



# New approach in the reuse of modified ground tire rubber as thermal and acoustic insulation to be used in civil engineering

X. Colom<sup>1</sup> · J. Girbau<sup>1</sup> · M. Marin<sup>2</sup> · K. Formela<sup>3</sup> · M. R. Saeb<sup>3</sup> · F. Carrillo<sup>1</sup> · J. Cañavate<sup>1</sup>

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## Abstract

The concern for the amount of end-of-life tires generated each year has arisen from constant research directed to their valorisation. Herein we propose a new material, which is constituted by GTR with a binder, as acoustic and also as a thermal insulator for civil engineering. The insulator can also include the fibre mat present in the tire, seldomly considered as a recyclable sub-product. To provide insight into the insulating behaviour of these materials, four mathematical models have been tested and compared with the experimental results of thermal conductivity. The Lewis-Nielsen modelization presented good accuracy with deviations of less than 3%. A statistical analysis has also been conducted on the experimental data showing that the parameter with more effect on thermal conductivity is thickness (differences up to 43%) being particle size, less important (ca 6%). In acoustic properties, different effects can be observed depending on the frequency range, being the density the most relevant. From the mathematical, statistical and experimental analysis can be deduced that good insulation properties would be achieved in materials with: low density, porous; including mat and thick. The effect of these parameters causes variations of thermal conductivity from 0.189 to 0.117 W/m·K and in sound absorption coefficient from 0.06 to 0.6.

**Keywords** Ground tire rubber · Elastomeric waste · Acoustical properties · Thermal properties

## Introduction

In the quest for implementing a circular economy, the development of new uses for discarded materials is paramount. The increase in the production of waste requires an effort to integrate the residua in applications where high amounts of materials at their end of life can be absorbed. The field of civil engineering, because of its high consumption and its specific features, is very appropriate for the recycling of different products by the way of incorporation of the waste, usually blended with other products, to structural uses. This

approach allows not only the recycling of waste but also the consumption of raw materials [1–4].

Over the last few years, most countries have realized the importance and need for recycling, given the pace of society's consumption and the proliferation of plastic waste in natural environments as well as the growing pollution on a global scale.

One of the biggest problems lies in the recycling of elastomeric waste. Until a few years ago, rubber waste was burned and used as fuel (energy recovery). However, the approval of the directive 2008/98/EC, which is the current regulatory framework for the production and management of waste in the European Union, highlights that the goal should rather be in consonance with the principles of the waste hierarchy, that would be: first, preventing the generation of neglected tires, secondly, promoting their reuse and recovery through recycling, and only in third position, recovering energy and end disposal [5, 6].

Because of their properties, composites are materials widely used, presenting at the same time a way to include a subproduct into a material with interesting properties. This feature makes them suitable for the recycling and reuse of elastomeric waste. In fact, several types of composites

✉ X. Colom  
xavier.colom@upc.edu

<sup>1</sup> Chemical Engineering Department, Universitat Politècnica de Catalunya Barcelona Tech, Colom, 1, Terrassa, 08222 Barcelona, Spain

<sup>2</sup> Mechanical Engineering Department, Escola Tècnica Superior d'Enginyeria Rovira I Virgili University, 43007 Tarragona, Spain

<sup>3</sup> Department of Polymer Technology, Faculty of Chemistry, Gdansk University of Technology, Gabriela Narutowicza 11/12, 80-233 Gdansk, Poland

including waste, have been developed for civil applications. Vishnu and Singh studied asphalt-concrete including different types of waste for pavements [7], Yao et al. worked on the addition of elastomeric waste in concrete [8] and Gabrys explored the recycled concrete to a mix of concrete and waste tire mixture [9].

However, considering the properties of the elastomeric materials, a suitable application for them could be based in the field of insulation, thermal, soundproofing [10], or vibrations.

The overall noise level in the world is alarmingly high basically because of the technological environment in which we develop our activities. It is well known that noise pollution not only makes it more difficult to relax, but it also causes stress and is a real threat to our health [11]. Soundproofing means protection against the transmission of noise. The goal is that sound waves going through a material lose as much energy as possible to avoid transmission.

The importance of having good acoustic insulators that act at the same time as thermal insulators is fundamental in the fields of construction and civil engineering. The EU is making great efforts to promote the manufacture of good thermal and acoustic insulators using waste materials to reduce CO<sub>2</sub> emissions, according to the commitment of the European Directives on energy performance of buildings and Environmental Noise [12].

To know the capacity of some materials to act as acoustical insulators, the coefficient of absorption and critical frequency are two important parameters. Critical frequency is the frequency from which a rigid barrier begins to absorb some of the energy of the incident waves. This critical frequency will depend on the thickness of the rigid barrier, where penetration frequency is related to the thickness of the material. The absorption or attenuation coefficient is a criterion for assessing the ability of a material to absorb sound. It is defined as the quotient between the incident energy and the energy absorbed by a material. Absorption coefficients depend on the frequency and are used in architectural acoustics. The sound absorption coefficient of a material at a given frequency will always be between 0 and 1 where 1 indicate that the material is completely absorbent.

A global absorption coefficient of a material, considering the full spectrum of frequencies, is measured according to the UNE-EN ISO 354: 2004 standard. This global absorption coefficient defines the sound absorption capacity of a material. The energy absorbed is quantified by the ratio between the absorbed energy ( $E_a$ ) and the incident energy ( $E_i$ ) per unit area.

The absorption coefficient depends on the physical characteristics [13, 14] of the material and the relative position between the absorber and the incident wave. ISO 11654 is

used to compare sound absorbers, which classifies products from A (maximum absorption coefficient) to E (from 0.15 to 0.25). This standard provides a weighted sound absorption index and is another simplification based on  $\alpha_p$ . The values of  $\alpha_p$  are compared with the fixed reference curves and based on them, the product is classified, and we obtain its  $\alpha_w$ , where  $\alpha_p$  is the practical coefficient of sound absorption and depends on the frequency and  $\alpha_w$  coefficient measures frequency-weighted sound absorption with classes ranging from A (maximum absorption) to F (reflection), in the extreme cases [15].

The value of the absorption coefficient of a material depends also on the roughness of the material, and especially, on its porosity. The loss of energy by viscoelastic processes due to the pass of air through the material, which can be characterized by the resistance to the pass of air flow; thermal conduction between material and air; and the diffraction of the sound wave due to the surface irregularities of the material.

The sound absorption is tested according to the UNE-EN ISO 354 standard, which is based on a reverberation camera for frequencies 500, 1000 and 2000 Hz and the UNE-EN ISO 11654 standard, using impedance tubes or Kundt tubes which are systems currently used for the study of the acoustic properties of the tested materials. Thus, by means of these tests it is possible to obtain, depending on the frequency, the acoustic impedance, and the absorption coefficient of different materials.

In another way, thermal insulation implies the reduction of the transfer of heat between objects in contact. The capacity of thermal insulation [16–18] of a material is the inverse of its thermal conductivity. Thermal conductivity [19–21] is a physical property that describes the material feature to transfer heat by conduction, that is, by direct contact and without material exchange. It is an intensive magnitude that does not depend on the material or mass amount. As mentioned before, the inverse of thermal conductivity is thermal resistivity or insulation.

The aim of the manuscript is the implementation of an innovative elastomeric composite material with acoustical and thermal insulation for application in the construction and civil engineering fields. The proposed material is a compound made with scrap tires in the form of ground Tire rubber (GTR). Some other researchers as Valente et al. [22], have proposed the use of GTR in cement-based sandwich composites, in our case the cement is not included in the mix, using only GTR, fibers obtained from the recycling of the tires and PUR as an agglomerate agent.

In a previous work [10] we explored the possibility of using GTR as an acoustic insulator, a subject seldom reported in the literature, except in some publications, like

the articles of Sambucci and Valente who included this perspective in their studies of GTR and concrete blends [23].

In this case, we have simplified the processing of fabrication and have aimed for a material that can act also as a thermal insulator. The eco-elastomeric insulating panel is completely recyclable at the end of its life as construction material. The study contributes to (i) a better use of resources and raw materials for the insulation industry, (ii) the reduction of the environmental impact and the implementation of ecofriendly insulation material in the construction sector, (iii) improving the noise pollution and the energy efficiency of buildings and (iv) the reduction of CO<sub>2</sub> emissions, according to the commitment of the European Directives on the energy performance of buildings and Environmental Noise.

## Theoretical background

### Models for the analysis of thermal conductivities in a porous composite GTR

To validate the accuracy of the experimental results, the thermal conductivities of the GTR composites, considered as porous materials with spherical pores have been compared to reference values found in literature [24, 25].

The expressions of these models are listed as Eqs. (1–4).  $K_c$  is the thermal conductivity of samples;  $K_g$ , thermal conductivity of air  $0.023 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ;  $K_m$  is the thermal conductivity of GTR  $0.186 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  and  $V_g$  is the volume of air.

Series model:

$$K_c = \frac{K_g K_m}{K_g (1 - V_g) + K_m V_g} \quad (1)$$

Parallel model

$$K_c = K_g V_g + K_m (1 - V_g) \quad (2)$$

Maxwell- Eucken Model

$$K_c = \frac{2K_m + K_g - 2(K_m - K_g)V_g}{2K_m + K_g + (K_m - K_g)V_g} \quad (3)$$

Lewis Nielsen Model

$$K_c = K_m \left[ \frac{1 + ABV_f}{1 + BV_f\Psi} \right], B = \frac{K_g}{K_m} - 1, \Psi = 1 + \left( \frac{1 - V_r}{V_r^2} \right) V_g, A = k_E - 1 \quad (4)$$

The values of A and  $V_r$  for this model are 1.5 and 0.637. [25]

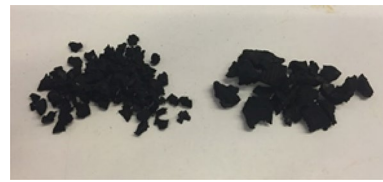


Fig. 1 Particle size of 2–3 mm (left) and 5–7 mm (right)



Fig. 2 Polyester mat of recycled fiber from tire

## Material and methods

### Materials

The main raw material used for this work was ground tyre rubber supplied by GMN Maials Spain. Two ranges of particle sizes (2–3 mm and 5–7 mm) (Fig. 1) were considered for the study. Ground tyre rubber is obtained from the shredding of the tyres of vehicles in special processing plants and it is considered a common initial product to recycle car tires.

The composition of the rubber according to our thermogravimetric analysis is: natural rubber 25%, synthetic rubber 32%, carbon black 33%, SiO<sub>2</sub> 5%, other additives (e.g. curing system, processing aids, etc.) 5%. The particle size distribution has been published previously by Colom et al. [5].

A high-viscosity polyurethane resin (SikaBond T53 manufactured by Sika), with a content of 5%, was used as a binder. The high viscosity of the resin confers an adequate structure to the compound.

To produce the compounds, both components were mixed in proportions 95% of GTR and 5% of PUR and in some of them a mat constituted by the tire fibers was included. These fibers (Fig. 2) are included in the tires as reinforcement, are generally made of polyester, and, when the tires are ground, they appear floating on the surface of the tire powder causing trouble in the grinders. For this reason, the companies producing GTR collect them and are interested in finding a use for this subproduct. These fibers are included in the samples because they could be interesting for their insulation properties.

The obtained GTR/PUR compounds were molded into 20 and 30-mm-thick samples at 160 °C for 12 min under a pressure of 4.9 MPa using a laboratory plate press type P

200E from Dr. Collin GmbH (Germany). Different samples, as a function of GTR size, thickness of sample, density and the incorporation of a mat made with the recycled fiber from tires (Fig. 2), have been obtained. The samples were coded as GTR/PUR–XYZW, where **X** takes the values of 1 for size particles of 2–3 mm and 2 for size particles of 5–7 mm; **Y** takes the values of 1 for thickness of 20 mm and 2 for thickness of 30 mm, **Z** take the values of A ( $d = 0.95 \text{ g/cm}^3$ ), M ( $d = 0.80 \text{ g/cm}^3$ ), B ( $d = 0.65 \text{ g/cm}^3$ ) and **W** takes the value of S (with mat) and N (without mat). So, a sample codified as Sample11HS means a sample of 2–3 mm of GTR particle size, a thickness of 20 mm, High density with fiber mat.

### Thermal conductivity

Thermal conductivity ( $k$ ) of the different samples has been calculated according to ISO 8302:1992. The heat transfer area was  $0.0225 \text{ m}^2$ . The heat flow (heat per time unit) was  $5.80 \text{ J/s}$  and the thickness depends on the sample: 20 or 30 mm.

### Sound absorption coefficient

An impedance tube was used to measure the sound absorption coefficient. The impedance tube measurements are based on the two-microphone transfer-function method according to the specification ASTM E1050, which describes the standard test method for impedance and absorption of acoustical materials using a tube in the frequency range of 500–6400 Hz.

The measurements were made using the Brüel&Kjær Impedance Tube Kit Type 4206 and two 1/4" Condenser Microphones Type 4187. The signals were analyzed with a portable Brüel&Kjær PULSE System with four input data channels (type 3560-C). Sample holders of 20 and 30 mm in thickness and 29 mm in diameter are provided.

Sound absorption is mainly influenced by porosity, flow resistivity and tortuosity.

In order to determine the porosity of GTR materials, it has been considered that the materials are constituted by an open cell of an elastic/rigid component surrounded by air. Under these conditions, the Porosity ( $W$ ) is the relation between the air volume ( $V_a$ ) and total volume ( $VT$ ).

The Flow resistivity ( $S$ ) is the capacity of the material to allow the flow of air through the bulk of waste material (GTR). It is calculated according to the equation  $S = (p_2 - p_1) / D \cdot (A/d)$ , where  $(p_2 - p_1)$  is the pressure between the two sides of material,  $D$  is the mean flow of air;  $A$  area and  $d$  is the thickness of analyzed material. In granular rubber materials like GTR the  $S$  depends on the particle size. Reference values for rubber crumbs are between 1000 and  $10,000 \text{ N/m}^4 \cdot \text{s}$  [14]

The tortuosity ( $T$ ) of a porous material is defined as the ratio of the flow path length to the straight distance between

the ends. On common granulated materials is calculated using a model of cylindrical geometry, considering an angle of  $\phi$  with respect to the normal of surface.  $T = 1/\cos^2\phi$ .

### Statistical analysis

Statistical analysis was performed on the results of the 24 experiments providing acoustic and thermal responses of the materials (full factorial design).

Acoustic data have been previously processed to obtain the absorption area as a function of the response to three frequency ranges: Low frequencies [500–2000 Hz), Mid frequencies [2000–4000 Hz) and High frequencies [4000–6500 Hz].

The formula to obtain the area under the analyzed step curve is:

$$\text{Absorption}_{\text{Area}_i} = \frac{\text{Absorption}_{\text{Freq}_i} + \text{Absorption}_{\text{Freq}_{i+1}}}{2} \cdot (\text{Freq}_{i+1} - \text{Freq}_i)$$

where: (i)  $\text{Absorption}_{\text{Freq}_i}$  is the Absorption value of the frequency  $\text{Freq}_i$  and (ii)  $\text{Freq}_{i+1}$  is the Frequency value of the frequency  $\text{Freq}_{i+1}$ .

The obtained absorption areas at each frequency are added starting from the lower frequency to the upper frequency of the analyzed range. For example, the absorption area of the whole Low-frequency range is calculated:

$$\text{Absorption}_{\text{Area}_{\text{LowF}}} = \text{Absorption}_{\text{Area}_{500}} + \text{Absorption}_{\text{Area}_{508}} + \dots + \text{Absorption}_{\text{Area}_{1992}}$$

Once the absorption area has been calculated for each range, an ANOVA model can be applied using the factor levels and the response (both in acoustics and thermal). An ANOVA model is a linear model using factors:

$$y = \beta_0 + \beta_1 X_1 + \dots + \beta_n X_n$$

where  $n$  depends on the number of levels and factors.

On this research, we have considered a significance level of 5% to decide if the null hypothesis is rejected. The hypothesis test applied to each coefficient of the model is the following:

$$H_0: \beta_i = 0 \text{ (i.e. this variable does not affect the response).}$$

$H_1: \beta_i \neq 0$  (i.e. this variable affects the response in a statistically significant manner).

## Results and discussion

### Analysis of thermal conductivity

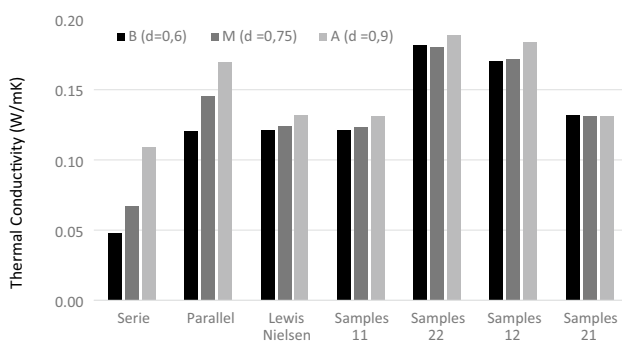
The results of experimental data and numerical simulations for the thermal conductivity as a function of density are presented in Fig. 3. The experimental results show how samples 22 (size particles of 5–7 mm and thickness of 30 mm) and 12 (size particles of 2–3 mm and thickness of 30 mm) have the highest thermal conductivity values ( $0.170$ – $0.189 \text{ W/mK}$ ). The figure also shows the influence of the porosity

on thermal conductivity. For each type of sample, a higher density (lower porosity) is related to a higher thermal conductivity. Comparing the experimental values with the different proposed models, from the point of view of the effect of the porosity, the consistency of the experimental data with the Lewis-Nielsen model is higher than in the other cases. In contrast, the parallel and series models clearly predict a higher influence of the porosity in the thermal conductivity that is not observed in experimental data. The deviation of the results obtained by the Lewis Nielsen model and the average experimental values is less than 3%, indicating a high reliability of the numerical analysis.

The effect of thickness on thermal conductivity is shown in Table 1. Thickness is the most affecting parameter, thicknesses of 30 mm define values 43% higher than those of 20 mm. The particle size and the presence of mat have a relative influence (6% and 3% respectively). As discussed before, density is an important parameter, samples labeled as A, which present high densities, (low porosity) have a higher thermal conductivity.

Table 2 shows the statistical analysis values of thermal conductivity, where the positive coefficients, marked in blue, mean that the level of these factors (size particles of 5–7 mm and thickness of 30 mm) is reached and the response will increase. The gray box color indicates the negative coefficients, when the level of this factor is reached, the response will decrease (inversely proportional relationship). The intercept indicates the value of the response when the experiment has low levels in all factors (for example: Size Particle 1, Thickness 1, Density B, Mat N).

According to the statistical values, the more affecting parameters are the thickness and, to a lesser extent, particle size. Low and medium density and the presence of a mat decrease the response. Although high density defines higher thermal conductivity, GTR/PUR/air samples exhibit a low



**Fig. 3** Thermal conductivity analysis according to models as a function of density (related to % of porous). Samples 11: size particles of 2–3 mm and thickness of 20 mm; Samples 12: size particles of 2–3 mm and thickness of 30 mm; Samples 21: size particles of 5–7 mm and thickness of 20 mm; Samples 22: size particles of 5–7 mm and thickness of 30 mm

**Table 1** Experimental values of the thermal conductivity of the samples

Samples	k [W/m·K]	Samples	k [W/m·K]
22AN	0.189	21BN	0.132
12AN	0.184	21AN	0.132
22AS	0.184	11AN	0.131
22BN	0.182	21MN	0.131
22MN	0.180	21AS	0.129
12AS	0.174	21MS	0.126
22MS	0.174	11MN	0.123
12MN	0.172	11BN	0.121
12BN	0.170	11AS	0.121
22BS	0.168	11MS	0.120
12BS	0.163	21BS	0.119
12MS	0.163	11BS	0.117

Samples code: XYZW X particle size 1: 2–3 mm; 2: 5–7 mm; Y thickness 1: 20 mm; 2: 30 mm, Z A (d=0.95 g/cm<sup>3</sup>), M (d=0.80 g/cm<sup>3</sup>), B (d=0.65 g/cm<sup>3</sup>) W S: mat; N: no mat

thermal conductivity because of their relatively low atomic density, weak interactions or chemical bonding, complex crystal structure, and high anharmonicity in their molecular vibrations [26]. To provide reference values, typical thermal conductivity values of some polymers vary from around 0.16 W/mK for epoxy resins to 0.58 W/mK for HDPE.

Comparing with other composite obtained from waste materials (i.e. rice husk 0.07 W/mK, cork 0.055 W/mK, and coffee chaff samples 0.076 W/mK) [27] samples of GTR/PUR/air are interesting insulating materials for several applications (i.e. civil engineering, electrical, others...) due to their ease of production, lightweight, low cost and provides a solution for the reuse of end of life tires.

**Table 2** Statistical analysis of the values of thermal conductivity

Thermal	Estimate	Std. Error	t value	Pr(> t )
(Intercept)	1.22E-01	1.39E-03	88.20	<2.00E-16
Thickness2	4.85E-02	1.70E-03	28.55	3.73E-15
Size_particle2	7.25E-03	9.81E-04	7.39	1.52E-06
DensityM	2.75E-03	1.70E-03	1.62	1.25E-01
DensityA	6.00E-03	1.70E-03	3.53	2.77E-03
MatS	-7.42E-03	9.81E-04	-7.56	1.14E-06
Thickness2:DensityM	-1.25E-03	2.40E-03	-0.52	6.10E-01
Thickness2: DensityA	6.00E-03	2.40E-03	2.50	2.38E-02

Samples code: Thickness 1: 20 mm, 2: 30 mm Size particle 1: 2–3 mm, 2: 5–7 mm; density A (d=0.95 g/cm<sup>3</sup>), M (d=0.80 g/cm<sup>3</sup>), B (d=0.65 g/cm<sup>3</sup>) Mat S: mat; N: no mat

## Acoustical analysis

As detailed in the methodology, the frequency range has been divided into 3 groups: low frequencies (500–2000 Hz), mid frequencies (2000–4000 Hz) and high frequencies (4000–6500 Hz). Table 3 shows the average values of the different samples as a function of these frequency ranges.

The samples that show the higher sound absorption values in the whole frequency range are 21BS (size particles of 5–7 mm, thickness of 20mm, low density with mat), 22BS (size particles of 5–7 mm, thickness of 30 mm, low density with mat), 11BS (size particles of 2–3 mm, thickness of 20 mm, low density with mat), and 12BS (size particles of 5–7 mm, thickness of 30 mm, low density with mat). According to these results, the common features for high sound absorption are low density and the presence of a mat inside the sample. Although the thickness cannot be underestimated, a minor effect of the particle size and thickness in the absorption in the whole range of frequencies is observed. Especially the particle size seems not affecting at all. The obtained results are in accordance with Asdrubali et al. [28] who found that the compactation (an increase of density) of granulate materials has a negative influence on the adsorption of sound. As could be expected, compacted granulated materials absorb less. When the density decreases, the air is included inside the interstices of the granulated rubber with an increase of microporosity, the continuous changes of conducting phase from solid to air are responsible for the dissipation of sound energy [28].

Analyzing the samples by specific frequency ranges, different behaviors can be observed. At low frequencies, the samples with low density (B) and the presence of a mat with a thickness of 30 mm (2), where particle size has less effect, present the most significant values. The highest values in

sound absorption correspond to 12BS samples with a value of 0.676, very close to 21BS with a sound absorption value of 0.671. The results obtained at low frequencies are similar to those obtained by Pfretzschner et al. [29] who reported that the sound absorption values increase one octave when doubling thickness and an increase of the absorption coefficient with small particle sizes. Our results show that, in our case, the influence of the particle size is negligible.

Granular materials, such as ours, present better results with large thicknesses. As mentioned before, this is because sound absorption depends on the inherent characteristics of the material, porosity, flow resistivity and tortuosity. As reported by Swift et al. materials with high flow resistivity obtain maximum absorption values with high thickness [14].

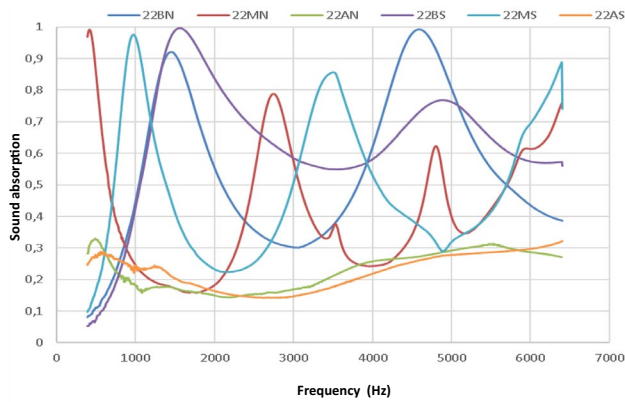
Although the particle size has practically no influence, at the lower frequencies it shows a certain effect. With a small particle size the porosity decreases, due to the compaction of the particles, increasing the airflow resistivity and the tortuosity, parameters that affect more at low frequencies and, therefore, the sound absorption at these values of frequencies is improved. This result is consistent with the results obtained by Segura et al. [30] where materials with small-size particle defined better acoustical absorption because of their lower specific acoustic impedance, and its inverse relation with the material absorption coefficient.

The sound absorption analysis for mid frequencies shows how, contrarily to the behavior observed at low frequencies, the samples with 20mm of thickness present better average values than the ones with 30mm of thickness. In the range of high frequencies, the behavior is analogous to the low frequencies, more thickness implies more sound absorption. According to Swift et al. [14] the visco-thermal effect becomes the main mechanism for sound absorption in porous samples when the sound path length increase.

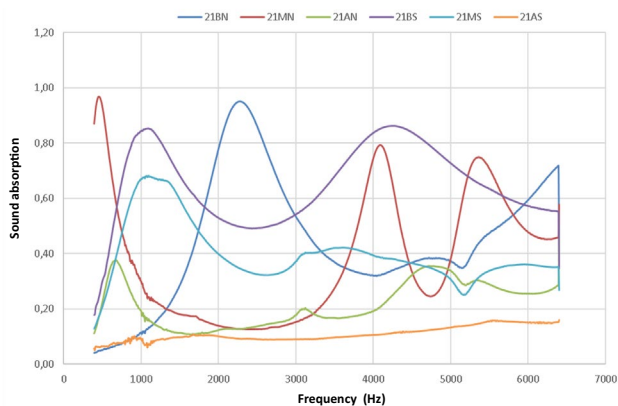
**Table 3** Sound absorption average values of the different samples as a function of the frequency ranges

	500–2000 Hz	2000–4000 Hz	4000–6500 Hz		500–2000 Hz	2000–4000 Hz	4000–6500 Hz
21BS	0.671	0.596	0.701	22MN	0.272	0.420	0.456
22BS	0.629	0.624	0.658	11BN	0.244	0.639	0.251
12BS	0.676	0.503	0.589	21MN	0.306	0.235	0.517
11BS	0.590	0.601	0.540	12AN	0.226	0.164	0.276
22BN	0.576	0.391	0.673	22AN	0.192	0.183	0.286
12BN	0.576	0.391	0.673	21AN	0.182	0.159	0.287
12MN	0.578	0.439	0.512	22AS	0.233	0.170	0.207
22MS	0.511	0.500	0.483	11MS	0.175	0.158	0.245
21BN	0.254	0.591	0.453	12AS	0.106	0.143	0.237
12MS	0.286	0.329	0.663	11AN	0.077	0.152	0.233
21MS	0.534	0.376	0.344	21AS	0.090	0.095	0.137
11MN	0.292	0.435	0.456	11AS	0.065	0.085	0.140

Samples code: XYZW X particle size 1: 2–3 mm; 2: 5–7 mm; Y thickness 1: 20 mm; 2: 30 mm, Z A ( $d=0.95 \text{ g/cm}^3$ ), M ( $d=0.80 \text{ g/cm}^3$ ), B ( $d=0.65 \text{ g/cm}^3$ ) W S: mat; N: no mat



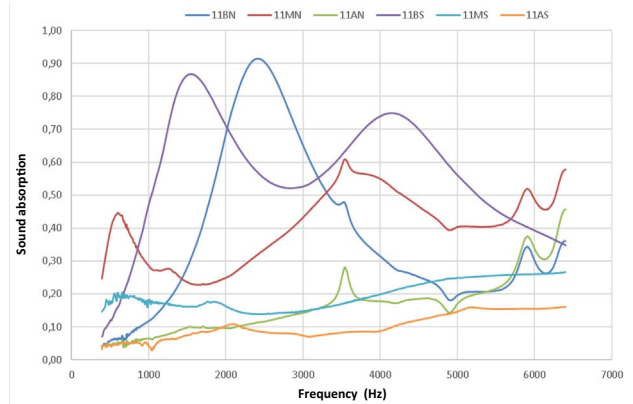
**Fig. 4** Comparative Sound absorption coefficient spectra for samples with size particles of 5–7 mm and thickness of 30 mm for different densities and presence or not of mat. (Samples code: XYZW X: particle size 1: 2–3 mm; 2: 5–7 mm; Y: thickness 1: 20 mm; 2: 30 mm, Z: A ( $d=0.95 \text{ g/cm}^3$ ), M ( $d=0.80 \text{ g/cm}^3$ ), B ( $d=0.65 \text{ g/cm}^3$ ), W: S, mat; N, no mat.)



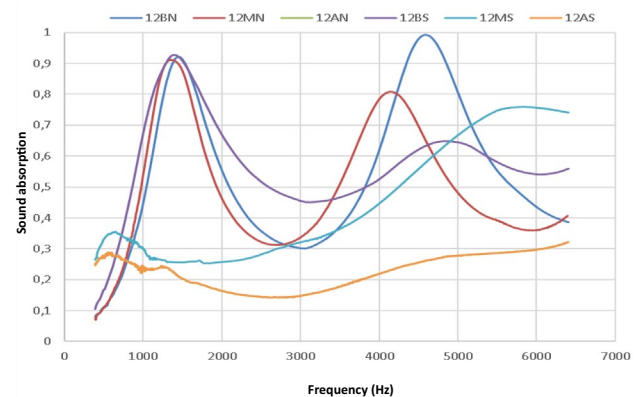
**Fig. 5** Comparative Sound absorption coefficient spectra for samples with size particles of 5–7 mm and thickness of 20 mm for different densities and presence or not of the mat

Another parameter that could have an effect on these results is the effect of the binder, which may increase the flow resistivity by a factor of 10.

Figures 4, 5, 6, 7, show the comparative sound absorption coefficient spectra for the analyzed samples. In all the figures two types of spectra are observed, one that corresponds to the samples of low and medium density and other related to the samples of high density. As previously mentioned, high-density samples are the ones with the worst acoustic performance. However, it can also be observed how the presence of mat shifts the sound absorption coefficient values to lower frequency ranges. This is because the fibrous structure of the mat defines a non-spherical irregular pore size that favors sound absorption at low frequencies, where the wave propagates asymmetrically causing the absorption of



**Fig. 6** Comparative Sound absorption coefficient spectra for samples with size particles of 2–3 mm and thickness of 20 mm for different densities and presence or not of the mat



**Fig. 7** Comparative Sound absorption coefficient spectra for samples with size particles of 2–3 mm and thickness of 30 mm for different densities and presence or not of the mat

a bigger amount of acoustic energy and then, the energy transmitted through the samples decreases [31].

Table 4 presents the statistical analysis of the values of the coefficients for the linear model applied to the frequency range between 500 and 2000 Hz (low frequencies). The factors that define the coefficient of the linear model of some level lower than the significance level (5%) have been considered.

The values show that the increase of the thickness from level 1 (20 mm) to level 2 (30 mm) improves the absorption by 0.115. If the density level increases from low (B) to medium, (M) the absorption decreases by 0.0508 and if it changes from low (B) to high (A), the absorption would decrease by 0.243. When the sample includes mat, the absorption is increased in 0.229 without considering the interactions. Interactions allow the combination of two factors to examine their values. Analyzing the interaction

**Table 4** Statistical analysis of the coefficients applied to the frequency range between 500 and 2000 Hz (low frequencies)

Low frequencies	Estimate	Std. error	t value	Pr(> t )
(Intercept)	3.55E-01	6.09E-02	5.83	2.03E-05
Thickness2	1.15E-01	4.61E-02	2.50	2.29E-02
DensityM	- 5.08E-02	7.98E-02	- 0.64	5.33E-01
DensityA	- 2.43E-01	7.98E-02	- 3.05	7.28E-03
MatS	2.29E-01	7.98E-02	2.87	1.07E-02
DensityM:MatS	- 2.14E-01	1.13E-01	- 1.90	7.51E-02
DensityA:MatS	- 2.75E-01	1.13E-01	- 2.43	2.63E-02

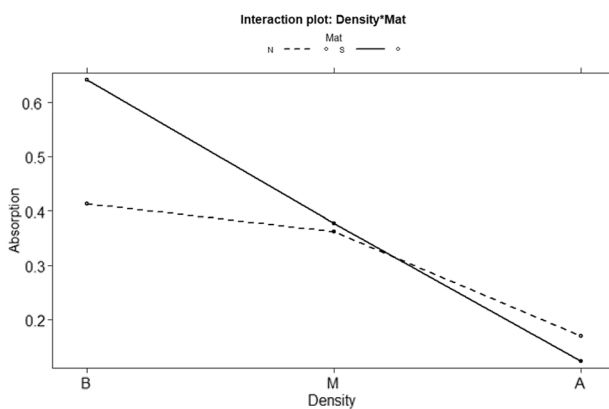
between density and mat, i.e. sample 11BS the absorption value would be 0,584 according to the linear model (Sound Absorption (0.584)=0.355+0.115 · 0-0.0508 · 0-0.243 · 0+0.229 · 1-0.214 · 0-0.275 · 0). Comparing this value with the experimental value for 11BS (0.5896), the percentual difference is only 1%. Instead, in sample 11BN, all levels are low and therefore the value of the intercept is 0.355. If the value obtained by the linear model is compared to the experimental value of 11BN (0.2436), the difference is 37%.

The Adjusted R-squared coefficient of the model is 0.7042, implying that the model is suitable to analyze the relationships between variables. The p value of the model is 7.89·10<sup>-5</sup>, then, considering a significance level of 5%, the null hypothesis is rejected. The model is considered statistically significant.

Figure 8 shows the interactions between density and mat, the sound absorption changes with the combination of the levels of the analyzed factors. According to Fig. 8 with the low value of density the sound absorption increases compared to the other two levels, but in the case of No Mat, the model obtains a similar response to the average density. For a high-density value and No Mat (N) it obtains a better response than a sample with Mat (S). The interaction between medium density (M) and Mat (S) is not statistically significant with a P value 0.07 > 0.05.

Analyzing the range of mid frequencies: 2000 and 4000 Hz (Table 5) it is relevant that the coefficients of the linear model, define negative t values. It means that all the analyzed factors decrease sound adsorption. An increase of the thickness from 20 to 30 mm would decrease the absorption by 0.129 (excluding interactions). Increasing the density of the low level (B) to the middle (M) significantly decreases the absorption by 0.306; and from low to high density (A), the absorption would decrease by 0.484.

Interactions should be considered for level 2 of thickness (30 mm), where for low-density samples the sound absorption decrease by 0.129 units compared to a thickness of 20 mm. The Adjusted R-squared coefficient of the model is 0.852, this means that the model allows to analyze of the relationships between variables. The p value of the model is



**Fig. 8** Interactions between density and mat

2.628·10<sup>-6</sup>, therefore, considering a significance level of 5%, the null hypothesis is rejected and the model is considered statistically significant.

Table 6 shows the coefficients of the linear model performed for the frequency range between 4000 and 6000 Hz (high frequencies). The factors that define the level lower than the significance level (5%) have been analyzed. For this range of frequencies, the t values show as an increase in thickness improves sound adsorption and an increase in density reduces the value of sound adsorption.

The coefficient R squared has been calculated and the value was 0.6878, indicating that this is a good model for describing response variables. According to this regression model and P-Value parameter for high frequencies, thickness, with a P-value of 0.0112, has an effect on sound adsorption results and density (P-Value 1.89·10<sup>-6</sup>) has a great influence on sound adsorption.

From the experimental results and the statistical study, it can be concluded that the analysed parameters (particle size, thickness, density and presence of mat) affect in a different way depending on the frequency range.

**Table 5** Statistical analysis of the coefficients applied to the frequency range between 2000 and 4000 Hz (medium frequencies)

Mid frequencies	Estimate	Std. error	t value	Pr(> t )
(Intercept)	6.51E-01	4.42E-02	14.72	2.52E-10
Thickness2	- 1.29E-01	5.11E-02	- 2.54	2.29E-02
DensityM	- 3.06E-01	5.11E-02	- 5.99	2.47E-05
DensityA	- 4.84E-01	5.11E-02	- 9.48	1.00E-07
Size_particle1:MatN	- 2.34E-02	4.17E-02	- 0.56	5.82E-01
Size_particle2:MatN	- 6.35E-02	4.17E-02	- 1.52	1.49E-01
Size_particle1:MatS	- 9.04E-02	4.17E-02	- 2.17	4.67E-02
Thickness2:DensityM	2.51E-01	7.22E-02	3.47	3.41E-03
Thickness2:DensityA	1.72E-01	7.22E-02	2.38	3.10E-02

**Table 6** Statistical analysis of the coefficients applied to the frequency range between 4000 and 6000 Hz (high frequencies)

High frequencies	Estimate	Std. error	t value	Pr(> t )
(Intercept)	5.08E-01	4.21E-02	12.071	1.23E-10
Thickness2	1.18E-01	4.21E-02	2.794	1.12E-02
DensityM	− 1.08E-01	5.16E-02	− 2.088	4.98E-02
DensityA	− 3.42E-01	5.16E-02	− 6.624	1.89E-06

The most overall affecting parameter is the density, for all frequency ranges, samples with low density give the best results. High thickness and mat improve the response for high frequencies and low frequencies retaining the sound absorption at mid frequencies. The particle size is the parameter that has less effect on the acoustical properties.

## Conclusions

The use of GTR as a thermal and acoustic insulator with minimal processing, only using an adequate binder can provide a new way to recycle the end-of-life tires including the fibers, which are seldomly considered as a recycling candidate.

The Lewis-Nielsen modelization presented more accuracy with the experimental results than the other models studied for thermal conductivity, with deviations of less than 3%.

In terms of thermal conductivity, statistical and experimental studies showed that high thermal conductivity is achieved in the samples with: large thickness (sample of 30 mm better than that of 20 mm); large particle size (5–7 mm better than 2–3 mm); without mat and with a high density due that these samples present less porosity.

In terms of sound absorption, statistical and experimental studies implied that the samples with the higher values are: samples with low density, samples including mat, samples that are thicker (30 mm). The parameter with less influence on the sound absorption is the particle size of the GTR.

According to both results, good insulation properties (high sound absorption and low thermal conductivity) would be achieved with materials with features like: low density with many pores; which include mat; and thick. However, thickness may be compromised in some applications depending on the priority given to acoustic or thermal insulation. Although the effect is low, it can be noted that small particles size is preferable to large particles.

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