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The Use of Waste Tyre Rubber Recycled Products in Lightweight Timber Frame Systems as Acoustic Insulation: A Comparative Analysis of Acoustic Performance

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Abstract: The current European standards demand more energy-efficient, comfortable, and sustainable buildings and encourage the incorporation of recycled materials in building construction. Timber buildings are successfully competing with traditional building materials in addressing these challenges; however, one of the weaknesses of timber systems is their limited sound insulation capacity. One material that can fit into the sustainability aims of timber construction and improve its acoustic performance is recycled ground tyre rubber (GTR), which, on top of this, is a serious environmental problem. This paper presents research on the use of GTR materials combined with timber systems in order to improve their acoustic performance. Three different types of GTR products (granulate, rolls, and sheets) of different thicknesses and densities are selected and are combined with different sound-absorbing materials (mineral wool, cellulose, and wood fibre) inside a lightweight timber sandwich system. In this study, the first qualitative approach, the acoustic performance of the different resulting systems is compared based on the sound pressure level difference measured in a custom-made reduced-size transmission chamber. Secondly, the sound reduction index of four selected specimens is measured in an accredited sound transmission laboratory. The results show that, for all the lightweight timber systems included in this research, introducing a GTR layer improves the acoustic performance of the system.

Keywords: sustainability; ground tyre rubber (GTR); recycled tyre rubber; sound insulation; timber construction; multilayer materials

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1. Introduction

In the last decade, car production has increased, reaching a worldwide annual production level of over 70 million units (only light vehicles) [1], and the estimated current vehicle fleet size is around 1.3 billion [2]. Due to new environmental regulations, car companies are shifting their industrial focus towards manufacturing more environmentally sustainable products (e-mobility), although the production of electric cars is still under 2% of global sales [3]. However, tyre wires have not evolved so quickly towards sustainability; they are still non-biodegradable products and barely recyclable.

At present, the automotive industry generates around 1.5 billion waste tyres worldwide every year [4,5]. This equates to approximately 2.5 million tons of waste tyres in the European Union (EU) alone each year [6,7]. All this material is accumulated in landfill sites without any recovery treatment and, often, without adequate environmental control. Since tyres (composed of rubber and steel) are non-biodegradable and because of their short life span (average 4 years), the stockpiles of tyre waste are increasingly accumulating. These stockpiles are a serious environmental risk due to the toxicity of tyres and the high risk of fire, putting human health at risk from soil, water, and airborne pollution [8,9]. Despite environmental regulations, the treatment and recycling of tyres is a slow, complex, and expensive process, which is not yet capable of absorbing the waste generated. However, in recent years, an alternative solution aiming at decreasing the amount of used tyres from storage centres has been explored; it consists of transforming tyres into a base material for other uses such as civil construction or the building industry [10–12]. Unlike other toxic materials, it is not necessary to carry out a complete process to recycle tyres; it is enough to shred them to obtain rubber granulate, chips, or fine rubber powder, which is introduced into the industrial chain as a reuse material. This material, ground tyre rubber (GTR), can be used in different contexts such as manufacturing elastomers, replacing filler materials, providing soil improvement, as concrete aggregates, as thermal- and/or acoustic-insulating material, as finishing materials, and in many other civil engineering applications [13,14].

In fact, one of the industries that can best incorporate this GTR material is the construction industry due to its traditional ability to use recycled materials. Currently, a large percentage (around 70% in UE) of the materials used in construction are already recycled materials. GTR can replace sand, plastics, and/or acoustic insulators as a building material. Moreover, from an environmental and sustainability point of view, this material can be highly compatible with new industrialised timber constructions. Wood, as a natural material, is a CO_2 reservoir (it is estimated to have an approximate sequestration potential of 1.47 kg of CO_2, with 1.07 kg of CO_2 produced for each kg of wood), which it captures and retains during the growth of trees [15]. In addition, the construction sector must respond to new quality standards in sound insulation. It is estimated that around 65% of European citizens live in urban environments exposed to noise levels that exceed healthy levels [16]. Although new buildings are designed with high levels of thermal insulation, the main materials used for thermal insulation are not always acoustically effective [17]. Therefore, there is a need to focus on the introduction of new materials to meet this challenge. Introducing GTR in construction systems as acoustic insulation would maintain this same philosophy at the design level, with the construction itself serving as a container, in a controlled environment, for non-recyclable materials during the life of the building. At the same time, the physical and mechanical properties of GTR complement one of the main shortcomings of wooden constructions, the lack of impact and airborne sound insulation.

This study is part of a line of research whose general objective is related to sustainable construction, included in the term "sustainable" aspects, such as the use of recycled materials, the use of wood, energy efficiency, and the acoustic performance of sustainable constructive solutions. In order to focus the scope of this research, the first objective is to study and analyse the ecological impact of the construction industry and some of the different strategies available to reduce this ecological impact. This is performed by presenting a brief overview about the use of recycled materials, the use of wood as a sustainable material, and the thermal and acoustic properties of already-existing and new recycled and sustainable constructive solutions. The secondary objective of this paper is to study, upon request of a local company (MEDGON Passivhaus), if the acoustic performance of a typical constructive solution wood panel/mineral wool/wood panel improves when including a GTR layer. Furthermore, the acoustic performance of different construction solutions based on the combination of wood and GTR with other sustainable materials, such as wood fibre and crushed cellulose, is evaluated as alternative constructive solutions.

2. A Brief Overview of Different Aspects Affecting the Ecological Impact of Construction Materials and Their Corresponding Thermal and Acoustic Performance

2.1. Recycled Materials in Construction

According to reports from the European Union, construction, demolition, and renovation activities, just from the residential building sector, generate around 900 million tons of waste per year. Almost 35% of the world's waste is generated in Europe, and this rate is expected to increase every year [18].

This construction and demolition waste (CDW) causes two major environmental problems. On the one hand, it generates large volumes of waste which must be treated and stored adequately in order to reduce the environmental pollution generated by improper management. On the other hand, when the building sector needs to demolish old constructions to build new ones, this CDW is replaced by new construction materials that consume, again, large volumes of raw materials. In fact, the EU Waste Framework Directive (2008/98/EC and 2048/851) [19,20] required that member states set a target for the recycling of non-hazardous CDW at a minimum of 70% of its weight by 2020. According to the final report published by the European Union [18], at present, this objective has only been fully achieved by some European countries, mainly in Central Europe. Due to this commitment, the construction sector is leading the investigation on how to incorporate recycled materials in the execution of civil engineering and architectural projects [21,22].

2.2. Wood: A Sustainable Material in Building Constructions

Due to climatic change challenges, in 1997, some countries (the European Union among them) signed the Kyoto Protocol in order to reduce CO_2 emissions [23]. Moreover, the European Commission has released a new growth strategy aiming to transform the European Union (EU) into a modern economy where there are "no net emissions of greenhouse gases in 2050". To achieve these zero emission rates, environmental and energy efficiency construction design rules have been recently introduced in building standards [24]. Another relevant factor related to the building sector in the context of emission reduction is heating/cooling energy reduction, which of course shall always be considered [25]. In this emission reduction context, the impact of building materials has been deeply analysed, and wood products have become a very attractive sustainable building material [26].

2.2.1. Wood as a 100% Sustainable Material and a CO_2 Container

Wood is a natural and organic material. Trees, through photosynthesis, transform nutrients from the soil and the CO_2 captured from the air in its own structure: wood, leaves, fruits, etc. This means that trees, while growing, absorb CO_2 from the air and become "carbon storages". Each wood species can capture different amounts of CO_2, depending not only on the wood density and growth speed but also on the type of forest management and final wood product [27]. It is well known that hardwood species (with a density above 600 kg/m^3) are able to store around 1.2–1.65 tonnes of CO_2/m^3 and softwood species (with a density around 450 kg/m^3) are able to store around 0.92 tonnes of CO_2/m^3 [28,29].

It is also well known that forests can be cultivated and, if managed in a sustainable and orderly manner, can be an inexhaustible source of material and extremely effective CO_2 containers. It is estimated that with the actual global forest mass, it would be possible to store 80% of all the world's CO_2 production [30]. But in fact, most artificial forests have a limited lifetime (rotating time), and this is a limitation for the total storage capacity. In the case of construction timber (softwood), this is usually around a 25-year rotation period [31]. The trees processed by the construction industry as timber products convert buildings into carbon storages along their use life too [32]. Moreover, the use of wood as a substitute for other traditional building materials has a lower energy cost [33]. Some studies showed that a 17% increase in wood used in the built environment has a direct impact on carbon emissions, reducing them by 20%. This estimation was based on using wood instead of brick, aluminium, and other building products [34]. These direct reductions in energy, and therefore in CO_2 emissions, are due to the fact that wood is "naturally manufactured" using solar energy, whereas the manufacture of traditional building materials (brick, steel, cement, aluminium, etc.) requires industrial processes (oven, smelting, and others) with high energy consumption [35]. In addition, wood is a soft and light (low-density) material compared to these traditional materials, so the energy required for its transformation (cutting, milling, etc.), transportation, construction, and, finally, demolition is much lower [36].

Another advantage of wood used in construction is that, once the life cycle of the building has been reached, the wood obtained from demolition can be reused to a large extent (reuse of products), recycled (reuse of material), or used as biomass to produce energy (energy recovery) [37]. Thus, in recent years, several European Research Projects have been developed where academia and industry partners collaborate in order to research the use and reuse of building components, such as the CaRewood project [38] and InFutUReWood Project [39]. Other researchers have developed new timber structural products using low-quality wood and demolition wood [40]. For example, the timber products recovered from demolition can be used as raw construction material [41], as material to manufacture new timber products such as laminated beams [42], cross-laminated timber (CLT) [43], or other structural products [44]. Finally, when timber has undergone several reuse or recycling steps, it can finally be used as biomass for energy generation [45]. This cascading use of solid wood, laminated timber products, wood-based panels, chemical products, and final biomass production was first suggested as early as in the 1990s [46], although at present, there is much deeper knowledge concerning its economic, environmental, and social benefits [47].

2.2.2. Timber Construction: Timber Frame and CLT

Currently, there are two different types of timber constructions: timber frame and mass timber systems. Timber frame has been traditionally and widely used in Northern European countries for the construction of single-family or multi-storey dwellings of limited height [48], while mass timber systems have been used in Europe since 1990 with the development of cross-laminated timber (CLT) [49]. This timber product is used to build high-rise residential buildings in the EU, usually designed as high-quality, sustainable, and energy-efficient constructions [50].

2.2.3. Sound Insulation in Timber Construction

Although it is true that other strategies can be used (layers, thicknesses, damping, de-solidarization, etc.), sound insulation is fundamentally governed by the mass and rigidity of the materials. Compared to other traditional building materials (brick, concrete, steel, etc.), wood is a light and porous material whose density varies according to each species, from 150 kg/m^3 for Balsa wood (*Ochroma pyramidale*) to nearly 1150 kg/m^3 for Palo Santo wood (*Bulnesia sarmientoi*). However, in general, the density of wood used in construction varies between 380 and 450 kg/m^3 for softwood and 600–750 kg/m^3 for hardwood [51]. Furthermore, wood can be considered an elastic material due to its low elasticity modulus, which varies between 7000 and 15,000 MPa for the species most commonly used in construction, compared to the elasticity modulus of concrete (35,000 MPa) or steel (210,000 MPa). These two properties of wood, low density and low elastic modulus, lead to limited sound insulation, both considering airborne and impact sound. Therefore, the sound insulation of wooden buildings is a challenge that must be analysed, designed, and tested for each specific building typology [52].

2.3. Insulation in Construction: Energy Savings and Sound Insulation

Many traditional building systems were based on massive wall elements, where the lack of thermal insulation was compensated by the high thermal inertia and the lack of acoustic insulation by the massiveness (weight) and low requirements.

It was in the 1970s, after the Stockholm Conference of the United Nations [53], when more demanding standards were developed in the field of thermal insulation in construction. This change was brought about by a number of factors, but the key trigger was probably the economic impact on industrialised societies of the rising price of oil [54].

The awareness about the need for building acoustic standards came much later and at different speed and requirement levels around the world [55].

At present, most building construction wall/facade systems are "sandwich type", which means that, in between the outer sides of the system, there is a cavity which can be empty or partially or totally filled with a thermal- and/or acoustic-insulating material.

2.3.1. Currently Used Materials for Improved Thermal and Acoustic Performance in Buildings

The new acoustic demands of society are forcing the consideration of the acoustic performance of thermal insulation products in construction systems. Often, traditional thermal insulators are used for both thermal and acoustic purposes, which is not always the right solution. Tables 1 and 2 show the density, thermal conductivity, and sound absorption coefficient of the most commonly used insulating materials, from natural origin and non-natural origin.

Table 1. Natural-origin insulating materials commonly used in building construction.

Material	Density (kg/m^3)	Thermal Conductivity ($W/m{\cdot}K$)	Sound Abs. Coef. (500 Hz)	References
Cellulose	30–80	0.041–0.050	0.53–0.90	[56,57]
Coconut fibres	75–125	0.040–0.045	0.34–0.83	[58–60]
Cork fibres	110–170	0.039–0.050	0.39–0.85	[61,62]
Flax fibres	20–100	0.035–0.075	0.54–0.84	[57]
Hemp fibres	20–90	0.040–0.060	0.25–0.60	[57,60]
Jute fibres	35–100	0.038–0.055	0.20–0.56	[59,63]
Kenaf fibres	30–180	0.034–0.053	0.42–0.95	[60,64,65]
Sheep wool	10–25	0.034–0.054	0.36–0.90	[60,66–68]
Straw bale	50–150	0.053–0.065	0.70–0.78	[69,70]
Wood fibres	50–270	0.042–0.050	0.16–0.32	[57,60,71]

Table 2. Non-natural-origin insulating materials commonly used in building construction.

Material	Density	Thermal Conductivity	Sound Abs. Coef.	References
	(kg/m^3)	($W/m{\cdot}K$)	(500 Hz)	
Expanded Polystyrene (EPS)	18–35	0.029–0.041	0.22–0.65	[72]
Extruded Polystyrene (XPS)	20–40	0.025–0.035	0.20–0.65	[72,73]
Fibreglass wool	13–100	0.030–0.045	0.45–0.80	[72,74]
Perlite	80–225	0.047–0.061	0.20–0.75	[75–77]
Polyurethane (PUR)	30–80	0.020–0.027	0.67–0.80	[72]
Rock wool	30–180	0.033–0.040	0.29–0.90	[72,74,78]
Vermiculite	80–200	0.047–0.070	0.50–0.80	[77,79]

2.3.2. New Recycled Materials for Improved Thermal and Acoustic Performance in Buildings

In the context of a world more and more concerned about sustainability and ecology, there is increasing interest and research on recycled material (organic or not) as alternative thermal- and acoustic-insulating materials for the building industry [80–84]. Both industrial recycled products and raw recycled products are commonly used. Table 3 shows the density, thermal conductivity, and sound absorption coefficient of the most commonly used recycled insulating materials.

Table 3. Recycled insulating materials commonly used in building construction.

Material	Density	Thermal Conductivity	Sound Abs. Coef.	References
	(kg/m^3)	($W/m{\cdot}K$)	(500 Hz)	
Recycled cotton fibres	25–45	0.036–0.044	0.66–0.95	[85]
Recycled fibreglass wool	100–165	0.038–0.050	-	[86]
Recycled polyethylene terephthalate (PET)	15–60	0.034–0.039	-	[87]
Recycled rubber	500–930	0.100–0.140	0.20–0.80	[88,89]
Recycled textile fibres	200–500	0.041–0.053	-	[90,91]

At present, exploring alternative sustainable materials for potential future commercialization is a strong field of research. Thus, some researchers are testing thermal and sound insulation material from ceramic shells [92], textile waste [93,94], recycled glass waste on a matrix resin [95], paper and cardboard waste [96], or carpet waste [97], just to mention a few. But among the most interesting materials from the point of view of their environmental impact used as thermal and acoustic insulation in construction is GTR. There is increasing research developing new products based on elastomeric waste residues and recycled tyres [62,98]. The absorption properties of GTR have also been investigated in different formats of granulated [99] composites, finding a good theoretical model that could be used to predict the absorption coefficient for samples made of granular melted GTR and also for more rigid samples obtained by mixing the granular materials with polyurethanes as a binder.

2.4. GTR as a Recycled Material in Building Construction

GTR-based materials in general have a rather low modulus of elasticity and medium–high density, and they may be used as thermal and acoustic insulators [100]. For that reason, they have been used in several building applications in recent years. This section summarizes the most relevant applications found in the literature.

2.4.1. General Civil and Building Construction Uses

GTR is often used in civil construction as a geotechnical additive in order to improve the mechanical properties and deformation behaviour of some types of soil [14]. Some researchers have focused on improving granular soils (mainly sand and gravel), mixing this kind of soil with ground tyre rubber in different percentages in order to improve their compaction, permeability, and compression properties [101]. A similar study was performed on clay soils, and the results showed an improvement in the permeability and resistance behaviour of poor clay soils [102,103]. In addition, there have been several recent studies exploring the use of raw GTR mixtures [104] and the use of cement-GTR [105] or mortar-GTR mixtures [106] in expansive clay soils. These studies have shown significant improvements in the geotechnical properties and stability of expansive clay soils, one of the major problems in building foundations.

GTR can also be used to partially replace gravel in the manufacture of asphalt for roads [107]. The use of low percentages of GTR in the mixture induces a good interaction with the asphalt matrix, providing some advantages such as increasing ductility, avoiding brittle breaks, reducing the weight of asphalt slabs, or improving behaviour and resistance in freeze environments [108]. Furthermore, the use of a recycled material such as GTR saves between 6% and 13% of fuel used in the asphalt-manufacturing process without affecting the final asphalt properties [109].

Another use in construction is the aggregation of GTR as part of the composition of concrete. By replacing part of the gravel with GTR particles, a more sustainable concrete is produced, keeping the GTR waste inert within the material [110]. Nevertheless, some studies have found that the use of GTR in very fine cutting or powder tyre rubber alters the chemical properties of the concrete, improving the adhesion of the cement paste on the one hand [111], but modifying the chemical performance and reducing the durability and protection of the reinforcement [112]. In addition, tests carried out by varying the percentage of GTR incorporated into concrete (5–30%) have shown significant changes in the physical properties (water absorption, void index, specific density) and mechanical properties (compressive strength, flexural tensile strength, modulus of elasticity) of the concrete [113]. GTR concretes are lighter and more flexible than conventional concretes, with relative density decreases of 22–52%. This conditions its common structural use, but nevertheless gives it very attractive properties in terms of seismic behaviour. Some researchers have studied external reinforcement with fibre-reinforced polymer (FRP) for concrete including low percentages of GTR in the concrete mixture, with the aim of increasing its compressive strength but maintaining its elastic properties, being used as a structural material in seismic areas [114].

2.4.2. New Uses as Sound Insulation

The use of elastic materials as anti-impact foils (floating floors) has been common practice in construction since the second half of the 20th century. In this line of research, there are studies on the use of GTR to improve the performance of building solutions with regard to impact noise [115,116], but there are few with regard to airborne noise [117,118].

Although it is true that its low porosity and high elasticity make it a more efficient material as an impact sound insulation material for use in slabs and floors, there are several studies investigating its airborne sound insulation properties by manufacturing GTR insulation boards in an epoxy matrix [119]. The results show that these panels (GTR + epoxy) can hardly compete with specific acoustic materials but still can be a competitive solution for uses with medium-to-low acoustic requirements. Nevertheless, the use of GTR for airborne sound insulation purposes can be considered to improve the acoustic performance of conventional building materials/systems. In fact, the introduction of low percentages of GTR aggregates, replacing arid, in concrete allows an improvement in the acoustic performance compared to conventional concrete [120]. This type of concrete has a slightly lower density, but this improves its acoustic absorption performance (15%) and its sound insulation at low frequencies, making it a good candidate as cladding material in urban areas [121]. Thus, one of the direct applications of these GTR concretes is their use in the manufacture of acoustic barriers, reducing noise pollution along roadsides [122].

Other researchers have followed this same line of incorporating GTR in the manufacture of building materials (bricks, blocks, concrete, and other wall materials) to improve acoustic performance. Specifically, by adding different GTR dosages in the mortar, they have found significant improvements in sound attenuation [123].

All the previous references researched how to improve the acoustic performance of a building material by adding GTR in the manufacturing process, but another possible use of GTR is as an elastic interlayer in a sandwich-type constructive solution, just as it is used for impact sound reduction. The use of GTR products together with wood panels has strong potential since wood used in building construction, due to its low density and high porosity, does not provide adequate airborne and impact sound insulation. These approaches involve the incorporation of GTR blankets into wooden sandwich panels [124]. But even in recent years, the possibility of manufacturing mixed wood-GTR materials has been studied, both in non-structural [125] and structural element formats [126], which, through the introduction of GTR during manufacture, significantly improve their acoustic performance, mainly in terms of impact sound insulation [115]. In addition to general eco-friendly building materials where the wood captures CO_2 as it grows, constructive solutions behave as GTR containers.

2.4.3. New Uses as Thermal Insulation

Another use that is currently being researched is the development of building materials made from GTR with improved thermal insulation properties [127]. For example, polyurethane foams with GTR particles [128], GTR sheets [118], or heat insulation composites [129] are being developed for thermal isolation. In addition, other research has focused on the incorporation of GTR aggregates into traditional building materials, such as concrete, to partially improve their thermal properties [130]. However, the improvements in these materials are limited compared to current high-quality thermal insulation commercial systems.

2.5. Performance Evaluation in Building Acoustics

When talking about building acoustics, one must differentiate between the performance of constructive elements or systems evaluated under laboratory conditions (ISO 10140 series) and the performance of a finished building in situ (ISO 16283 series). Laboratory measurements provide reliable information to perform reasonable estimations of the final acoustic performance of the building once it is built, based on the mechanical and acoustical properties of the building elements, systems, and design.

All building product manufacturers (windows, doors, gypsum board-based solutions, brick-based solutions, concrete-based solutions, etc.) must test their products and/or systems under laboratory conditions to be able to put them on the market. These laboratory values are extremely important both as inputs for acoustic performance estimation programs and as a comparative marketing tool. Unfortunately, these tests are rather expensive since they have to be performed in ad hoc laboratories with very strict construction and measurement conditions and using quite large samples (10 m^2).

When new building products are developed or existing ones are being improved, it becomes complicated to conduct all the prototype tests in accredited laboratories. This is why, often, developers choose to work (at the prototype stage) either with simulation programs or with scale models, which can easily be modified and tested in a laboratory or even in their own facilities.

In line with this idea, some researchers have carried out work on the design and construction of a small-size acoustic transmission box [131,132]. Although these types of scaled boxes are not standardised, research has shown that it is possible to obtain limited but reliable results with small, inexpensive, and easily constructed sample materials [133]. The experimental research shown hereinafter also explores the use of scaled facilities and prototypes to investigate airborne sound insulation improvement in diverse mixed CLT/GTR constructive systems.

3. Materials and Methods

As previously mentioned, the experimental part of this study was conducted upon request of a local company (MEDGON Passivhaus), which was interested in comparing the acoustic performance of different construction solutions based on the combination of wood and tyre rubber waste with other sustainable materials. Based on the aspects of ecological impact and thermal and acoustic behaviour shown in the brief overview, some acoustic insulators were selected for this research. For that, in addition to GTRs in different formats and thicknesses, wood fibre, cellulose, and rock wool isolation were included in these tests.

Another requirement was to perform a comparison based on scale prototypes and using custom-made, economical testing procedures. For this reason, we decided to design and build a reduced-size “sound transmission box” and use it to measure the sound pressure level difference of small samples (0.2 m^2) in order to compare their performance. The samples were built according to the company’s research interest. In light of the results, some specific samples were selected to be tested in an accredited laboratory with standardized procedures but also on reduced-size samples (1.8 m^2).

3.1. Small-Size Acoustic Box

Since the prototype box was designed with the aim of its future use within a company’s Research and Development (R&D) department, there were strong design limitations. For example, the size had to be small enough to be transportable, storable, and easily used by a single operator. This of course was a strong handicap for the test, but still, since the results were intended to be used only to compare the tested samples, we decided to continue with the study as projected.

The box was made of two volumes of different geometry, size, and volume. Figure 1 shows the final dimensions and detailed test setup. The multilayer composition of the box’s walls was, from inside to outside, as follows: plywood board with HPL laminate (15 mm), high-density plasterboard (2 × 13.5 mm), rock wool (60 mm), and plywood board (22 mm).

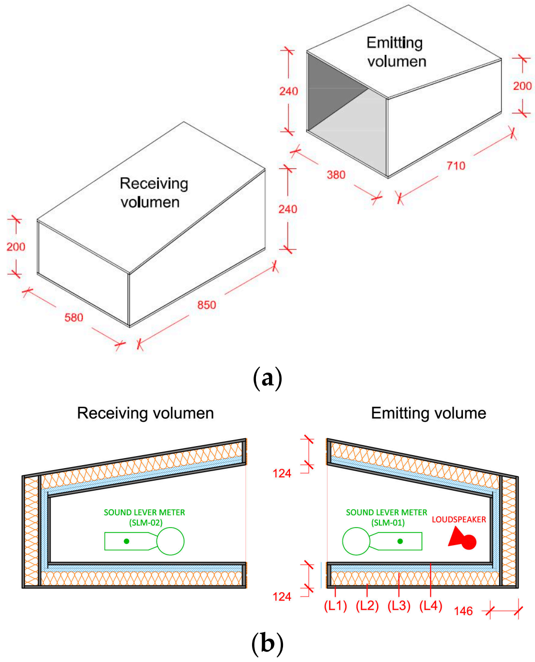


Figure 1. Acoustic box design. (**a**) Internal dimensions (mm). (**b**) Layer composition, where L4 = plywood board with HPL laminate (15 mm); L3 = high-density plasterboard (2 × 13.5 mm); L2 = rock wool (60 mm); L1 = plywood board (22 mm).

As can be seen in Figure 2a, the opening was covered with an elastomeric material to avoid rigid connection between the samples and each side of the box. In Figure 2c, one can observe how both volumes were mechanically adjusted by placing the sample under study between them. The test box was standing on rubber wheels, with the aim of isolating it from possible external vibrations.

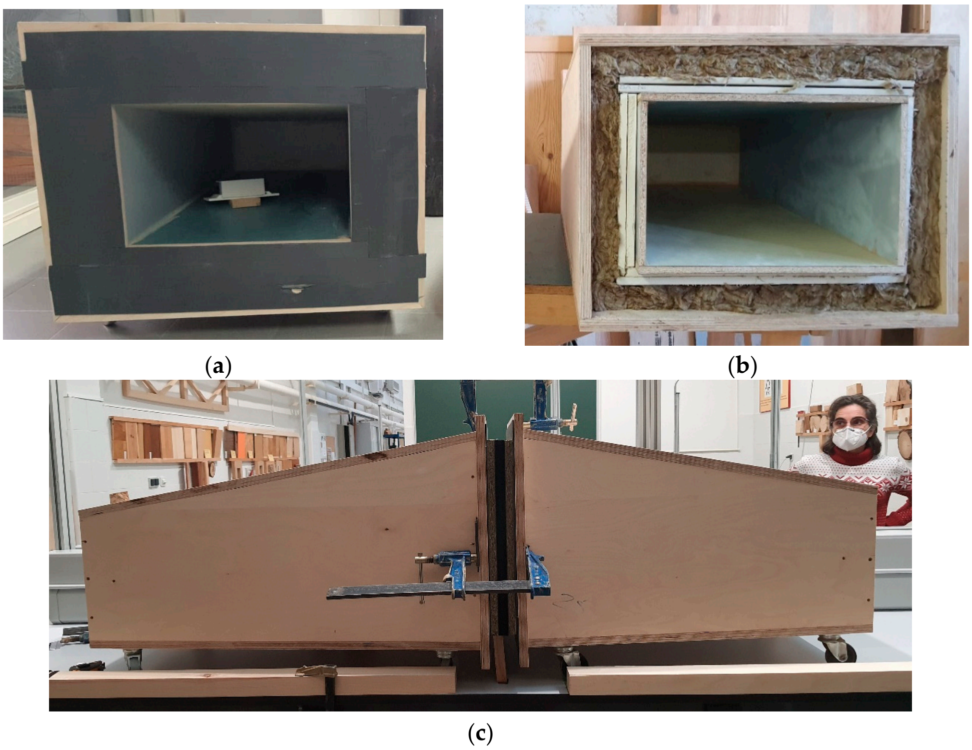


Figure 2. (**a**) Acoustic box opening. (**b**) Acoustic box detailed section. (**c**) A sample placed between both sides of the box.

The limitations of this test are due, on the one hand, to the reduced dimensions of the box (both volume chambers < 0.2 m^3), which implies that modal behaviour is predominant. The sound field inside is not diffuse, and thus, the sound pressure level is extremely dependent on the measurement point. In order to reduce the variability in the measured SPLs due to the lack of diffusion of the sound field inside the boxes, both sound level meters (SLM-01 and SLM-02) were placed on fixed supports designed for this purpose. The idea was to ensure that all the measurements were always made in the same position and, thus, would be equally affected by the modal distribution.

Another potential limitation, on the other hand, is the effect of possible indirect transmissions. It should be noted that this second limitation was reduced significantly thanks to the design of the box itself, to its high-sound-insulation lateral walls (Figure 2b), and to placing an elastic interlayer between the samples and the box, as shown in Figure 2a. Therefore, the main limitation of the test is related to the sound field generated inside the box.

The test itself consisted of producing a pink noise-like signal on one side of the box and simultaneously measuring the sound pressure levels on both sides of the sample, in 1/3 octave bands from 100 Hz to 5 kHz, and later calculating the SPL difference. The source was a small loudspeaker with a Bluetooth connection permanently located on the emitting side (right). The sound pressure levels were measured simultaneously with two sound level meters, with one located on each side of the sample: SOLO 01 dB (SML-01) and B&K 2250 (SML-02). The results of the SPL differences should provide qualitative information about the behaviour of the different tested samples and allow a preliminary comparison between them, but they cannot be generalized to real samples and sizes used in building construction. This is a non-standardized, custom-designed measurement method.

3.2. Laboratory Tests: Standardized Comparative Tests

In this case, the tests were carried out in the transmission chambers of an accredited laboratory (Audiotec company) and following ISO 10140-2 for airborne sound insulation measurements but using small-sized samples (875 mm × 2050 mm) placed in a door opening (Figure 3). All the measurement equipment was class 1.

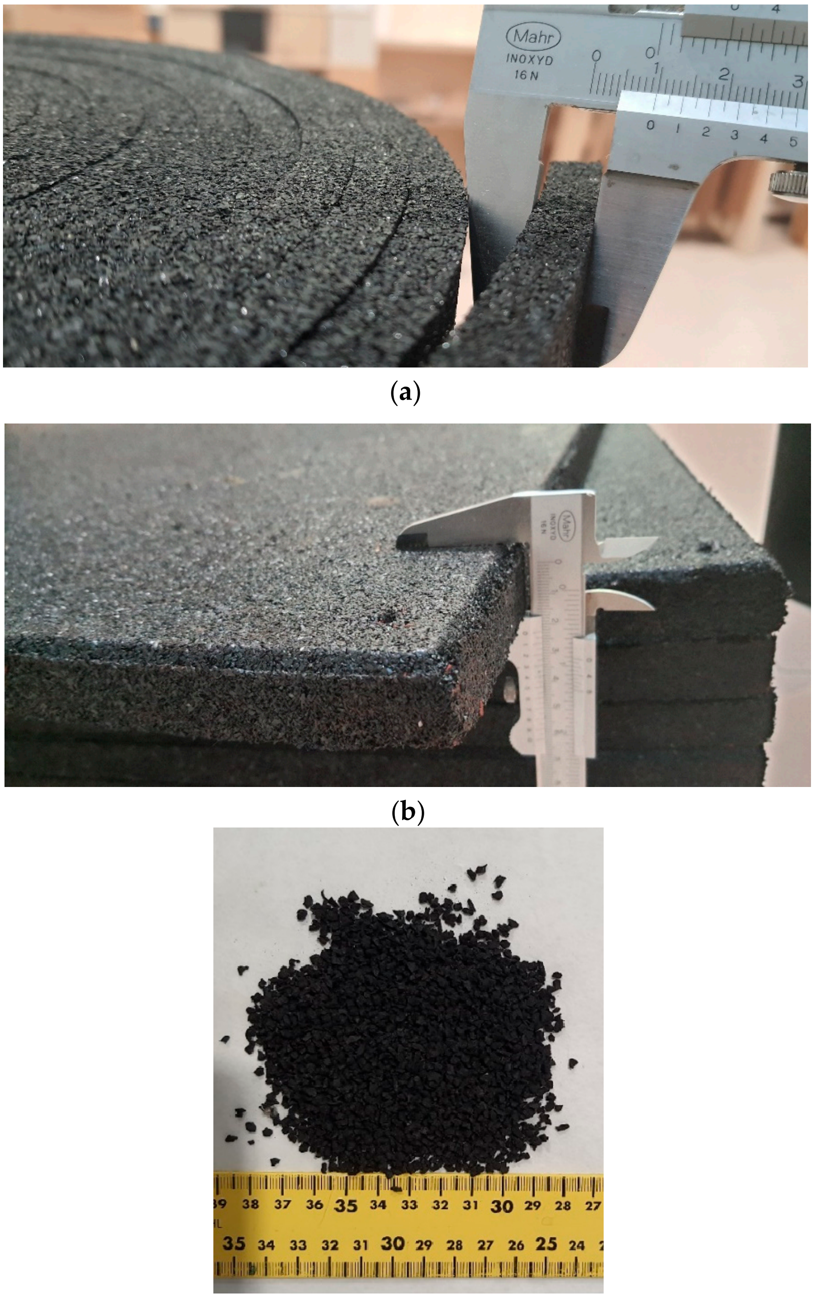
Figure 3. Sample manufacturing in laboratory.

3.3. Materials' and Samples' Description

The GTR material was selected based on results from previous studies [134,135]. Table 4 summarizes the different formats of GTR used in the different stages of the study. As shown in Figure 4, all the material was provided by BERLÁ (Valladolid, Spain) in 4 different formats: rolls (6 mm and 10 mm), sheets (22 mm), and granules (2.5–4 mm).

Table 4. GTR material formats (from BERLA SA).

Product	Code	Thickness	Description
Roll	GTR6	6 ± 1 mm	GTR rubber roll of 1500 × 10.000 mm. Nominal density of 980 kg/m^3
Roll	GTR10	10 ± 1 mm	GTR rubber roll of 1500 × 10.000 mm. Nominal density of 780 kg/m^3
Sheet	GTR22	22 ± 1 mm	GTR rubber sheet of 500 × 500 mm. Nominal density of 900 kg/m^3
Granules	G4	2.5–4 mm	GTR rubber granules of 2.5–4 mm diameter. Apparent density of 600 kg/m^3



(**a**)

(**b**)

(**c**)

Figure 4. GTR material used on tests in different formats: (**a**) Roll. (**b**) Sheet. (**c**) Granules.

The inclusion of the granulated form of GTR was upon specific request from MEDGON, since they were interested in evaluating its use combined with their usual solution based on mineral wool. The use of granulated GTR should be clean and easy to implement in their facilities.

Besides the GTR materials, test specimens were manufactured using other materials, as described in Table 5.

Table 5. Other materials used in specimens.

Product	Code	Thickness	Description
Structural particle board (class P5)	P5	16 ± 1 mm	Panel of 1200 × 2450 mm. Nominal density of 670 kg/m^3
Ultracoustic-R mineral wool	Ultracoustic-R60	60 ± 5 mm	Panel of 600 × 1350 mm. Nominal density of 30 kg/m^3
AISLAnat, cellulose-based material	Cellulose 60	60 ± 5 mm	Compacted product Nominal density of 65 kg/m^3
STEICO flex F308, wood fibre material	Wood fibre 112	110 ± 10 mm	Panel of 600 × 1220 mm. Nominal density of 50 kg/m^3

Table 6 describes all the sandwich samples which were tested in the acoustic box. The dimensions of the panels were 500 mm × 400 mm, and the effective box opening size was 380 mm × 240 mm.

Table 6. Samples tested for sound pressure difference level in acoustic box.

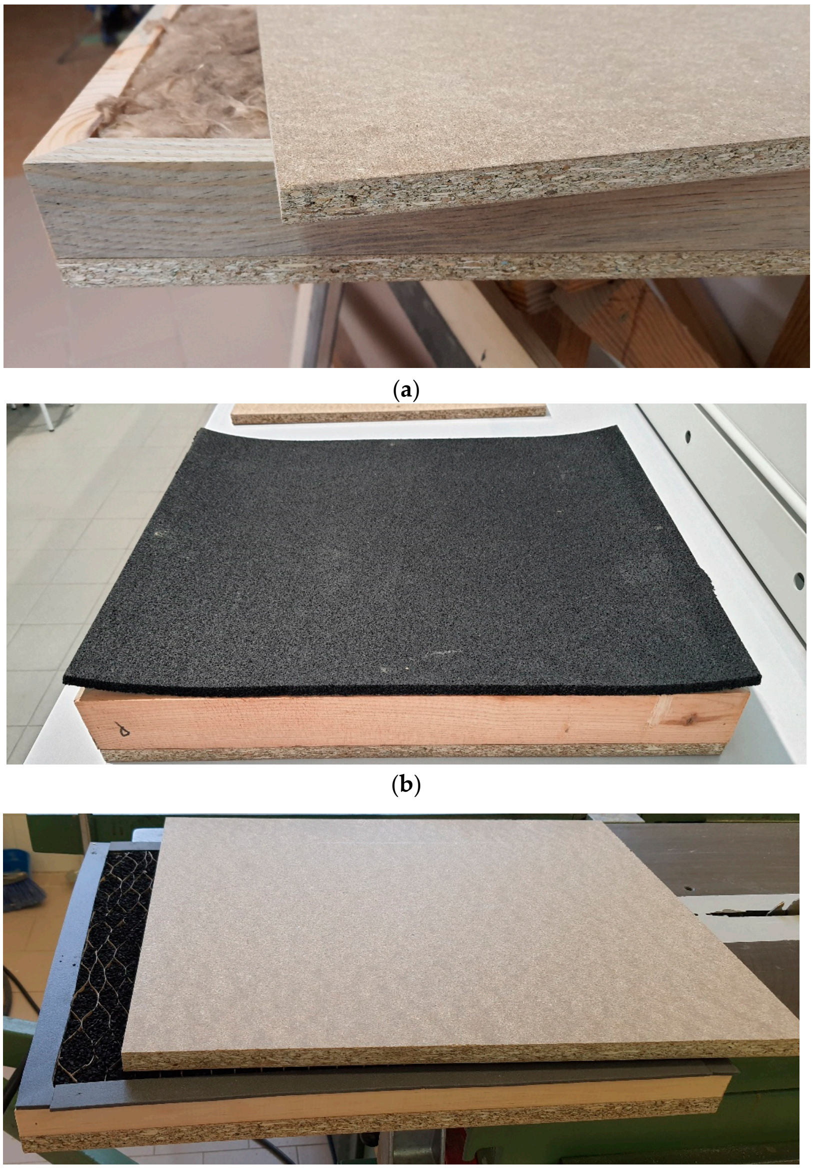
Specimen Code	Inside Composition	Layer Thickness (mm)	Total Thickness (mm)
S01	P5 + GTR10 + P5	16 + 10 + 16	42
S02	P5 + GTR22 + P5	16 + 22 + 16	55
S03	P5 + G4 (25) + P5	16 + 25 + 16	57
S04 *	P5 + Ultracoustic R60 + P5	16 + 60 + 16	92
S05	P5 + Ultracoustic R60 + GTR10 + P5	16 + 60 + 10 + 16	102
S06	P5 + Ultracoustic R60 + G4 (25) + P5	16 + 60 + 25 + 16	117
S07	P5 + cellulose 60 + P5	16 + 60 + 16	92
S08	P5 + cellulose 60 + GTR10 + P5	16 + 60 + 10 + 16	102
S09	P5 + cellulose 60 + G4(25) + P5	16 + 60 + 10 + 16	117
S10	P5 + wood fibre 112 + P5	16 + 112 + 16	144
S11	P5 + wood fibre 112 + GTR10 + P5	16 + 112 + 10 + 16	154
S12	P5 + wood fibre 112 + G4 (25) + P5	16 + 112 + 25 + 16	169

* reference specimen based on MEDGON's specifications.

When the samples included GTR in its granulated form, a paper-based honeycomb structure was used as a supporting structure (see Figure 5c). The height was 25 mm; thus, any sample including the granulated GTR included the code G4 (25). The corresponding surface mass of the GTR layers (once built in the panels) was 5.8 kg m^{-2} for GTR6; 7.8 kg m^{-2} for GTR10; 19.8 kg m^{-2} for GTR22; and approximately 15 kg m^{-2} for the G4 (25) granulated solution.

In this study, and according to MEDGON's instructions, increasing the thickness of the constructive solution was not a problem as it usually is for most building companies. Therefore, some samples combining two different materials became much thicker than the reference sample: the reference sample S04 was 92 mm thick, while S12 reached 169 mm, which is a thickness increase of about 1.8.

Figure 5 shows the assembly of some of the samples described in Table 6.



(**a**)

(**b**)

(**c**)

Figure 5. Composition of some samples tested on acoustic box. (**a**) Open specimen S04. (**b**) Open specimen S05. (**c**) Open specimen S03.

As will be shown in the next section, it was observed from the acoustic box tests that adding a GTR layer to the reference sample increased the SPL difference almost over the full frequency range. Upon request from the interested party (MEDGON), some of the previously tested constructive solutions were selected to be tested in an accredited sound transmission laboratory. Moreover, the company was interested in testing an additional constructive solution including a thin 6 mm GTR layer, which has a lower cost than the 10 and 22 mm materials. These samples were coded as L1, L2, L3, and L4. The L1 sample corresponds to the previous reference sample S04. Sample L2 included a 6 mm layer of a GTR roll with a volumetric density of 980 kg/m^3. L3 corresponds to S05; that is, it included a 10 mm GTR layer with a volumetric density of 780 kg/m^3. Notice that, in this case, the 6 mm GTR sample density was higher than the 10 mm GTR sample. Finally, sample L4 corresponds to S06 and included the 25 mm granulated G4 layer (ø2.5–4 mm) with a granule density of 600 kg/m^3, placed in a honeycomb structure. The four assembled samples had, in consequence, different surface mass values, as shown in Table 7.

Table 7. Samples tested for sound reduction index in accredited laboratory.

Specimen Code	Inside Composition	Surface Mass (kg/m^2)	Total Thickness (mm)
L1 = S04	P5 + Ultracoustic R 60 + P5	23.6	92
L2	P5 + Ultracoustic R 60 + GTR6 + P5	29.9	98
L3 = S05	P5 + Ultracoustic R 60 + GTR10 + P5	31.4	102
L4 = S06	P5 + Ultracoustic R 60 + G4(25) + P5	34.4	117

Figure 6 shows the assembly of some of the samples described in Table 7.

(**a**) (**b**)

Figure 6. Composition of some samples tested in accredited laboratory. (**a**) Open sample L2 before tests. (**b**) Ready-to-test sample L2.

4. Results and Discussion

4.1. Custom Acoustic Box

The sound pressure level differences (SPLDs) measured in the acoustic box with the different samples are shown in Table 8. As previously mentioned, these results are to be considered only qualitatively; that is, they have no relation at all to any sound reduction index measured neither in situ nor under laboratory conditions.

Table 8. Result of sound pressure level difference for each specimen tested.

Frequency	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10	S11	S12
100 Hz	33.05	30.55	32.23	38.72	37.47	42.32	41.55	44.07	39.91	31.43	33.25	39.15
125 Hz	35.57	35.97	33.34	34.5	39.02	42.29	40.21	40.62	40.94	39.39	37.39	37.37
160 Hz	32.51	33.63	32.31	31.86	35.10	34.58	34.32	36.04	29.93	35.59	31.04	29.34
200 Hz	28.41	35.48	28.62	38.50	47.81	46.93	38.82	44.03	50.03	37.00	37.08	34.89
250 Hz	32.29	33.94	34.18	19.54	29.95	26.22	24.12	35.84	42.39	34.25	23.87	33.88
315 Hz	22.30	25.82	23.07	21.46	27.22	22.72	16.75	27.60	35.27	21.11	20.27	30.39
400 Hz	37.09	38.49	38.03	32.44	38.19	36.60	39.17	46.01	45.29	38.70	40.67	48.95
500 Hz	28.82	32.92	32.77	20.96	25.67	24.37	28.29	35.39	31.31	26.44	37.18	45.44
630 Hz	40.64	44.64	44.79	32.23	38.38	36.97	39.83	47.09	42.07	40.61	50.15	56.34
800 Hz	32.88	37.28	38.87	28.35	33.25	34.89	32.67	37.23	42.75	34.93	43.31	43.43
1 kHz	33.26	39.03	42.82	31.46	35.37	30.96	39.64	40.04	39.66	38.59	41.37	48.13
1.25 kHz	37.84	34.79	45.42	43.63	46.35	47.25	45.93	46.11	44.88	45.54	41.77	49.45
1.6 kHz	44.48	42.80	45.55	38.65	44.14	43.17	43.21	45.56	41.10	50.75	39.08	46.22
2 kHz	43.35	44.92	45.73	35.05	39.48	35.50	37.58	42.71	42.58	48.22	43.10	44.69
2.5 kHz	45.22	47.56	45.84	38.31	46.36	40.35	39.80	47.09	44.71	50.10	40.40	50.85
3.15 kHz	45.2	48.98	47.24	38.79	49.61	44.07	41.87	47.68	44.92	48.45	40.19	46.32
4 kHz	49.73	53.56	51.22	40.83	53.71	45.79	43.19	52.13	47.91	52.74	43.98	51.48
5 kHz	52.49	55.96	57.32	43.86	56.51	50.78	46.44	55.62	53.33	54.38	48.37	55.92

A direct comparison between samples including different absorbing materials is not possible, mainly due to the fact that the wood fibre layer is much thicker than the cellulose and ultracoustic layers. In order to better understand the results, the numerical values shown in Table 8 are hereinafter presented in different comparative figures.

To start, Figure 7 shows a comparison of the same basic sandwich without sound-absorbing material and with three different forms of GTR inside. It corresponds to samples S01, S02, and S03. Then, Figures 8–10 and 12 show different comparisons according to the absorption material used in the sandwich: ultracoustic, cellulose, and fibre wood, respectively. Concerning notation, bear in mind that GTR and G4 stand for different forms of ground tyre rubber products, as explained in Section 3.3.

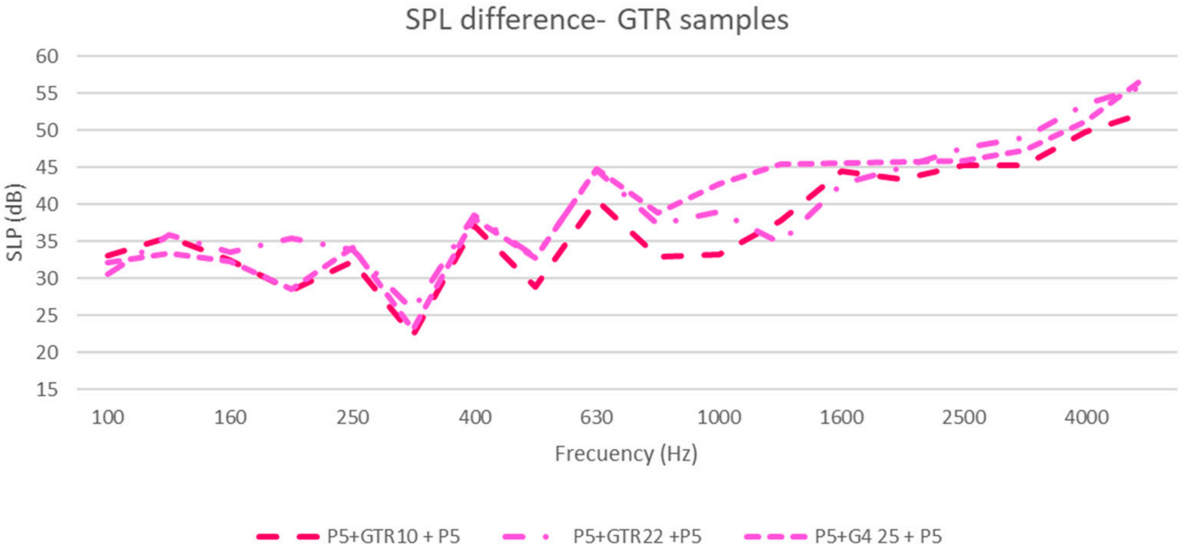


Figure 7. SPL difference in samples without sound-absorbing material (S01, S02, and S03).

When no sound absorption material was included in the panel and three different forms of GTR interlayers were compared, it was observed that GTR10 performed slightly worse than GTR22 and G4(25). This could be due to the much smaller surface mass of GTR10 compared to the others. On the other hand, GTR22 had a slightly higher surface mass than G4 (25), but the performance difference between both products was noticeable only in very few third-octave bands. This result is interesting since, when combining the properties of GTR products with a sound-absorbing material, the trends are not the same.

Figure 8 shows the results for the samples using mineral wool as an absorber. The sample without any GTR layer (S04) is the so-called "reference" sample, since it corresponds to the constructive solution type used by MEDGON. The other curves represent the results when incorporating a 10 mm layer of the roll form (GTR10) (S05) and the granulated form (G4(25)) layer (S06). Both samples including ground tyre rubber increased the SPLDs over the full frequency range under study. The performance of the GTR10 sample was better above 2000 Hz compared to the G4 (25), which was not expected.

In any case, the combination of two materials enhanced the overall performance of the constructive solution.

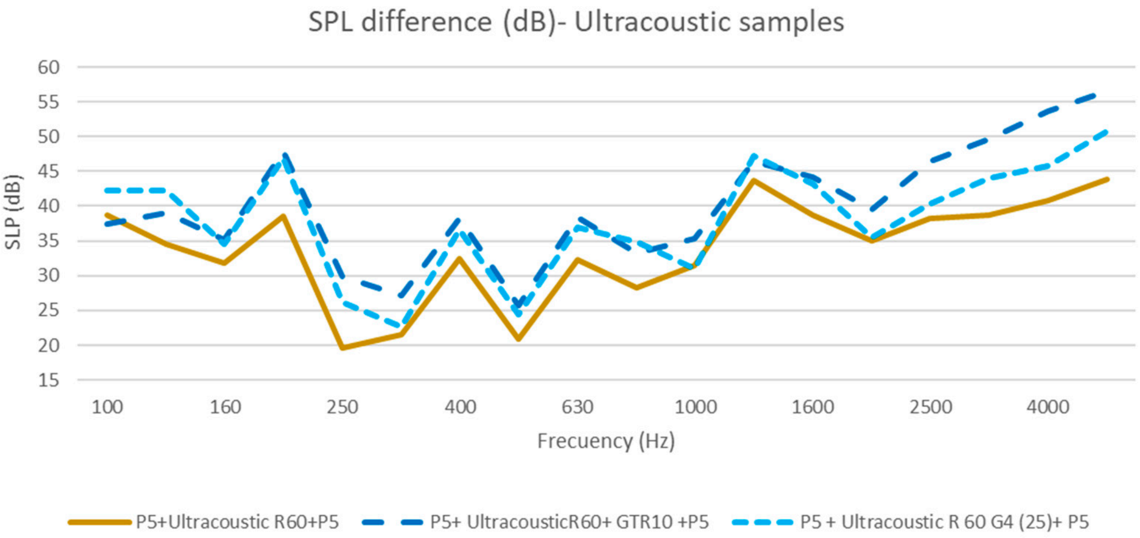


Figure 8. SPL difference in samples using mineral wool as sound absorber (S04, S05, and S06).

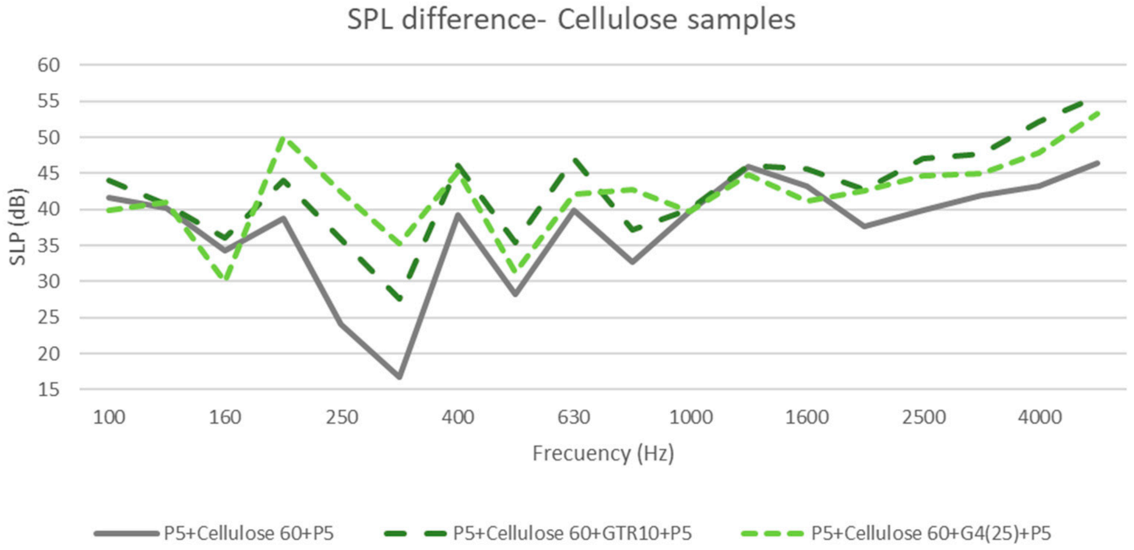


Figure 9. SPL difference in samples using cellulose as sound absorber (S07, S08, and S09).

Figure 9 shows the results for the samples using cellulose as an absorber. The three curves represent on one hand the reference value with no GTR (S07) and on the other hand the results when incorporating a 10 mm layer of the roll form (GTR10) (S08) and a granulated form (G4(25)) layer (S09).

It is also clearly observed that incorporating any format of GTR in the panel increased the SPLDs over the full frequency range. For the cellulose samples, each GTR solution enhanced the panel performance in different frequency ranges.

The last comparison was made for samples using fibre wood as an absorber. The three curves represent the results without GTR (S10), including GTR10 (S11) and G4(25) (S12). In the case of fibre wood as a sound absorber, the granulated form of GTR clearly performed better than the GTR10.

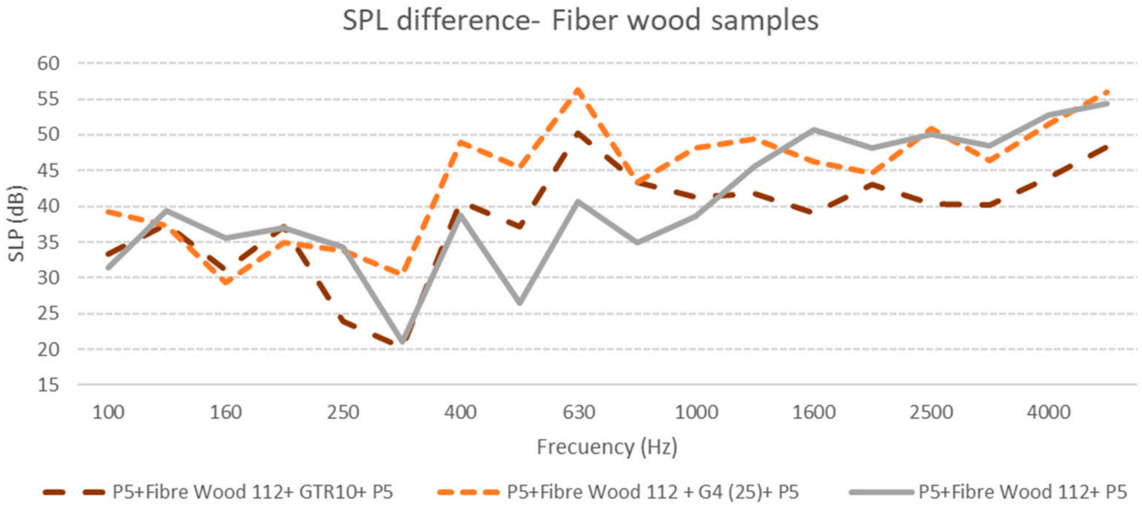


Figure 10. SPL difference samples using fibre wood (S10, S11, and S12).

As preliminary and qualitative results, it can be concluded that adding a GTR layer into a constructive panel already using an absorbing material will improve the acoustic performance of the constructive solution over the full frequency range. All samples show a similar pattern, with peaks and dips at the same third-octave bands, although more or less pronounced depending on the sample. The dips observed at 315 Hz and 500 Hz are most likely related to the shape and dimensions of the box and to the panels used to build the box. The P5 panels used in the sandwiches have a width h = 16 mm, a superficial mass density of 11.5 $kg \cdot m^{-2}$, and an estimated Young's modulus of $1.5 \cdot 10^{10}$ $N \cdot m^{-2}$, which, considering panels of 0.5 × 0.4 m, correspond to a first modal resonance frequency of f_{11} = 339 Hz, which lies within the 315 Hz third-octave band (280.6–353.6 Hz).

Although we expected to find a larger improvement when using the G4 (25) GTR solution (based on higher surface mass than GTR10 and on potential dissipation phenomena in the gaps between the granules), the results are not conclusive, since in some third-octave bands and in some specific samples, the results when using GTR10 are better. This could be due to an inhomogeneity in the granulated form distribution, as shown in Figure 11, even though the density of the granulated layer was calculated to be the same in all the samples. Working with granulated GTR is not simple and thus must be studied further in the future, since it is an interesting easy-to-use residue.


(**a**) (**b**)

Figure 11. Inhomogeneous granulated GTR distribution found when mounting (**a**) and dismounting (**b**) some samples including the G4(25) layer.

Additionally, it was observed that for the samples examined in this study, the constructive solutions with higher SPL differences were those using fibre wood, although this does not lead to any conclusive decision concerning the absorbers, since the fibre wood samples were much thicker than the cellulose and mineral wool samples.

The main clear result obtained from this preliminary set of measurements is the fact that adding a GTR layer can be a good alternative to provide higher sound insulation to basic existing wood panel sandwiches. But the results do not provide enough insight to properly rank the tested solutions.

4.2. Laboratory Tests

In order to verify the effect of adding different GTR layers to the reference sample in a controlled environment, samples L1, L2, L3, and L4 described in Section 3.3 were built and tested under laboratory conditions. Since the acoustic box results were not conclusive, the selection of these samples was agreed on with MEDGON as an interested party on the project.

As can be observed in Figure 12 and Table 9, adding a GTR layer to the reference sample improved the acoustic performance of the constructive solution differently depending on the GTR type. The results show, for samples L2 (GTR6) and L4 (G4(25), an improvement up to 3.0 dB for Rw and around 4 dB for RAtr. This improvement seems more noticeable in the lower-frequency range (100 and 125 Hz) and around the coincidence dip at 2000 Hz. Sample L3 including the GTR10 provided less sound insulation improvement than the two other samples.

It was also observed that the L2 sample, which included a GTR6 roll, provided better airborne sound insulation than the L3 sample, which included a GTR10 sheet. This is probably due to the different GTR volumetric density. That is, in this case, it is not the full panel's surface mass which determines the airborne sound insulation improvement but rather the GTR volumetric density. As can be seen in Table 7, L2 had a lower surface mass than L3, whereas GTR6 included in L2 had a higher volumetric density (980 kg·m^{-3}) than GTR10 included in L3 (780 kg·m^{-3}).

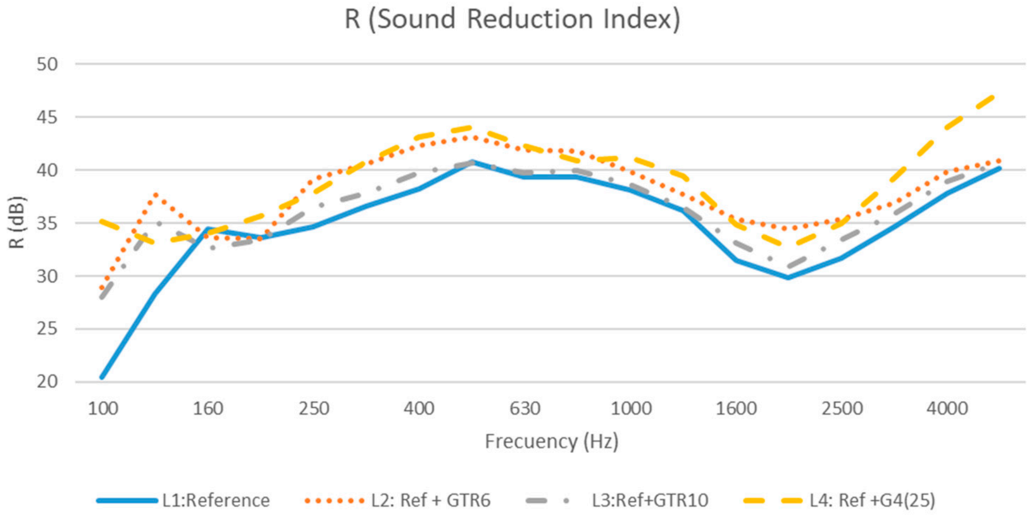


Figure 12. L1, L2, L3, and L4 sound reduction index in accredited laboratory.

Table 9. Rw, R(A), and R(Atr) results for L1, L2, L3, and L4 in accredited laboratory.

		L1 (Reference)	L2 (L1 + GTR6)	L3 (L1 + GTR10)	L4 (L1 + G4(25))
Rw (C;Ctr)	dB	35 (−2;1)	38 (−1;0)	36 (−1;0)	38 (−1;0)
R(A)	dBA	34.1	37.4	35.3	37.6
R(Atr)	dBA	33.6	37.5	35.5	37.7

where Rw = overall insulation calculated according to Standard ISO 717-1:2013 [136]. R(A) = overall insulation in dBA according to Spanish standard CTE-DB-HR [137]. R(Atr) = overall insulation in dBA for dominant outdoor car noise [137]. Note for Table 9: R(A) and R(Atr) were calculated using the 100–5000 Hz frequency range as required in [134]; thus, they cannot be compared to Rw + C or Rw + Ctr, which were calculated from 100 to 3150 Hz and used C and Ctr spectra, respectively.

5. Conclusions

From the literature review, it was found that the use of recycled materials in construction is becoming increasingly important in the industry. In this context, GTR has been mainly used in the production of concrete and asphalt as a substitute for sand. However, the use of GTR is not yet explored enough as an acoustic or thermal insulator in building construction. Some studies have investigated its use as an impact sound insulator and in acoustic barriers or absorbing screens (mainly concrete-GTR panels), but not as a specific airborne sound insulation material. Its potential application to improve airborne sound insulation in timber structures is also very limited, even almost non-existent at present. It is thus necessary to keep researching recyclable materials with robust acoustic and thermal performance, especially in conjunction with timber structures, where acoustic insulation is currently one of the weakest points.

Concerning the preliminary qualitative study performed in a custom acoustic box to investigate different sustainable materials to be used in combination, it is concluded that including a GTR layer in traditional wood/absorber sandwich panels can improve the overall acoustic performance of the panels concerning airborne sound insulation. Nevertheless, the inconclusiveness of the acoustic box concerning which GTR solution is more suitable when combined with different absorbers points to the need for further research, especially if this scale box is intended to be used as a preliminary decision-making tool.

On the other hand, the laboratory tests performed with mineral wool as an absorber confirm this conclusion and point out the fact that the volumetric density of the GTR layer plays a key role in the acoustic improvement.

The request made by the local company (MEDGON Passivhaus) was to investigate the acoustic performance of different construction solutions based on wood and including ground tyre rubber (GTR), and this main objective was reached, albeit at a preliminary stage. The inclusion of GTR solutions in the samples will improve the performance of their reference sample, which includes just mineral wool. Although for their manufacturing procedure, the granulated form seemed better, the investigation did clearly prove the advantage of the granulated form compared to the roll form (both solutions have different thicknesses). The use of alternative absorbers such as cellulose also proved to be an option.

The normalized measurements according to ISO standards performed on a selection of samples also showed that including even a very thin GTR layer in the traditional wood/sound absorber sandwich panels provides a significant increase in the sound reduction index, reaching up to 3 dB for Rw.

Further research is needed to evaluate the cost/benefit effect of using different-density and -thickness GTR products. It is also necessary to research possible manufacturing processes using GTR granules and some kind of binding material to guarantee the homogeneous distribution of the granules. Lastly, the qualitative results presented in this paper shall be further confirmed with additional normalized tests to quantitatively evaluate solutions based on other sustainable materials such as cellulose and fibre wood.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

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Conflicts of Interest: The authors declare no conflict of interest.

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