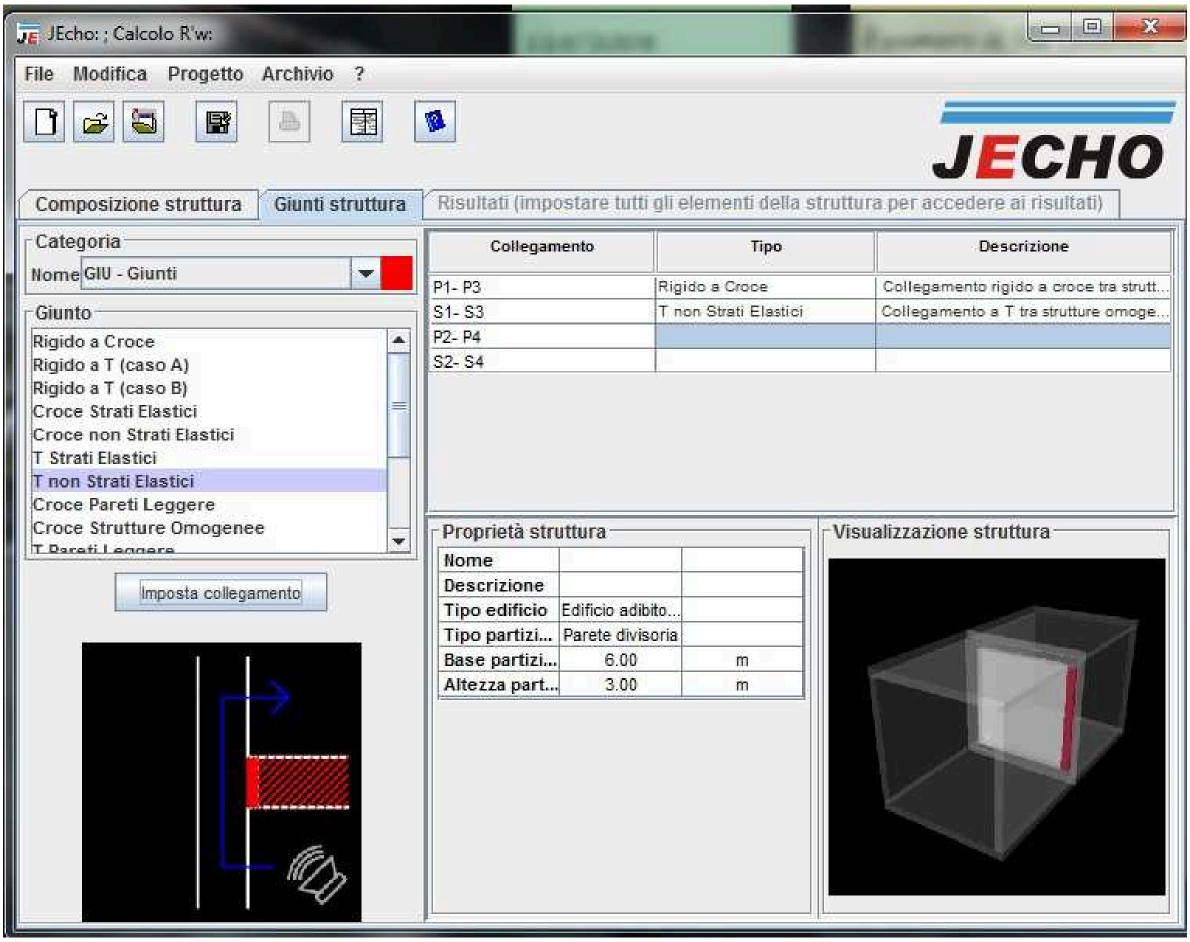


Figure 10: JEcho interface.

In addition to these tools, a new software, **CeIPT**, for the calculation of thermal bridges is developing.

During the PhD the software were subjected to analysis and validation. As input data experimental values obtained at the laboratories of the Department of Industrial Engineering (DII) were chosen. The software then have shown a good degree of correspondence with the benchmarks.

INTERSTITIAL CONDENSATION AND PHASE SHIFT

Interstitial condensation means that the humidity during the winter period can accumulate inside the masonry, and in the building supporting structure: the accumulation does not always occurs, but it is important that the masonry could be able to dispose the excess humidity during the summer months. The diffusion of water vapor to the outside is very important as it avoids the damage of the bearing structure of the building over time by humidity, and the loss of the properties of the insulating materials in the masonry as they accumulate moisture. The thermo-hygrometric check is a particular calculation procedure that allows to understand which of the winter months are critical for the thermal envelope from the point of view of the accumulation of interstitial condensation.

In summer, there is a reverse heat flux respect of the winter, the materials that compose the envelope elements transmit the heat, due to solar radiation, to the interior. When the internal surface temperature is higher than the one of the air of the internal environment, radiation and convective exchanges are activated and they contribute to increase the temperature of the environments. The opaque envelope, due to its thermal inertia, plays an important role in determining the internal conditions of comfort during the hot season. In particular the presence of the insulation allows to reduce the contributions of heat transmission through the shell. The heat wave that passes through the structure is then damped down.

The phase shift is the duration that the heat wave takes to flow from outside to inside through a building material. Greater is the phase shift, longer the time of passage of the heat inside your building will be. The phase shift, therefore, is the difference in time between the time with the maximum temperature outside and the time with the maximum temperature inside, and must not be lower than 8/12 hours; the damping expresses the ratio between the maximum variation of the external temperature ΔT_e and the internal temperature ΔT_i in reference to the average temperature of the inner surface. The comfort benefit in the summer period grows, increasing the values of phase shift and damping of the thermal flow. The effect of the mass is to create a phase shift between the peak of external heat and the internal one, the effect of the insulation is to attenuate the intensity of this peak.

THERMAL BRIDGES

Thermal bridges are the parts of a building characterized by constructive discontinuity such to determine heat loss. This phenomenon is due to the different thermal characteristics of the materials close together in the shells. According to the characteristics, thermal bridges can be of geometric type (corners, edges), constructive (contact areas between materials with different thermal conductivity) or accidental (defects of construction and insulation).

Thermal bridges are areas characterized by high thermal conductivity compared to the rest of the building and are located, generally, in the points of contact between different materials and construction systems as well as in heating areas in contact with external air or colder volumes.

The heat dispersions created through the thermal bridges determine a lower temperature of the internal spaces and, consequently, increasing of energy consumption for the heating of buildings. The low internal temperatures may also induce the formation of condensation in the thermal bridge, developing of moisture and mold.

Is possible to solve damaging effects of thermal bridges with some different solutions. Both in existing buildings or new constructions, a very effective system to prevent heat loss can be reached applying a thermal insulation composed of panels fixed outside of the building. Another solution on the whole building is the use of ventilated facades and of internal insulation.

In the presence of complex thermal bridges, for example referred to balconies and overhangs, it may be better to rebuild the affected portion for its totality. In many cases, in fact, the reconstruction without interruption or the inclusion of special plugs in the structures can be crucial in the elimination of the thermal bridge. If heat losses are relate to the windows, the most effective remedies are the use of insulating glass windows and thermal break.

Locate and correct the thermal bridges in buildings is of fundamental importance for the health of the environment and also for the overall energy savings of buildings and is, therefore, a prerequisite for the economic value of buildings.

VALIDATION OF A NEW SOFTWARE: CELPT

CelPT is a new developing software for the calculation of the thermal bridges. In this work are presented some observation done during the tool’s improvement.

Figure 11: CelPT first window.

The interface of the program allows to compose a thermal bridge model starting from predefined structures. The interface of the program allows to compose a thermal bridge starting from predefined structures. The bridge's evaluation can be done in a section chosen by an intuitive screen but in the software there is no explicative legend.

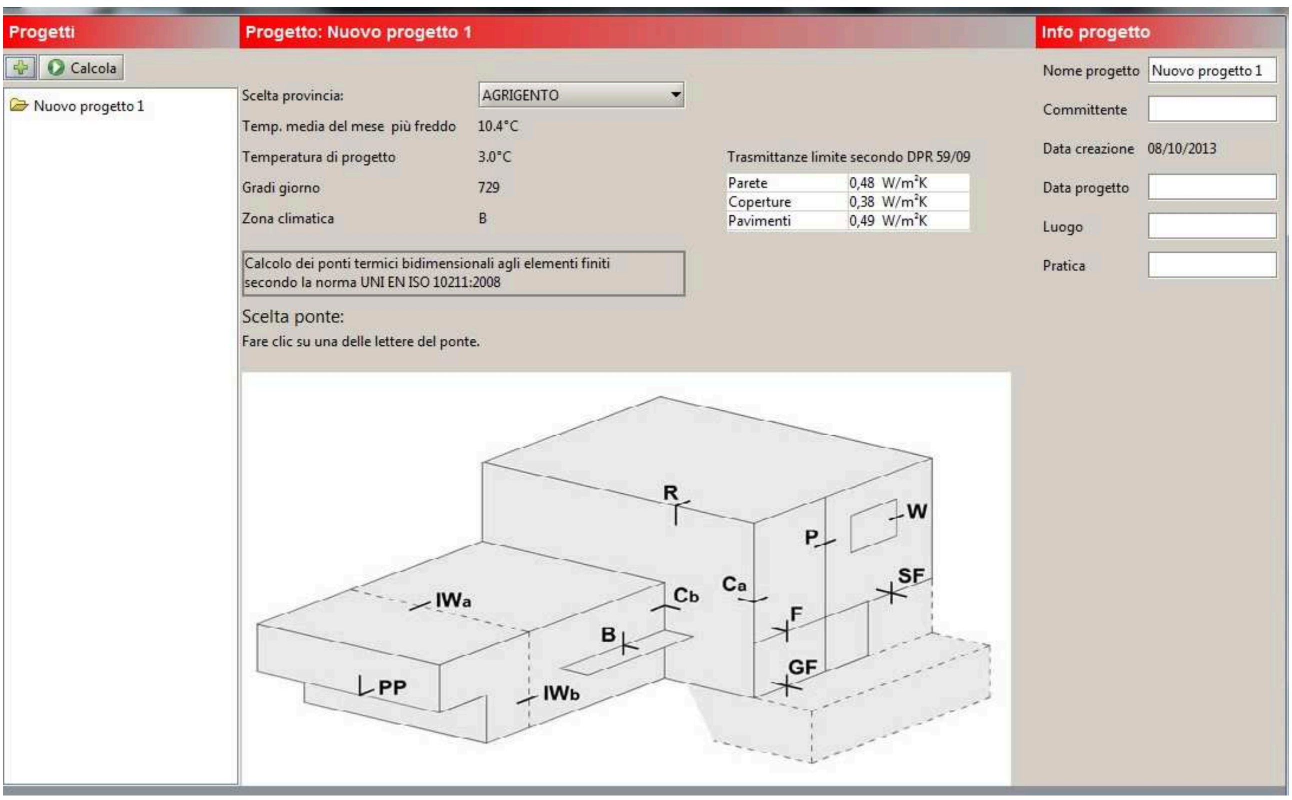


Figure 12: CelPT interface.

It is useful to have structures of thermal bridges already "ready to use" and that speeds up the work, however, it should introduce the possibility of increasing the layers of material or otherwise modify the predefined solutions to allow the calculation of the thermal bridges of different structures from those present by default in the program. If a material is inserted manually and not among those on the list, the software does not give the possibility to include the new lambda proposed and corrects it with an existing one.

The calculation is performed with the methods of UNI EN ISO 14683 and EN ISO 10211 and it allows the evaluation of the coefficients ψ according to the type of thermal bridge, the external geometric dimensions and thermal characteristics of the materials used. The coefficient is the parameter, expressed in W/mK, which allows to evaluate the major dispersions due to the presence of a thermal bridge. The product between the coefficient ψ and the length (or depth) of the thermal bridge is the value of dispersive coefficients H [W/K] and they have to be added to the dispersions of the walls, coverings and window frames for the evaluation of the energy losses.

In modeling the energy dispersion of the wall of a pillar as the product of transmittance U for the area A of the wall, the thermal bridge is add through the coefficient ψ multiplied by the length L of the thermal bridge itself. The sum of the two dispersive coefficients describes the behavior of the whole wall.

Comparing the thermal bridges performed by CelPT with another different finite element program the resulting graphs are similar, therefore there is a good match in the calculation of the thermal bridge, but calculating manually the total transmittance U in the second software, this is different from the one expressed automatically by CelPT. This could be due to a systematic error of the program, or to a calculation made differently, but this is not easily verifiable since the program CelPt does not specify how the transmittance is calculated, and does not specify the lengths of the elements considered and, as already mentioned, does not allow to enter them manually.

To follow some comparisons of the performances of simple thermal bridges.

1. Attic wall

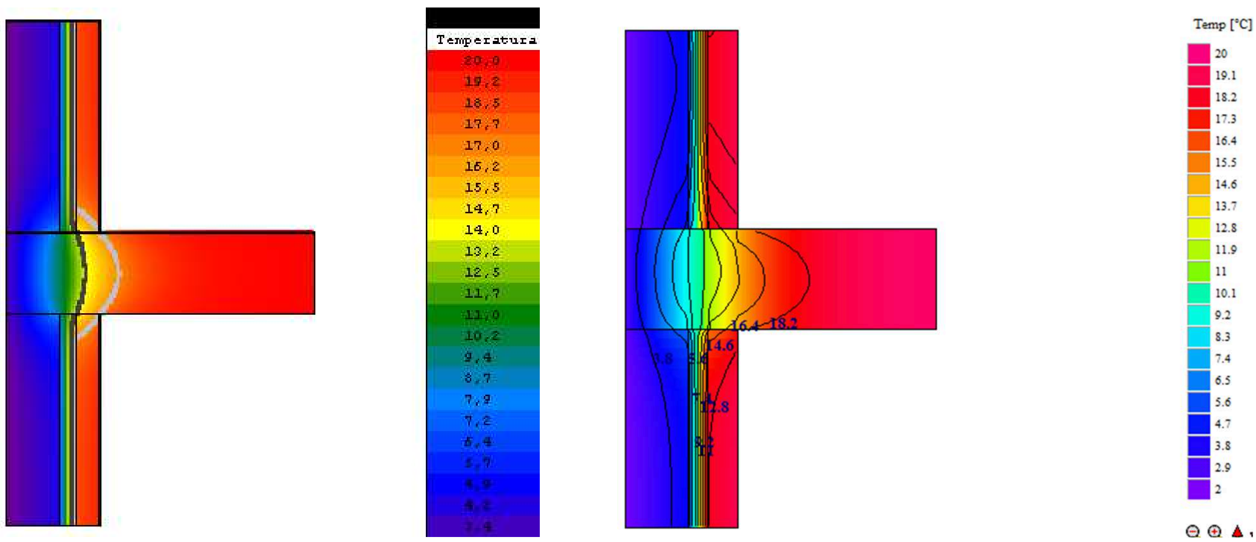


Figure 13: Thermal bridge of an attic wall performed with CelPT and Heat 2.4.

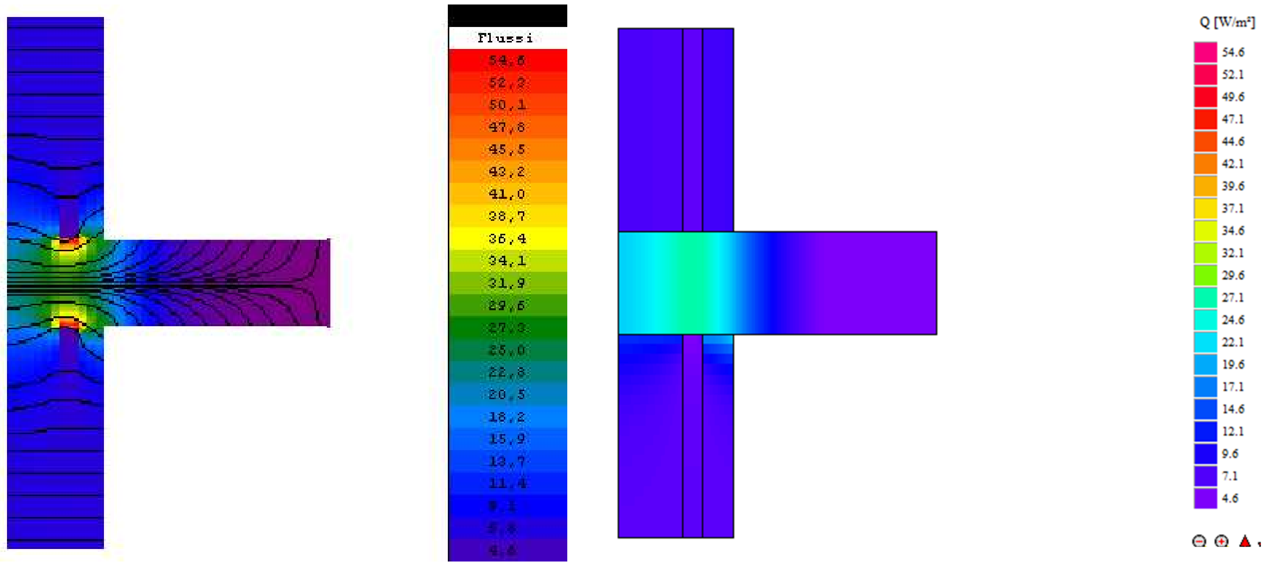


Figure 14: Fluxes performed by CelPT and Heat 2.4.

2. Pillar in the corner

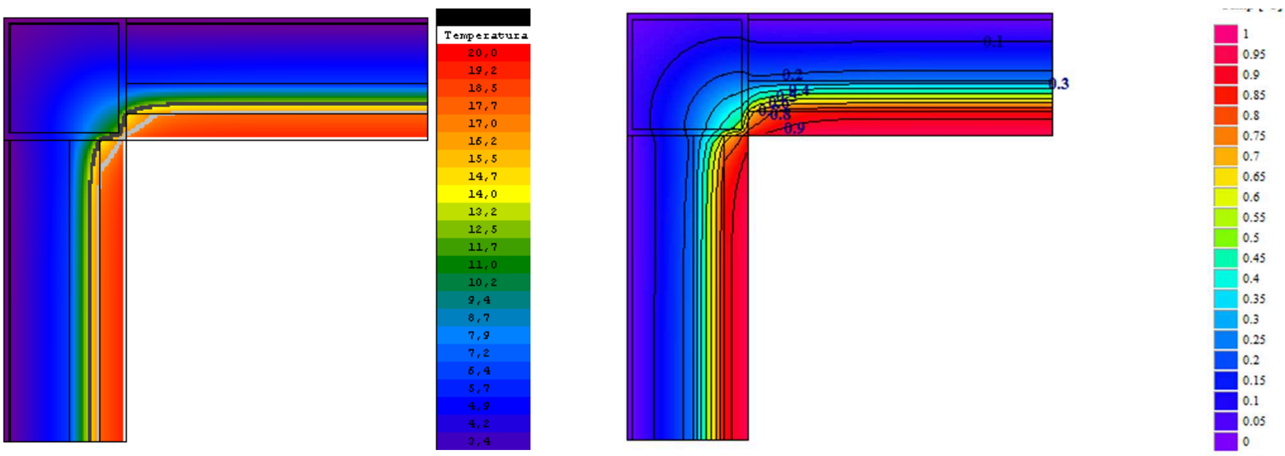


Figure 15: Thermal bridge of apillar in the corner performed with CelPT and Heat 2.4.

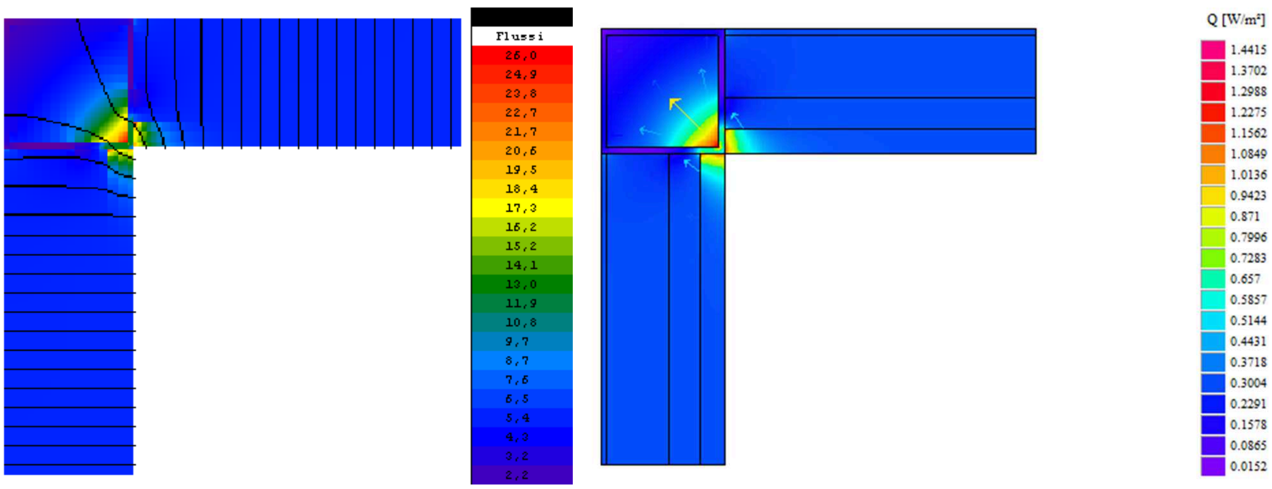


Figure 16: Fluxes performed by CelPT and Heat 2.4.

CHAPTER 3

ACOUSTIC APPLICATIONS

INTRODUCTION

The sound in an elastic means, for example the air, can be described as a sequence of compressions and rarefactions of pressure that cause a variation of the density of the means themselves compared to the one at the equilibrium stadium.

Sound fields in rooms are of primary importance in the study of sound insulation. This is the reason why tests on insulation materials and combined systems are done in laboratory to evaluate their performance and predict their behavior in situ.

Move away from a source of sound is the best method to protect oneself from its effects. This rule can only be completely verified in ideal free field conditions. If there is a point or non-directional source and far enough away from the receptor the sound waves are spherical. All points are reached by the perturbation at the same distance from the source simultaneously and this cause them to vibrate in phase. In terms of unit time, the vibration energy transmitted at every instant by the source corresponds to the sound power, so the sound intensity captured by a given receptor diminishes as the square of the distance from source rises. For waves that propagate freely, the intensity is proportional to the square of the amplitude of the pressure that decreases proportionally with the distance.

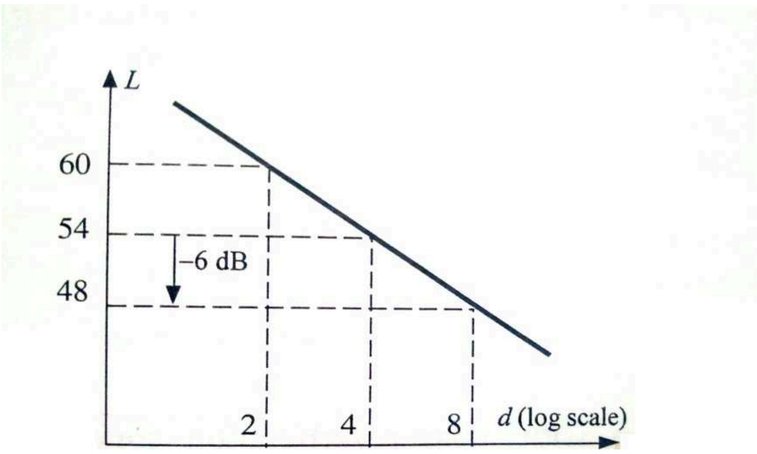


Figure 17: Fall-off levels with distance.

In a closed room the sound waves bounce on the walls creating many virtual sound sources. The closed space is a reverberated or diffuse field. If the walls were perfect reflectors, the sound pressure level should grow indefinitely, but in nature this is not possible and they transmit some portion of the sound outside or absorb them, or both.

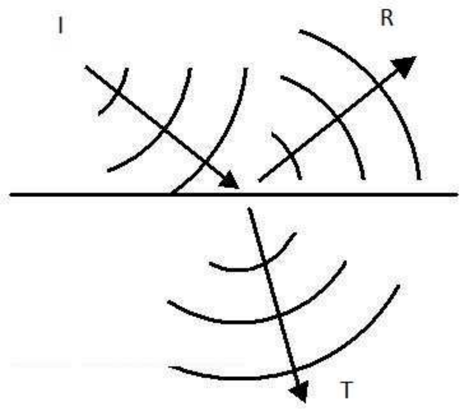


Figure 18: Wave incident, reflected and transmitted.

LABORATORY MEASUREMENTS

AIRBORNE SOUND INSULATION

The sound insulation is the prevention of the transmission of the sound divided in:

- airborne sound insulation, that is the one against noise produced in the air by music, traffic, voices, atmospheric agents;
- impact sound insulation, the one against noise originating on a structure directly by steps, vibrations, moving objects.

To determine the way in which sound energy can be transmitted to the wall (that could be a partition or any device used to screen sound source) we can express the transmission loss of sound by the inverse of the transmission factor, that is the ratio between the transmitted power and incident power and it could be a value between 0 (soundproof wall) and 1 (sound transparency).

1)

$$\tau = \frac{W_t}{W_i}$$

The sound reduction index *R* is the inverse of the transmission factor *t* expresses in decibel (dB). In laboratory this index is determined by measuring the sound pressure level L_{p1} in the transmission room (where there is the sound source) and simultaneously the sound pressure level L_{p2} in the receiving room (on the other side of wall). So we calculate the *R* value as the following

2)

$$R = L_{p1} - L_{p2} - 10log\frac{A}{S}$$

where A is the equivalent absorption area of the receiving room and S is the area of the wall testing. But transmission goes completely through the wall only under conditions of complete vibrational insulation of the rooms. In the real case, a large portion of the sound is transmitted also through the other parts of a building structure like ceilings, adjacent walls, piping and so on. Those are called

lateral flanking transmissions. In laboratory the two rooms are designed to not involve lateral transmission so we can assume that all sound is transmitted via the test element and that the structure plays no role.
Laboratory airborne sound insulation proofs are principally used to compare the sound insulation performances of different test elements and to estimate the sound insulation *in situ*.

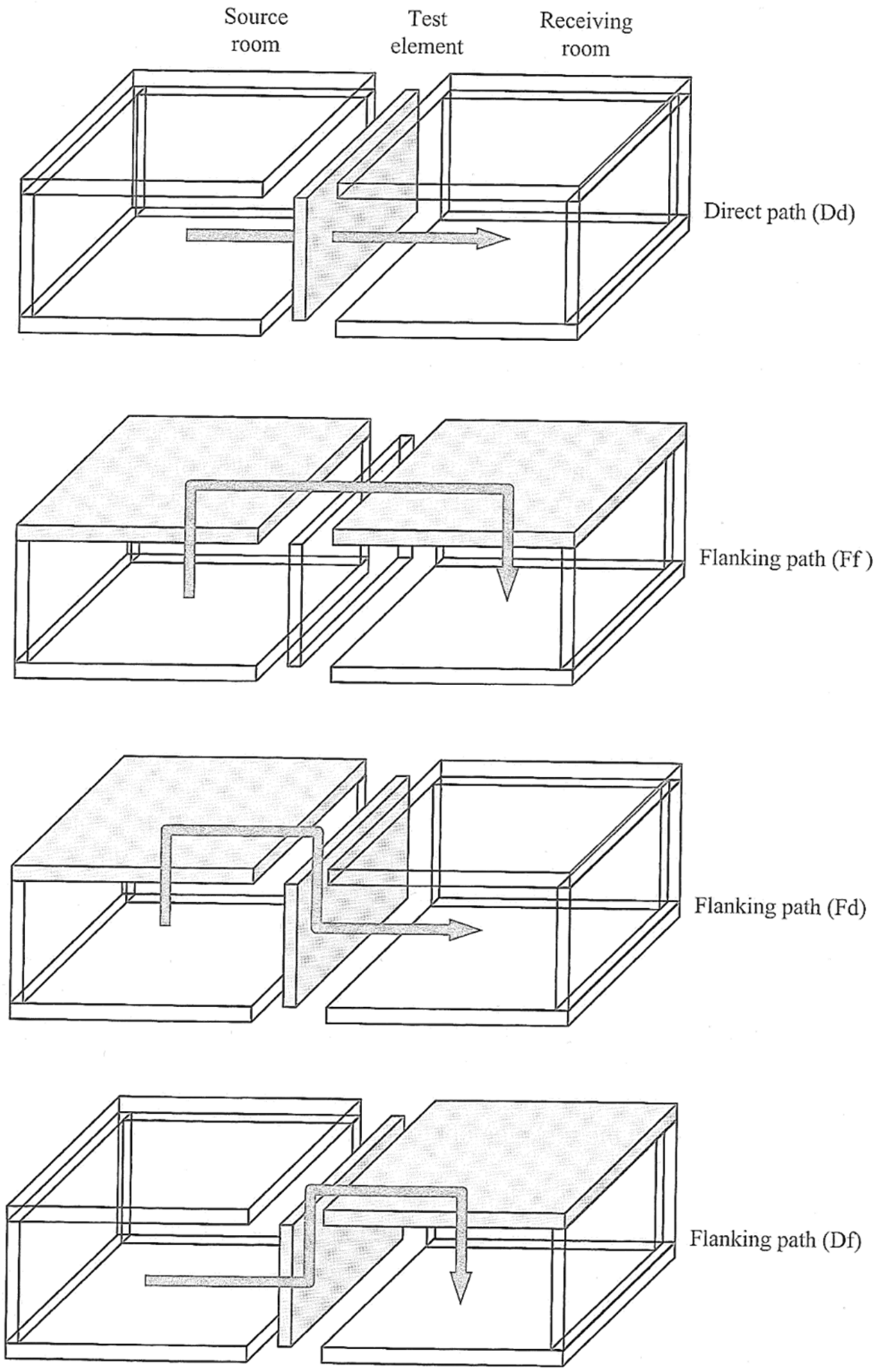


Figure 19: Transmission paths between two adjacent rooms.

The procedure to measure the acoustic properties in laboratory is defined by standard ISO 10140 “Laboratory measurement of sound insulation of building element”.
The standard ISO 717-1 “Rating of sound insulation in building elements” defines the sound insulation quantities for airborne sound insulation in buildings and of building part called single-number and takes into account the different spectra of noise level of different noise sources inside a building and traffic outside the building.
The purpose of this part of ISO 717 is to standardize a method permitting to convert the values of acoustic insulation by air as a function of frequency in an evaluation index that characterizes the acoustic performances.
The single number obtained by the sound reduction index is called weighted sound reduction index R_w and it is calculated by comparing the third octave band spectrum of R with a reference curve. This curve is shifted upwards in 1 dB steps until the sum of the unfavorable deviations of the transmission loss curve below the reference curve over the 16 one-third octave bands does not exceed 32 dB. When the reference curve is shifted to meet this criteria, the weighted sound reduction index R_w is given by the value of the reference curve at 500 Hz.

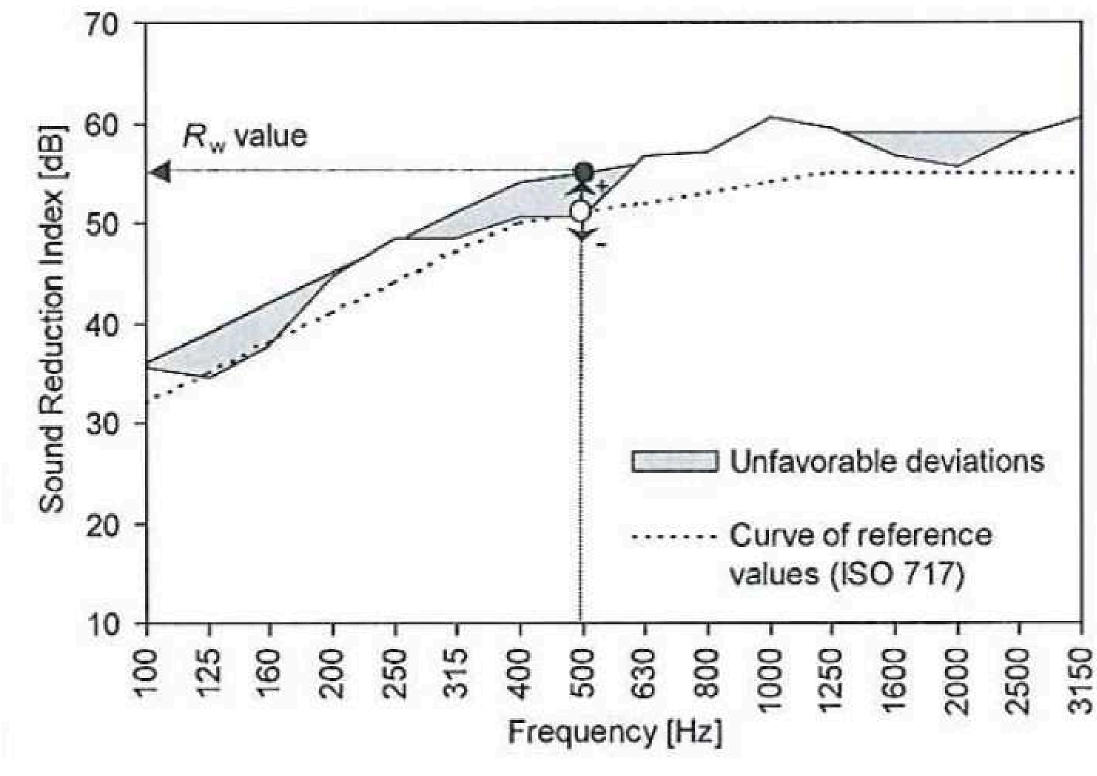


Figure 20: Procedure for evaluating single-number quantities according to ISO 717-1.

The tests of airborne sound insulation in laboratory are so characterized by the partial reconstruction of structures used or to be used in buildings, which are tested by evaluating the acoustic performance according to the methods suggested by the existing standards. The tests in exam were carried out in the laboratory of acoustics LABACUS University of Padua and at the ITC -CNR in Milan. In summary, the laboratory procedure is the following: there are two rooms connected horizontally and identified respectively as the transmitting room (where you placed the sound source) and receiving room. The element to be tested is mounted in an opening of the partition wall between the two rooms. In the transmitting room is generated a diffuse sound field through a speaker that emits pink noise and that is placed in two fixed positions. Then the levels of sound pressure in both chambers in the frequency range between 100 Hz and 5000 Hz are measured, while the equivalent absorption area of the receiving room is calculated by measuring the reverberation time. The levels are then corrected through the measurement of the background noise in the receiving room.

ROOFS

TESTS ON AN INSULATION SYSTEM FOR ROOFS

A system that combines high performance acoustic and thermal has been researched: the system combines the use of the panels for acoustic insulation in mineralized wood wool (mww) type N and roofing panels in polyurethane rigid foam to minimize the thermal exchanges with outside: in winter it avoids dispersion of heat, in the summer it prevents interior overheating. The roof ensures a high living acoustic and thermal comfort and it reduces the cost of air conditioning and heating. The advantages of a system of this type are also found in the ease of installation and the lightness of the materials, some of which are ecobiocompatible ones.

In the winter the panel in polyurethane rigid foam has an inner core with closed cells and has a very low thermal conductivity (λ_D = 0.024 W/mK). This will drastically limit the heat losses in the winter period. In the summertime the panel in mww type N has a high thermal inertia due to the high specific heat and high density. This ensures best properties of phase shift and attenuation.

For the laying, the mww type N panels offer a stable and uniform mechanical support with high compressive strength. They are applied to the upper roof slab, well-aligned and staggered. After that there is the laying of polyurethane rigid foam, panel covered with an aluminum foil, that has a coated steel batten, ribbed and perforated. That system ensures a support for the roof covering in addition to the static strength, promoting also the ventilation of underlayer. The system is extremely simple to install, it requires normal tools and does not require skilled labor. The pose is therefore safer, faster and cheaper.

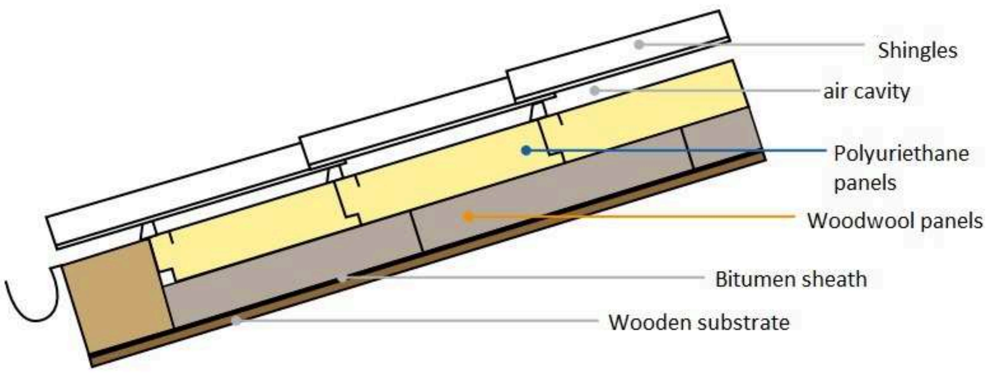


Figure 21: Scheme of the system.

Figure 22: Photo of the system.

The test was conducted in the Laboratory of the University of Padova in October 2011 and it was so divided:

1. comparative measurement of two different kind of wooden board;
2. comparative measurement of the between bare board and board with bitumen layer;
3. complete package system.

All the measurements were done according to the standard ISO 10140-2, "Acoustics - Laboratory measurement of sound insulation of building elements - Part 2: Measurement of airborne sound insulation", and the standard ISO 717-1, "Acoustics - Rating of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation".

First step: comparison between bare boards

The same test was conducted two times, firstly it involved a wooden bare board of thickness 20 mm and secondly another wooden bare board of thickness 25 mm. The test area was 10,08 m^2.The measurements were made with 6 microphone positions for each room and 2 positions of the source in the transmitter room; the sampling duration was 10 s and the disturbing signal utilized was pink noise.

Figure 23: Photos of the wooden bare board installation.

The results were very similar and the difference was only 1 dB.

Wooden board 20 mm		Wooden board 25 mm	
R_w	**22 dB**	R_w	**23 dB**
C	-1	**C**	1
C_{tr}	-2	C_{tr}	-3
$C_{100-5000}$	0	$C_{100-5000}$	1
$C_{tr50-5000}$	-2	$C_{tr50-5000}$	-3

Table 1: Results of single number index.

f	Wb 20	Wb 25
100	16.1	15.6
125	13.5	13.0
160	12.5	13.6
200	12.8	14.4
250	14.3	15.3
315	16.7	17.2
400	18.5	19.8
500	17.8	18.9
630	19.6	20.5
800	20.4	21.3
1000	22.1	22.2
1250	23.7	23.3
1600	24.2	24.4
2000	24.9	25.6
2500	25.9	27.3
3150	25.3	27.4
4000	24.1	26.6
5000	27.0	29.9
Rw	22	23

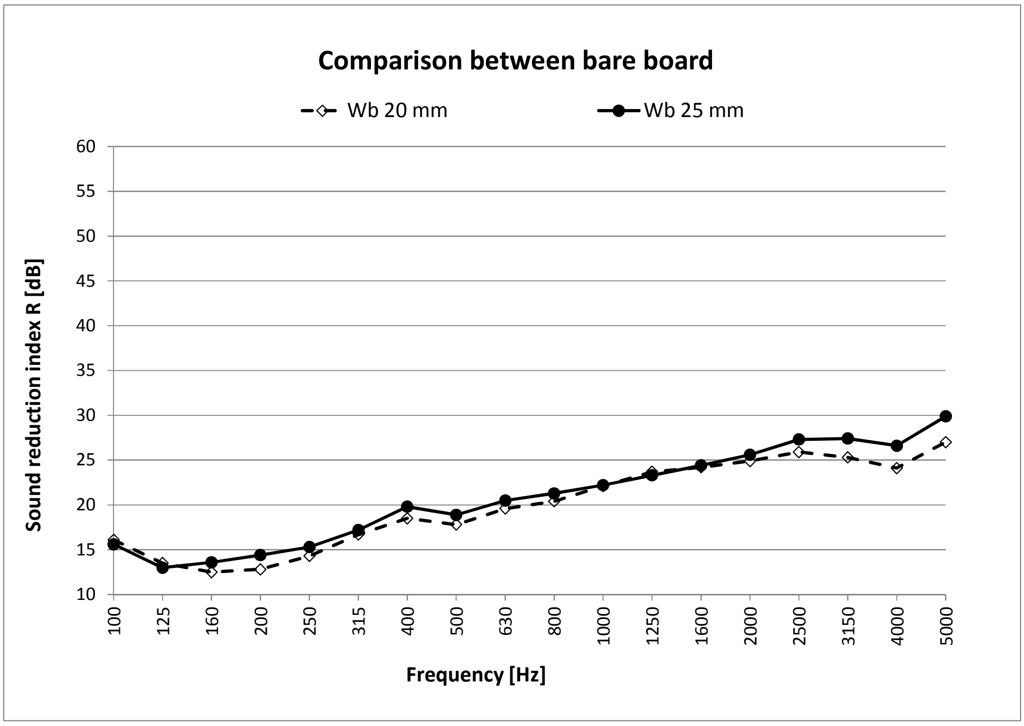


Figure 24: Graphic of the results of the two wooden bare boards.

Second step: comparison between bare board and board with bitumen layer

Figure 25: Photos of the bare board and of the board with bitumen layer.

After the test on the wooden bare board it was added a bitumen layer of the thickness 4 mm. The bitumen layer changed significantly the R_w value.

Wooden board 25 mm		Wb 25 mm+bitumen	
R_w	**23 dB**	R_w	**27 dB**
C	-1	**C**	0
C_{tr}	-3	C_{tr}	-3
$C_{100-5000}$	0	$C_{100-5000}$	1
$C_{tr50-5000}$	-3	$C_{tr50-5000}$	-3

Table 2: Results of single number index.

f	Wb 25	Wb +bl
100	15.6	20.2
125	13.0	17.0
160	13.6	17.0
200	14.4	18.3
250	15.3	20.0
315	17.2	22.0
400	19.8	23.2
500	18.9	22.7
630	20.5	23.8
800	21.3	24.2
1000	22.2	25.6
1250	23.3	28.5
1600	24.4	31.0
2000	25.6	34.9
2500	27.3	37.7
3150	27.4	41.5
4000	26.6	43.8
5000	29.9	47.5
Rw	23	27

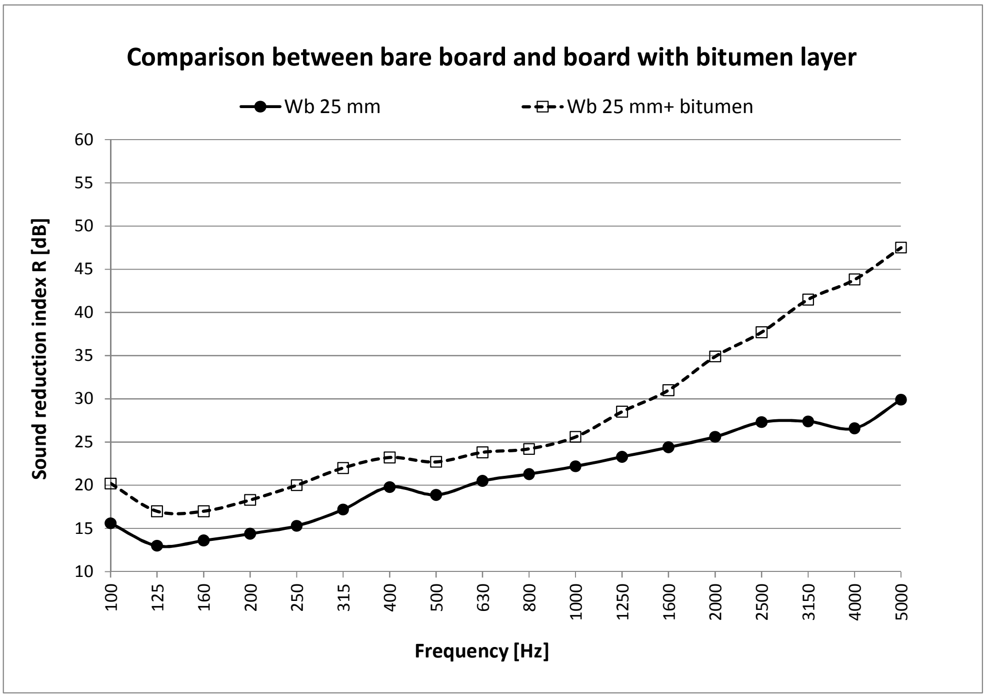


Figure 26: Graphic of the results of the wooden bare board and the board with bitumen layer.

Third step: the complete package

Finally the entire system (wooden board, bitumen layer, mww type N layer, polyurethane rigid foam layer and roof covering) was tested, so it could be reached the Rw= 40 dB value, that is the required value from the market.

Complete package	
R_w	**40 dB**
C	-2
C_{tr}	-7
$C_{100\text{-}5000}$	-1
$C_{tr50\text{-}5000}$	-7

Table 3: Results of single number index.

Figure 27: Photos of the complete package system.

f	Cp
100	22.5
125	21.9
160	21.6
200	24.7
250	26.9
315	31.5
400	35.1
500	36.4
630	40.8
800	44.0
1000	46.9
1250	48.9
1600	54.3
2000	58.6
2500	61.0
3150	62.8
4000	64.1
5000	65.7
Rw	40

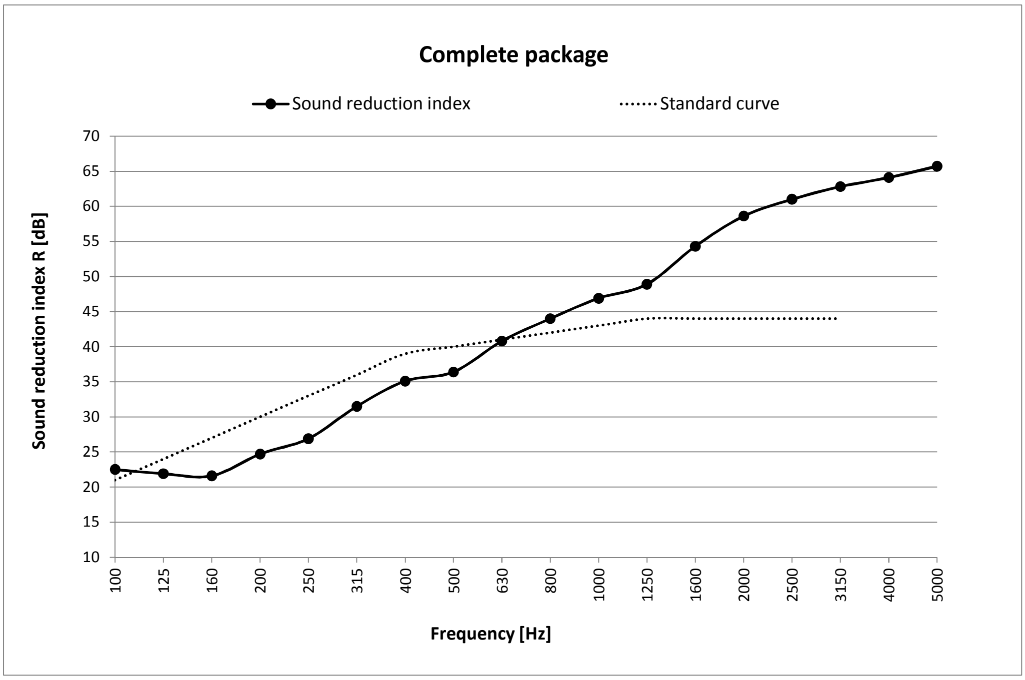


Figure 28: Results of the complete package.

Further investigation

To investigate carefully other changes on the results another test was done in order to evaluate the influence of the roof covering used in the measurements. So the proof without covering roof, but still with the rest of the package, was done. Those tests were made on the wooden board of thickness 20 mm and not on the one of thickness 25 mm.

Figure 29: Photos of the package with and without covering.

Complete package (Wb 20 mm)		Package without covering	
R_w	36 dB	R_w	34 dB
C	-1	C	-1
C_{tr}	-5	C_{tr}	-4
$C_{100-5000}$	0	$C_{100-5000}$	0
$C_{tr50-5000}$	5	$C_{tr50-5000}$	-4

Table 4: Results of single number index.

The results had shown a ΔR_w= 2 dB, that is not so much. But if we see the frequency spectrum we can notice that there is a bigger difference at the medium-high frequency (1600-2500 Hz).

f	+c	-c
100	23.1	30.0
125	24.8	29.6
160	20.0	21.4
200	21.5	21.3
250	21.2	21.8
315	25.9	26.2
400	31.4	29.3
500	33.0	30.2
630	36.6	32.3
800	43.0	35.6
1000	45.5	35.6
1250	49.7	37.4
1600	54.5	40.1
2000	57.5	41.3
2500	59.9	46.4
3150	62.1	52.3
4000	63.0	53.0
5000	66.5	55.9
Rw	36	34

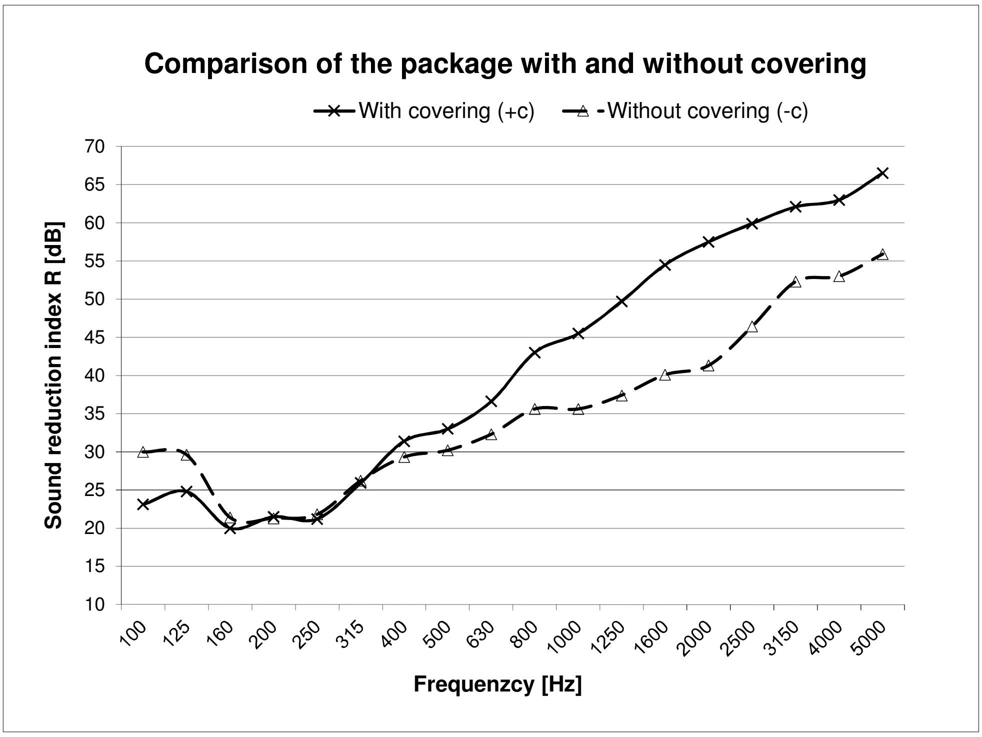


Figure 30: Results of the tests with and without covering on the wooden board of thickness 20 mm.

IMPACT SOUND

In addition to the transmission of noise by air there is another source of noise: the transmission of noise from an environment to another due to the impact of a body with a solid surface. The rigid structures, especially the floors, are stimulated by different kinds of impacts that determine disturbing mechanical vibrations. In this range, the noise is especially generated by the patter on floors and this is the reason that we study the phenomena of impact noise in laboratory.

The laboratory is composed by two overlapping rooms, between which is opened a space where it could be installed a floor or where there is fixed a concrete bare board.

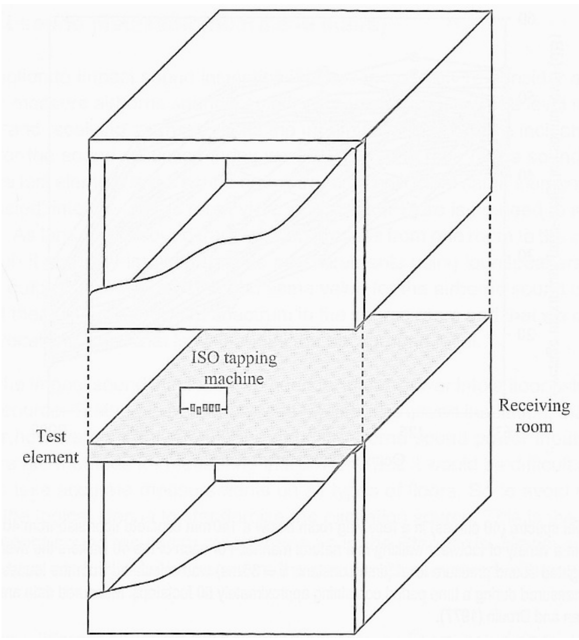


Figure 31: Scheme of the two laboratory rooms.

Several descriptors characterize the impact noise of the floors. In the European context is generally used the pressure level normalized impact sound L_n [dB] (in laboratory) so described

3)

$$L_n = L_i + 10 \log \frac{A}{A_0}$$

where L_i is the average of the pressure levels in the receiving room, when on the floor there is a normalized impact machine working. A [m³] is the equivalent absorption area of the receiving room described as

4)

$$A = 0{,}16 \frac{V}{T}$$

V [m^3] is the room volume and T[s] is the reverberation time, A_0 is the reference equivalent absorption area equal to 10 m^2. Due to the fact that the measure requires the acquisition of the noise level only in the receiving room there is the necessity to have a standard device for generating impact noise, so that the impact source generates a constant and reproducible force on the pavement. For now the ISO standards require a machine that has five hammers weighting 0,5 kg each that fall on the floor with a frequency of ten times per second.

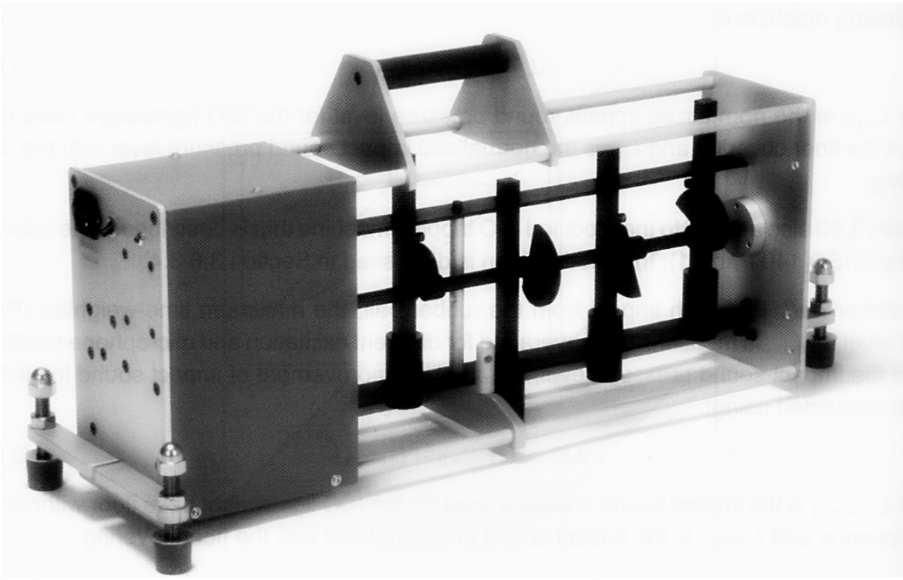


Figure 32: Impact sound standard machine.

The reference standards for the measurement of sound insulation in the laboratory are the ISO 10140-3, “Acoustics - Laboratory measurement of sound insulation of building elements - Part 3: Measurement of impact sound insulation”, ISO 10140-5, “Acoustics - Laboratory measurement of sound insulation of building elements - Part 5: Requirements for test facilities and equipment”, and, for the calculation of the single number L_{nw}, the standard ISO 717-2, “Acoustics - Rating of sound insulation in buildings and of building elements - Part 2: Impact sound insulation”.

In order to measure the level of impact noise the machine impact source must be placed at 45 ° of the texture of the floor on at least four points of the test area. In the lower room the non-weighted sound pressure level is measured in at least four distributed points. Then the logarithmic mean of the measurements is calculated in bands of 1/3 octave and in the frequency range between 100 Hz and 3150 Hz. The source must distance from the edges of the slab at least 0.5 m and the microphones have to be away from each other and from the wall at least 0.7 m. The background noise is measured in the receiving room and also the reverberation time.

According to the ISO 717-2 the single number L_{nw} could be calculated by translating in steps of 1 dB a broken reference line compared with the curve in bands of 1/3 octave of the noise impact level measured. The operation stops when the amount of unfavorable deviations between the curve and the broken line is closer to 32 dB and not more. The value at 500 Hz corresponds to the index of the noise impact level.

At this point, to know how much the performance of a floor is, it must be known the reduction of the impact noise due to the type of floor considered. This is calculated by doing firstly the measurement on the bare floor, (for example concrete), than the same test on the insulated floor. Then the difference from the levels measured will be done to obtain the ΔL in frequency of 1/3 octave band. Then this difference ΔL must be subtracted at the values of a reference slab provided by the standard, and the resulting is a curve of values called $L_{n,r}$, whose index will be called $L_{n,r,w}$. The index of the reference slab is 78 dB so it can be applied the following:

5)

$$\Delta L_w = 78 - L_{n,r,w}$$

It should be noted that the single number, sound reduction index or sound impact index, represents a simplification, so it is always advisable to see the frequency spectrum of the entire measure to understand the behavior of a structure.

DYNAMIC STIFFNESS

An important properties for the evaluation of the behavior of the insulated floors could be the dynamic stiffness especially for the floating floors. This value gives many information on the mechanical performances of materials and their resistance to compression. The dynamic stiffness is correlated with the reduction of the impact level, generally in fact, less the s' value is, better the ΔL_n is.

The reduction of the impact noise starts from the resonance frequency f_0, so it could be good to know this value for a floor where a floating floor is applied. The dynamic stiffness helps us to know the resonance frequency by this correlation

6)

$$f_0 = 160\sqrt{\frac{s'}{m'}}$$

The accuracy of the measurement of dynamic stiffness and the correct interpretation of the standards (ISO 29052-1 and EN 12354-2), has a great influence on the calculation of the reduction of impact noise starting from the stiffness itself.

For the measurements of dynamic stiffness the samples with square base are prepared and they are compressed by a load steel plate with a layer of plaster between them. The sample of material is laid on a marble plan, it is covered by a polyethylene sheet on which the plaster is cast and then it is covered by another layer of polyethylene before application of the load plate. At the center of the plate a shaker is positioned powered by a sinusoidal signal concentrated at low frequencies (5-300 Hz). The acceleration is detected on three different points of the specimen by a force sensor connected to a signal analyzer.

The apparent dynamic stiffness of material s'_t [MN/m³], was calculated by the following relationship:

7)

$$s'_t = 4\pi^2 m'_z (f_r)^2$$

where f_r is the fundamental resonance frequency measured of the mass-spring system and m'_z is the applied weight expressed in kg/m².

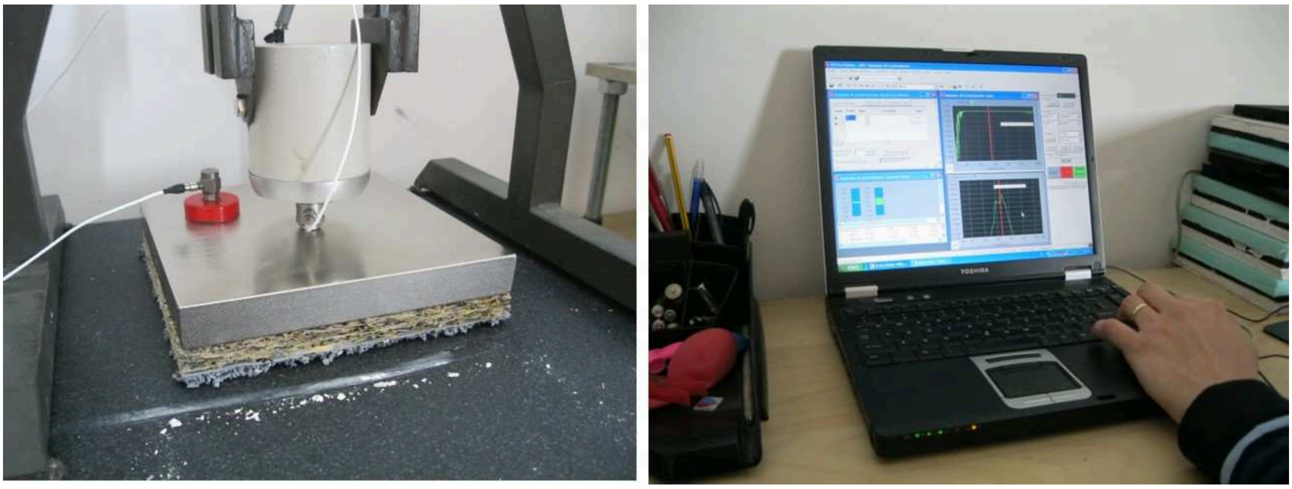


Figure 33: Photos of the test apparatus.

FLOORS

The experimental knowledge in the field of acoustic properties of building systems for horizontal internal closures are based on assessments that are made, according to the measurement methods normed on a reference structure integrated by the upper layers of integration and finishing or on a complete building element. In the first case the effects of reducing the impact noise level induced by the layers of decoupling introduced between the structural part and that of finishing top of the system are evaluated, allowing, among others, to make direct comparisons between different types of materials of decoupling or floating floors in equal support structure. In the second case, instead, the overall performance of sound insulation is rated against airborne noise and structural offered by a specific construction system that includes the element with structural capabilities.

The different approach to the analysis of the acoustic behavior of the horizontal structures depends on several considerations related to both test methods, and to the type of data obtainable. The determination of the acoustic properties of the typical materials used for floating floors and their comparison requires a specific analysis that does not suffer interaction with the support structures, while the determination of the acoustic performance of the interior construction system necessarily requires the verification of the system itself and its variants.

DRY SYSTEMS FOR IMPACT NOISE INSULATION OF FLOORS IN LABORATORY

Dry systems have been successfully used in the last years and the diffusion in the market has grown a lot, especially in floating floor applications. These systems are made of a resilient material supporting a rigid layer (a single or multiple layer of cement, gypsum, wooden boards, generally reinforced with fibers) and because of the easiness and rapidity of laying they are often preferred to traditional massive cement-based floating screeds.

The use of dry systems made by panels consisting of mineralised spruce wood-wool bound with Portland cement combined with recycled rubber is a good solution for improving acoustic performance of floors. This kind of dry systems is very interesting not only from the acoustic point of view, but also for environmental sustainability. In fact both materials derive from recycled elements or from ecological and bio-compatible production cycles. Those kind of materials were use in this work to investigating the impact sound insulation performance of some solutions based on products typically found in the traditional screed market, comparing the two different applications: dry and wet.

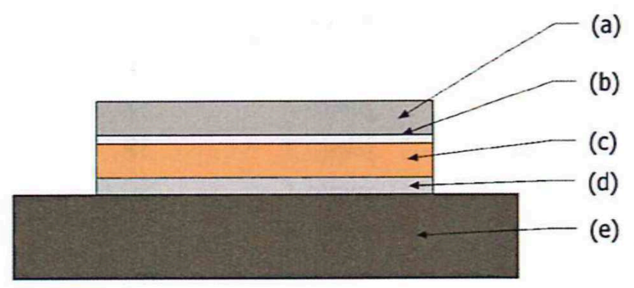
PRODUCTS SELECTION AND EVALUATION

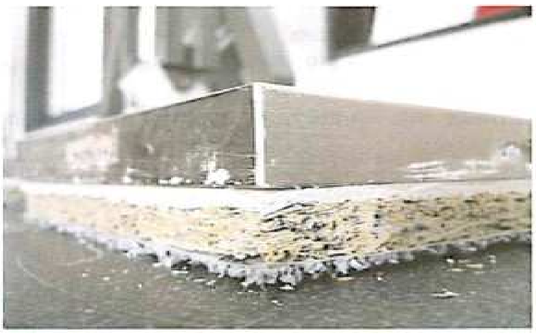
This research has been focused mostly on products made with mineralised wood wool, mostly used as sound absorption panels for rooms reverberation control and as thermal and acoustic insulation layer in partition walls, made with natural raw materials, in combination with the rubber, made of EPDM granules or SBR granules and fibers glued to a tear-resistant backing used widely in the floating screed technology, come from the reuse of waste at the end of life cycle. The products were chosen within a selection of materials by means of measurements of dynamic stiffness.

DYNAMIC STIFFNESS EVALUATION

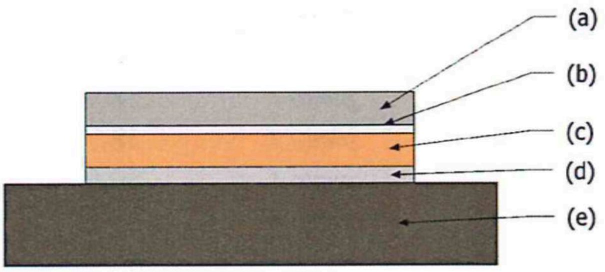
The dynamic stiffness has been measured in laboratory, with and without gypsum layer, to check if this testing condition could be critical for the choice of the best combination of products. Four samples of 20x20 cm size were tested for each combination. Samples are composed by a combination of two resilient materials: mineralized wood wool (15-20 mm), EPDM or SBR rubber granules mats (5 mm) or elasticized polystyrene (15 mm) between two layers of mineralized wood wool (5 mm).

The measurement of dynamic stiffness were made on four samples of eight combinations of materials for a total of 32 tests. The different combinations were so divided:

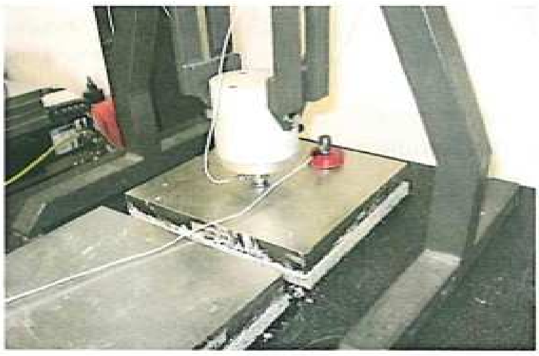
Combination 1 **Samples from 1 to 4**		a) steel plate b) gypsum layer c) woodwool, 15 mm d) EPDM, 6 mm e) base



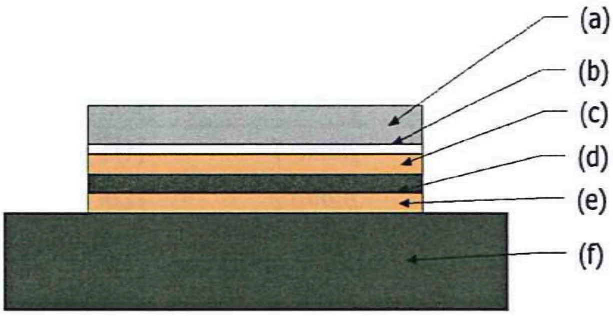
Combination 2
Samples from 5 to 8



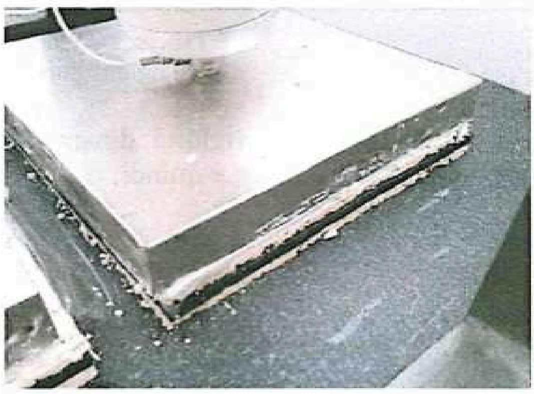
a) steel plate
b) gypsum layer
c) woodwool, 15 mm
d) SRB, 5 mm
e) base



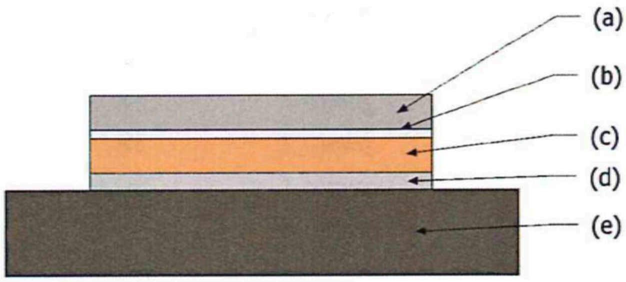
Combination 3
Samples from 9 to 12



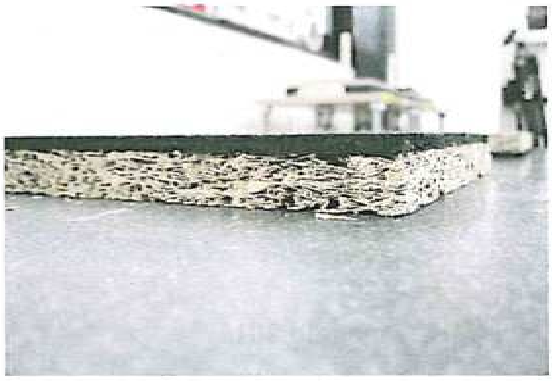
a) steel plate
b) gypsum layer
c) woodwool, 5 mm
d) SRB, 10 mm
e) woodwool, 5 mm
f) base



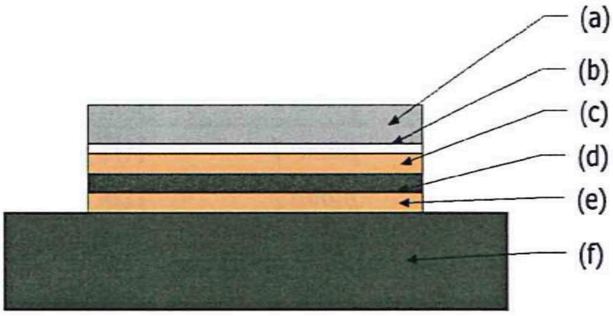
Combination 4
Samples from 13 to 16



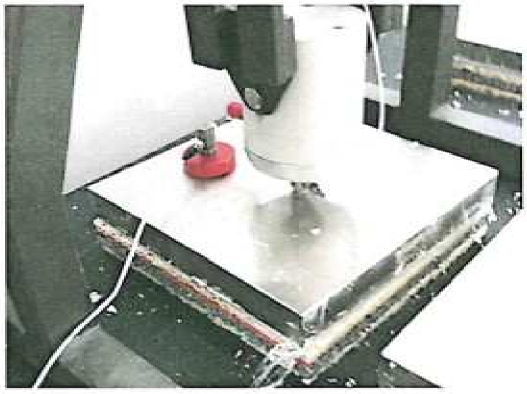
a) steel plate
b) gypsum layer
c) woodwool, 15 mm
d) SRB, 6 mm
e) base



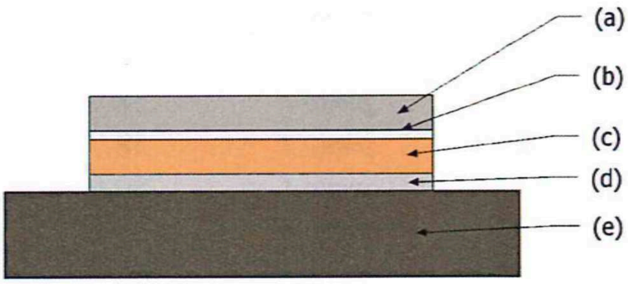
Combination 5
Samples from 17 to 20



a) steel plate
b) gypsum layer
c) woodwool, 5 mm
d) EPDM,10 mm
e) woodwool, 5 mm
f) base



Combination 6
Samples from 21 to 24



a) steel plate
b) gypsum layer
c) woodwool, 20 mm
d) EPDM,10 mm
e) base

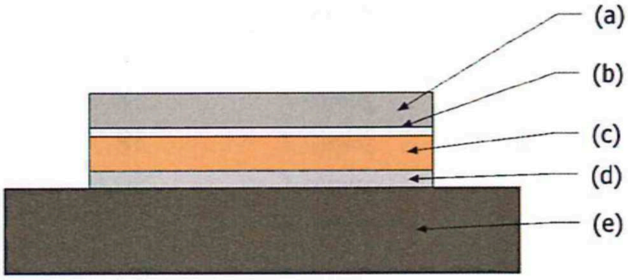
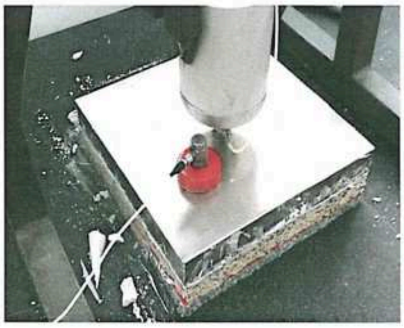
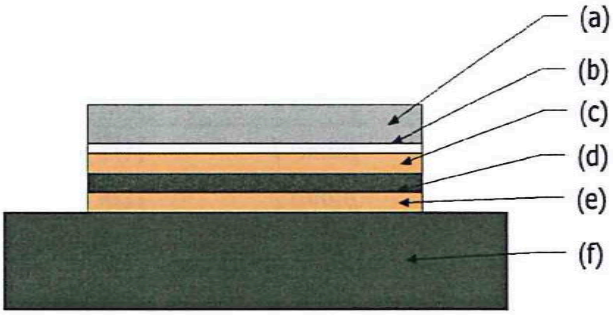
		
Combination 7 Samples from 25 to 28		a) steel plate b) gypsum layer c) woodwool, 15 mm d) EPDM,6 mm e) base
	 	
Combination 8 Samples from 29 to 32		a) steel plate b) gypsum layer c) woodwool, 5 mm d) EPDM,6 mm e) woodwool, 5 mm f) base
		

Table 5: The stratigraphies and the photos of the 8 combinations.

The tests have been carried out with and without gypsum layer between the sample and the steel plate to check if this testing condition could be critical for the choice of the best combination of products in relation to the type of use. The results show a quite big deviation from the two methods of testing, however the application of this intermediate load distribution layer acts proportionally in increasing the dynamic stiffness, if compared to the data obtained without gypsum.

Test number	1	2	3	4	5	6	7	8
Materials	Ww 15+ EPDM 5	Ww 15+ SBR 5	Ww 5+ SBR 10+ Ww 5	Ww 20+ SBR 6	Ww 5+ EPDM 6 +Ww 5	Ww 20+ EPDM 10	Ww 15+ EPDM 6	Ww 5+ EPDM6 +Ww 5
s'_t +gypsum	27	39	89	94	34	57	79	48
s'_t -gypsum	21	27	49	50	17	18	47	27

Table 6: Results of dynamic stiffness.

After the measurements the first and the second configuration samples were chosen for the impact noise tests.

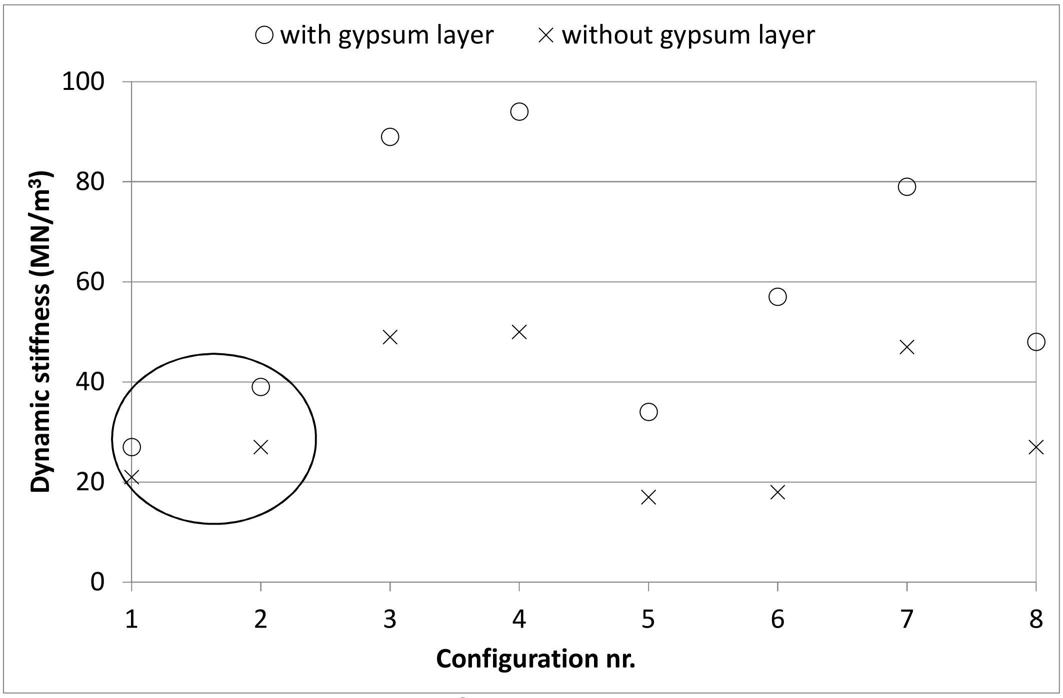


Figure 34: Summary of the results.

IMPACT NOISE MEASUREMENT

Tests of impact noise reduction have been carried out in laboratory according to ISO 10140 standard, on a sample with a surface of 12 m². The general layout of all the samples is shown in Figure 35.

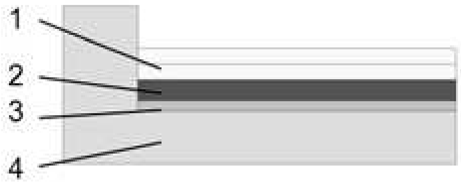


Figure 35:(1) fibres-reinforced cement board (2 layers), (2) upper resilient layer, (3) lower resilient layer, (4) base floor.

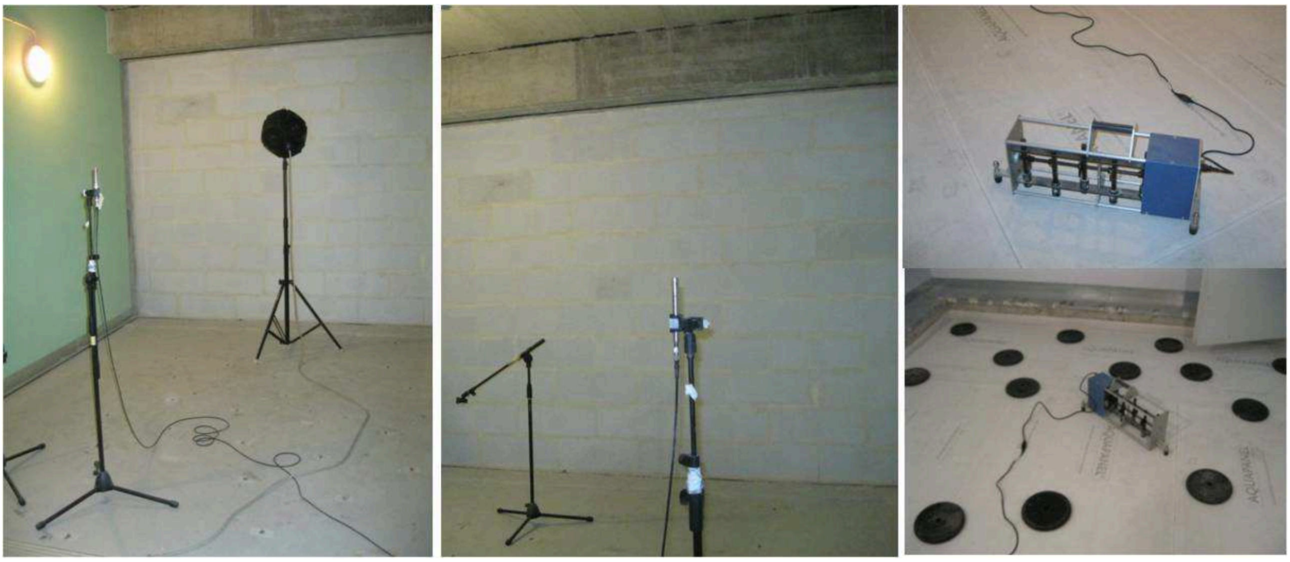


Figure 36: Photos of test conditions.

The measurements were performed on 4 different samples (from upper to lower):

- sample A: wood wool panels (15 mm), resilient rubber mats (EDPM, 5 mm);
- sample B: wood wool panels (15 mm), resilient rubber mats (SRB, 5 mm);
- sample C: wood wool panels (2 layers, 20 mm);
- sample D: wood wool panels (15 mm), elasticized polystyrene (10 mm).

A combination of six normalized impact noise generator positions and six microphone positions were used, for a total of 36 measurements.

Firstly it were tested the samples on a concrete slab floor: the results obtained show good values, considering the average thickness of 45 mm.

Bare floor	Sample	L_{nw}	ΔL_{nw}
Cement board	A	51	26
	B	53	23
	C	51	25
	D	56	20

Table 7: Impact noise results on a concrete slab.

The behavior of the four systems is very similar, and in terms of global performance, the impact sound reduction improvement ΔL_w is between 20 dB and 26 dB.

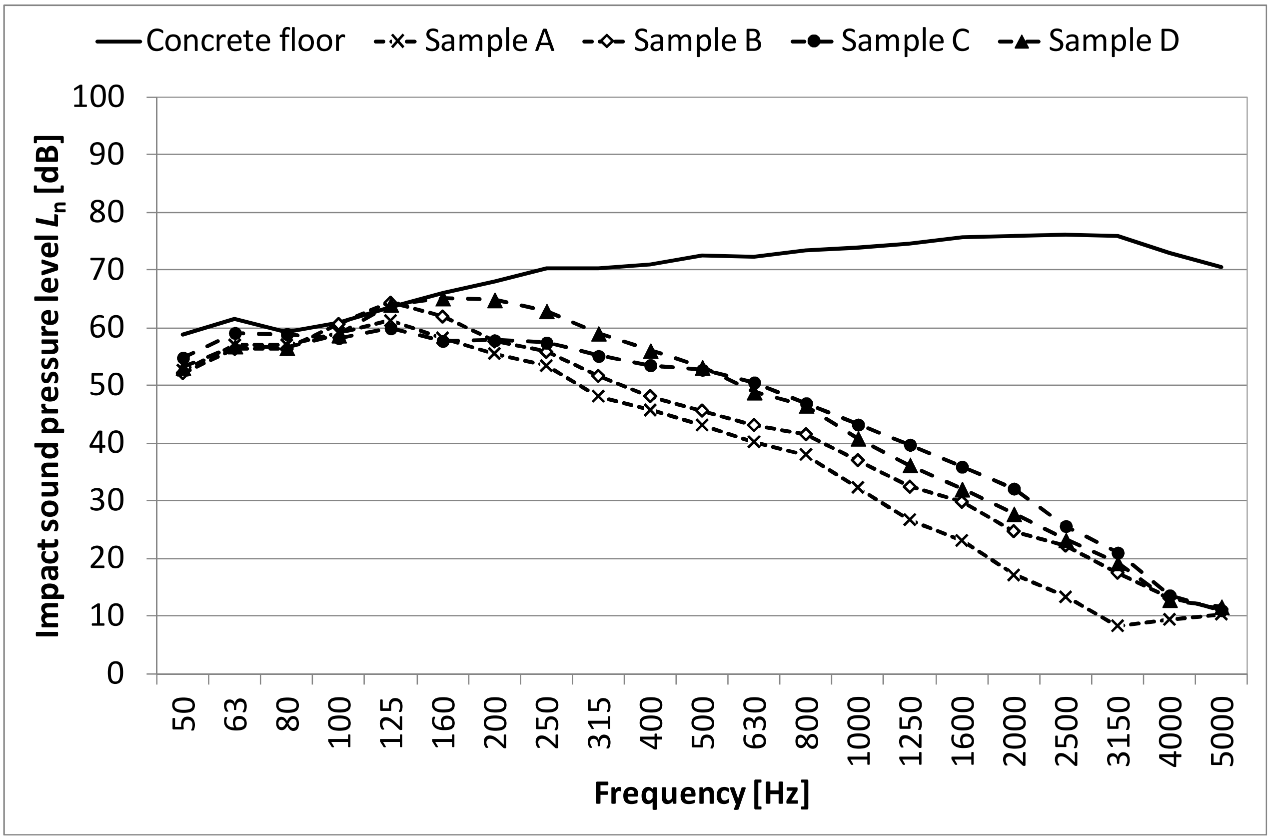


Figure 37: Impact sound pressure levels recorded on the concrete slab for the four samples.

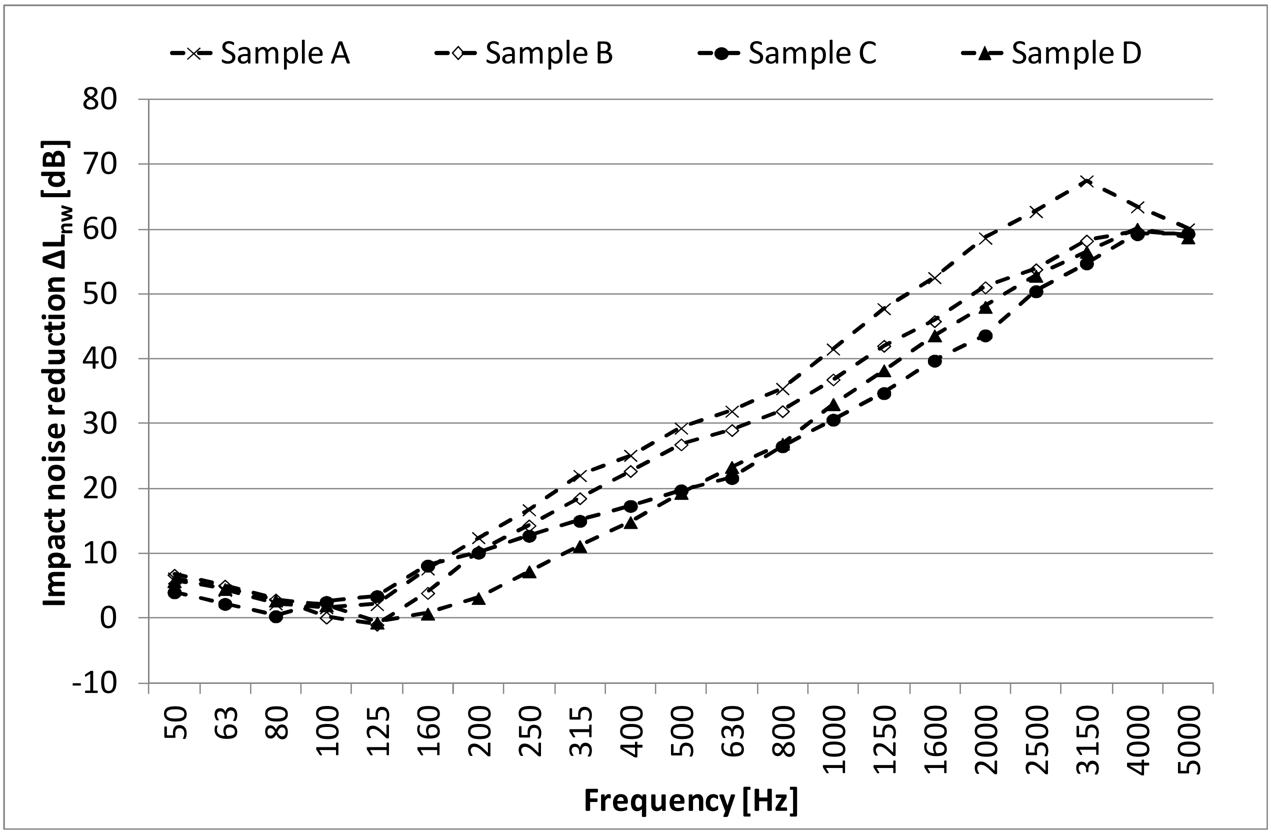


Figure 38: Impact sound reduction on the concrete slab for the four samples.

	Level: f [Hz]										
	50	**63**	**80**	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**
Sample A	52.6	57	57	59.1	61.2	58.2	55.5	53.4	48.1	45.7	43.1
Sample B	52.1	56.3	56.3	60.6	64.3	61.9	57.6	55.8	51.6	48.1	45.6
Sample C	54.8	59.1	58.9	58.2	59.9	57.7	57.8	57.4	55.1	53.5	52.7
Sample D	53.1	56.8	56.5	58.7	64	65.1	64.8	62.9	59	56	53.1

	Level: f [Hz]										
	630	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**	L_{nw}
Sample A	40.2	38	32.3	26.7	23.1	17.1	13.3	8.3	9.4	10.3	51
Sample B	43.1	41.5	37	32.4	29.8	24.7	22.2	17.5	13.1	11.2	53
Sample C	50.5	46.9	43.2	39.7	35.9	32.1	25.6	21	13.6	11	51
Sample D	48.8	46.5	40.8	36.2	32	27.7	23.2	19.2	12.8	11.6	56

Table 8: Impact noise levels on the concrete slab for the four samples.

Figure 39: Photos of the mounting of sample A on concrete slab.

Figure 40: Photos of the mounting of sample B on concrete slab.

Figure 41: Photos of the mounting of sample C on concrete slab.

Figure 42: Photos of the mounting of sample D on concrete slab.

On the concrete slab, a deeper investigation on the sample loading conditions has been done. In particular, for all the samples the measurements have been repeated applying some weights on the cement boards, for a total additional load of about 20 kg/m². The differences in the results were not neglectable and in some cases the single number rating was influenced by this method. In Figure 43 the differences between the measurements with and without the additional loads are shown. From the results it seems that increasing the load, the recorded level is higher at all frequencies. This could suggest that the system is not working as a pure mass-spring system, but its behavior is probably between a resonantly reacting floating floor and a locally reacting covering. At the same time, leaving the layers not connected (through screws or other connections) also helps improving the noise reduction.

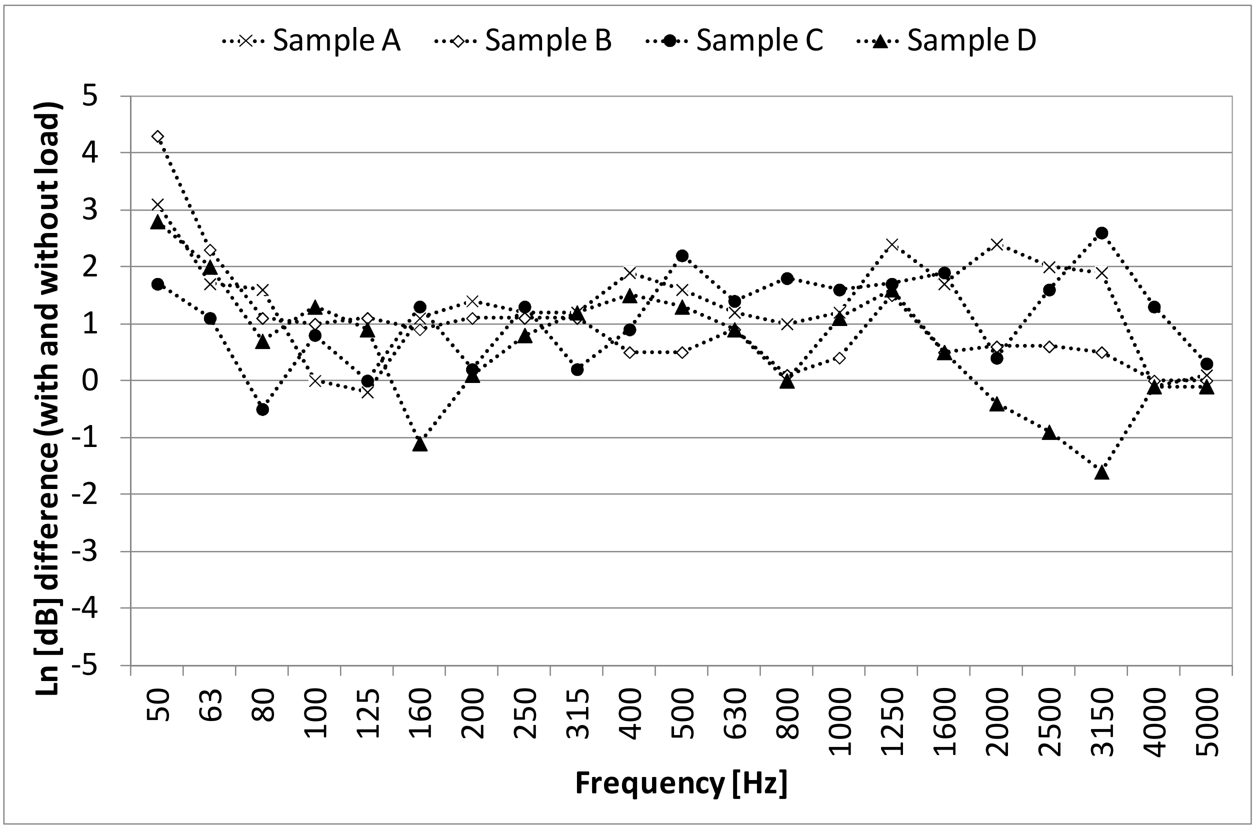


Figure 43: Differences of normalized impact sound pressure level evaluated with and without the additional weights on the floor surface.

The same samples have been installed and measured on a beam and hollow block floor in laboratory. The reduction properties of the coverings are well preserved on this particular floor and the good behavior in the middle and high frequency range seems to be very efficient on the protection from the critical radiation peak around 2500 Hz, typical of these kinds of floors.

Bare floor	Sample	L_{nw}	ΔL_{nw}
Beam and hollow block	A	49	26
	B	51	25
	C	50	27
	D	55	22

Table 9: Impact noise results on a beam and hollow block floor.

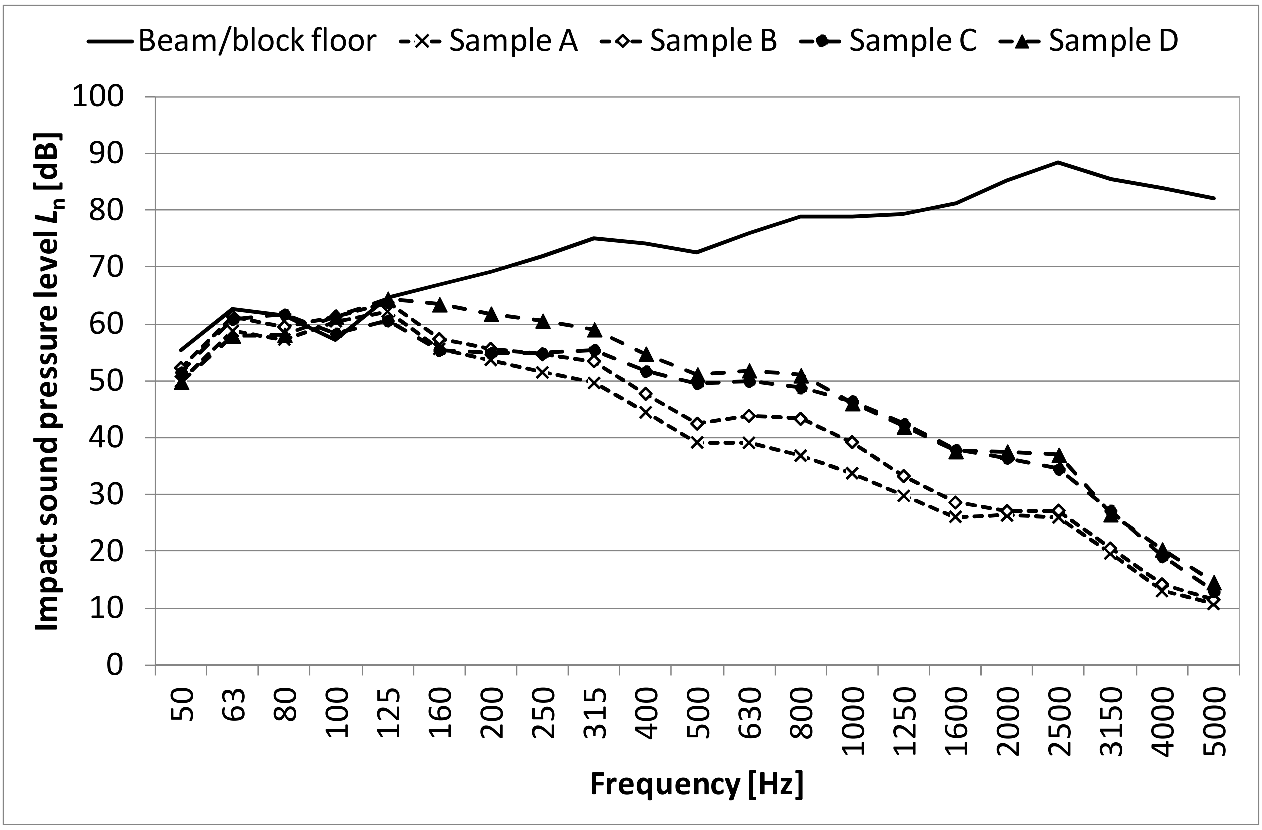


Figure 44: Impact sound pressure levels recorded on the beam and hollow floor for the four samples.

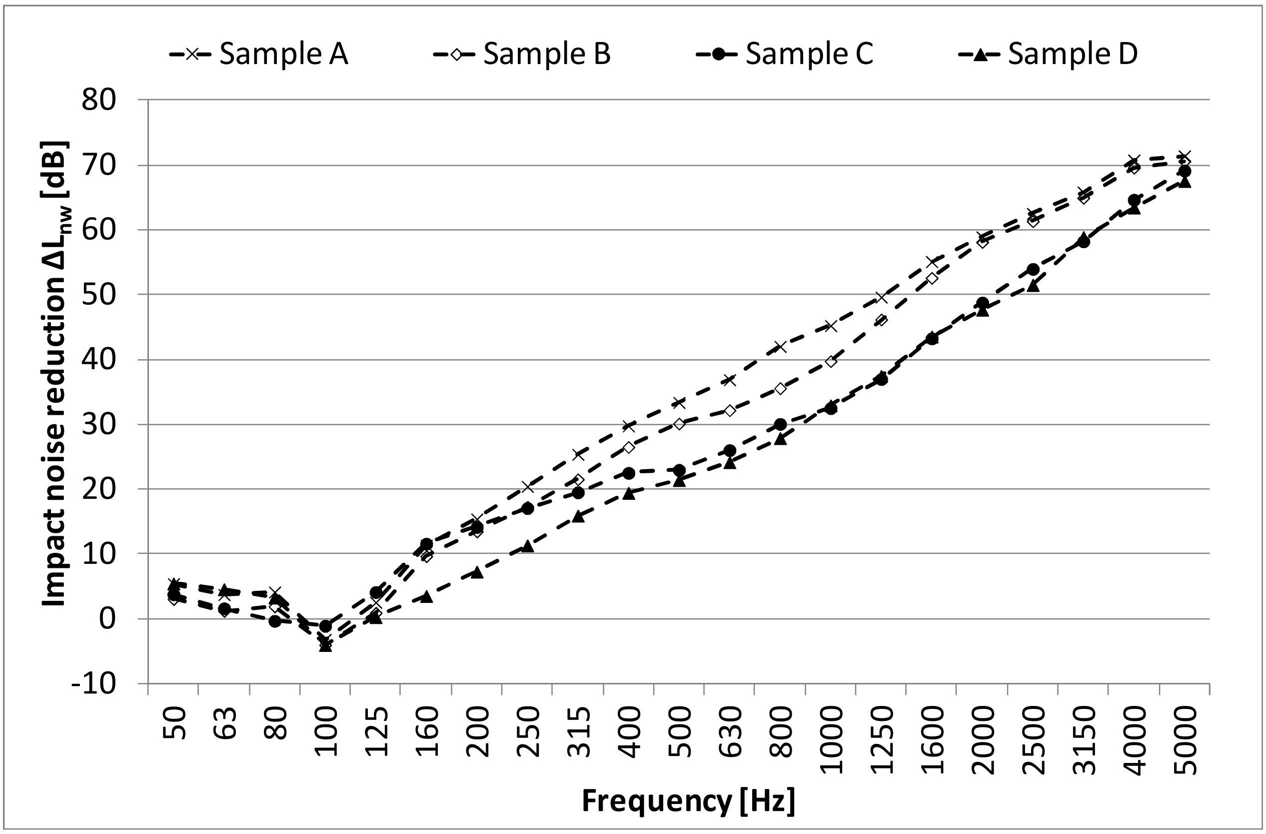


Figure 45: Impact sound reduction on the beam and hollow block floor for the four samples.

	Level: f [Hz]										
	50	63	80	100	125	160	200	250	315	400	500
Sample A	49,9	58,7	57,2	60,4	62,2	55,6	53,7	51,5	49,6	44,4	39,2
Sample B	52,2	61,3	59,5	61,3	63,8	57,3	55,6	54,7	53,4	47,7	42,4
Sample C	51,5	60,9	61,7	58,3	60,6	55,4	54,9	54,8	55,4	51,7	49,6
Sample D	49,8	57,9	58,1	61,3	64,4	63,5	61,8	60,6	59,1	54,8	51,1

	Level: f [Hz]										
	630	800	1000	1250	1600	2000	2500	3150	4000	5000	L_{nw}
Sample A	39.1	36.8	33.7	29.8	26.1	26.3	26.0	19.6	13.0	10.7	49
Sample B	43.8	43.3	39.2	33.2	28.6	27.1	27.2	20.5	14.2	11.5	51
Sample C	50.0	48.8	46.4	42.4	37.9	36.5	34.5	27.2	19.1	13.0	50
Sample D	51.8	51.0	46.0	41.9	37.6	37.6	37.0	26.6	20.3	14.6	55

Table 10: Impact noise levels on the beam and hollow block floor for the four samples.

COMPARISON BETWEEN DRY AND WET MOUNTING SYSTEMS

The measurements were compared with previous tests made on the same resilient layer loaded by a traditional sand and cement screed. The results show that the impact sound pressure level reduction can be improved using dry solutions, up to 3-4 dB on the rating index, although the superficial mass is much lower (35 kg/m² instead of 90 kg/m²).

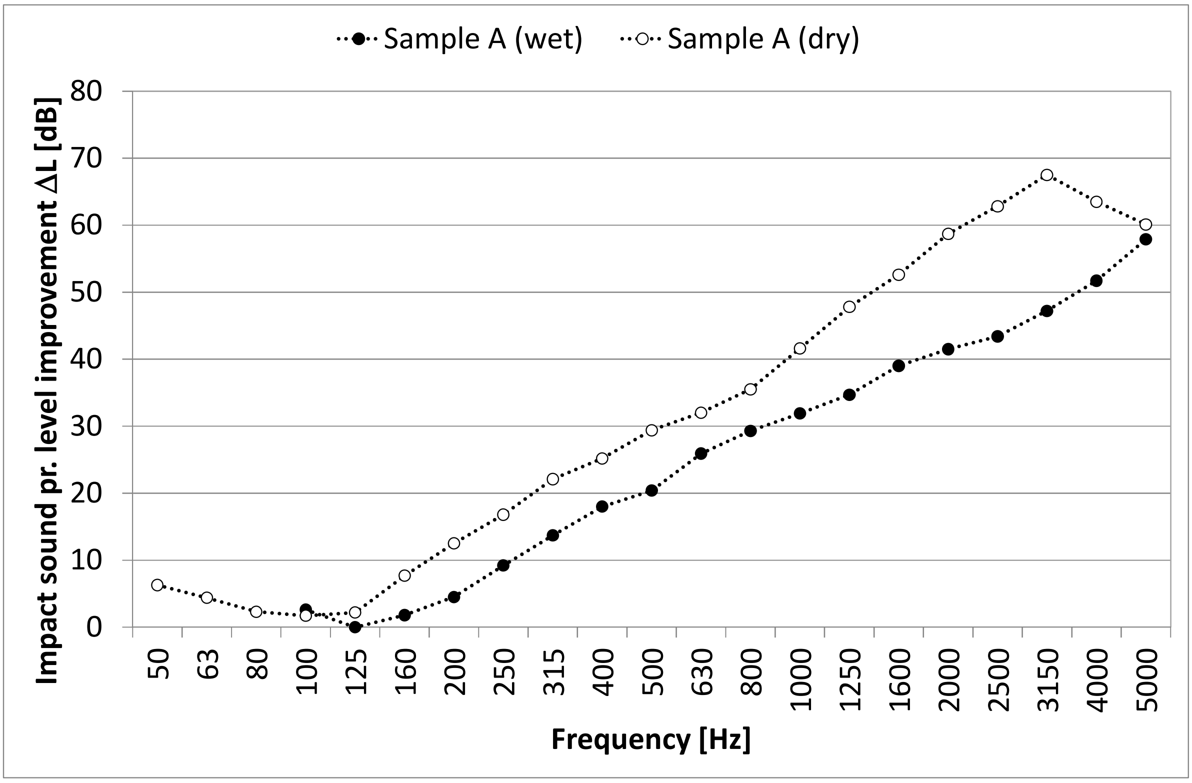


Figure 46: Impact sound pressure levels attenuation for sample A, compared to a traditional sand and cement floating screed (only with the lower resilient layer, a mat made of EPDM rubber).

It seems that the dry system gives an advantage, if compared to the traditional massive screed, by lowering the resonance frequency and improving the reduction curve as a consequence. It has not been found yet, if this increasing in performance is related to the method of measuring the dynamic stiffness, with and without the gypsum layer, that acts as a surface shape matching layer between the flat steel plate and the rough surface of the samples and at the same time distribute the load uniformly on the sample.

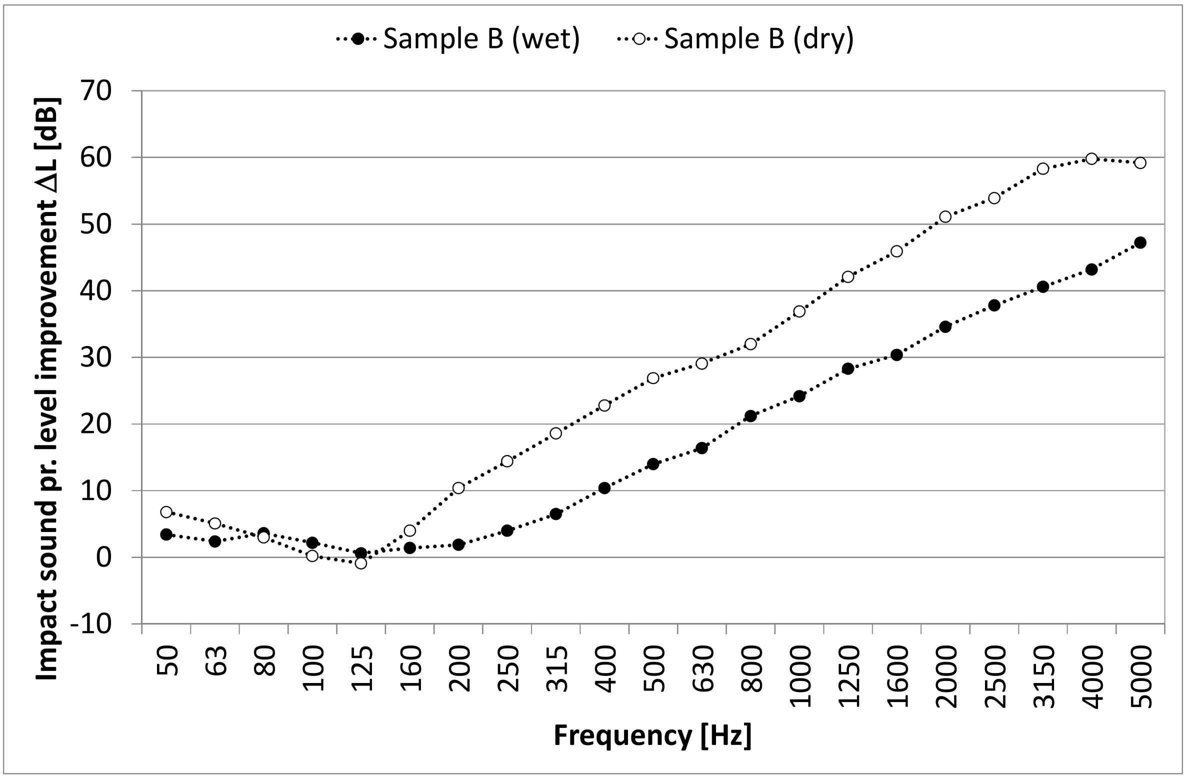


Figure 47: Impact sound pressure levels attenuation for sample B, compared to a traditional sand and cement floating screed (only with the lower resilient layer, a mat made of SBR rubber).

The dry floating floor systems for impact sound insulation seem to be practical, efficient and provide an excellent insulation. Testing these systems in laboratory is still the best method to understand their behavior, since the correlation between the global performance and the characteristics of the resilient products and the floating mass is not as linear as for the well known traditional cement screeds. Further investigations should be done on the fastening conditions of the floors' layers, since in this study it has not been taken into account. However this kind of mounting is widely used, especially in the renovation projects, so the recorded data could be directly used to estimate a floor performance in a real case. An application on a wooden floor structure could also be experimented, to have a good overview on the main floor construction technologies.

HYPOTHESIS ON A WOODEN FLOOR

Starting by the spectrum proposed by the standard ISO 10140-5 for cement bare boards (column 2 of figure x) and for lightweight wooden floors (column 4 of figure 48) it were done some hypothesis for the behavior of the not measured lightweight.

Frequency Hz	$L_{n,r,0}$ for heavyweight floors dB	$L_{n,t,r,0}$[a] for lightweight floors C1 and C2 dB	$L_{n,t,r,0}$[a] for lightweight floors C3 dB
100	67	78	69
125	67,5	78	72
160	68	78	75
200	68,5	78	78
250	69	78	78
315	69,5	78	78
400	70	76	78
500	70,5	74	78
630	71	72	78
800	71,5	69	76
1 000	72	66	74
1 250	72	63	72
1 600	72	60	69
2 000	72	57	66
2 500	72	54	63
3 150	72	51	60
$L_{n,r,0w}$ or $L_{n,t,r,0w}$ dB	78	72	75
$C_{I,r,0}$ or $C_{I,t,r,0}$ dB	−11	0	−3

[a] The index, t, is used to distinguish results for lightweight floors from those for heavyweight floors; it originates from the word "timber".

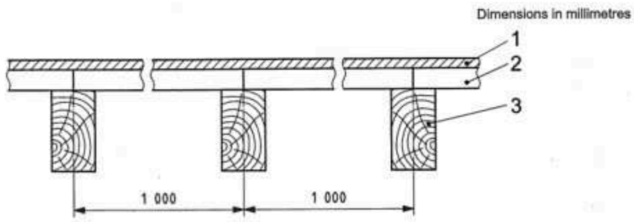


Figure 48: One-third octave band values of the reference curve for all reference floors with the corresponding single-number rating. The lightweight reference floor structure.

Firstly was made a comparison between the levels measured in the laboratory, from the concrete bare floor in laboratory, and the levels presumed taking the same delta measured, starting from bare floor proposed by legislation. If these levels are similar, it could be reasonable to take the same method to make a rough estimate of the levels of other types of slab such as the one in wood.

The spectra showed very similar frequency values between the measured and the standard, so it could be done the same procedure to hypothesize the levels on a wooden floor.

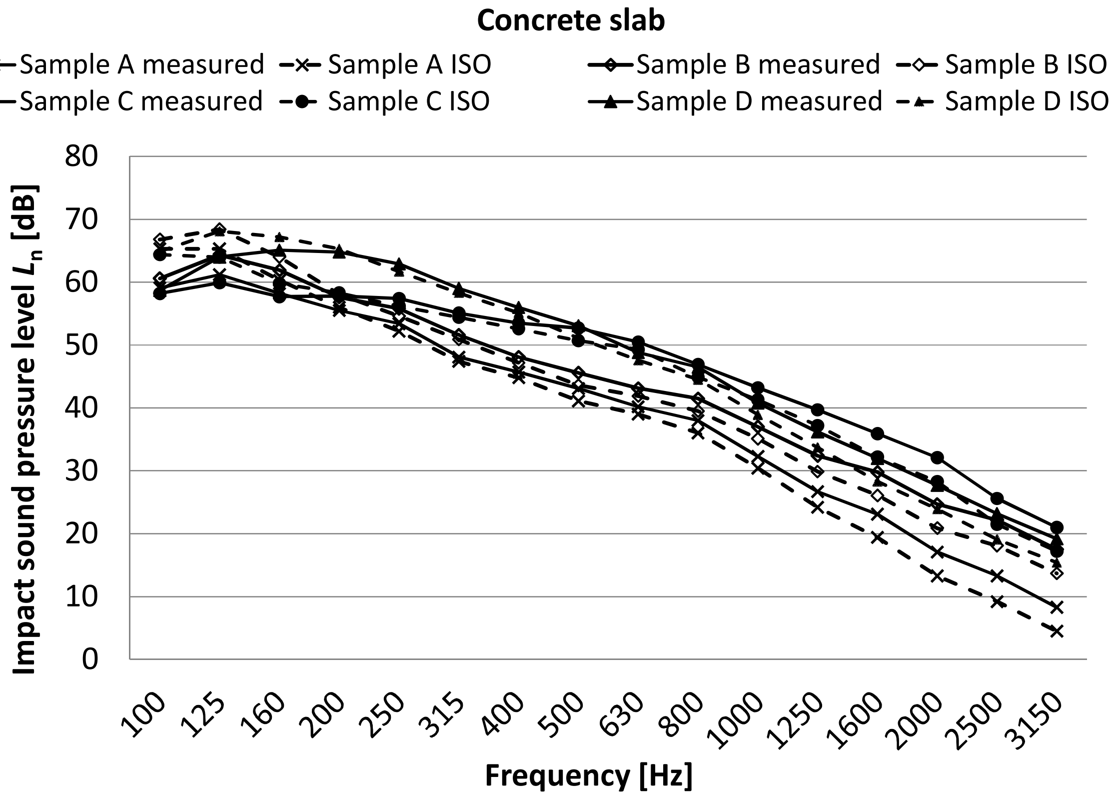


Figure 49: Comparison between the measured levels on a concrete slab in laboratory and the levels obtained starting by the bare board proposed by ISO 10140-5.

Secondly the levels on a wooden floor were calculated starting from the levels for the lightweight structure in the standard and applying the delta measured in laboratory.

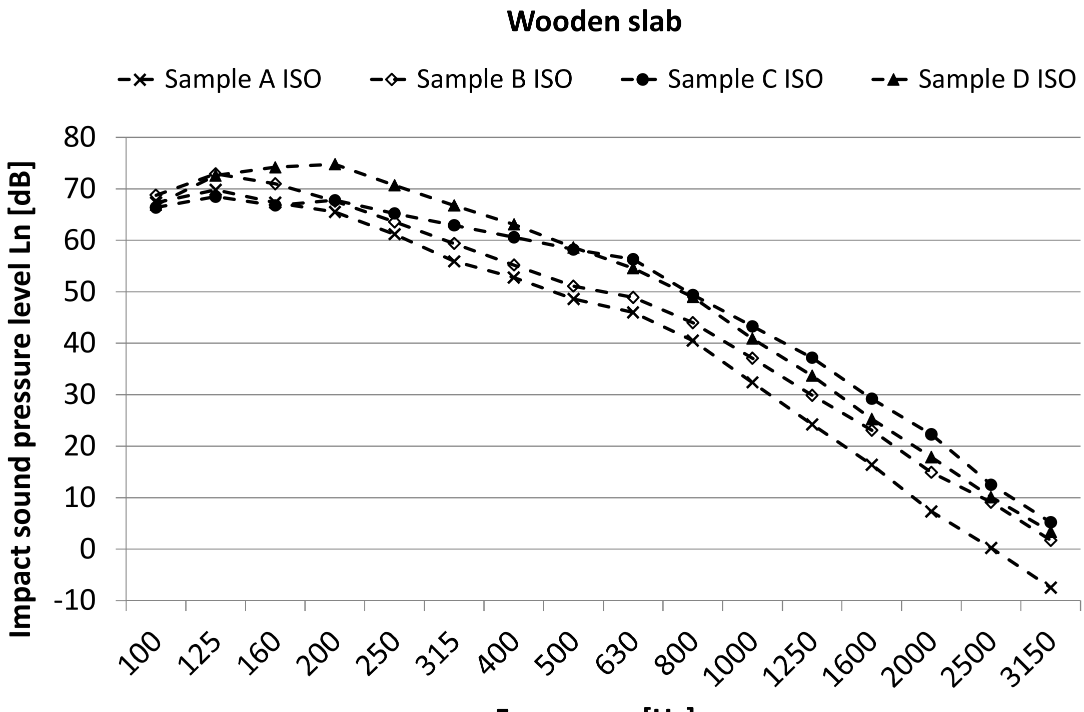


Figure 50: Hypothetical levels on a wooden floor starting from the ISO lightweight structure.

CHAPTER 4

SOUND ABSORPTION AND REVERBERATION TIME

INTRODUCTION

In the broadest sense, a sound wave is any disturbance that is propagated in an elastic medium, which may be a gas, a liquid, or a solid. Noise is defined as any unwanted sound perceived by the hearing sense of a human being. Excessive noise can impair hearing, and may also put stress on the heart, the circulatory system, and other parts of the body. Numerous national and local government laws have been enacted to limit excessive noise. Such regulations are typically grouped together based upon the land use characteristics and the proximity to residential or other sensitive areas.

The loss of intensity of sound happens in two ways: first the spreading out of the energy of the wave. This is because the wavefronts are expanding spherically, but not losing any energy. Since the area of the wavefront is increasing but the total energy is not, the energy per unit area is decreasing. This gives rise to the $1/r^2$ dependence. Secondly the dissipation of the energy of the wave. This is because the wave itself is losing energy, due to absorption of the energy as it reflects off the walls, or even dissipation in the motion of the molecules of the gas, having to do with the viscosity of the gas. This attenuation will have an exponential dependence on distance. Absorption is the conversion of the sound energy to other forms of energy. The combined effect of scattering and absorption is called attenuation.

An important point to consider for the acoustic of a room is the energy reduction of sound waves when they are reflected by walls as well as during their free propagation in the air. These loss mechanisms influence the strenghts of the direct sound and all reflected components and therefore all acoustical properties of the room.

The attenuation of sound waves in the free medium becomes significant only in large rooms and at relatively high frequencies; for scale model experiments, however, it causes serious limitations. The situation is different in the case of the absorption to which sound waves are subjected when they are reflected. The magnitude of wall absorption and its frequency dependence varies considerably from one material to another.

Sound waves are reflected hiting a hard surface. Providing an absorbent surface can reduce some of the reflected sound. In a room, soft materials such as absorbent ceiling panels, carpeting on the floor, and drapes or special absorbent wall coverings, will reduce noise by reducing the reflected sound. Only reflected sound can be treated as described, while direct sound will not be affected.

ABSORPTION MATERIALS AND STRUCTURES

The absorbent materials and the elements are widely used in the acoustic environments, especially on the ceiling, when you want to reduce the energy reverberated sound. Their use allows the control of the reverberation time and, opportune distances from the sound source, the total sound pressure level in the environment.

The ability of the materials to absorb sound energy is usually expressed with an absorption coefficient *α*. This absorption coefficient is defined as the ratio of sound energy absorbed by a given surface, to the sound energy incident upon that surface. The absorption coefficient can vary from 0 to 1; so if α=0.9, then 90% of the sound energy will be absorbed. The absorption coefficient is dependent on the frequency, and is usually published for octave, or 1/3 octave, bands. Most porous absorbers are more efficient at high frequencies, while improving the materials thickness, or mass, can increase low frequency absorption.

There are two basic types of sound-absorbing systems: porous materials and resonance absorption. The firsts absorb the sound field through the porosity; the acoustic energy is dissipated by viscous friction within the pores of the material. In the second type the resonance could start from a cavity or it can be mechanical. In both cases it could be associated the mechanical system to a mass spring system: the force is given by acoustic field, the oscillating mass may be the mass of air enclosed in a cavity, or the mass of a membrane. The spring is formed from the air enclosed in the cavity. At the resonance frequency of the system, there is a maximum of oscillation, then a maximum of dissipation.

Porous Materials

Porous materials can be mineral fibers, open cell foams, carpets, wood wool fibers, and they are characterized by an open pores structure or interconnected each others, where the sound wave is dissipated, through viscous and thermal effects. Porous and fibrosis materials differ between themselves as the firsts are constituted by fibers of different nature while the seconds resulting from the aggregation of foam or inert. These types of sound absorbing materials are described by a series of physical parameters such as flow resistivity, porosity, tortuosity, the magnitudes viscous and thermal characteristics.

The flow resistivity is an intrinsic property of the material. The measurement of air flow through a material is a physical property useful in evaluating its performance as an acoustic absorber. The specific flow resistance is one of the properties that determines both the sound absorbing and sound transmitting properties of a material. It measures how easily air can enter into a porous structure, as well as the resistance that flow meets within the structure. Flow resistivity is independent of the area or thickness of the tested material. Flow on resistance, since it is measured with a steady, laminar flow of air, does not provide any direct information about the frequency dependent behavior of the sample. The frequency dependent characteristics of a material are generally obtained from an experimental measurement of its acoustic impedance. Within a certain limit, the more resistant the material is, the higher energy dissipation, and consequently the higher absorption. This parameter is defined as the pressure difference that is generated at the ends of the material traversed by the air flow, divided by the speed of the flow and the thickness of the material.

The flow regime in a porous solid is directly related to the pore size of the material, and can thus give an indication as to how easily pressure waves can penetrate the material. By this parameter is possible to calculate the absorption coefficient and the characteristic acoustic properties of a porous material. The materials that have large holes have also low resistance, while in high-strength materials, the pores or fibers are very tight and determine a large dissipation.

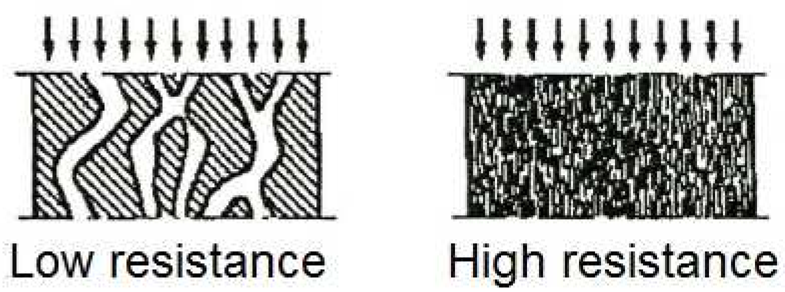


Figure 51: Structures of materials with low and high resistance.

The Knudsen number can characterize the flow regime in porous solids:

8)

$$Kn = \frac{\mathrm{l_m}}{\mathrm{l_c}}$$

where *Kn* is an adimensional number, l_m means the mean free path of air molecules (in meters) and l_c is the characteristic length (in meters). The characteristic length for this application is often taken to be the mean distance between pore walls. For the case of a spherical pore, this would equate to the pore diameter. When l_m is much smaller than l_c, the gas molecules are essentially moving in a free space.

The dominant flow regime through the material may be characterized as:

Kn <<1: viscous flow dominates

Kn ≈1: both viscous and molecular flow are important

Kn >>1: molecular flow dominates

When viscous flow dominates, pressure waves should be able to penetrate the material to a degree that allows enough internal reflections to make the material useful as an acoustic absorber. However, when molecular flow dominates, pressure waves will not be able to penetrate significantly into the material. Most of the acoustic energy will reflect off the surface, and limit its usefulness as an acoustic absorber.

The porosity is defined as the ratio of the volume of air contained within the material and the apparent volume, the geometrical dimension of the material. It can be described as the difference between 1 and the volume of the structure of the material, ie the volume of the material without the air, divided by the apparent volume:

9)

$$\Phi = 1 - \frac{\mathrm{V_{structure}}}{\mathrm{V_{apparent}}}$$

Almost all of the sound-absorbing materials have a porosity that is greater than 0.9 so the acoustic waves can penetrate into the material, and only a small percentage of the incident wave is reflected. Inside the material the energy is dissipated by friction.

Tortuosity is a measure of the “non-straightness” of the pore structure of the porous material. More complex is the path, more time a wave is in contact with the absorbent material. The evaluation of tortuosity by resistivity measurements presents several drawbacks. In particular, the complete saturation by a conducting fluid of a porous foam having a high flow resistivity is difficult to obtain without partially damaging the structure of the cells. In fibrous materials, this parameter is small, and generally ranges for values that are between 1 and 1.5, because the structure of the fibrous material allows an almost rectilinear propagation, while it is very significant in porous materials.

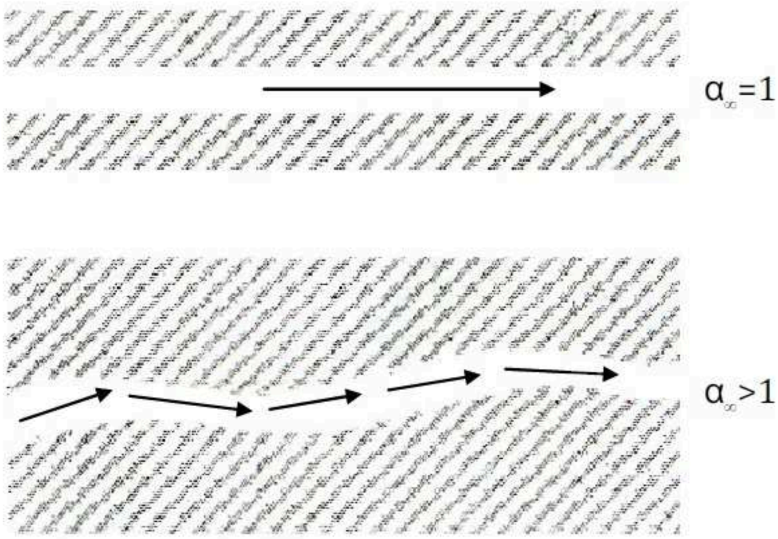


Figure 52: Tortuosity, examples of different paths of material.

Porous materials of varying density and composition are generally used as sound absorbers to convert sound energy into heat within the open pores of the material. In order to maintain the best absorption values of the chosen materials, the air channels should all be open to the surface so that sound waves can propagate into the material. Panel absorbers are often an option when low-frequency absorption is required. Thin, flexible panels are mounted away from the wall, creating a shallow air cavity. The air cavity between the panel and the wall provides a means for sound absorption at particular frequencies. Incident sound at the frequency of interest produces a resonant response in the panel-cavity that causes the panel to vibrate. Filling the cavity with a porous material can reduce the “sharpness” of the tuning. This type of solution can be cost inhibitive, and is usually employed to treat a specific tone or narrow band of an offending source, when traditional treatments are insufficient.

RESONANCE ABSORPTION

Every material has a natural mode of vibration known as the resonance frequency, which is dependent upon many characteristics, including mass. Lightweight structures under sound pressure can sometimes result in higher overall noise levels due to excitation of the base by the forcing of their frequency, thereby resulting in an amplification of the sound pressure level at that frequency. This can occasionally be seen in paneled buildings, or base structures, where at this effect is dominant and will actually amplify the sound source. The proper selection of vibration isolators becomes very critical in dampening the forcing frequency of the engine, and isolating it from the adjoining structure. Spring isolators with provision for internal damping may be required to prevent a reinforcement of vibrations at the fundamental frequency.

The mass law relates to the transmission loss of solid panels, and states that within a limited frequency range, the magnitude of the loss is controlled entirely by the mass per unit area of the wall. The law also states that the transmission loss increases 6 decibels for each doubling of frequency, or each doubling of the wall mass per unit area, up to a plateau frequency.

The resonators are systems that differ from the sound-absorbing porous materials for different mode of absorption. They are divided into two categories: cavity resonators and membrane resonators. Both use the mass-spring model.

10)

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

where f_0 is the resonance frequency, *k* the spring strength, and *m* the oscillating mass.

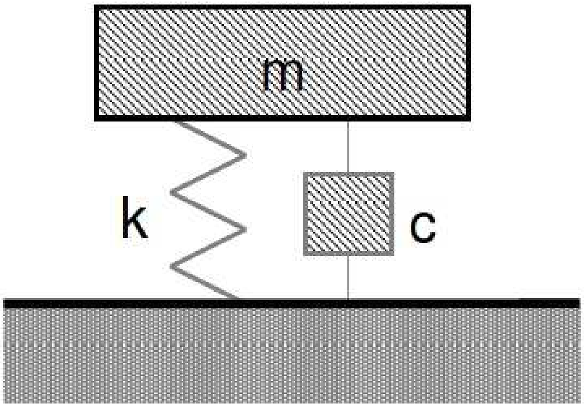


Figure 53: Mechanical mass- spring system.

In building acoustic the most utilized cavity resonators are the Helmoholtz's ones. They are composed by an air volume in a cavity open to the ambience by a very small hole called "neck". When the sound wave affects the neck, the air inside it starts to vibrate and becomes a "vibrant mass" and so the air inside the cavity that becomes an "acoustic spring". Regarding the membrane resonators they are systems consisting of a thin panel placed in front of a rigid wall and their behavior is like a vibrating mass and the air contained in the cavity as an acoustics spring.

Figure 54: Scheme of a membrane resonator.

When the excitation force, ie the frequency of the acoustic field is close to resonance frequency of the mass-spring system, the mass oscillates at the maximum by determining the greater energy dissipation.

EVALUATION OF OPTIMAL REVERBERATION TIME

There exist many parameters that describe acoustic quality of an enclosure. The importance of some has been already established by many researchers, but there is still no consensus on a set of parameters that should be taken into account while describing the acoustical quality of a room. This is due to differences in functionality of a given room, volume of rooms, distribution of absorption, and so on. One of the most important parameters describing the quality of the room is the reverberation time. A so-called optimum reverberation time can serve as an example of such problems. Numerous research studies show that rather than trying to achieve the optimum reverberation time for a given room, it is better to govern other acoustical parameters that influence acoustical quality. However one of the most relevant sensations of the sound field in rooms is still the cognition of reverberation.

During the past century were developed several formulae for predicting reverberation time empirically and theoretically, based on the assumption of homogeneous repartition of sound energy within the room, and consequently uniformly on distributed sound absorption. The problem of the reverberation time prediction for non-uniform distribution, however, remains so far, open for discussion and for finding solutions fitted better to practical application.

The first and most remarkable approach to describe the reverberation characteristics of an enclosure was found by W.C. Sabine around 1900. He established his theory on the basis of practical results, which he published. Since that, different approaches have been adopted to obtain equations that describe the reverberation characteristics. In the last 30 years, Schroeder (1965), Kosten (1965, Cremer and Müller (1978), Kuttruff (1975), Nilsson (1992), Tohyama et al. (1995) added some new issues to the theory of reverberation. In 1988 Arau presented an improved reverberation formula taking into account the nonuniform distribution of sound absorption. Lately, papers by Kutruff and Bistafa and Bradley, which dealt with the similar problems, appeared. A general description of the reverberation time based on Sabine's reverberation theory is still in common use. However, in the case of a room in which sound absorption is not uniformly distributed, the reverberation time frequency characteristics cannot be predicted accurately using Sabine's or other classical reverberation theories. These theories are based on the assumption that the sound field considered is completely diffuse. This will, in general, be sufficiently diffused if there are no large differences in the basic dimensions of the room, walls are not parallel, sound absorbing material is uniformly distributed, and most interior surfaces are divided into parts. In practice, almost none of these requirements is fulfilled. In 1959, Fitzroy introduced an empirically derived equation that considers non-uniform distribution of absorption. However, a thorough investigation of Fitzroy's equation revealed that in most cases the predicted reverberation time was generally too long.

According to the classical formula reverberation time is defined as time needed to decrease energy by 60 dB from its original level after instantaneous termination of the excitation signal. This parameter, originally introduced by Sabine, is given by equation:

11)

$$T_{60} = 0{,}16\frac{V}{A}$$

where V is the hall volume [m^3], A the total area of absorption [m^2], 0.16 is a coefficient introduced first empirically, depending on propagation conditions.

If the surface area of the room is S, Sabine's average absorptivity α is defined by:

12)

$$\alpha = \frac{A}{S}$$

The equation assumes that the sound energy is equally diffused throughout the room (homogeneous and isotropic). Actually, this condition is rarely fulfilled due to the large areas existing in a hall characterized by differentiated absorption. Therefore, in practice, there are several formulae describing the reverberation time. It was discovered by Eyring that the classical formula given by Sabine is not fulfilled when there is considerable room absorption. Eyring pointed out in his paper that Sabine's formula is essentially a "live" room formula as the reverberation time is shape dependent. He presented the revised theory thoroughly and derived a form of the reverberation time equation, which is more general than Sabine's formula. Eyring's formula is based on the mean free path between reflections. Eyring assumes that sound coming from a source in a room is successively reflected by boundaries having an average coefficient α. Each time a wave strikes one of the boundaries, a fraction (α) of the energy is absorbed, and a fraction ($1-\alpha$) is reflected. The number of reflections per second is numerically equal to the distance sound will travel in one second divided by the average distance between reflections.

On the other hand, Fitzroy states in his paper that it is possible to take into consideration not only physical, but also geometrical aspects of a sound field in an enclosure. In this way the sound field may tend to settle into a pattern of simultaneous oscillation along a rectangular room with three major axes: vertical, transverse, and longitudinal. Arau introduced a model of calculating the reverberation time for the case of asymmetrical distribution of absorption, assuming that the reverberation decay is a hyperbolic process. This decay is a superposition of three contributions: initial decay, first and second linear portion of the decay, and the third linear portion. If the enclosed space has a non-regular distribution of absorption, irregular shapes or is filled in, to a large extent, with equipment, decorative elements, etc., the predictions of the reverberation time should be based on the Nilsson model. This may improve predictions of the reverberation time for the irregular absorption distribution. An essentially rectangular space with irregular absorption distribution is quite common. In many office rooms absorption is applied only to the ceiling, all other surfaces being reflective. In such a case classical time reverberation formulae rarely solve the problem. Nilsson proposed that the sound field should be divided into the most characteristic part, i.e. tangential to the considered surface, and remaining parts of room surfaces. Kuttruff considers the case of the partially diffuse field within the room and introduces the concept of the reflection coefficient $\rho = 1 - \alpha$. Basing on the assumption that absorption coefficient α and hence ρ are independent of the angles, he made use of Lambert's law of diffuse reflection. By focusing on the overall reverberation time, and neglecting details of the decay process and additionally under the assumption of an exponential law for the time dependence of the irradiation strength over the whole surface of reflecting walls, he defined an absorption exponent α^*. The assumption of an exponential law is reasonable since, at least in rectangular rooms, the decay process of the sound energy will decrease exponentially.

For the laboratory measurements of sound absorption the method in the reverberation chamber is based on the availability of a large sample of the product (10-12 square meters) of which you want to measure the sound absorption coefficient. A surface of this dimension is enough to alter significantly the reverberation time of a room, so it is possible to estimate the absorbing power of a material from the variation of reverberation time caused by it.

MEASUREMENTS OF SOUND ABSORPTION COEFFICIENT IN LABORATORY

The ISO 354, however, requires that the measurement is done in a special room, called reverberation chamber. It is an environment, having a volume of about 200 m3, with very little absorption, and irregular shape or the presence of diffusing elements hung on the ceiling, so a perfect diffuse field is established, and the acoustic behavior of the room is correctly described by the Sabine formula:

13)

$$T_{60} = \frac{55.3}{c} \times \frac{\mathrm{V}}{A}$$

where *A* is the total area of absorption [m^2] obtained by:

14)

$$A = \sum_i \alpha_i \times S_i$$

Starting from the empty chamber, the reverberation time is measured in frequency. This value, T_1, gives, from the inverted Sabine's formula, the corrispondent area of sound absorption, A_1:

15)

$$A_1 = \frac{55.3}{c} \times \frac{\mathrm{V}}{T_1}$$

After that in the chamber about 10 m^2 of material to test is introduced and the measurement of the reverberation time, (now T_2), is again repeated. The value T_2 will be less than T_1 and as a consequence it will be that:

16)

$$A_2 = \frac{55.3}{c} \times \frac{\mathrm{V}}{T_2} = A_1 + \alpha_x \times S_x$$

where α_x is the sound absorption coefficient that is still unknow and S_x is its surface. So, to obtain α_x:

17)

$$\alpha_x = \frac{55.3 \times V}{c \times S_x} \times \left[\frac{1}{T_1} - \frac{1}{T_2}\right]$$

The test is done in 1/3 octave band to obtain the spectrum of absorption of the material.

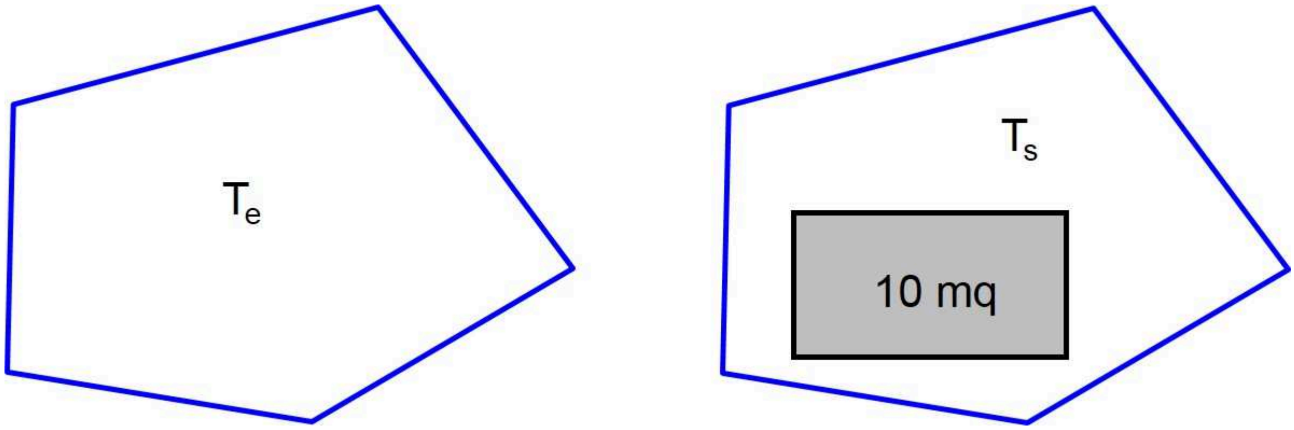


Figure 55: Schemes of the empty reverberation chamber, and then with the sample.

The α so measured is called "Alfa Sabine" or "sound absorption coefficient in diffuse field" because it is important to underline that the Sabine's formula is respected in the empty chamber but its validity changes when an absorbent material is introduced and concentrated in an area and not distribuited along the perimeter. In this case there is a sistematic error that gives higher value of sound absorption coefficient that in the real case. Therefore, the following empirical relationships that enable the conversion between the two different forms of the sound absorption coefficient are applied:

18)

$$\alpha_{Sabine} = 0.1362\ \alpha_{real}^{2} + 1.107\alpha_{real}$$

19)

$$\alpha_{real} = 2.584292 \times \sqrt{\alpha_{Sabine} + 1.9372} - 3.59691$$

Figure 56: Relation between Alfa Sabine and Alfa "real".

OPTIMAL REVERBERATION TIME APPLICATIONS

The cellular structure of the mww panel provides optimal values of specific resistance to air flow and so the viscous friction for the sound waves that pass through the panel. This is due to the microporosity and elasticity of the wood wool, and macroporosity, given by the interstices of the agglomeration wood-Portland cement. In addition, the characteristics of high internal damping of the material, combined with the rigidity of the panel, allow to obtain an efficiency of absorption particularly relevant, also for extended low-frequency sounds.

The most common situations in which problems of poor sound quality that can lead to discomfort could be: a noisy restaurant where it is almost impossible to communicate with a normal tone of voice, a waiting room or a commercial space in which there are no intelligible notices or communications, a meeting room or a classroom in which the stress is high voice of the speaker and the poor quality of perception of the listener; insufficient rest or confidentiality in offices, excessive reverberation in gymnasiums and exhibition space. Based on the intended use of an environment, the optimal values of reverberation time required for a correct perception of speech or music can be established as a first approximation. There are several reports that allow to consider the volume of an environment and the type of activity to be carried out related to the optimal value of the reverberation time at a certain frequency, then this calculation can be extended also to a wider range of frequencies. In any case, the optimal values thus obtained must be considered as guidelines only, as many other parameters contributing to the proper definition of the characteristics of optimum listening. The italian standard D.P.C.M. 5/12/97 prescribes that at frequencies 250, 500, 1000, 2000 Hz, the reverberation time shall not exceed 1.2 seconds to a classroom equipped with the presence of more than two persons and that in a gym it must not exceed 2.2 seconds. The current legislation does not prescribe limits to the time of reverberation of school canteens, but considered the intended use environment, in addition at the high sound pressure level in the interior, is assumed to take the limit for classrooms.

The UNI 11367 on acoustic classification of building units introduced the specific guidelines for the evaluation of interior acoustic characteristics of the environments (Appendix C). With others parameters are also reported the values of the optimum reverberation time average between 500 Hz and 1000 Hz to evaluate the interior acoustic characteristics of a room not occupied for two different listening conditions (spoken and sporting activities). These values are derived from the following relationships, expressed in function of the volume of the environment:

20)

$$T_{60,opt,spoken} = 0{,}32\log(V) + 0{,}03$$

21)

$$T_{60,opt,sport} = 1{,}27\log(V) - 2{,}49$$

In this work, to evaluate the performances of the false-ceiling in mineral wood wool panels for the control of reverberation time, a simulation of environments with increasing volume was carried out, both for uses that require a high quality of speech perception, and for sport environments in general. For the analysis of acoustic quality in relation to different uses, reverberation times of the volume of the environment have been evaluated. The considerations started from the relations in the UNI 11367 for the optimal values of the reverberation time.

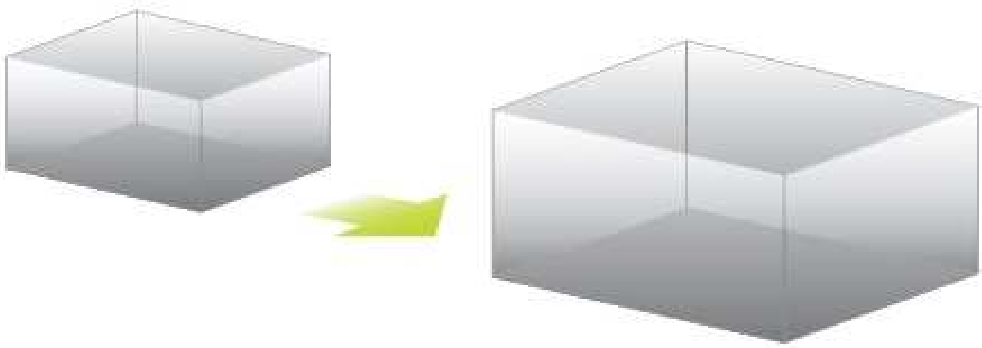


Figure 57: Scheme of enlarging volume.

To optimize the speech intelligibility of the environments, the internal volume was varied from 100 to 2000 m^3, with a ratio between the total area and volume between 1 and 0.5 and an average absorption coefficient of about 0.08 for the untreated environment, which corresponds a useful absorption surface which ranges from about 10 to 80 m^2. The resulting values of reverberation time thus varies from 1.7 to 4.3 seconds.

In the same environments was then introduced a continuous false-ceiling made with mineralized wood wool panels of 25 mm thickness an air gap of 75 mm. With this solution the average sound absorption coefficient grows to a value of 0.20 corresponding a useful absorption surface with ranges from about 25 to 270 m². The reverberation times obtained, thanks to the intervention that involved only the surface of the ceiling, vary now between 0.8 and 1.5 seconds. These values are very close to the optimal ones.

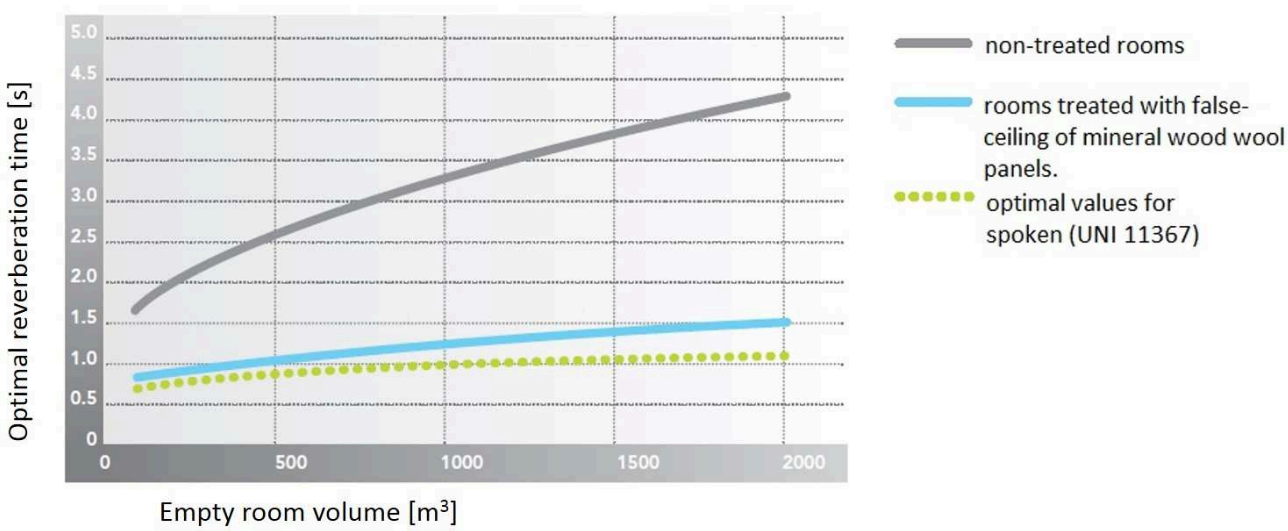


Figure 58: Optimal reverberation time values for spoken for treated and untreated rooms in function of the volume.

For environments intended for sports activities, the internal volume was varied from 2000 to 10000 m³, with a ratio between the total area and volume between 0.5 and 0.25 and an average absorption coefficient of approximately 0.08 for the untreated environment. It corresponds a useful absorption surface which ranges from about 95 to 245 m². The resulting values of reverberation time varies from 3.7 to 7 seconds.

The treatment of acoustic correction has been obtained with a false-ceiling similar to that used in the previous cases, with the same average absorption coefficient, which corresponds to a useful absorption surface which ranges from about 265 to 630 m². The reverberation times obtained thanks to this intervention now varies between 1.5 and 3 seconds values, in line with the optimal ones.

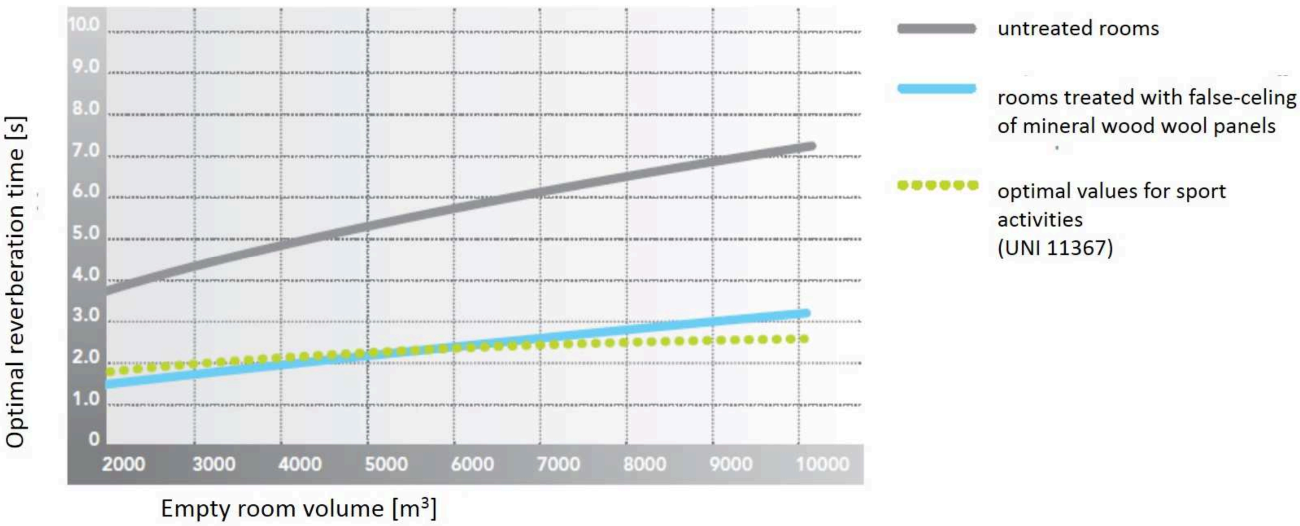


Figure 59: Optimal reverberation time values for sport activities for treated and untreated rooms in function of the volume.

The examples show how the use of a false-ceiling made with mineralized wood wool panels allows to achieve excellent results even for environments with different characteristics and sizes. It is important to underline that the systems for the control of reverberation time provide different performance at different frequencies according to the characteristics of the products used and the method of installation.

So a careful acoustic design of the environments starts from the knowledge of materials, which must be selected and used in accordance with the results to be achieved. An excess of sound absorption, for example, does not necessarily imply a benefit in terms of sound quality and can make an environment not suitable for certain uses, and it is the same for excess reverberation. It is therefore necessary to balance the absorption characteristics taking into account the mode of use of the environment and the interaction with furniture and occupants.

CHAPTER 5

DATABASE ANALYSIS

INTRODUCTION

Proper acoustic design of the living spaces can bring considerable benefits to the living comfort. Actions of sound insulation are designed to minimize the transmission of noise between two rooms. In order to obtain an efficient sound insulation is therefore necessary to use a partition good for reduce the airborne noise and minimize the flanking transmission. The (weighted) sound reduction index R_W is a key value for the definition of the properties of airborne sound insulation of building elements; it is defined according to the methods described by the standard ISO 10140-2 "Acoustic: laboratory measurement of sound insulation of building element".

The work carried out is based on the study of the sound reduction index of 224 vertical elements that differ by type of material and method of construction.

MEASUREMENTS LABORATORY OF SOUND INSULATION OF ELEMENTS OF BUILDING

The data used in this work were provided by University of Padova. The Acoustics Laboratory of the Department of Industrial Engineering, University of Padova has three reverberation chambers, comply with the requirements of the standards of the ISO 10140, and ISO 3741 SO 354 for the measurement of sound absorption materials and articles , the sound power emitted by machinery and apparatus and for the determination of the soundproofing properties of building elements. The laboratory conducts research and certification.

The Acoustics Laboratory, Department of Physics, University of Padova has double rooms for the measurement of airborne sound insulation of vertical elements of the building in accordance with ISO 10140: Acoustics - Laboratory measurement of sound insulation of building elements - Part 5 : Requirements for test facilities and equipment.

This legislation is intended to specify the characteristics and laboratory instruments for the determination of airborne sound insulation of walls, partitions, doors, windows, facades and facade elements according to the other parts of the same family of standards. The results obtained with this method can be used to design building elements with appropriate acoustic properties, to compare and classify the insulation characteristics of different elements.

Dimensional characteristics of construction are:

- Average size of the room A (wxdxh) 5.8 x3.3x4.1 m (non-rectangular)
- Average size of chamber B (LxWxH) 5.5 x3.2x4.4 m (non-rectangular)
- Dimensions of the mounting (W x H) 3.6 x2.8 m
- Depth of the mounting 1 m
- A chamber volume (net of the mounting) 78.6 m^3
- Volume of chamber B (net of the mounting) 78.2 m^3
- Volume of the mounting 10.6 m^3
- Room size A 102.74 m^2
- Room size B 99.37 m^2
- size of the mounting frame 14.85 m^2
- Surface width of the opening for the mounting of the elements under test 10.08 m^2
- Material of the mounting: reinforced concrete
- Features methodological measurement

• Frequency Range of measurement: 100-5000 Hz
• Range of additional frequency: 50-80 Hz
• Speakers and absorbers in the receiving room (B)
• Short Reverberation Room A (frequency range 50-5000 Hz, volume ~ 83 m^3): $1 < T60 < 4$ s
• Short reverberation chamber B (frequency range 50-5000 Hz, volume ~ 83 m^3): $1 < T60 < 2$ s
• Number of source positions: 2 (no agents at the same time)
• Number of microphones in every room: 6 (fixed locations)
• Values of repeatability over the frequency range 100-5000 Hz: $r < 0.5$ dB

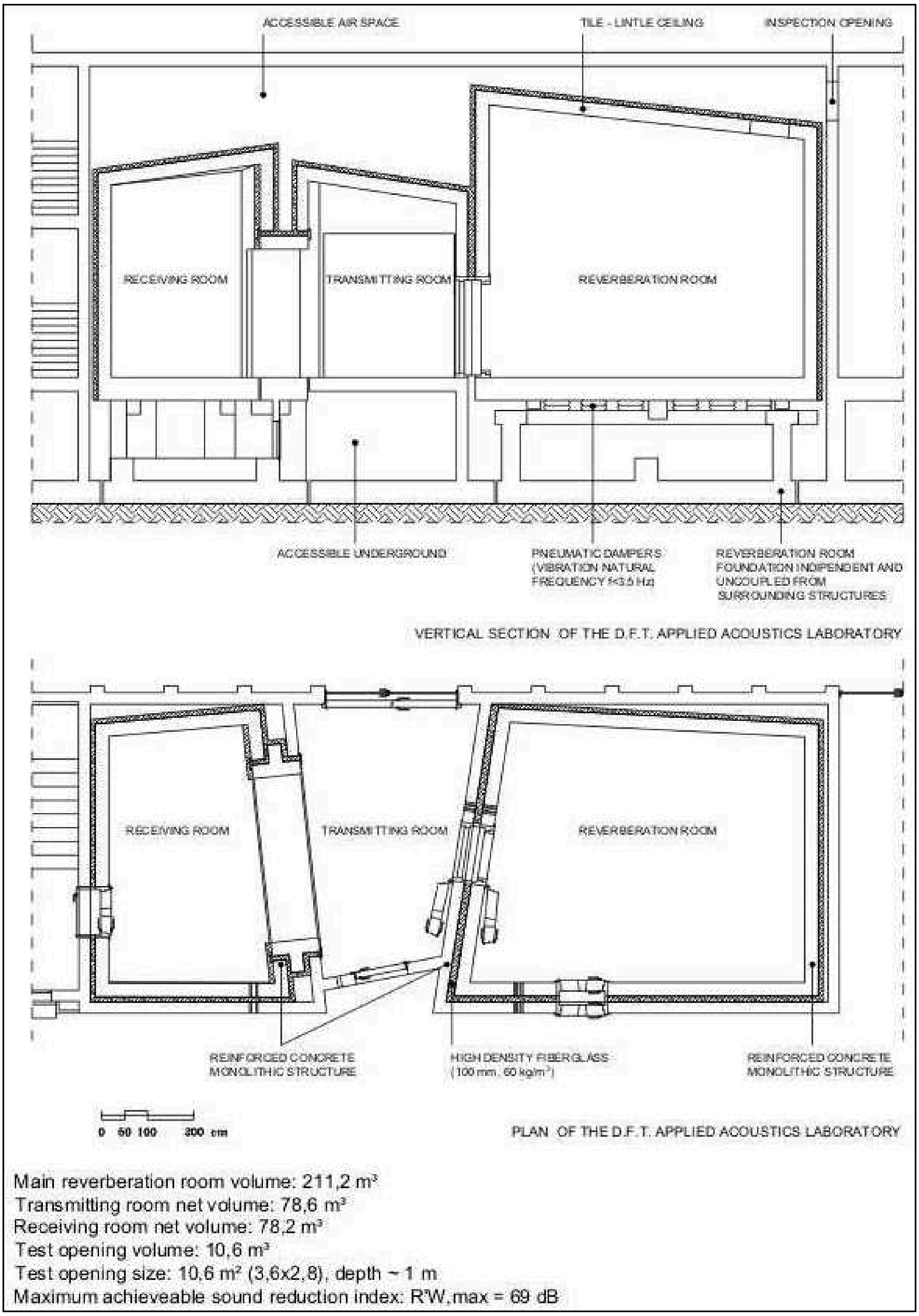


Figure 60: Scheme of the acoustic laboratory of the University of Padova.

According to the characteristics of the opening test of double rooms dimensional specifications and assembly of the elements tested are listed below.

Partitions:

- the size of the partition must be made by the 3.6 x2.8 ± 0.015 m;

- the installation must comply as much as possible the actual methods of construction and connection of the element, with the adoption of appropriate sealant around the perimeter of the element and between any joints between its components.

Doors, windows, facades and facade elements:

- if the element was smaller than the opening test, will be made a special partition stay where the item under test, with a sufficiently high sound insulation or not comparable with the estimate of the item under test;
- the doors are inserted in the special partition so that their lower side is next to the floor surface, so as to reproduce the actual installation conditions;
- if the item under test is opened, it will be mounted so that it can be opened and closed as actual conditions of use and will be submitted before the execution of the measures at least ten cycles of opening and closing.

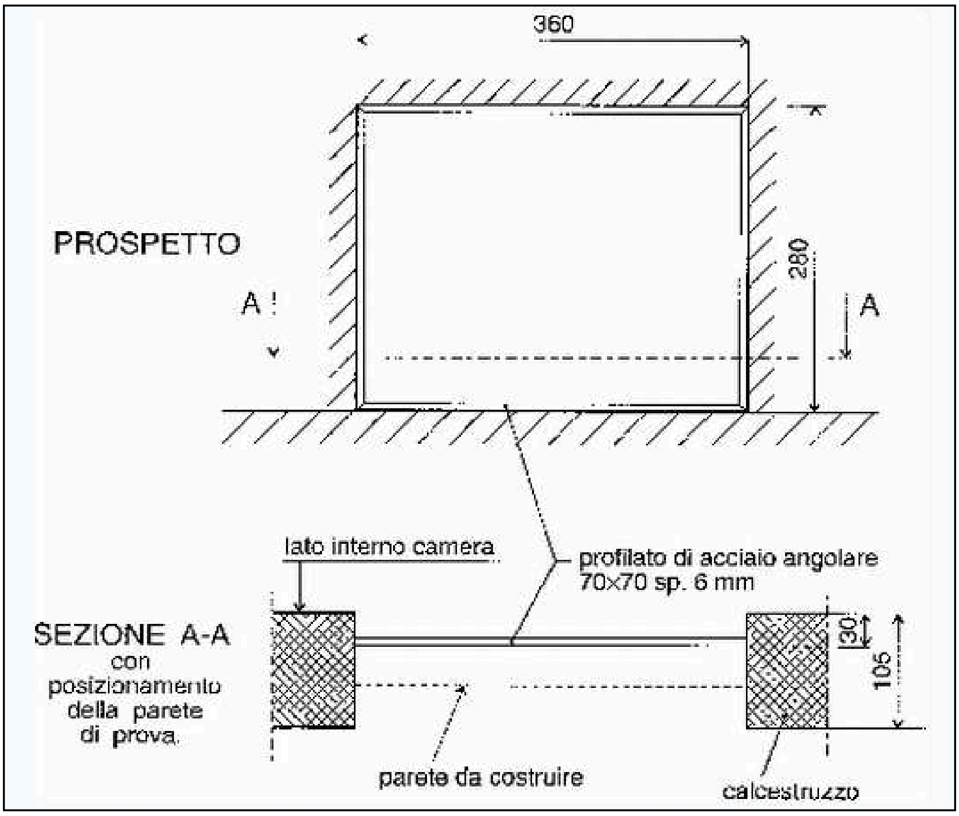


Figure 61: Perspective drawing of acoustic laboratory of University of Padova.

MEASUREMENTS ANALYSIS

The analysis of laboratory measurements of sound reduction was carried out dividing the tested elements into categories with common characteristics, performing an evaluation of the value of R_w and matching each case by means of a parametric analysis of the data available in order to determine, if possible, relations between statistical properties of the elements. The subdivisions of the elements is based on six different types:

- type of material;
- single walls vs. multilayer walls;
- covered walls;
- walls with cavity vs. walls without cavity;

- light weight walls vs. heavy walls.

By means of the statistical analysis have defined the following statistical indices:

- mean, median, mode, minimum and maximum value of the data series;
- deviation of the average, ΔR_{w1}: difference between the average of R_w of the series of sample data classified and the average of R_w of the total sample of 212 vertical elements analyzed;
- deviation of the average, ΔR_{w2}: difference between the average of R_w of the series of sample data that compose a subcategory of the classification made and the average of R_w of the series of data that make up the sample classified;
- standard deviation σ, coefficient of variation, CV.

The results of the parametrical analysis performed on the data set of vertical elements are highlighted in the following tables in which statistical indices are reported after calculation case by case.
The data set is grouped in a layer with program excel in a kind of database. Using the Excel's tools, these information can be rearranged for the five types of classification above mentioned.

SUBDIVISION BY TYPE OF MATERIAL

Using the filter of the column "subcategory" in the program excel is possible to divide by type of material the elements of database, calculating the position indices and dispersion one.

The 71% of the vertical elements is made of bricks, 13% of wood, modular walls from 4%, the 3% by gypsum board partitions and concrete walls, 2% for brick prebuilt walls and finally to one per cent from clay brick walls and paneled walls.

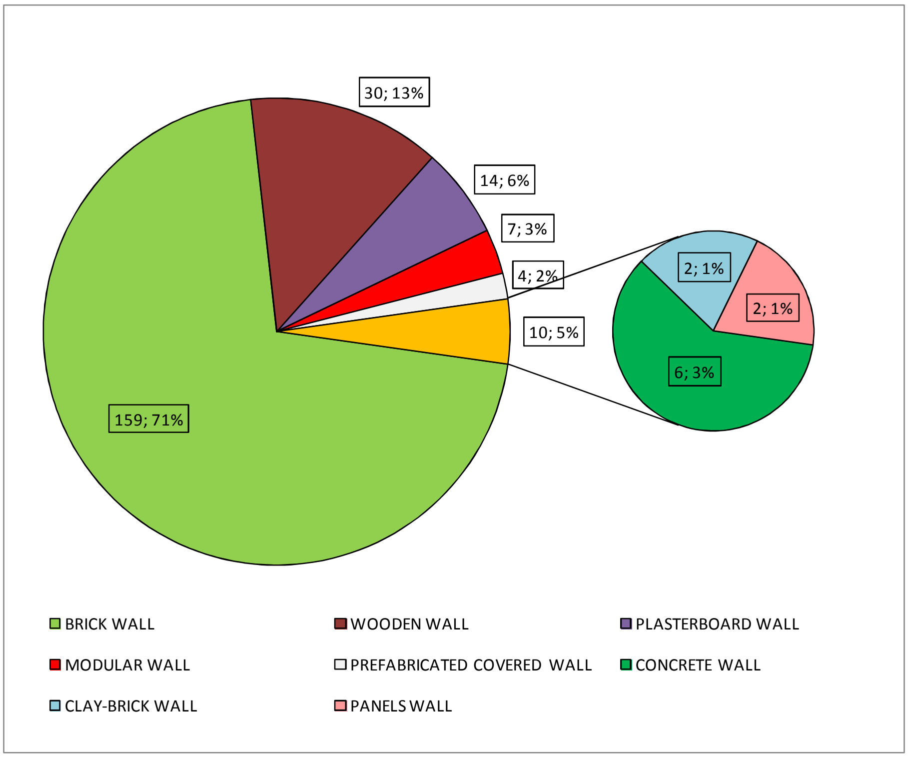


Figure 62: total observed data set. The values represent the number of elements for each partitions with relative percentage.

	N° elements	Mean R_w [dB]	Median R_w [dB]	Mode R_w [dB]	Mode [%]	Max R_w [dB]	Min R_w [dB]
BRICK WALL	159	53.5	54	55	14.5	68	32
WOODEN WALL	30	54.3	56	56	13.3	67	31
PLASTERBOARD WALL	14	60.1	59.5	59	21.4	70	53
MODULAR WALL	7	40.9	41	-	-	50	31
PREFABRICATED COVERED WALL	4	56.8	59	-	-	57	47
CONCRETE WALL	6	45.0	43.5	-	-	63	32
CLAY-BRICK WALL	2	40.5	40.5	-	-	43	38
PANELS WALL	2	43.5	43.5	-	-	52	35
TOTAL ELEMENTS	224	53.3	54	55	10.7	70	31

Table 11: Statistical parameters of total data set- materials.

	N° elements	ΔR_{w1}	max-min	σ	CV [%]
BRICK WALL	159	0.2	36.0	5.9	11.0
WOODEN WALL	30	1.0	36.0	8.9	16.4
PLASTERBOARD WALL	14	6.8	17.0	4.1	6.9
MODULAR WALL	7	-12.4	19.0	6.8	16.7
PREFABRICATED COVERED WALL	4	3.5	10.0	6.9	12.2
CONCRETE WALL	6	-8.3	31.0	10.1	22.4
CLAY-BRICK WALL	2	-12.8	5.0	-	-
PANELS WALL	2	-9.8	17.0	-	-
TOTAL ELEMENTS	224				

Table 12: Statistical parameters of total data set- materials.

This quantitative subdivision shows that the brick walls are those of most widespread in the construction field. The highest values of the statistical parameters are obtained for plasterboard walls, while the concrete elements have performance significantly lower than the average. There is a high variance values which denote the great variability of the data.
It can be stated that this type of subdivision does not allow to make significant considerations starting only from the average value of R_w.

SINGLE WALLS VS. MULTI-LAYER WALLS

The single walls are subdivided another time in the following way:

- wooden single walls, uncoated;
- brick single wall, uncoated;
- wooden single wall covered;
- brick single wall covered.

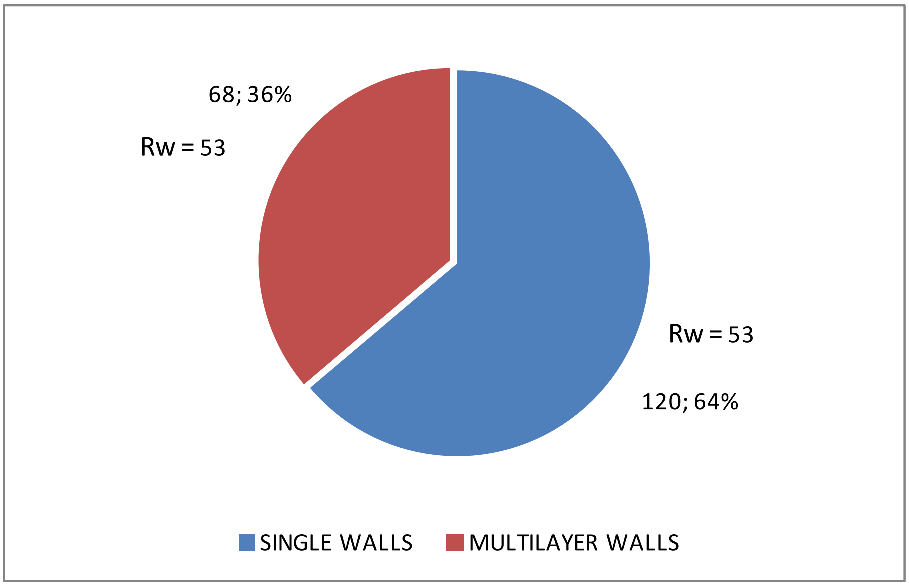


Figure 63: Total observed data set. The R_w is the moda. Number of items and relative percentage of elements for each group partition.

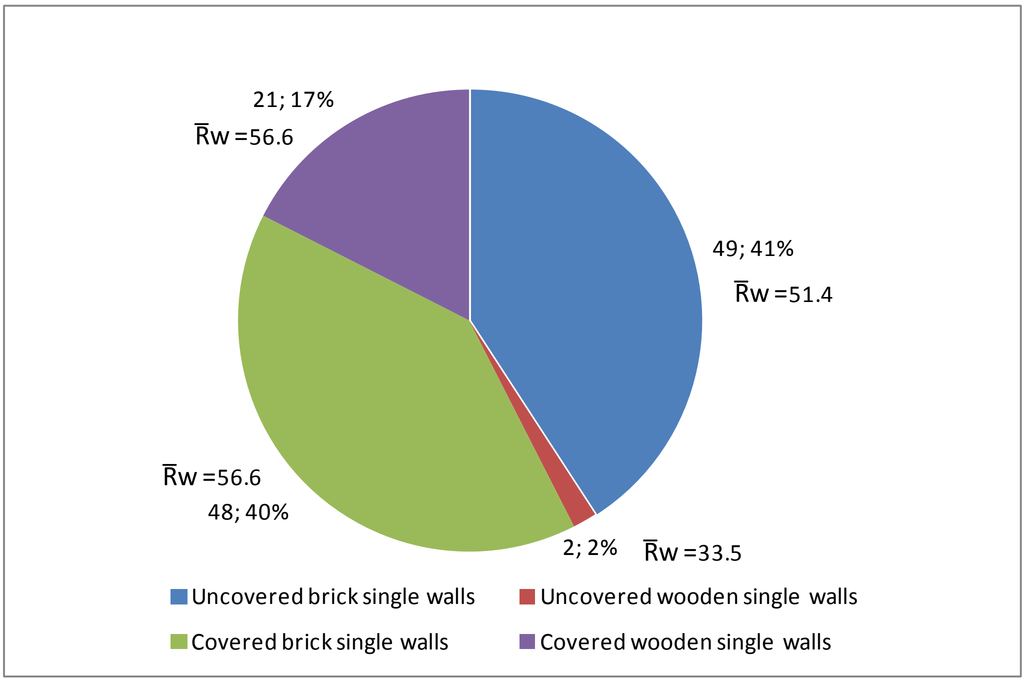


Figure 64: Mean value of single number index rounded at one place, with number of items and relative percentage for each group of wall.

In the same way it's possible to divide the multilayer elements in:

- uncovered multilayer wall;
- covered brick multilayer wall;
- gypsum board multilayer wall.

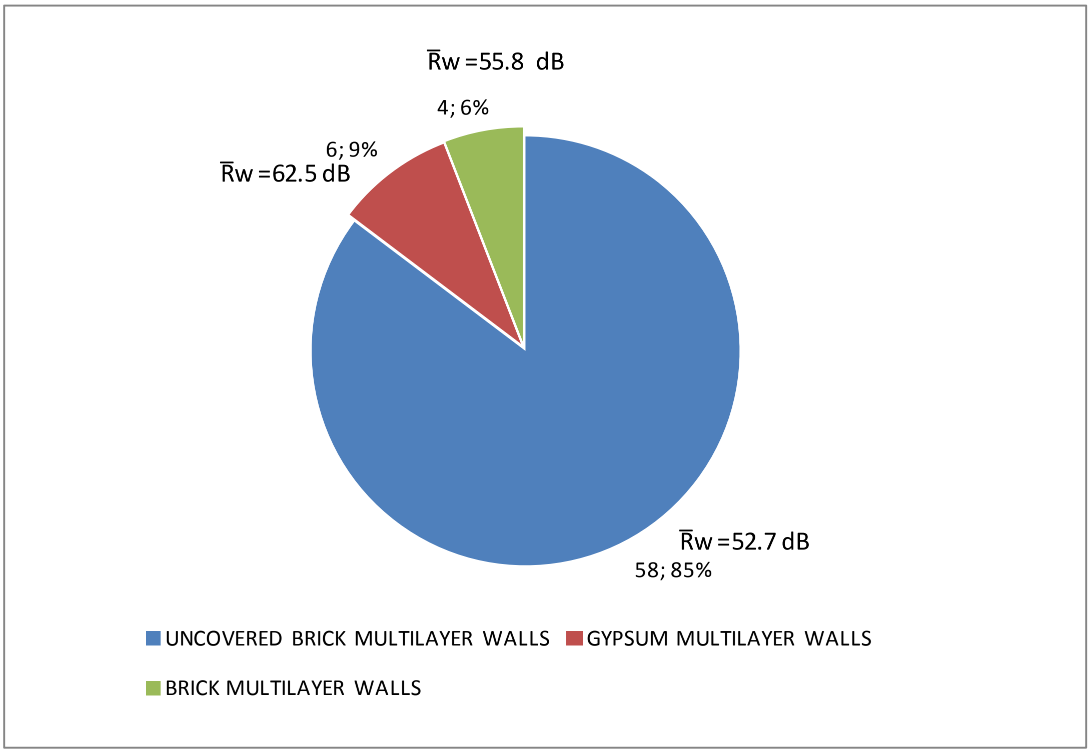


Figure 65: Mean value of single number index rounded at one place, with number of items and relative percentage in the box for each group of walls.

	N° elements	Mean R_w [dB]	Median R_w [dB]	Mode R_w [dB]	Mode [%]	Max R_w [dB]	Min R_w [dB]
SINGLE WALLS	120	54.1	55	53	9.2	68	31
UNCOVERED SINGLE WALLS	51	50.7	53.0	53	9.8	62	31
BRICK SINGLE WALLS	49	51.4	53	53	10.2	62	32
WOODEN SINGLE WALLS	2	33.5	33.5	-	-	36	31
COVERED SINGLE WALLS	69	56.7	56	56	10.1	68	48
BRICK SINGLE WALLS	48	56.6	56	55	12.5	68	48
WOODEN SINGLE WALLS	21	56.6	57	53,56,61	14.3	67	40

Table 13: Statistical parameters of data set- single walls.

	N° elements	Mean R_w [dB]	Median R_w [dB]	Mode R_w [dB]	Mode [%]	Max R_w [dB]	Min R_w [dB]
MULTILAYER WALLS	68	53.7	54	53	17.6	70	35
UNCOVERED BRICK MULTILAYER WALLS	58	52.7	53	55	12.5	58	35
COVERED MULTILAYER WALLS	10	59.8	59	58	20.0	70	52
GYPSUM MULTILAYER WALLS	6	62.5	62.5	-	-	70	57
BRICK MULTILAYER WALLS	4	55.8	55.5	-	-	60	52

Table 14: Statistical parameters of data set- multilayer walls.

	N° elements	ΔR_{w1}	ΔR_{w2}	max-min	σ	CV [%]
SINGLE WALLS	120	-0.9	-0.2	37.0	7.3	13.4
UNCOVERED SINGLE WALLS	51	2.5	3.2	31.0	7.9	15.7
BRICK SINGLE WALLS	49	1.8	2.5	30.0	7.3	14.1
WOODEN SINGLE WALLS	2	19.7	20.4	5.0	3.5	10.6
COVERED SINGLE WALLS	69	-3.5	-2.8	20.0	5.7	10.0
BRICK SINGLE WALLS	48	-3.4	-2.7	20.0	5.4	9.5
WOODEN SINGLE WALLS	21	-3.7	-3.0	27.0	7.9	13.8

Table 15: Statistical parameters of data set- single walls.

	N° elements	ΔR_{w1}	ΔR_{w2}	max-min	σ	CV [%]
MULTILAYER WALLS	68	-0.5	0.0	35.0	3.8	7.0
UNCOVERED BRICK MULTILAYER WALLS	58	0.5	1.0	23.0	3.8	7.2
COVERED MULTILAYER WALLS	10	-6.6	-6.1	18.0	5.5	9.2
GYPSUM MULTILAYER WALLS	6	-9.3	-8.8	13.0	4.8	7.8
BRICK MULTILAYER WALLS	4	-2.6	-2.1	8.0	3.9	6.9

Table 16: Statistical parameters of data set- multilayer walls.

It is evident as uncovered single walls present a value R_w of about 3 dB lower than the mean of the examined elements and a value of mode 2 dB less than the totality of the elements. The most responsible for the lowering of the value of sound insulation are the two wooden elements with low value of R_w.

For single covered wall, the uniformity of mean value equal to 56.6 dB for each types of materials (wood and brick) is well stated. This fact leads us to make some further reflections on the covering as a very important characteristic to calculate R_w with reference to wall's material. The table 13 shows how the range of variation of the index R_w is very wide. The mean of the sound reduction index R_w for the multilayer walls is equal to 53.7 dB for all elements, and the most representative value, that it is represented by mode, is equal to 53 dB. From a detailed analysis of the first classification made is visible how the covered multilayer walls have sound reduction index that range from 3.0 to 8.8 dB, higher than the average value of the total elements examined.

COVERING WALLS

To evaluate the influence of covering on sound reduction index R_w it is performed a first subdivision depending on the positioning of the covering:

- covering of the receiving side of the wall;
- covering of the transmitting side of the wall;
- covering both sides.

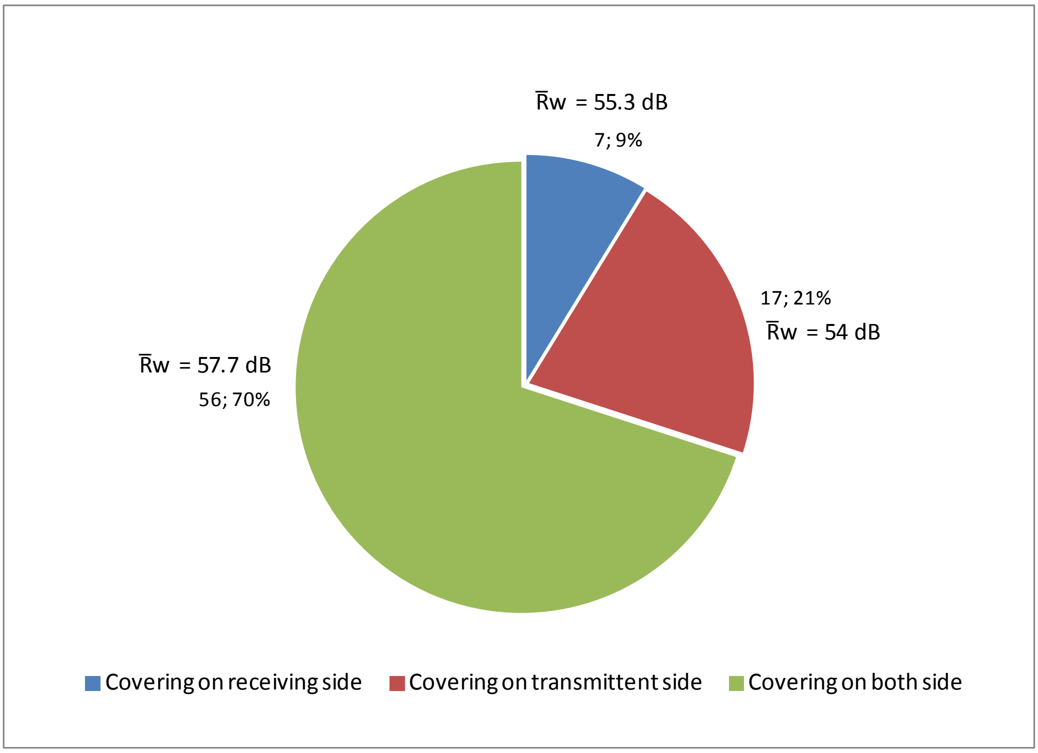


Figure 66: Mean value of single number index rounded at one place, with number of items and relative percentage for each group of walls.

	N° elements	Mean R_w [dB]	Median R_w [dB]	Mode R_w [dB]	Mode [%]	Max R_w [dB]	Min R_w [dB]
COVERING ON RECEIVING SIDE	7	55.3	55	53	28.6	63	50
COVERING ON TRANSMITTENT SIDE	17	54.0	55	48, 54, 55 *	17.6	59	48
COVERING ON BOTH SIDE	56	57.7	58	62	10.7	68	49
TOTAL ELEMENTS	80	56.7	56	56	10	68	46

Table 17: Statistical parameters of data set. *= trimodal value.

In general, the coated elements have a value of R_w 3 dB higher than the average of all vertical elements analyzed. The subcategory "coating on both sides", on average exceed by more than 4 dB total average value and has a value of mode of which 62 dB is the highest so far reported. The coating positioned on the side of the transmitting room provides the worst performance insulation. The high value of mode for covered elements on both sides is a symptom of how the coating influences in a decisive way the sound reduction index R_w.

WALLS WITH CAVITY VS. WALLS WITHOUT CAVITY

Another classification was finalized to study the influence of the cavity the sound reduction index for building elements.

This classification is also divided in:

- presence of air in the cavity;
- cavity totally or partially filled with sound-absorbing panels;
- cavity totally or partially filled with mineral wool.

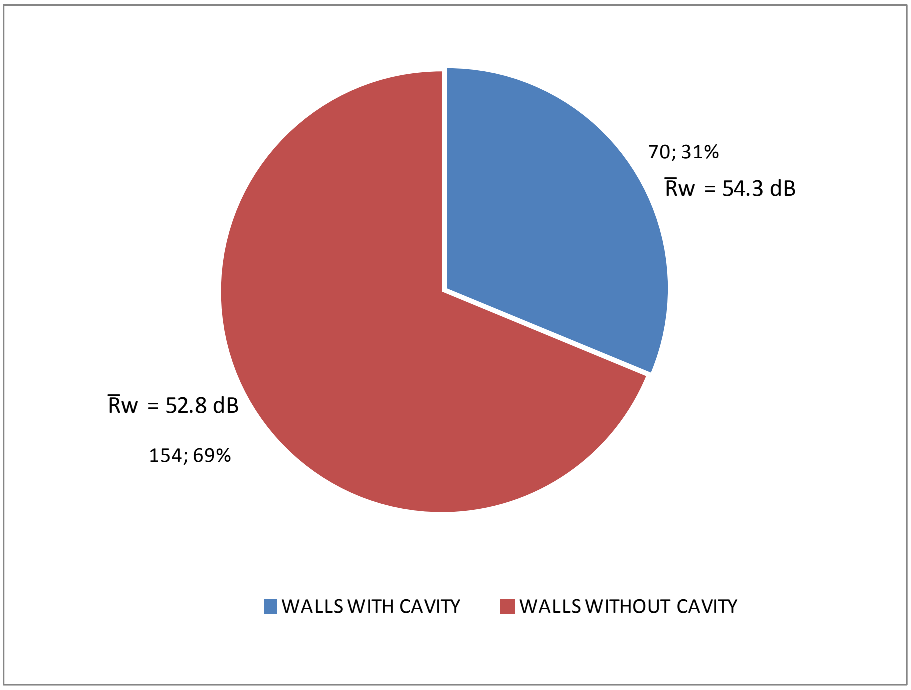


Figure 67: Mean value of single number index rounded at one place, with number of items and relative percentage for each group of walls.

	N° elements	Mean R_w [dB]	Median R_w [dB]	Mode R_w [dB]	Mode [%]	Max R_w [dB]	Min R_w [dB]
WALLS WITH CAVITY	70	54.3	54	53	18.5	70	44
ACOUSTIC PANELS	44	53.6	54	55	27.3	58	46
AIR	15	53.4	53	53	20.0	70	44
ROCKWOOL	11	58.2	59	59	27.3	67	49
WALLS WITHOUT CAVITY	154	52.8	54	53	7.8	68	31

Table 18: Statistical parameters of data set.

	N° elements	ΔR_{w1}	max-min	σ	CV [%]
WALLS WITH CAVITY	70	1.1	26	4.3	7.9
ACOUSTIC PANELS	44	0.4	12	2.3	4.3
AIR	15	0.2	26	6.3	11.8
ROCKWOOL	11	5.0	18	5.4	9.3
WALLS WITHOUT CAVITY	154	-0.4	37	8.3	15.7

Table 19: Statistical parameters of data set.

Statistical analysis shows that on average the index of sound insulation for both categories it is around the mean value taken from the analysis on the whole sample of the elements; a slight improvement in performance occurs with walls filled with panels in cavity.

The value of variance shows once again the great variability of the sound reduction index, except for the case of walls that present in the cavity absorbing panels; this might suggest that, as already stated in the previous subdivisions, the influence greater is to be research in the coating or in the type of material of the element.

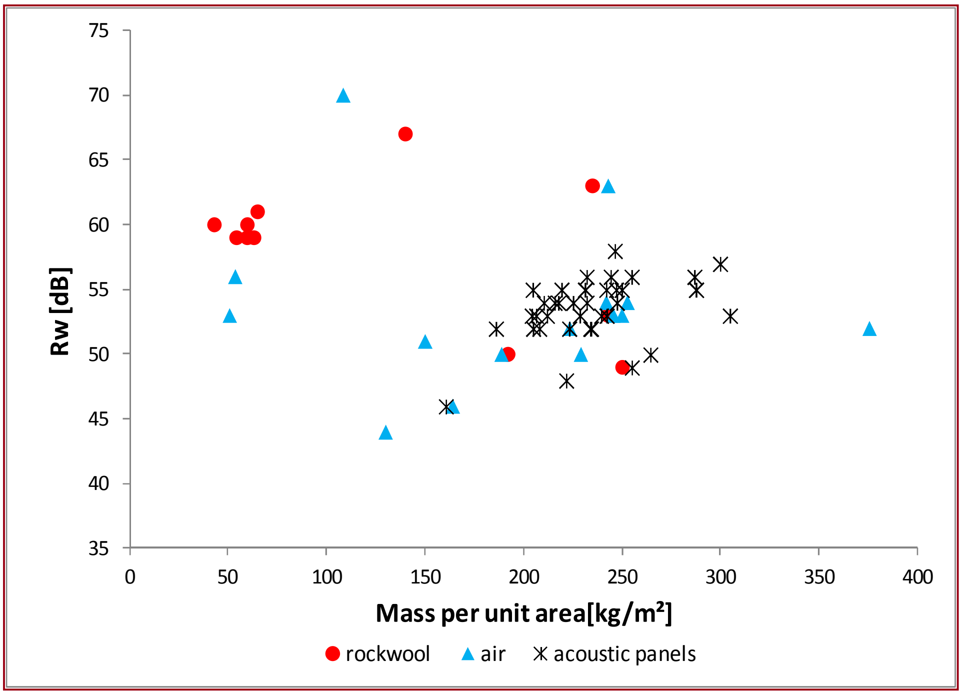


Figure 68: Correlation Rw-superficial density for walls subdivide by type of elements into cavity.

The graph above, by relating the index R_w with the surface mass, shows no clear relationship between the two parameters, due to the presence of cavity so it can be stated the presence of cavity in the walls does not produce a marked improvement of the sound reduction index R_w.

LIGHTWEIGHT WALLS VS. HEAVY WALLS

The subdivision was performed using the definition of lightweight wall, that is a wall with surface mass per unit area less than 100 kg/m².

The result is a classification based solely on the value of the superficial density with 32 elements defined lightweight, mainly attributable to elements in wood and plasterboard, and 155 “heavy” elements which includes brick walls and covered wooden elements.

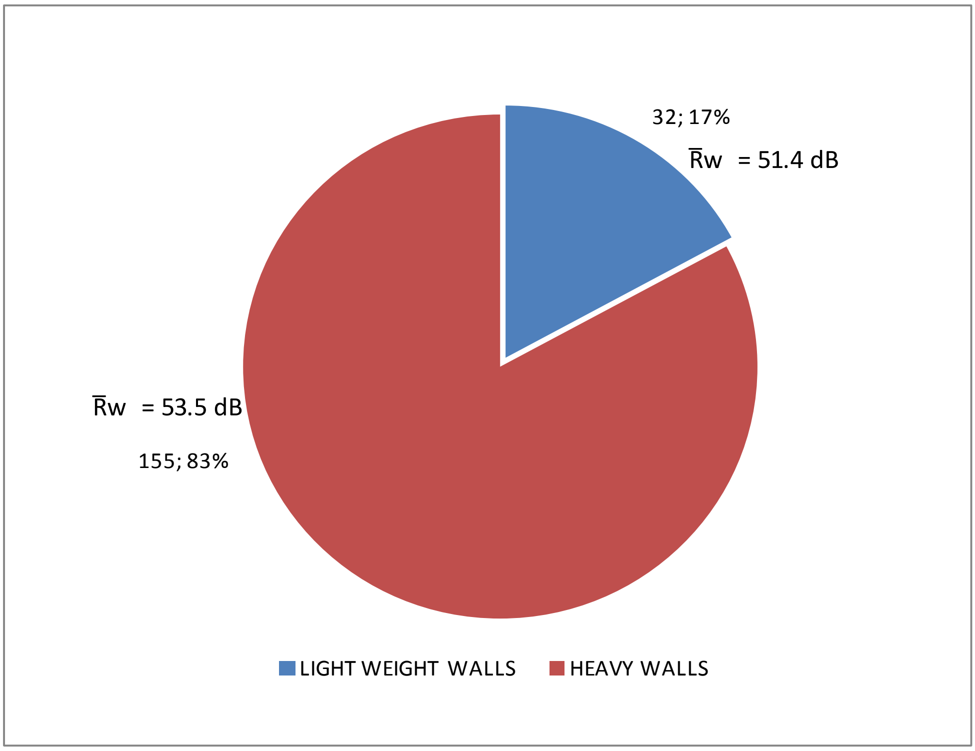


Figure 69: Mean value of elements, with number of items and relative percentage for each group of walls.

	N° elements	Mean Rw [dB]	Median Rw [dB]	Mode Rw [dB]	Mode [%]	Max Rw [dB]	Min Rw [dB]
LIGHT WEIGHT WALLS	32	51,4	55	59	18,8	65	31
HEAVY WALLS	155	53,5	54	53	12,9	70	32

Table 20: Statistical parameters of data set.

	N° elements	ΔRw1	max-min	σ	CV [%]
LIGHT WEIGHT WALLS	32	-1.8	34	11.3	21.9
HEAVY WALLS	155	0.3	38	6	12

Table 21: Statistical parameters of data set.

The analyzed data sample is composed for 86% of heavy elements; statistical analysis shows us how the mean value of R_w for the lightweight elements is lower by almost 2 dB compared to heavy walls; on the contrary, the value of mode is greater to lightweight walls and this statement shows us how R_w is not always best descriptor, especially if you do not have a significant quantity of data.

The value of the variance for the walls is very high which indicates a high variability in the data, showing a non-obvious correlation between properties of the elements. Again, the statistical analysis stresses how the coating of the walls influences in a decisive way the value of the sound reduction index, more visible in the case of lightweight walls.

POSSIBLE TYPOLOGICAL USE STARTING FROM PERFORMANCES

Starting from the total amount of measurements, it is possible to plot a graph (figure 70) correlating the sound reduction index with the mass of the walls and make some observations. Firstly the data set is divided between "light walls" (from 0 to 100 kg/m^2), "heavy walls" (from 101 to 400 kg/m^2) and "very heavy walls" (above 400 kg/m^2). Secondly the R_w values is arranged by application.

Generally, below R_w = 50 dB the walls are used for internal "partitions" in the same architectonical unit. In this range, in fact, there are modular walls (used especially for offices), some wooden walls and some simple concrete walls. Except three cases, which are mainly brick walls made from thick interlocking elements simply plastered, there aren't very heavy walls in this range.

The most part of the tests is included into the interval between 50 dB and 60 dB, that is the range in that we can found the most of the applicative realizations. In this range there are the most of the brick walls, that are the commonly used and a consistent part of the wooden walls. Those are especially the solutions used for divide living units. Almost all of the "very heavy walls" are in this interval.

For what that concerns the "light walls", in this range we can found the plasterboard walls and some wooden walls. Above 60 dB there are special partitions, walls that are used for particular applications that required a strong insulation. For the refurbishment, the covered walls can give suitable results.

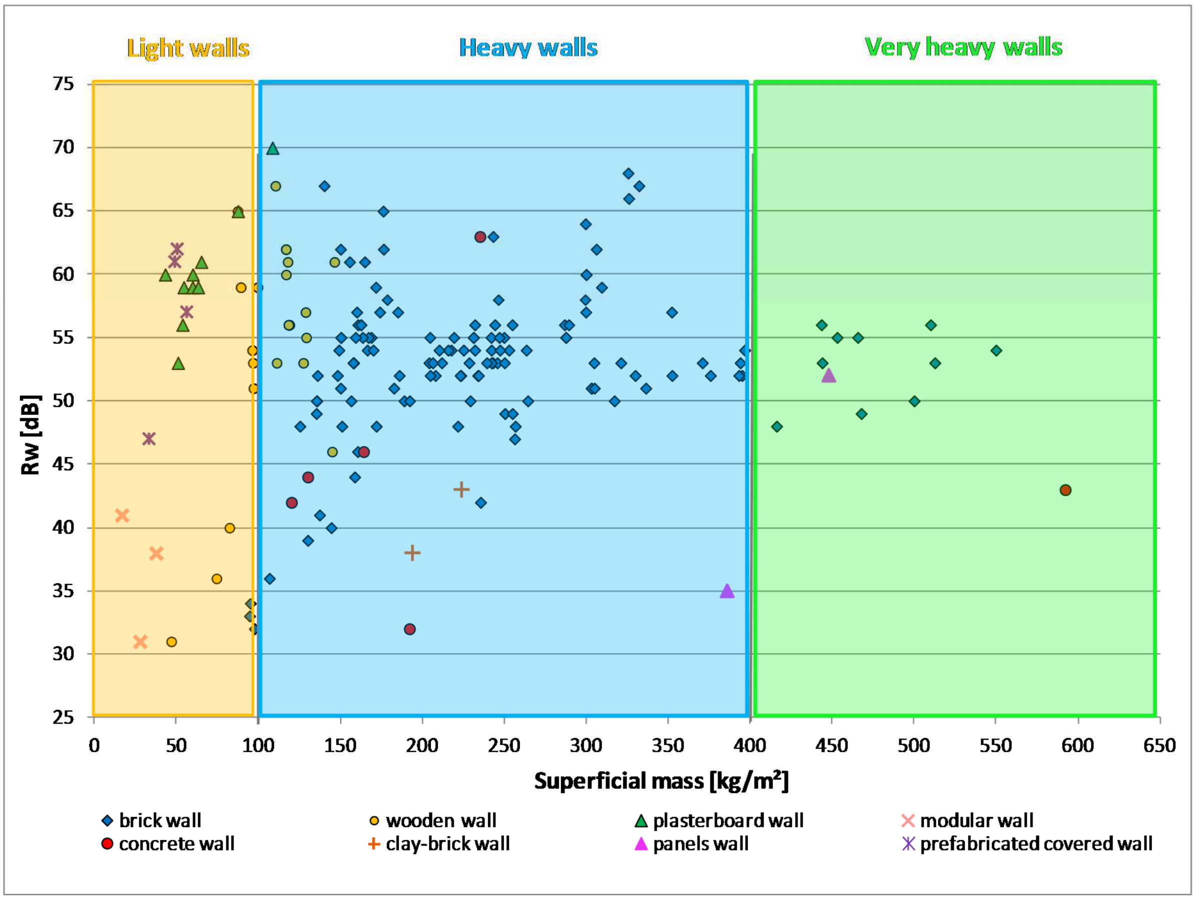


Figure 70: Correlation Rw-superficial density for the subdivision by type of material.

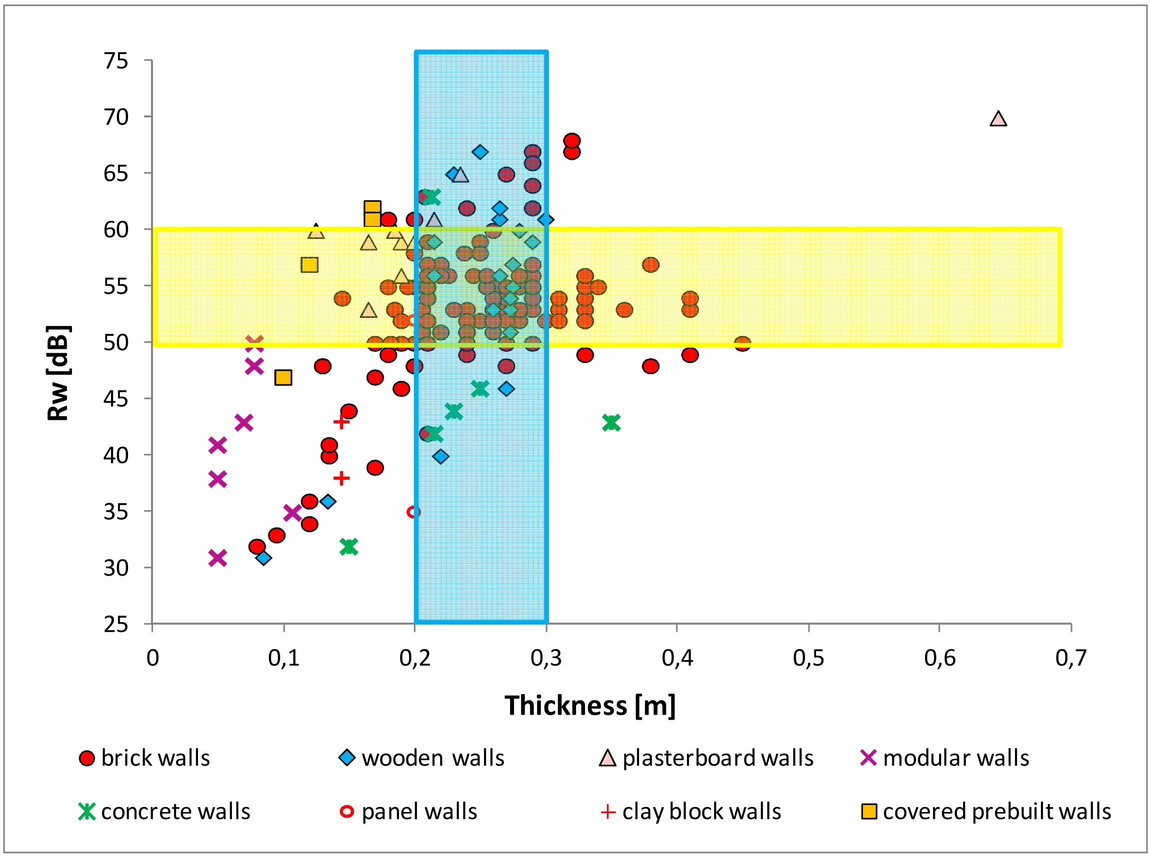


Figure 71: Correlation Rw-thickness for the subdivision by type of material.

Analogously, it is possible to analyze the correlation between R_w mean value and the walls thickness. So, the figure 71 shows how, in the main band from 50 dB to 60 dB, the most current value of thickness is included in the range between 20 cm and 30 cm. Here there are the most of the brick and wooden walls. If it is needed the same R_w value but with a more narrow thickness it could be choose another type of walls, like plasterboard walls or some covered prebuilt walls, but if it requires a lower R_w with thin thick, it could be choose modular walls or some simple brick walls. So it is reasonable to study a matrix graph that helps to visualize immediately what is needed for an acoustic building project.

In conclusion the parametrical analysis is based on the evaluation of Sound Reduction Index Weighted Rw in accordance with standard UNI EN ISO 717-1:2007.

The total elements under consideration are 224 and the large groups are the brick walls with 159 elements and wooden walls with 30 elements.

The most interesting statistical parameter of this analysis is the mean: it allows us to understand which wall ensure has the better performance between those under consideration. The mode doesn't show always its utility for our purposes, because in some case the data set is too short to find a significant value of this parameter or it constitute a low percentage of total amount of items. Only two case the mode is purposeful: wooden walls and plasterboard walls in which the mode constitute about 20% of total elements.

In detail, the covering of the walls has a great influence on the sound reduction index. In the case of single wall, the covering enhances the R_w about 9 dB while for multi-layer walls the increase is about 7 dB. It's not a coincidence that a multi-layered wall has the best value of R_w equal to 70 dB. The worst performance pertains to a wooden wall. The wooden walls are the lightweight elements with the lowest mean value.

The presence of the cavity in the walls doesn't change so much the performances but the insertion of some material into the cavity can enhance the average acoustic performance from about 2 dB to 6 dB for cavity filled with mineral wool.

The analysis presented in this work is based on parametrical relationships and on simplify standard method for the evaluation of sound reduction index that don't reflect the soundproofing performances in situ because in laboratory the flanking transmission is neglected. This consideration suggests the need for further research to improve the knowledge about the influence of construction techniques on the soundproofing performances experimentally determined.

Finally, considerations for the major applications were done starting from a matrix of R_w and mass consistence. It could be useful to find quickly available solutions for building designing. Analogously it could be useful the same kind of graph but with a correlation between R_w mean value and the walls thickness.

CHAPTER 6

CORRELATION BETWEEN SOUND REDUCTION AND THERMAL IMPROVEMENT

INTRODUCTION

The energy becomes everyday more expensive, so it becomes necessary to use it more sparingly and to conserve it more carefully. The main objective of the thermal insulation is to keep the energy through saving consumption. A bad sound insulation can provoke stress and diseases for the occupants of an environment. For those reasons it could be helpful have at the same time good thermal and acoustic insulation.

In this chapter is investigated if a relation between thermal improvement of the environments structures and sound reduction improvement can exist. That could help the designer to find simultaneously solution for a better thermal and sound insulation. For this reason a large group of walls structure was evaluated in its thermal insulation properties after that acoustic tests were done. The results obtained from these two verifications were then analyzed together to do some considerations.

Acoustic and thermal insulation plays a key role in the characteristics of energy saving and comfortable living in modern building. Often, however, high thermal and acoustic characteristics of building structures are difficult to obtain at the same time because of the different physics of two phenomena.

This work analyses experimental measurements of sound reduction index, according to ISO 10140 series Standards, carried out in the Acoustics Laboratory of the Department of Industrial Engineering of the University of Padova (Italy). The sound reduction index and the sound reduction improvement index of different types of lined walls was measured and then thermal transmittance was calculated for each structure.

STRUCTURES AND MATERIALS INVESTIGATED

The structures investigated were chosen from a database of walls made with selected materials. These walls are partitions or external walls. The selection of materials is normally left rather wide to initially keep options open as the design develops. In order to fully satisfy the design requirements is essential to correctly select the most appropriate design, materials, and manufacturing processes.

The principal types of structures are the following:

- brick partitions plastered on one side and covered on the other side with mineral wood wool panels and plasterboards;
- brick walls covered on both sides with mineral wood wool panels and plasterboards;
- brick partitions plastered on side and covered with insulation panels and plasterboards on the other side;
- walls of autoclaved concrete covered on both sides with mineral wood wool panels finished with plasterboards;
- multilayers wood partitions covered with dry-lining gypsum board;

- brick or multilayers wood walls with exterior insulation and finishing system.

The walls of the same tipology differ each other for thickness, number of layers of panels or plasterboards, kind of mineralized wood wool panels.

For the purpose of calculating the thermal transmittance the resistance of every material used was checked starting from the conductivity of the material itself.

So the principal conductivities for each material are charted in table 22:

MATERIAL	THICKNESS [m]	CONDUCTIVITY [W/mK]
Mineralized wood wool panel	From 0.02 to 0.05	0.035-0.067
Brick for partition	From 0.08 to 0.12	0.227-0.4
Autoclaved concrete	From 0.08 to 0.12	0.119
Plasterboard	From 0.09 to 0.15	0.2
Brick	From 0.12 to 0.30	0.2-0.207
Plaster	0.015	0.9
Multilayers wood	0.135	0.13
Dry-lining gypsum board	0.125	0.32
Air		0.026

Table 22: Principal conductivities and thickness of some materials used.

SOUND REDUCTION INDEX R

Measures of sound reduction index, according to ISO 10140 series Standard, were carried out in the Acoustic Laboratory of the Department of Industrial Engineering at the University of Padova.

Sound reduction index is defined as ten times the common logarithm of the ratio of the sound power, W_1,that is incident on the test element to the sound power, W_2, radiated by the test element to the other side:

22)

$$R = 10 log \frac{W_1}{W_2}$$

measured in dB.

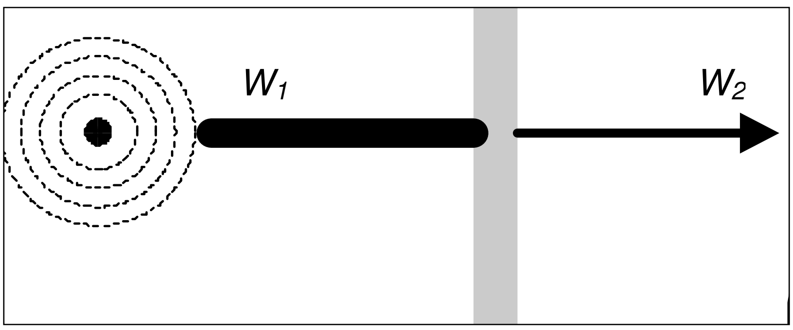


Figure 72: Transmission path in laboratory.

For laboratory measurements using sound pressure, the sound reduction index is calculated using:

23)

$$R = L_1 - L_2 + 10log\frac{S}{A}$$

where L_1 is the energy average sound pressure level in the source room [dB], L_2 is the energy average sound pressure level in the receiving room [dB], *S* is the area of the free test opening in which the test element is installed [m^2], *A* is the equivalent sound absorption area in the receiving room [m^2]. The derivation of this equation from the previous equation assumes that the sound fields are diffuse and that the only sound radiated into the receiving room is from the test element.

The energy average sound pressure level is determined using the follow equation:

24)

$$L = 10log\frac{p_1^2 + p_2^2 + \cdots + p_i^2}{np_0^2}$$

where p_1, p_2, ..., p_n are root-mean-square sound pressures at *n* different positions in the room [dB].

In practice, the sound pressure levels are usually measured and the energy average level, *L*, shall be determined using the equation:

25)

$$L = 10log\left(\frac{1}{n}\sum_{j=1}^{n} 10^{\frac{L_j}{10}}\right)$$

where L_1, L_2, ..., L_n are the sound pressure levels at *n* different positions in the room [dB].

Equivalent sound absorption area, A, is calculated from the reverberation time using Sabine's formula given like:

26)

$$A = 0{,}16\frac{V}{S}$$

where *V* is the receiving room volume [m^3], *T* is the reverberation time [s] as already seen in chapter 4.

IMPROVEMENT OF AIRBORNE SOUND INSULATION, ΔR

Sound reduction improvement index, ΔR, is defined as the difference between the sound reduction indices of the basic element with and without the lining for each one third octave band:

27)

$$\Delta R = R_{with} - R_{without}$$

Characterizing a lining alone requires that its acoustic performance be independent from the basic structure to which it is fixed but the effect of the lining is dependent on the properties of the basic structure. The lining shall be mounted to the basic element as in practice. The lining shall be linked to the flanking parts of the laboratory as in practice, but there shall be no strong coupling between the basic element and the lining via the edges of the laboratory flanking elements. The curing period of the lining and its fixing shall be long enough to reach final conditions. The sound reduction index of the basic element shall not change during the two measurements, hence it shall either be at its final condition or the two measurements shall be carried out within a sufficiently short time interval. For masonry and concrete, this requires a curing period of not less than two weeks. Alternatively, the time lag between the two sound reduction measurements shall not exceed one third of the curing time elapsed before the first measurement.

GENERAL PROCEDURE

Two horizontally rooms are used, one being designated the source room and the other the receiving room. The test element is mounted in an opening in the partition between those rooms. In the source room, a diffuse sound field is generated by loudspeaker at two fixed positions. The average sound pressure levels are measured in the source and receiving rooms in the frequency range of 100 Hz to 5000 Hz. The equivalent sound absorption area in the receiving room is calculated from reverberation time measurements. Sound pressure levels in the receiving room are corrected for background noise. In the case of sound insulation improvement systems, such as acoustical linings, this procedure is repeated for the basic element and that the element with the lining under test.

WEIGHTED SOUND REDUCTION INDEX, R_W, AND SPECTRUM ADAPTATION TERMS C AND C_{TR}

Sound reduction indeces in one-third-octave band are compared with reference values, according to ISO 717-1, within the range 100 Hz to 3150 Hz. Reference curve is shifted in increments of 1 dB towards the measured curve until the sum of unfavourable deviations is as large as possible, but not more than 32,0 dB (measurement in 16 one-third-octave bands).

Spectrum adaptation term, C and C_{tr}, are also calculated according to ISO 717-1 and may be used to characterize the sound insulation with respect to many type of noise.

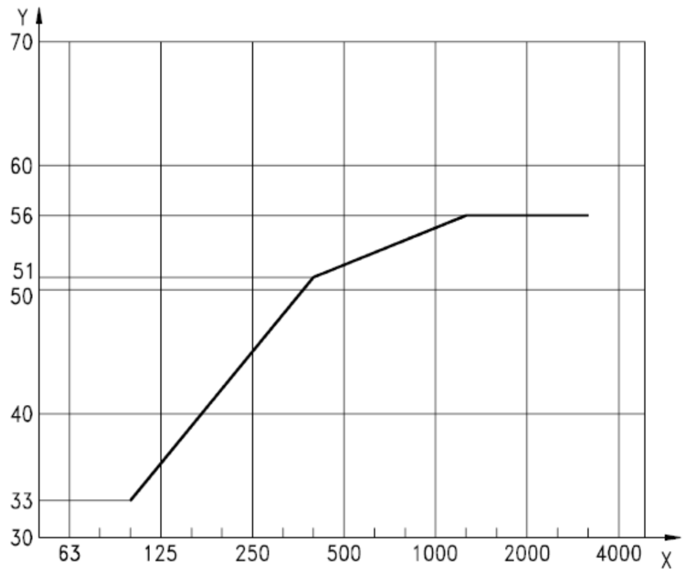


Figure 73: ISO 717-1 reference curve.

Type of noise source	Relevant spectrum adaptation term
Living activities (talking,music,radio,TV) Children playing Railway traffic at medium and high speed[a] Highway road traffic at >80 km/h[a] Jet aircraft, short distance Factories emitting mainly medium-and high frequency noise	C (Spectrum No. 1)
Urban road traffic Railway traffic at low speeds[a] Aircraft, propeller driver Jet aircraft, large distance Disco music Factories emitting mainly low and medium frequency noise	C_{tr} (Spectrum No. 2)
[a] In several European countries, calculation models for highway road traffic noise and railway noise exist, which define octave bands levels; these could be used for comparison with spectra Nos. 1 and 2.	

Table 23: Relevant spectrum adaptation term for different types of noise source.

THERMAL INSULATION CALCULATIONS

The heat is transmitted through a body when it is subjected to a temperature difference. The energy is transferred from point at a higher temperature to a point with lower temperature. The reduction of the transfer of thermal energy between objects of differing temperature is called thermal insulation. The insulating capability of a material is measured with thermal conductivity. Low thermal conductivity is equivalent to high insulating capability.

The transmittance *"U*" is defined as the flow of heat that passes through a unit area subjected to temperature difference equal to 1 °C, it is linked to the characteristics of the material that constitutes the structure and is assumed equal to the inverse of the sum of the thermal resistances of the layers. Thermal transmittance *U* is a measure of the rate of heat loss of a building component. It is expressed as W/m^{2}K. The *U* is calculated from the reciprocal of the combined thermal resistances of the materials in the element, air spaces and surfaces, also taken into account is the effect of thermal bridges, air gaps and fixings. To calculate *U*-Values it is important to know the thermal conductivity *"λ"* from which it can be evaluated the thermal resistance *R,* which is the parameter that better describes the thermal behaviour in the steady-state condition.

The thermal conductivity is the rate at which heat is transmitted through a material, measured in W/mK. The thermal efficiency of the material is better when the value is lower. The *λ*-value is a property of the material. The thermal resistance is measured in m^{2}K/W and is equal to the thickness of the material divided by the conductivity of that material.

28)

$$R = \frac{S}{\lambda}$$

To determine the overall resistance of the element the resistances of each material within an element are added together. The higher the *R*-value, the more efficient the insulation. So the thermal transmittance U can be calculated from thermal resistance and expressed as

29)

$$U = \frac{1}{R}$$

where U is the overall thermal transmittance [W/m^2 K], R is the thermal resistance [m^{2}K/W].

And for more than one material it becomes:

30)

$$U = \frac{1}{\sum R_i}$$

The method described above was then applied to structures made from the walls and materials listed first.

For the calculation of transmittance, the thermal resistance offered by the air layer in direct contact with a technical element that constitutes a closure or a partition inside of an environment was assumed equal to 0.04 m^{2}K/W for the external and 0.13 m^{2}K/W for the inside.

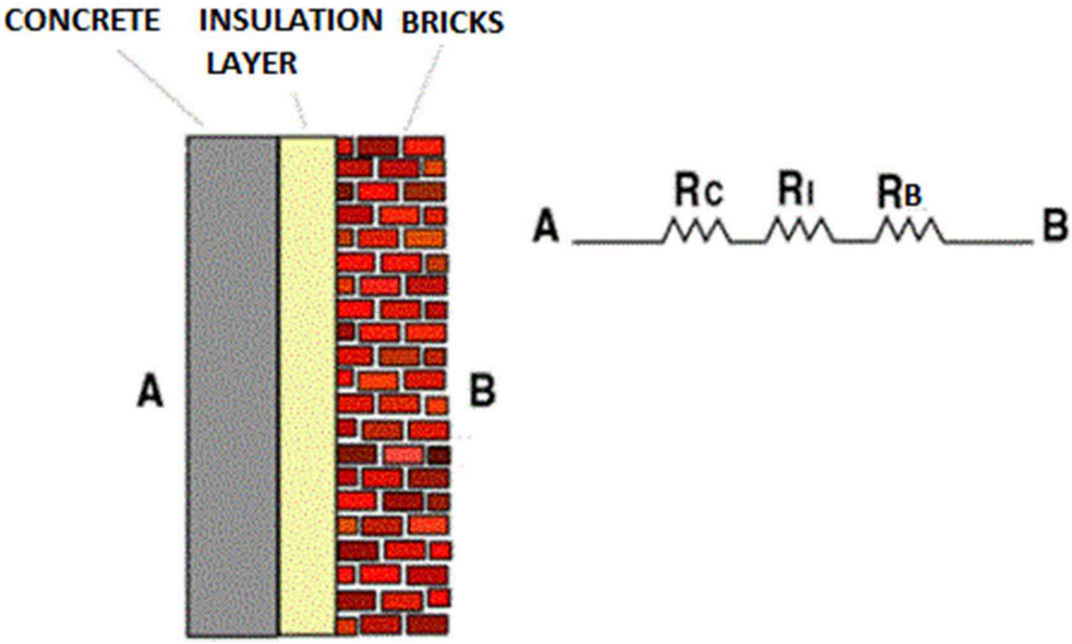


Figure 74: Scheme of multilayer resistances.

EXPERIMENTAL RESULTS

It have been considered 92 walls (17 base walls and 75 lined walls). For these walls the sound reduction index was already investigated and in this work the transmittance has been calculated. The results were then collected in graphics to understand if there would be an interesting correlation between the sound reduction improvement and the thermal insulation improvement. Firstly a graph of the sound reduction index values and of the thermal transmittance values was done. Then was checked the representation of the delta-values of both the indexes named above.

The graphs are shown below:

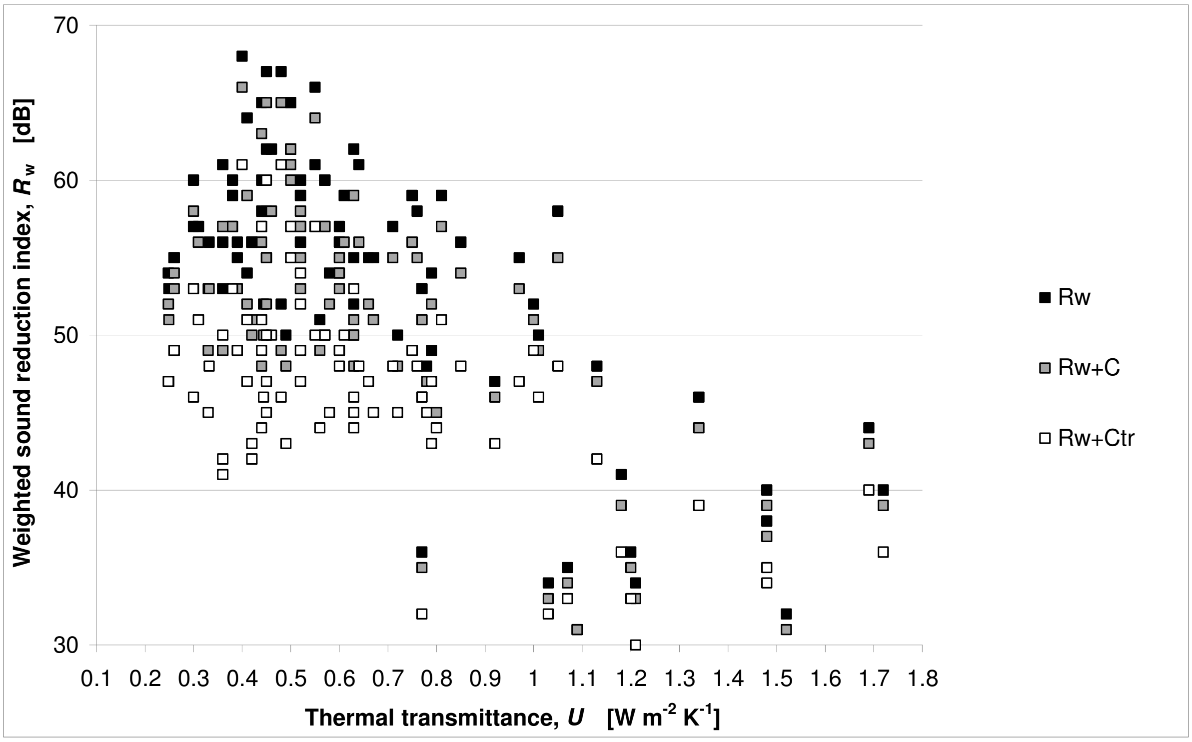


Figure 75: Weighted sound reduction index vs thermal transmittance.

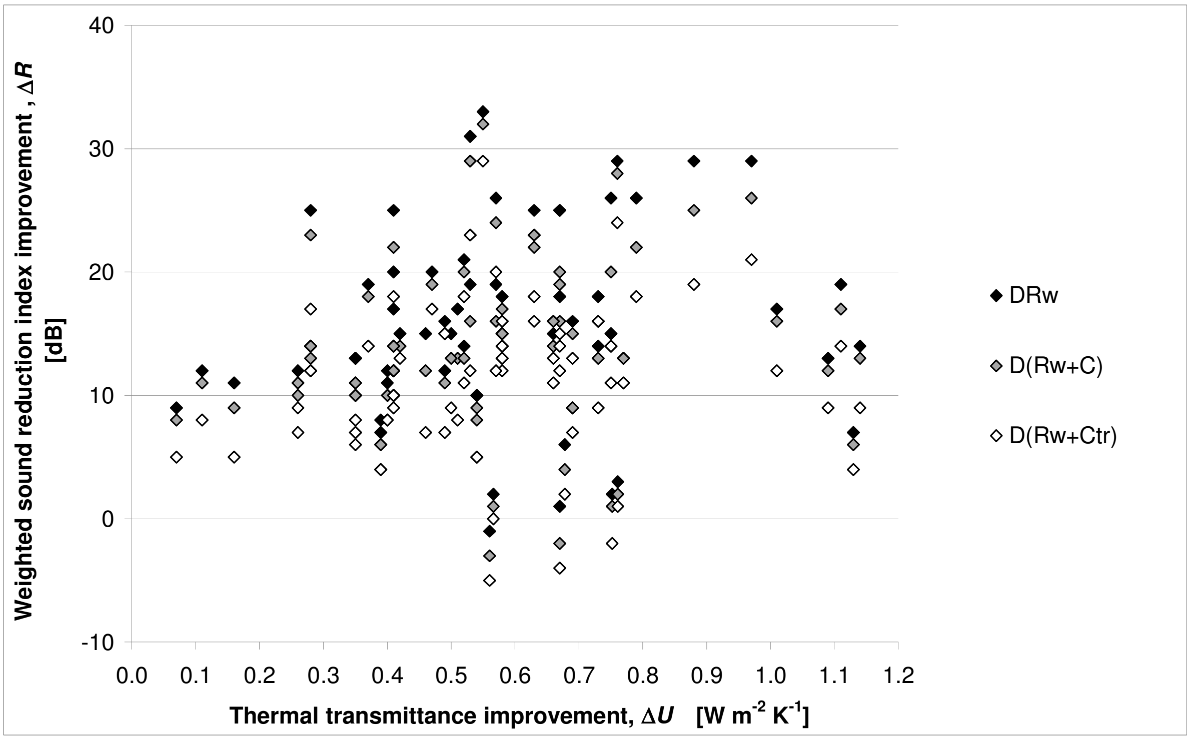


Figure 76: Weighted sound reduction index improvement vs thermal transmittance improvement.

The results, as it can be seen in the graphs shown, do not seem to have an evident correlation between the two parameters and any hypothesis of a systematic behavior cannot be done.

WEIGHTED SOUND REDUCTION INDEX IMPROVEMENT OF LAYERS

If additional layers are fixed to a homogeneous basic structural wall the airborne sound insulation can be improved or reduced depending on the resonance frequency f_o of the system.

For additional layers built with metal or wooden studs or battens not directly connected to the basic structural element, where the cavity is filled with a porous insulation layer with an air resistivity $r \geq 5$ kPa s/m^2 according to EN 29053 "Acoustics – Materials for acoustical applications – Determination of airflow resistance", the resonance frequency f_o is calculated by:

31)

$$f_0 = 160\sqrt{\frac{0{,}111}{d}\left(\frac{1}{m'_1}+\frac{1}{m'_2}\right)}$$

where d is the depth of the cavity [m], m'_1 is the mass per unit area of the basic structural element [kg/m^2], m'_2 is the mass per unit area of the additional layer [kg/m^2].

For basic structural elements with a weighted sound reduction index in the range of 20 dB ≤ R_w ≤ 60 dB, the resulting weighted sound reduction index improvement as a result of an additional layer can be estimated from the resonance frequency f_o (rounded to the nearest integer value), according to table 24. For resonance frequencies lower than 200 Hz the value also depends upon the weighted sound reduction index of the basic structural element.

Resonance frequency f_o of the lining in Hz	ΔR_w in dB
≤80	35-R_w/2
100	32-R_w/2
125	30-R_w/2
160	28-R_w/2
200	-1
250	-3
315	-5
400	-7
500	-9
630-1600	-10
> 1600	-5

NOTE 1 For resonance frequencies below 200 Hz the minimum value of ΔR_w is 0 dB.

NOTE 2 Values for intermediate resonance frequencies can be deduced by linear interpolation over the logarithm of the frequency.

NOTE 3 R_w denotes the weighted sound reduction index of the bare wall or floor in dB.

Table 24: Weighted sound reduction index improvement by a lining, depending on the resonance.

CHAPTER 7

CONCLUSIONS

As part of the doctoral work the study of sound insulation and thermal-energy performance of building elements has been addressed, especially focusing on the issues related to the acoustic performance of walls and floors in laboratory, through the application of appropriate insulating materials, mainly wood wool panels mineralized with Portland cement. This study was possible thanks to the availability of laboratories comply with the directives UNI ENISO 10140, and an allocation of devices for the measurement of the mechanical characteristics of small samples.

The studied wood wool materials have very interesting sound-absorbing characteristics and considerable advantages to use in the building: they are products made from raw materials not synthetic (wood, concrete) offering a moderate contribution to the acoustic insulation of buildings, in addiction they increase the thermal resistance of the structures in which they are applied, so they are able to effectively cover a large amount of applications.

The analysis has been addressed on airborne sound insulation of walls in laboratory containing materials with wood wool mineralized Portland cement. Walls in plasterboard entirely single and double structure were arranged; materials were then applied also in relining of masonry walls. The course of the experiment made it possible to select the optimal combinations of materials available, with the aim of developing products with specific business benefits. The results of this work could be expanded by future investigations.

The study of the correlation between dynamic stiffness and the impact noise reduction could be deepened by accelerometer measurements conducted on bare floors and insulated floors, to verify the actual resonant frequencies of buildings and calibrate the choice of predictive formulas. For the same purpose, the measures of dynamic stiffness could be conducted on large samples prepared on the real floors in laboratory.

The same kind of correlation study between dynamic stiffness and impact noise reduction has highlighted the need to evaluate very precisely both the acoustic parameters and the static and dynamic parameters of the insulating materials used as substrate for floating floors. In particular, the methods of preparation of the sample in the tests of dynamic stiffness must be followed very carefully, because approximations not accurate may generate big deviations results and overestimate the performance of materials. The presence of the gypsum layer between the sample and the load plate causes a displacement of the resonant frequency towards higher values for all the materials tested.

For the impact noise on floors it could be very interesting doing further investigations, especially laboratory tests, on wooden floors. It could result an easy and light laying solution in particular for refurbishment.

The acoustic absorption data emerged from the tests in the reverberation chamber and the use of predictive models have shown how the materials in wood wool mineralized with Portland cement are suitable for the correction of the reverberation time of rooms and respond to the design demand for environments used for speech and also places where there are sports or music activities.

The study the acoustic properties of building elements coming from review of laboratory experimental data of the sound reduction index defined by ISO 10140 standard "laboratory measurement of sound insulation of building element" was done. The standard define procedure to determine the so-called single-number values results from measured insulation spectra regarding physical aspects and feature of psychoacoustic impact, like annoyance and privacy, or exposed people. The evaluation of sound reduction index values of different buildings elements is useful to give a preliminary view of the soundproofing performances in order to adopt better solutions in the field. The analysis was carried out on laboratory experimental data provided by the Acoustics Laboratory of the Department of Industrial Engineering of University of Padova. A parametrical analysis of the sound reduction index R_w was conducted on 224 building elements, in particular the walls. The elements were divided following different criteria evaluating the statistical indices of sound reduction index R_w and relating the results in table. A clear visualization (chapter 5) of element's composition is made using pie chart, while the research of correlation between mass per unit area (or thickness) and sound reduction index R_w revealed interesting mass-law and thickness-law. The analysis results verify the theoretical concepts so the greater is the mass per unit area the more is the sound reduction index, and multilayer walls have better soundproofing performances than single walls when both are uncovered.

The wood wool panels analyzed in this work have been shown to have interesting properties in several aspects in their use in the building. Their versatility and ease of installation, in accordance with current legislation, permit to do further tests to evaluate new applications continually addressed to the thermal-acoustic comfort in the observance of energy conservation and environmental sustainability.

APPENDICES

A TABLES OF THE AIRBORNE SOUND INSULATION LEVEL

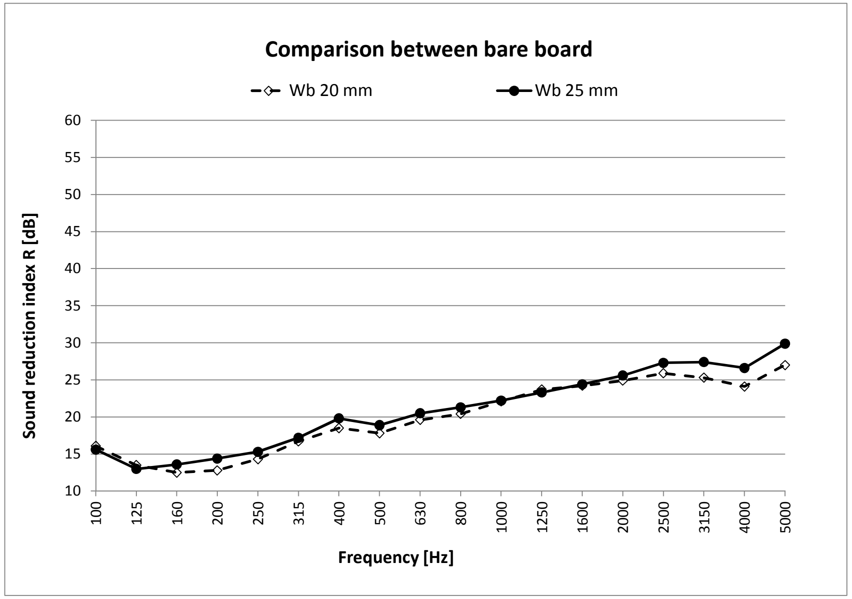
A.1 MEASUREMENTS DONE ON ROOFS

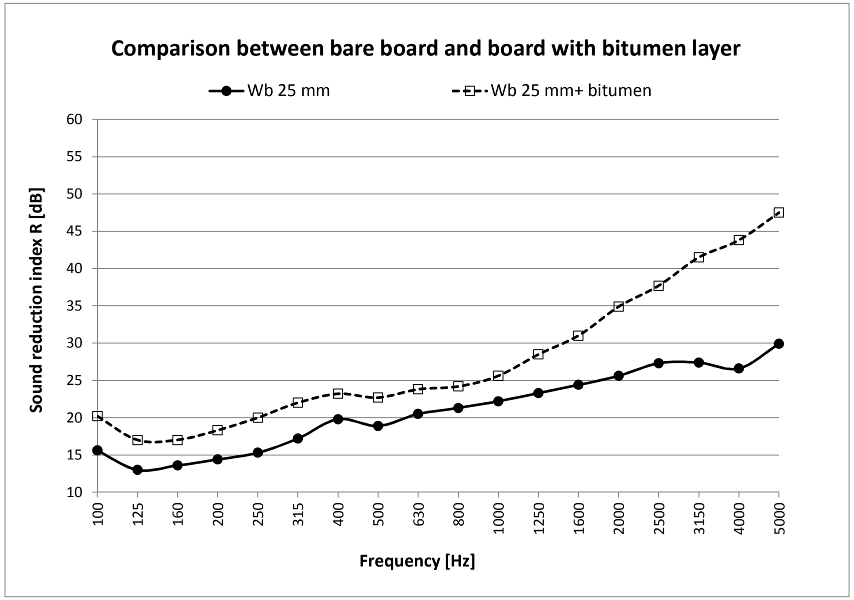
Table 25: Frequency values of sound reduction index of roofs.

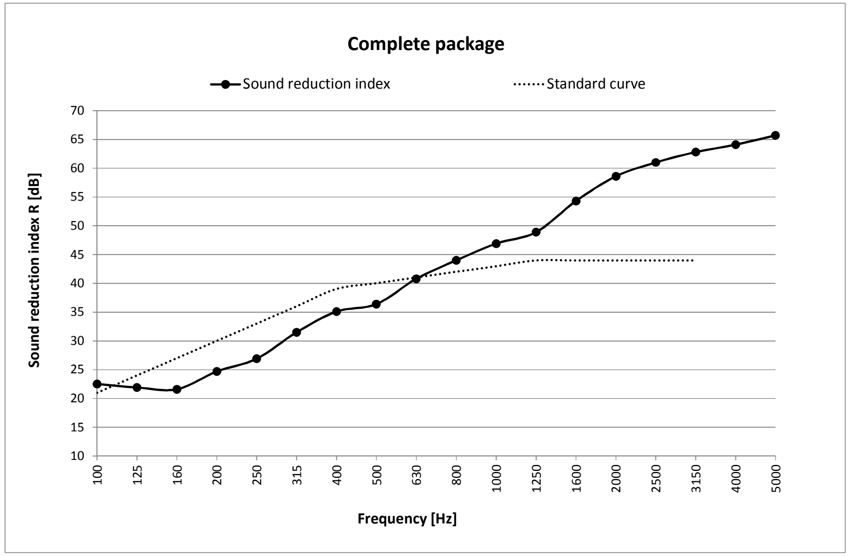
	Wooden board 20 mm	Wooden board 25 mm	Wooden 25+bitumen layer	Complete package
***f* [Hz]**	***R* [dB]**	***R* [dB]**	***R* [dB]**	***R* [dB]**
100	16.1	15.6	20.2	22.5
125	13.5	13.0	17.0	21.9
160	12.5	13.6	17.0	21.6
200	12.8	14.4	18.3	24.7
250	14.3	15.3	20.0	26.9
315	16.7	17.2	22.0	31.5
400	18.5	19.8	23.2	35.1
500	17.8	18.9	22.7	36.4
630	19.6	20.5	23.8	40.8
800	20.4	21.3	24.2	44.0
1000	22.1	22.2	25.6	46.9
1250	23.7	23.3	28.5	48.9
1600	24.2	24.4	31.0	54.3
2000	24.9	25.6	34.9	58.6
2500	25.9	27.3	37.7	61.0
3150	25.3	27.4	41.5	62.8
4000	24.1	26.6	43.8	64.1
5000	27.0	29.9	47.5	65.7

R_w	22	36	34	23
C	-1	-1	-1	-1
C_{tr}	-2	-5	-4	-3
$C_{100-5000}$	0	0	0	0
$C_{tr50-5000}$	-2	5	-4	-3

Date	10/10/2011	19/10/2011	19/10/2011	21/10/2011
***T* [°C]**	22	21	21	20
***U* [%]**	36	50	53	56


Comparison between bare board
Wb 20 mm
Wb 25 mm
Sound reduction index R [dB]
Frequency [Hz]


Comparison between bare board and board with bitumen layer
Wb 25 mm
Wb 25 mm+ bitumen
Sound reduction index R [dB]
Frequency [Hz]


Complete package
Sound reduction index
Standard curve
Sound reduction index R [dB]
Frequency [Hz]

B TABLES OF SOUND IMPACT NOISE

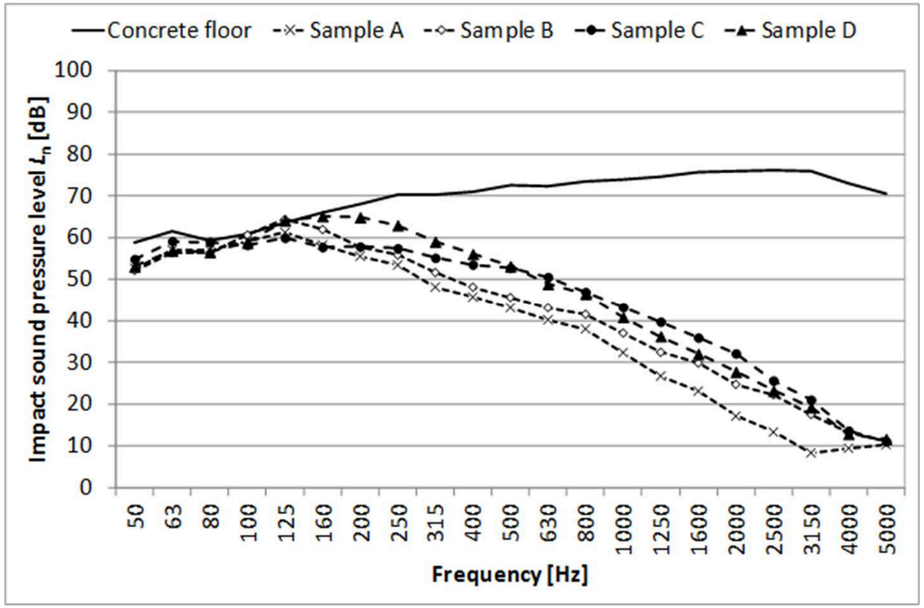
B.1 IMPACT SOUND PRESSURE LEVELS ON FLOORS

Table 26: Impact noise levels on the concrete slab for the four samples.

	Sample A	**Sample B**	**Sample C**	**Sample D**
***f* [Hz]**	**L_n [dB]**	**L_n [dB]**	**L_n [dB]**	**L_n [dB]**
50	52.6	52.1	54.8	53.1
100	57	56.3	59.1	56.8
125	57	56.3	58.9	56.5
160	59.1	60.6	58.2	58.7
200	61.2	64.3	59.9	64
250	58.2	61.9	57.7	65.1
315	55.5	57.6	57.8	64.8
400	53.4	55.8	57.4	62.9
500	48.1	51.6	55.1	59
630	45.7	48.1	53.5	56
800	43.1	45.6	52.7	53.1
1000	40.2	43.1	50.5	48.8
1250	38	41.5	46.9	46.5
1600	32.3	37	43.2	40.8
2000	26.7	32.4	39.7	36.2
2500	23.1	29.8	35.9	32
3150	17.1	24.7	32.1	27.7
4000	13.3	22.2	25.6	23.2
5000	8.3	17.5	21	19.2

L_{nw} [dB]	51	53	51	56

Date	15/10/2012	12/10/2012	19/10/2012	17/10/2012
***T* [°C]**	20	21	19,5	21
***U* [%]**	75	70	70	75


Concrete floor
Sample A
Sample B
Sample C
Sample D
Impact sound pressure level L_n [dB]
Frequency [Hz]
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000

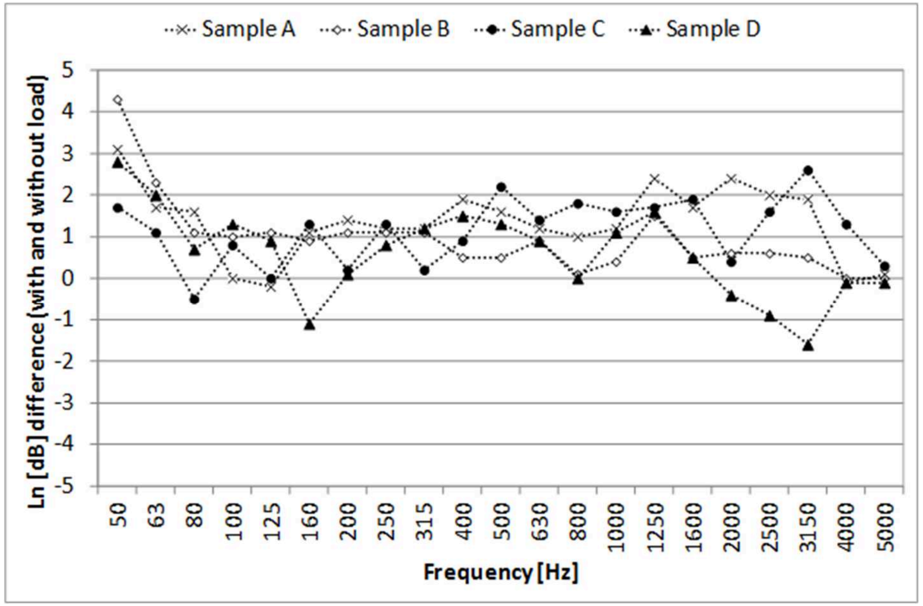
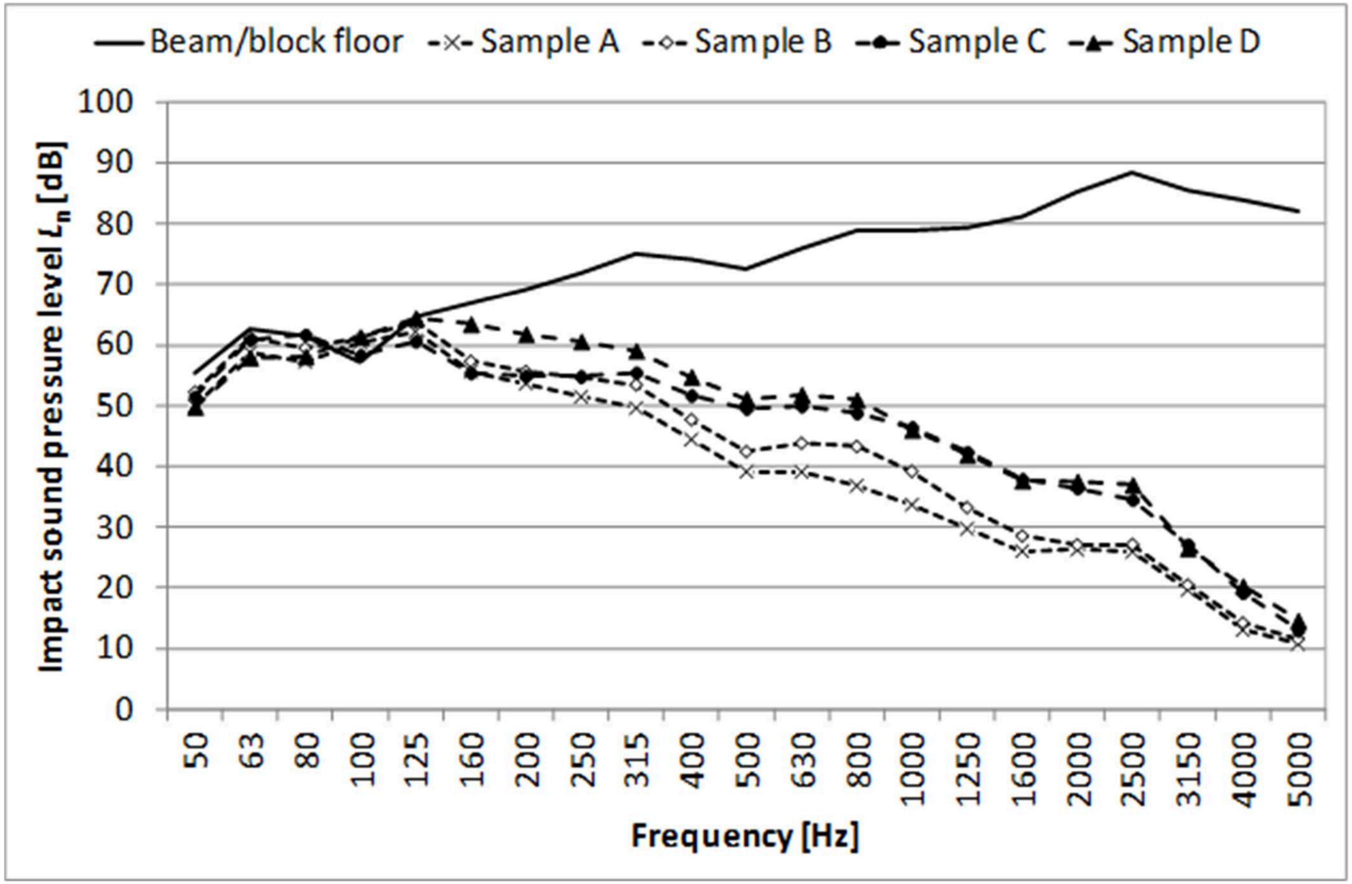

Sample A
Sample B
Sample C
Sample D
Ln [dB] difference (with and without load)
Frequency [Hz]
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000

Table 27: Impact sound pressure levels recorded on the beam and hollow floor for the four samples.

	Sample A	Sample B	Sample C	Sample D
f **[Hz]**	L_n **[dB]**	L_n **[dB]**	L_n **[dB]**	L_n **[dB]**
50	49.9	52.2	51.5	49.8
100	58.7	61.3	60.9	57.9
125	57.2	59.5	61.7	58.1
160	60.4	61.3	58.3	61.3
200	62.2	63.8	60.6	64.4
250	55.6	57.3	55.4	63.5
315	53.7	55.6	54.9	61.8
400	51.5	54.7	54.8	60.6
500	49.6	53.4	55.4	59.1
630	44.4	47.7	51.7	54.8
800	39.2	42.4	49.6	51.1
1000	39.1	43.8	50.0	51.8
1250	36.8	43.3	48.8	51.0
1600	33.7	39.2	46.4	46.0
2000	29.8	33.2	42.4	41.9
2500	26.1	28.6	37.9	37.6
3150	26.3	27.1	36.5	37.6
4000	26.0	27.2	34.5	37.0
5000	19.6	20.5	27.2	26.6

L_{nw} **[dB]**	49	51	50	55

Date	7/12/2012	7/12/2012	7/12/2012	7/12/2012
T **[°C]**	15	15	15	15
U **[%]**	70	70	70	70



Beam/block floor
Sample A
Sample B
Sample C
Sample D
Impact sound pressure level L_n [dB]
100
90
80
70
60
50
40
30
20
10
0
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
Frequency [Hz]

Table 28: Levels on a concrete slab obtained starting by the bare board proposed by ISO 10140-5.

	Sample A	Sample B	Sample C	Sample D
f **[Hz]**	L_n **[dB]**	L_n **[dB]**	L_n **[dB]**	L_n **[dB]**
100	65.3	66.8	64.4	64.9
125	65.3	68.4	64	68.1
160	60.3	64	59.8	67.2
200	56	58.1	58.3	65.3
250	52.2	54.6	56.2	61.7
315	47.4	50.9	54.4	58.3
400	44.8	47.2	52.6	55.1
500	41.1	43.6	50.7	51.1
630	39	41.9	49.3	47.6
800	36	39.5	44.9	44.5
1000	30.4	35.1	41.3	38.9
1250	24.2	29.9	37.2	33.7
1600	19.4	26.1	32.2	28.3
2000	13.3	20.9	28.3	23.9
2500	9.2	18.1	21.5	19.1
3150	4.5	13.7	17.2	15.4

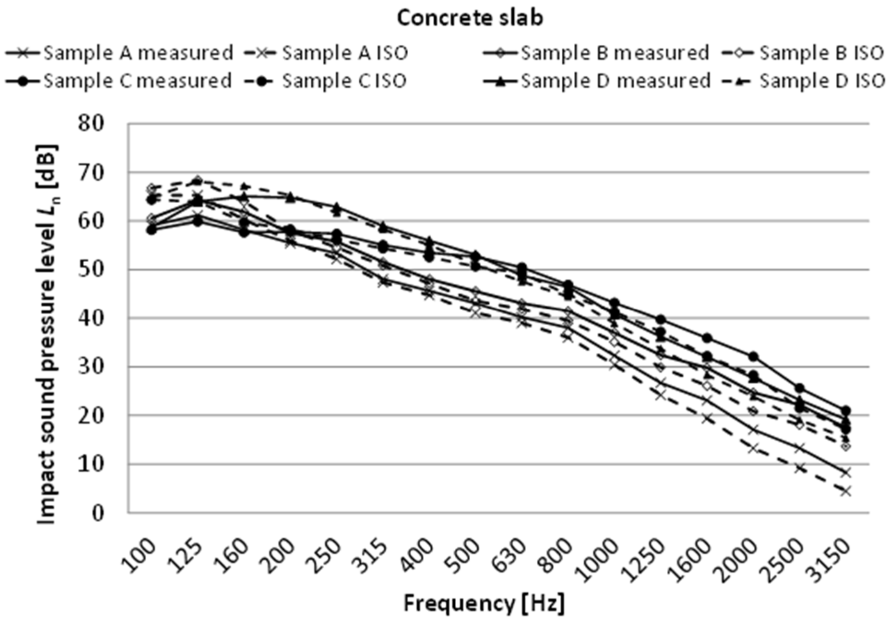
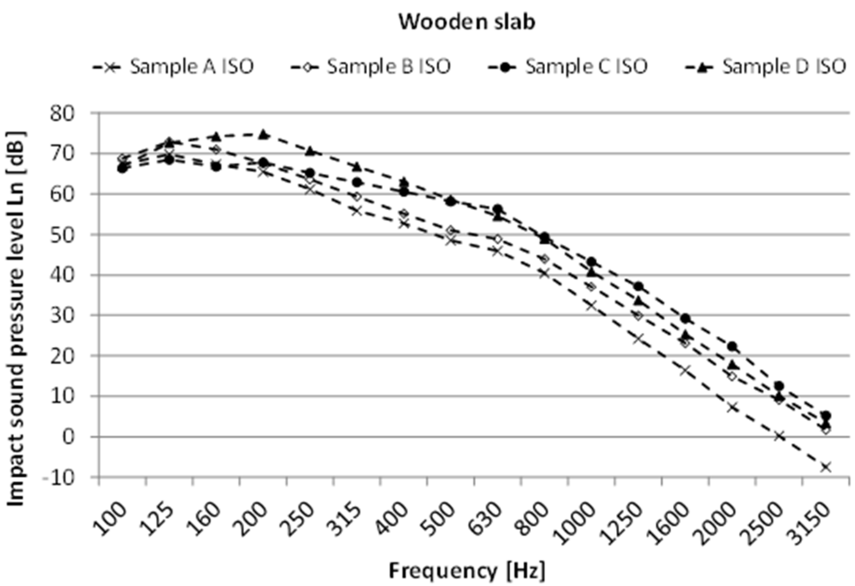


Table 29: Hypothetical levels on a wooden floor starting from the ISO lightweight structure.

	Sample A	Sample B	Sample C	Sample D
***f* [Hz]**	**L_n [dB]**	**L_n [dB]**	**L_n [dB]**	**L_n [dB]**
100	67.3	68.8	66.4	66.9
125	69.8	72.9	68.5	72.6
160	67.3	71	66.8	74.2
200	65.5	67.6	67.8	74.8
250	61.2	63.6	65.2	70.7
315	55.9	59.4	62.9	66.8
400	52.8	55.2	60.6	63.1
500	48.6	51.1	58.2	58.6
630	46	48.9	56.3	54.6
800	40.5	44	49.4	49
1000	32.4	37.1	43.3	40.9
1250	24.2	29.9	37.2	33.7
1600	16.4	23.1	29.2	25.3
2000	7.3	14.9	22.3	17.9
2500	0.2	9.1	12.5	10.1
3150	-7.5	1.7	5.2	3.4



B.1 Impact noise reduction on floors

Table 30: Impact noise reduction on a concrete slab for the four samples.

	Sample A	**Sample B**	**Sample C**	**Sample D**
***f* [Hz]**	**ΔL_n [dB]**	**ΔL_n [dB]**	**ΔL_n [dB]**	**ΔL_n [dB]**
50	6.3	6.8	4.1	5.8
100	4.4	5.1	2.3	4.6
125	2.3	3	0.4	2.8
160	1.7	0.2	2.6	2.1
200	2.2	-0.9	3.5	-0.6
250	7.7	4	8.2	0.8
315	12.5	10.4	10.2	3.2
400	16.8	14.4	12.8	7.3
500	22.1	18.6	15.1	11.2
630	25.2	22.8	17.4	14.9
800	29.4	26.9	19.8	19.4
1000	32	29.1	21.7	23.4
1250	35.5	32	26.6	27
1600	41.6	36.9	30.7	33.1
2000	47.8	42.1	34.8	38.3
2500	52.6	45.9	39.8	43.7
3150	58.7	51.1	43.7	48.1
4000	62.8	53.9	50.5	52.9
5000	67.5	58.3	54.8	56.6

ΔL_{nw} [dB]	26	23	25	20

Date	15/10/2012	12/10/2012	19/10/2012	17/10/2012
***T* [°C]**	20	21	19,5	21
***U* [%]**	75	70	70	75

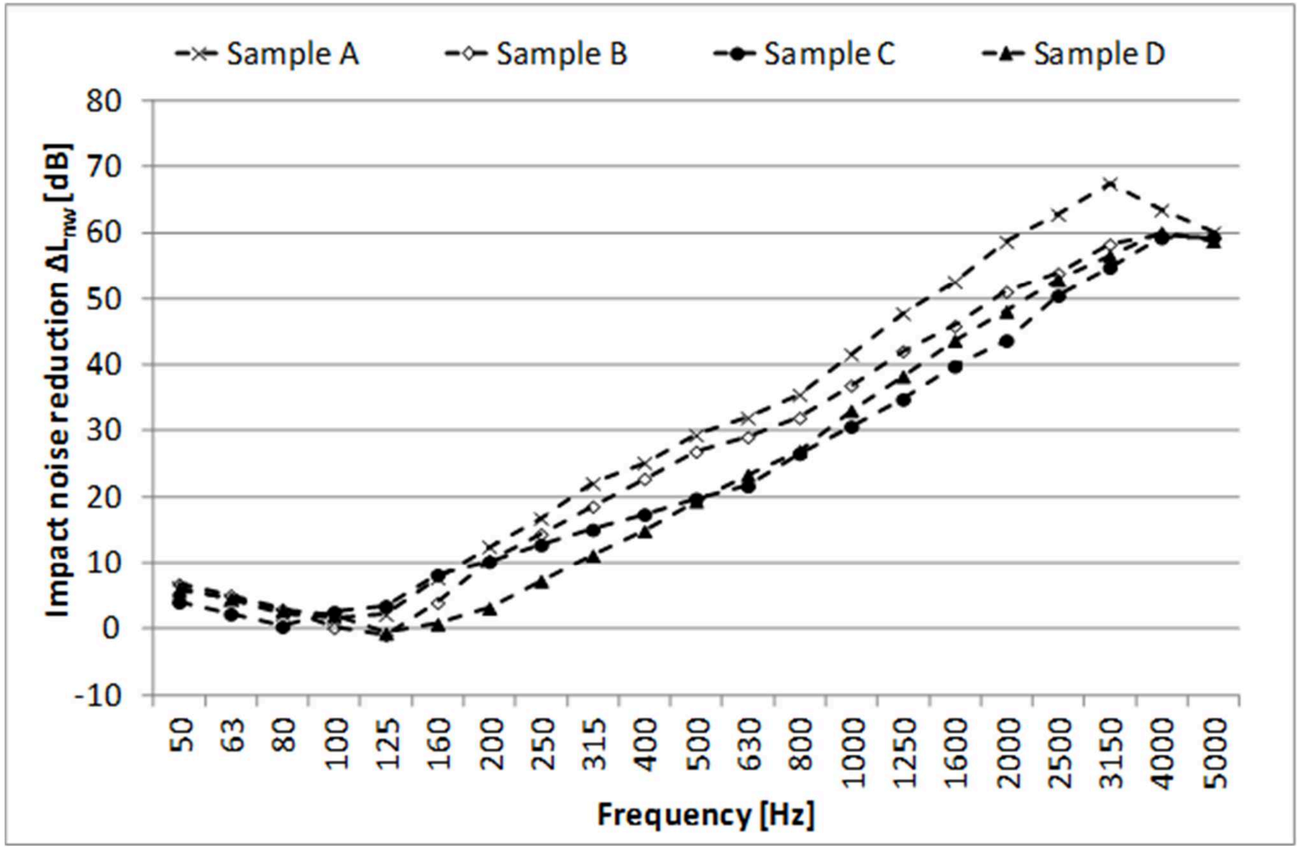
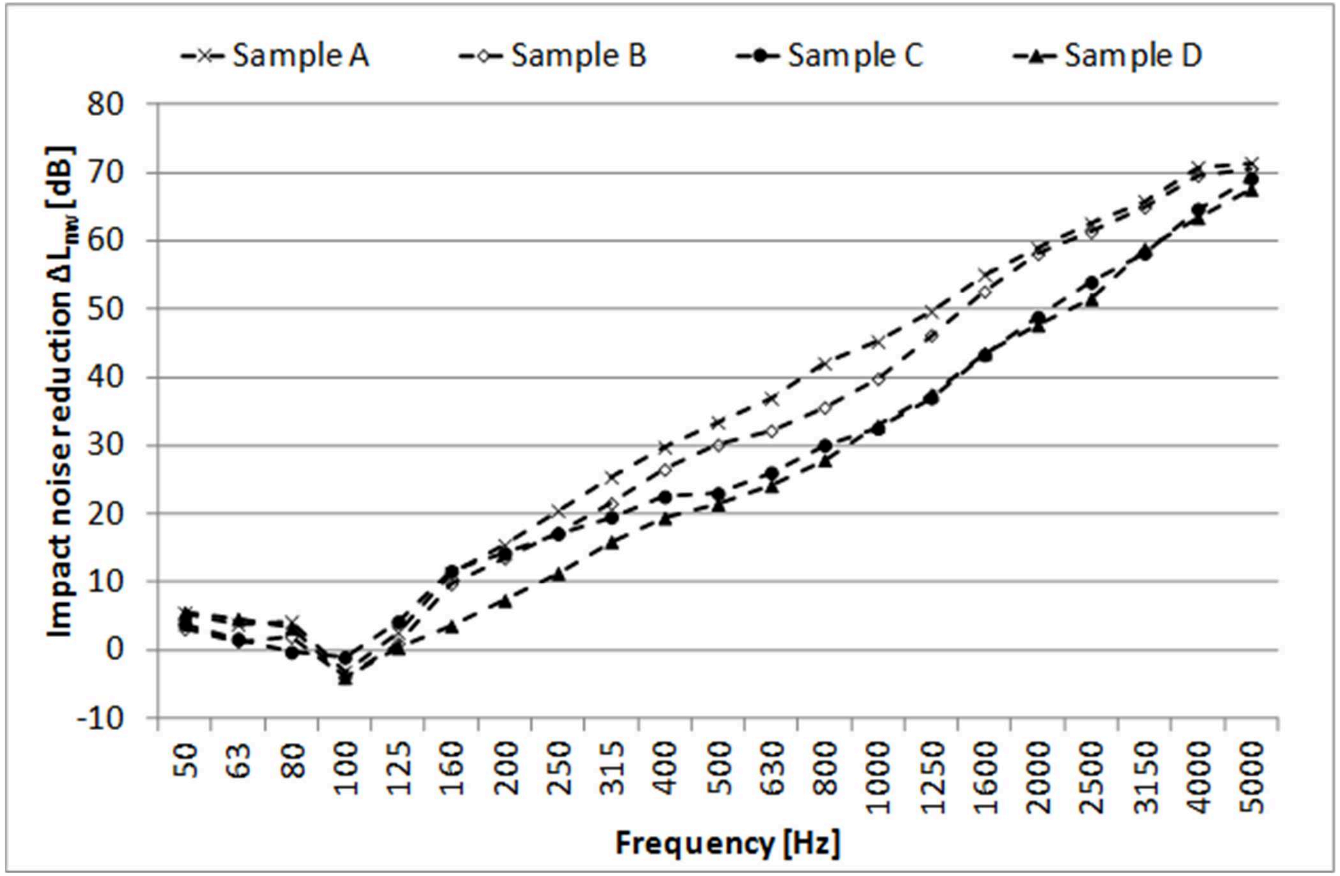

Sample A
Sample B
Sample C
Sample D
Impact noise reduction ΔLnw [dB]
80
70
60
50
40
30
20
10
0
-10
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
Frequency [Hz]

Table 31: Impact noise reduction on a beam and hollow floor for the four samples.

	Sample A	Sample B	Sample C	Sample D
***f* [Hz]**	**ΔL_n [dB]**	**ΔL_n [dB]**	**ΔL_n [dB]**	**ΔL_n [dB]**
50	5.4	3.1	3.8	5.5
100	3.8	1.2	1.6	4.6
125	4.1	1.9	-0.3	3.3
160	-3.2	-4.0	-1.1	-4.0
200	2.6	0.9	4.1	0.3
250	11.4	9.7	11.6	3.5
315	15.4	13.5	14.2	7.3
400	20.5	17.3	17.1	11.3
500	25.4	21.5	19.5	15.9
630	29.8	26.5	22.5	19.4
800	33.4	30.1	23.0	21.4
1000	36.9	32.2	26.0	24.1
1250	42.0	35.6	30.1	27.9
1600	45.2	39.8	32.5	32.9
2000	49.6	46.2	37.0	37.5
2500	55.1	52.6	43.3	43.5
3150	58.9	58.1	48.8	47.7
4000	62.5	61.3	54.0	51.5
5000	65.8	64.9	58.2	58.9

ΔL_{nw} [dB]	26	25	27	22

Date	7/12/2012	7/12/2012	7/12/2012	7/12/2012
***T* [°C]**	15	15	15	15
***U* [%]**	70	70	70	70



Sample A
Sample B
Sample C
Sample D
Impact noise reduction ΔLnw [dB]
80
70
60
50
40
30
20
10
0
-10
50
63
80
100
125
160
200
250
315
400
500
630
800
1000
1250
1600
2000
2500
3150
4000
5000
Frequency [Hz]

C TABLES OF DYNAMIC STIFFNESS

C.1 DYNAMIC STIFFNESS MEASUREMENTS

Table 32: Characteristics of the samples. Configuration 1, samples 1 to 4.

Samples	Weight sample [kg]	Weight gypsum [kg]
S. #1	0.434	0.221
S. #2	0.386	0.220
S. #3	0.430	0.174
S. #4	0.442	0.246

Table 33: Results for the single sample. Configuration 1, sample 1 to 4.

Sample	Resonance frequency f_r (force zero) [Hz]		Resonance frequency f_r (single sample) [Hz]	Apparent dynamic stiffness s'_t [MN m^3]
#1	Point 1	55.8	56.0	25.1
	Point 2	56.4		
	Point 3	55.6		
#2	Point 1	56.7	56.6	25.7
	Point 2	56.3		
	Point 3	56.9		
#3	Point 1	58.9	59.1	27.9
	Point 2	58.7		
	Point 3	59.9		
#4	Point 1	61.2	60.8	29.7
	Point 2	60.5		
	Point 3	60.8		

$$s'_t = 27 \text{ MN m}^3$$

Table 34: Characteristics of the samples. Configuration 2, samples 5 to 8.

Samples	Weight sample [kg]	Weight gypsum [kg]
S. #5	0.454	0.225
S. #6	0.456	0.203
S. #7	0.404	0.215
S. #8	0.421	0.190

Table 35: Results for the single sample. Configuration 2, sample 5 to 8.

Sample	Resonance frequency f_r (force zero) [Hz]		Resonance frequency f_r (single sample) [Hz]	Apparent dynamic stiffness s'_t [MN m^3]
#5	Point 1	70.3	68.4	37.5
	Point 2	66.7		
	Point 3	68.1		
#6	Point 1	71.3	69.8	39.0
	Point 2	68.4		
	Point 3	69.8		
#7	Point 1	65.6	68.5	37.6
	Point 2	70.0		
	Point 3	70.0		
#8	Point 1	71.9	71.8	41.2
	Point 2	71.9		
	Point 3	71.6		

s'_t= 39 MN m^3

Table 36: Characteristics of the samples. Configuration 3, samples 9 to 12.

Samples	Weight sample [kg]	Weight gypsum [kg]
S. #9	0.402	0.151
S. #10	0.360	0.112
S. #11	0.401	0.218
S. #12	0.415	0.181

Table 37: Results for the single sample. Configuration 3, sample 9 to 12.

Sample	Resonance frequency f_r (force zero) [Hz]		Resonance frequency f_r (single sample) [Hz]	Apparent dynamic stiffness s'_t [MN m^3]
#9	Point 1	102.8	104.2	86.4
	Point 2	105.6		
	Point 3	104.4		
#10	Point 1	103.1	103.2	84.3
	Point 2	102.8		
	Point 3	103.8		
#11	Point 1	107.5	108.2	93.8
	Point 2	108.7		
	Point 3	108.4		
#12	Point 1	109.1	107.9	92.9
	Point 2	107.5		
	Point 3	107.1		

s'_t= 89 MN m^3

Table 38: Characteristics of the samples. Configuration 4, samples 13 to 16.

Samples	Weight sample [kg]	Weight gypsum [kg]
S. #13	0.501	0.229
S. #14	0.497	0.213
S. #15	0.527	0.250
S. #16	0.517	0.282

Table 39: Results for the single sample. Configuration 4, sample 13 to 16.

Sample	Resonance frequency f_r (force zero) [Hz]		Resonance frequency f_r (single sample) [Hz]	Apparent dynamic stiffness s'_t [MN m^3]
#13	Point 1	113.9	113.6	103.6
	Point 2	112.3		
	Point 3	114.6		
#14	Point 1	109.1	109.8	96.5
	Point 2	110.0		
	Point 3	110.3		
#15	Point 1	105.4	104.9	88.5
	Point 2	105.0		
	Point 3	104.4		
#16	Point 1	105.3	104.9	88.9
	Point 2	105.0		
	Point 3	104.5		

s'_t= 94 MN m^3

Table 40: Characteristics of the samples. Configuration 5, samples 17 to 20.

Samples	Weight sample [kg]	Weight gypsum [kg]
S. #17	0.531	0.263
S. #18	0.556	0.273
S. #19	0.548	0.240
S. #20	0.520	0.257

Table 41: Results for the single sample. Configuration 5, sample 17 to 20.

Sample	Resonance frequency f_r (force zero) [Hz]		Resonance frequency f_r (single sample) [Hz]	Apparent dynamic stiffness s'_t [MN m^3]
#17	Point 1	66.1	66.7	35.8
	Point 2	67.1		
	Point 3	66.8		
#18	Point 1	76.1	76.3	47.0
	Point 2	76.7		
	Point 3	76.2		
#19	Point 1	63.2	63.8	42.7
	Point 2	63.9		
	Point 3	64.3		
#20	Point 1	65.1	65.1	34.1
	Point 2	65.0		
	Point 3	65.2		

s'_t= 34 MN m^3

Table 42: Characteristics of the samples. Configuration 6, samples 21 to 24.

Samples	Weight sample [kg]	Weight gypsum [kg]
S. #21	0.641	0.219
S. #22	0.683	0.226
S. #23	0.644	0.215
S. #24	0.618	0.177

Table 43: Results for the single sample. Configuration 6, sample 21 to 24.

Sample	Resonance frequency f_r (force zero) [Hz]		Resonance frequency f_r (single sample) [Hz]	Apparent dynamic stiffness s'_t [MN m^3]
#21	Point 1	84.4	85.1	58.0
	Point 2	85.4		
	Point 3	85.5		
#22	Point 1	88.8	89.1	63.7
	Point 2	89.1		
	Point 3	89.5		
#23	Point 1	83.3	83.4	55.7
	Point 2	83.8		
	Point 3	83.1		
#24	Point 1	78.6	78.7	49.3
	Point 2	78.4		
	Point 3	79.0		

s'_t= 57 MN m^3

Table 44: Characteristics of the samples. Configuration 7, samples 25 to 28.

Samples	Weight sample [kg]	Weight gypsum [kg]
S. #25	0.619	0.114
S. #26	0.691	0.107
S. #27	0.624	0.100
S. #28	0.670	0.100

Table 45: Results for the single sample. Configuration 7, sample 25 to 28.

Sample	Resonance frequency f_r (force zero) [Hz]		Resonance frequency f_r (single sample) [Hz]	Apparent dynamic stiffness s'_t [MN m^3]
#25	Point 1	104.1	104.1	85.7
	Point 2	104.1		
	Point 3	104.1		
#26	Point 1	93.8	94.4	70.4
	Point 2	93.8		
	Point 3	95.6		
#27	Point 1	103.4	103.4	84.4
	Point 2	103.4		
	Point 3	103.3		
#28	Point 1	97.2	96.8	73.9
	Point 2	97.2		
	Point 3	95.9		

s'_t= 79 MN m^3

Table 46: Characteristics of the samples. Configuration 8, samples 29 to 32.

Samples	Weight sample [kg]	Weight gypsum [kg]
S. #29	0.576	0.097
S. #30	0.619	0.095
S. #31	0.574	0.088
S. #32	0.528	0.093

Table 47: Results for the single sample. Configuration 8, sample 29 to 32.

Sample	Resonance frequency f_r (force zero) [Hz]		Resonance frequency f_r (single sample) [Hz]	Apparent dynamic stiffness s'_t [MN m^3]
#29	Point 1	71.9	72.2	41.1
	Point 2	71.9		
	Point 3	72.8		
#30	Point 1	81.2	81.1	52.0
	Point 2	81.6		
	Point 3	80.0		
#31	Point 1	76.6	75.6	45.0
	Point 2	75.1		
	Point 3	75.1		
#32	Point 1	83.3	83.0	54.3
	Point 2	83.9		
	Point 3	81.7		

$$s'_t = 48 \text{ MN m}^3$$

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