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Multilayer Granular Recycled Rubber for Its Application to Technical Flooring

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Abstract: The aim of this study is to investigate the static and dynamic behaviour of multilayer materials manufactured from granular recycled rubber applied to technical flooring. The studied samples were manufactured by varying their thickness, density and granulometry, as these are the parameters that determine the performance of these rubbery materials. Two mechanical tests, static and dynamic, were carried out under controlled conditions to evaluate the mechanical behaviour of these materials by means of its modulus of elasticity and dynamic stiffness. Relating dynamic stiffness to impact sound insulation, it can be concluded that these materials are suitable for use in technical flooring, such as in fitness facilities. The selection will vary for static and dynamic behaviour, with different materials suitable for different applications. In general, the most suitable material for high stiffness applications is the one that reached values of 67.3 MPa for the static modulus and 72.96 MPa for the dynamic modulus of elasticity. The results allow for the consideration of these materials as substitutes for the most commonly used materials, such as ethylene vinyl acetate.

Keywords: recycled rubber; dynamic stiffness; natural frequency; modulus of elasticity

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1. Introduction

The environmental problems caused by end-of-life tires (ELT), and the consequent environmental policies, make companies pay attention to their products and manufacturing methods [1–3]. For this reason, many products manufactured from recycled rubber have appeared during the last decades. These recycled products reduce the number of scrapped tires and the amount of waste. Some of these new products have been utilized in flooring, specifically in pavements designed for impact and sound insulation, such as in sports fields.

A review of the research on the mechanical properties of granular soils blended with recycled rubber inclusions was conducted by Tasalloti et al. [4]. The experimental data and results of the analyses are presented and discussed in terms of the effects of rubber content and strength properties, along with dynamic characteristics. This study promotes the use of recycled rubber tires in civil engineering projects.

Waste management is a serious environmental problem as some researchers claim that polymer materials do not easily decompose [5].

The dynamic behaviour of recycled rubber, which is a viscoelastic material, has been studied because of its efficiency in absorbing energy. This is why it is commonly used in applications where impact forces must be absorbed. In addition, previous studies have shown that rubber improves acoustical properties when it is mixed with other materials [6].

Chettah et al. investigated recycled rubber granulates added to damp rectangular tubes. A model for calculating the displacement–force frequency responses was derived by means of the dynamic stiffness method (DSM) [7].

On the other hand, it is also known that greater porosity always gives higher values of acoustic insulation because the energy of the sound wave is absorbed inside the pores [8,9].

Therefore, it can be deduced that composite materials made of granular rubber present high sound-insulating properties [10]. One of the main applications consists of using rubber in pavements, as modified asphalt, as noise reduction is achieved by porous roads [11]. Other applications of waste tires are in seismic-isolation foundation systems [12] and playgrounds [13].

Other studies are related to other applications of the rubber, such as the research by Zhou Hong [14] and Swift [15], which focused on absorbers and noise barriers, respectively. There are other applications for the automotive industry, such as the work of Soto [16].

Sookprasert and Hinchiranan [17] studied the variations of mechanical properties of natural rubber by adding NR-PLA, resulting in an increase in the impact strength.

The performance of rubber components is governed by its dynamic behaviour, such as stiffness and damping properties that determine the transmission of vibrations through the material. The characterization has been conducted by an electrodynamic shaker [18]. Other authors have focused their research on simulations, such as the work conducted by Thaijaroen [19] to simulate the application of rubber materials as isolators.

As for the mechanical behaviour of rubber, the Young's Modulus, which is directly related to the stiffness, is a fundamental property to understand the mechanical response of the material [20].

Some other properties have an influence on the energy absorption of the materials, based on phenomenological models that require parameters such as tortuosity, porosity and the shape factor of the pore [21–23]. Other works are based on empirical models [24–27] that relate experimental sound-absorbing values to predicted ones.

Combining all the parameters that influence the impact- and sound-absorbing properties in the right way results in a suitable material for technical sports pavements. Gaining knowledge of these parameters and how these materials behave under dynamic forces would facilitate the proper design of these materials, depending on the final flooring application.

Nowadays, it is still unknown how to combine the parameters to obtain a multilayer composite material mainly made of granular recycled rubber coming from used tires that is able to offer the most suitable elastic, dynamic and acoustical properties for technical floors in fitness facilities.

Knowing the dynamic responses of these multilayer materials, it will be easier to predict whether they are suitable under specific conditions of impact and mechanical strength. This investigation will allow us to predict the behaviour of other rubbery materials with similar characteristics under the same working conditions.

This investigation focuses on the possibility of the replacement of typical flooring fitness mats with these new materials based on recycled rubber.

2. Materials

2.1. Recycled Rubber

The main source of natural rubber latex is the Hevea Brasiliensis, though there are many other plants that produce latex rich in isoprene polymers [28].

Nowadays, it is possible to manufacture synthetic rubber from unsaturated hydrocarbons. The main synthetic rubbers are polyisoprene, polybutadiene, nitrile rubber, neoprene and ethylene-propylene rubber, among others.

The advantage of an artificial rubber is that the structure is more homogeneous, and its behaviour is similar to natural rubber. On the other hand, natural rubber can be vulcanized due to double bonds in its structure. Its properties significantly differ after vulcanization. Table 1 shows some differences between natural and vulcanized rubber [29]:

Table 1. Comparison between natural and vulcanized rubber.

Properties	Raw Rubber	Vulcanized Rubber
Behaviour	Thermoplastic	Thermostable
Surface aspect	Sticky	Non-sticky
Tensile strength	Low	High
Elasticity	Low	High
Deformability	Low	Nonexistent

The manufacturing process of synthetic rubber involves a number of additives: vulcanization agents, accelerators, activators, plastifiers, anti-degradants, anti-reversion, retardants and reinforcements. Among the applications of granulated rubber from crushed tires, which are mainly found in fuels, include additives for asphalts, fillers for artificial grass, carpets and technical flooring.

2.2. Test Specimen Preparation

The rubber test specimens analysed in this paper were provided by a company that manufactures technical flooring for gyms. These products consist of a base layer composed of a mixture of recycled rubber grains from end-of-life tires mixed with a resin matrix and a surface layer made of vulcanized rubber. The surface layer has 3 mm thickness, and the base layer has two different thicknesses: 17 and 19 mm, which results in specimens of 20 and 22 mm, respectively (Figure 1).

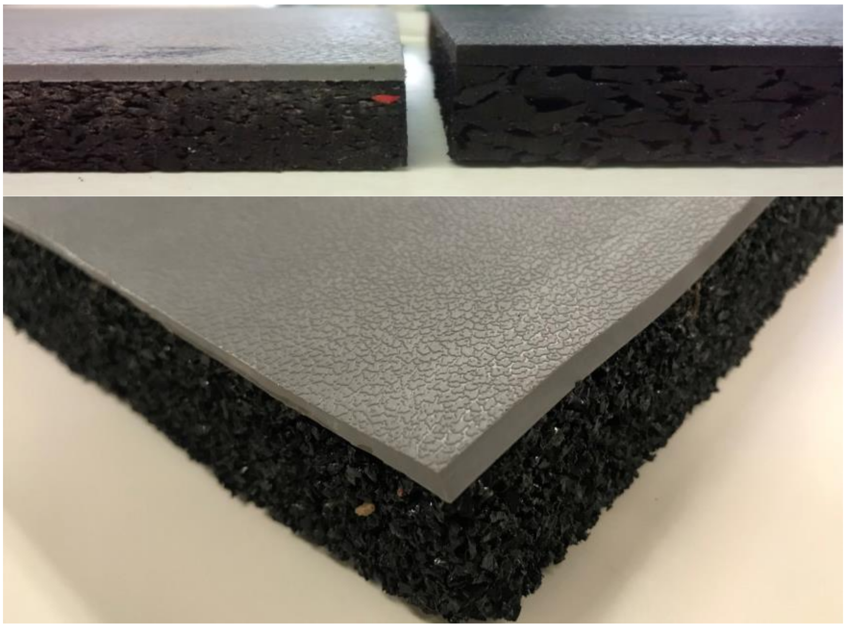

Figure 1. (**Top**) The two studied specimens with different thicknesses, densities and granulometries. (**Bottom**) The untreated/natural rubber layer and treated/vulcanized layer.

The surface layer is the one manufactured with treated cured rubber (under specific pressure and temperature conditions) and the bottom layer that comes in contact with the ground is made of untreated rubber from end-of-life tires.

The manufacturing process of the two layers is different. The surface layer is made in a steel mold at 165 °C with a pressure of 100 kg/cm^2 (9.8 MPa) for 12 min. On the other hand, the base or filler is made by mixing polyurethane resin (Voramer MR 1101) with recycled rubber grains. Then, both layers are assembled applying heat (at 125 °C) for 20 min. Figure 2 shows the microstructure of a sample at different scales.

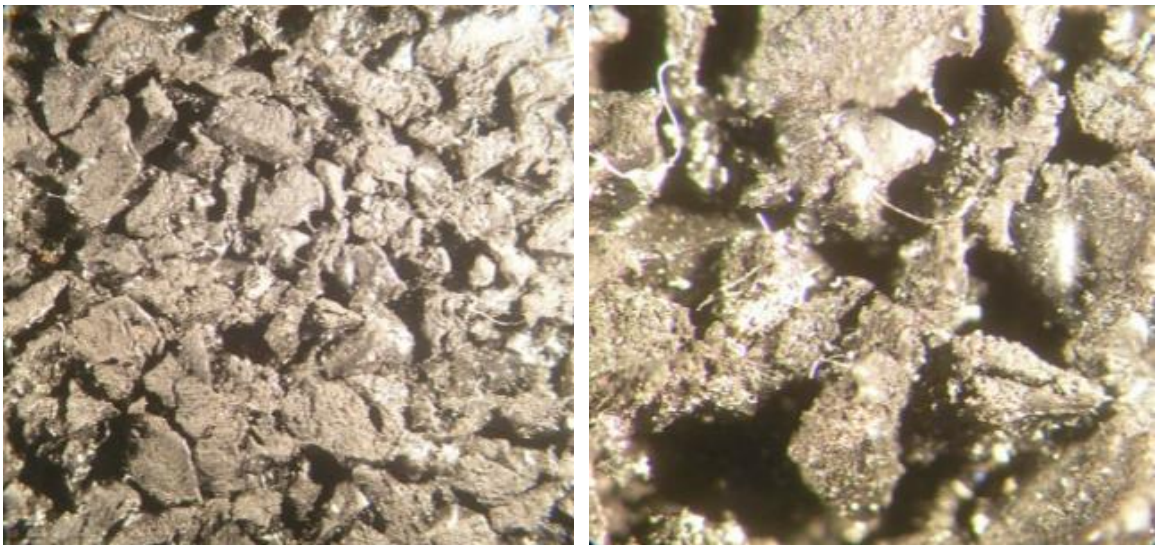

Figure 2. The structure of a rubber sample at two different photo enlargements.

3. Experimental Methods

This paper aims to study the static and dynamic mechanical behaviour of these multilayer rubbery materials, mainly composed of recycled rubber grains, by carrying out static and dynamic tests, specifically the static cantilever beam test and dynamic stiffness test.

In this study, twelve samples were analysed with different thicknesses, densities and granulometries. There were two thicknesses, three densities and two grain sizes. The values of these parameters are shown in Table 2:

Table 2. Parameter values of the materials.

Thickness (mm)	Density (g/cm^3)	Granulometry (mm)
$T_1 = 20$ $T_2 = 22$	$D_1 = 0.85$ $D_2 = 0.90$ $D_3 = 0.95$	$G_1 = 1–3$ $G_2 = 4–8$

Twelve samples were manufactured by combining these parameters.

3.1. Physical Properties

Among the physical properties that characterize a material, two have a major influence on dynamic behaviour: the specific gravity and porosity.

3.1.1. Specific Gravity

The specific gravity (SG) is the ratio of the mass of the material to the mass of the same water volume at the same temperature, 23 °C. This parameter was obtained following the recommendations of the standard ASTM D792-08 [30].

Specific gravity is a property measured to identify a material. Changes in density are due to localized differences in crystallinity, loss of plasticizer, or absorption of solvent, among other causes.

According to the standard, this test method is intended to determine the specific gravity of a specimen. To do that, a balance with a precision of at least 0.1 mg is recommended. The balance is equipped with a support for the immersion vessel.

The equipment is represented in Figure 3:

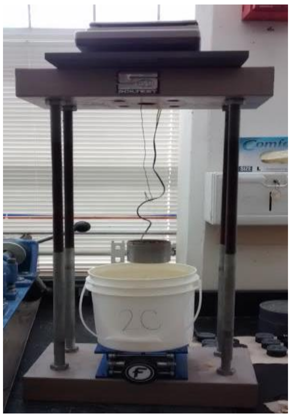

Figure 3. Measurement of the specific gravity.

The specific gravity is determined by Equation (1):

$$SG = \frac{a}{(a + w + b)} \tag{1}$$

where a is the bulk mass of the sample; w is the bulk mass of the container submerged in water; and b is the bulk mass of the saturated sample submerged in water. The specific gravity results are shown in Table 3:

Table 3. Specific gravity of the samples.

Samples	Container Mass with Air (g)	Container Mass with Water (g)	Container Mass and Sample (g)	Container Mass and Saturated Sample (g)	SG
T1D1G1	141.03	123.35	162.47	126.6	1.18
T1D1G2	141.03	123.35	162.86	126.89	1.19
T1D2G1	141.03	123.35	160.49	126.63	1.20
T1D2G2	141.03	123.35	161.42	126.2	1.16
T1D3G1	141.03	123.35	162.34	127.28	1.23
T1D3G2	141.03	123.35	162.78	126.72	1.18
T2D1G1	141.03	123.35	164.18	127.52	1.22
T2D1G2	141.03	123.35	163.56	126.71	1.18
T2D2G1	141.03	123.35	165.5	127.28	1.19
T2D2G2	141.03	123.35	162.22	126.64	1.18
T2D3G1	141.03	123.35	164.43	124.2	1.04
T2D3G2	141.03	123.35	163.7	126.47	1.16

3.1.2. Porosity

Porosity is the volume of the air between the rubber grains of the filler with respect to the total volume of the material. It is a very important parameter when characterizing materials as it has an influence on the mechanical properties of the material.

The percentage of pores can be obtained by means of Equation (2):

$$\text{Porosity } (\%) = 1 - \frac{\rho_{ap}}{(\text{SG} \times \rho_{water})} \tag{2}$$

ρ_{ap} denotes the apparent density of the material (kg/m^3); ρ_{water} denotes the density of the water (kg/m^3); and SG denotes specific gravity (dimensionless).

Table 4 shows the values of porosity.

Table 4. Porosity of the samples.

Samples	Apparent Density (kg/m^3)	Water Density (kg/m^3)	SG	Porosity (%)
T1D1G1	850	1000	1.18	28
T1D1G2	850	1000	1.19	29
T1D2G1	900	1000	1.20	25
T1D2G2	900	1000	1.16	23
T1D3G1	950	1000	1.23	23
T1D3G2	950	1000	1.18	20
T2D1G1	850	1000	1.22	30
T2D1G2	850	1000	1.18	28
T2D2G1	900	1000	1.19	24
T2D2G2	900	1000	1.18	24
T2D3G1	950	1000	1.04	8
T2D3G2	950	1000	1.16	18

3.2. Cantilever Bending Static Test

According to the bending theory, the deflection (y) of a cantilever beam subjected to a specific force is defined by Equation (3), as follows:

$$y = \frac{L^3 \cdot F}{3 \cdot E \cdot I} \tag{3}$$

L is the cantilever length (m), F is the applied force at the free end (N), I is the moment of inertia of the cross-section referred to the neutral axis (m^4) and E is the modulus of elasticity of the material (Pa). This formula allows us to determine the modulus of elasticity when the value of the deflection for a particular applied force is known.

Figure 4 shows the scheme of the static test.

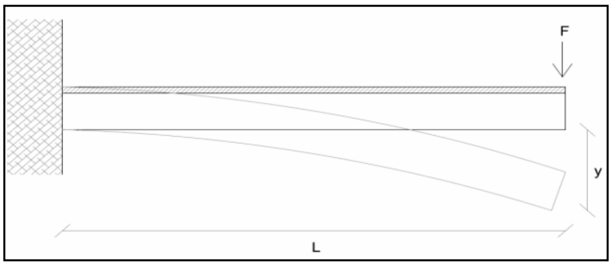

Figure 4. Scheme of the cantilever beam test.

Due to the two layers, this test has only been conducted to compare the behaviour of the materials. The test can only be considered as an estimate approach, as the modulus of elasticity obtained is not of each layer or each material, but the average elastic modulus of the multilayer material, considering it an equivalent elastic modulus.

3.3. Dynamic Modulus of Elasticity: Ultrasound Test

The non-destructive P-waves test was conducted according to the recommendations of the standard ASTM D2845-08 and used the following equipment:

- Signal generator.
- Two transductors, transmitter and receptor.
- One oscilloscope.

The ASTM D2845-08 has been withdrawn, but the method has been demonstrated to work with a high level of reliability in the results.

The equipment is a PUNDIT Plus Kit manufactured by CNS FARNELL with piezo-electric transductors of 54 kHz.

Figure 5 shows the scheme of the ultrasound test.

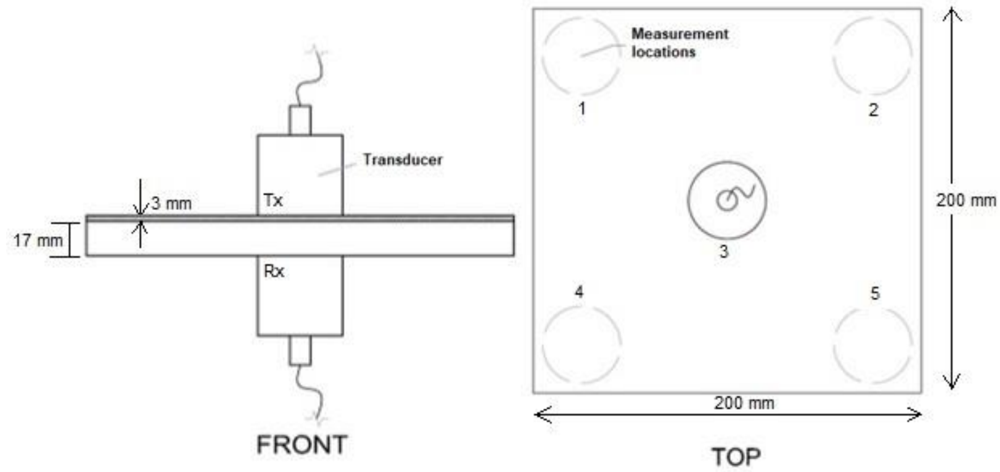

Figure 5. Ultrasound test scheme.

The propagation velocity of the wave in a composite material is determined by means of Equation (4):

$$v_c = \frac{L_1 + L_2}{\frac{L_1}{v_1} + \frac{L_2}{v_2}} \tag{4}$$

where L_1 is the thickness of layer 1 (surface layer: 0.003 m); L_2 is the thickness of layer 2 (0.017 or 0.019 m, depending on the sample); v_1 is the propagation velocity in layer 1; and v_2 is the propagation velocity in layer 2.

From the velocity, a modulus (M) can be obtained from Equation (5):

$$M = v^2 \cdot \rho \tag{5}$$

where ρ is the density of the material.

Finally, the dynamic modulus of elasticity is obtained by Equation (6):

$$E = \frac{M \cdot (1 + \mu)(1 - 2 \cdot \mu)}{(1 - \mu)} \tag{6}$$

where μ is Poisson's ratio.

3.4. Dynamic Stiffness Test

Dynamic stiffness is a parameter that defines the capacity of a material to conduct vibration energy, and consequently provides information about the impact sound attenuation of pavements.

The dynamic stiffness test was carried out according to the standard UNE EN 29052-1:1994, which establishes the method for the excitation of the loading mass using a calibrated impact hammer. As the standard recommends, a square steel plate with a 200 mm side with a maximum weight of 8 kg was used. Impact signals were recorded by an accelerometer and sent to a spectrum analyser. The scheme of the test is shown in Figure 6.

The dynamic stiffness (s_t) is determined from the natural frequency of the system, according to Equation (7):

$$s_t = 4 \cdot \pi^2 \cdot m_t \cdot f_r^2 \tag{7}$$

m_t being the total mass per unit area (kg/m^2) and f_r the natural frequency (Hz).

Dynamic stiffness is related to the attenuation of airborne sounds due to impacts. The higher the dynamic stiffness, the lower the impact sound insulation.

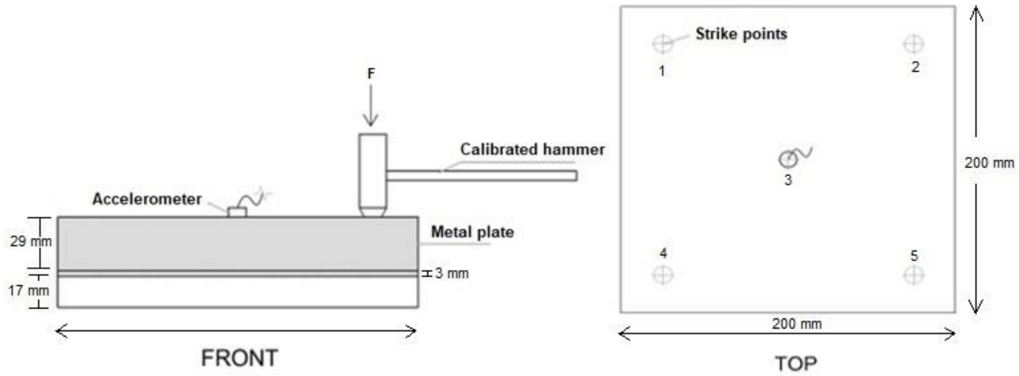

Figure 6. Front and top view of the dynamic stiffness test.

4. Results

The results allow us to relate the static and dynamic behaviour of these materials, depending on the thickness, density and granulometry of the samples.

4.1. Static Modulus of Elasticity (Cantilever Bending Static Test)

Table 5 shows the modulus of elasticity according to the cantilever bending test.

Table 5. Cantilever bending static test.

Samples	Density (kg/m^3)	E (MPa)
T1D1G1	850	49.55
T1D1G2	850	53.05
T1D2G1	900	54.99
T1D2G2	900	57.81
T1D3G1	950	53.68
T1D3G2	950	67.30
T2D1G1	850	48.39
T2D1G2	850	45.78
T2D2G1	900	47.71
T2D2G2	900	56.46
T2D3G1	950	48.39
T2D3G2	950	48.39

The lowest modulus of elasticity corresponds to T2D1G2, which had a thickness of 22 mm, density of 850 kg/m^3 and granulometry of 4 to 8 mm.

On the other hand, the highest value was for T1D3G2, which had a thickness of 20 mm, density of 950 kg/m^3 and granulometry of 4 to 8 mm.

Figure 7 shows graphs with the results of the modulus of elasticity for the samples.

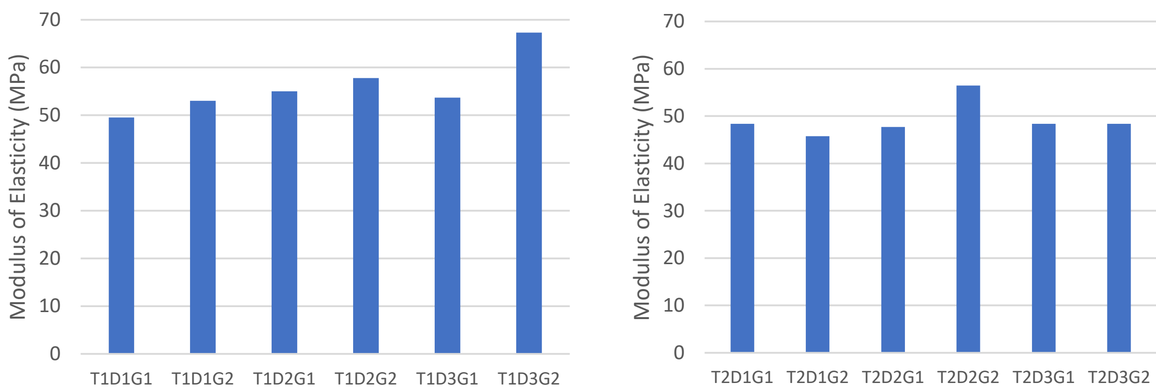

Figure 7. Modulus of elasticity values.

As a general approach, for the same thickness, the granulometry G2 presented higher values, and samples of thickness T1 had higher values for the modulus of elasticity.

4.2. Dynamic Modulus of Elasticity (Ultrasound)

Table 6 shows the values of the dynamic modulus of elasticity.

In general, samples of thickness T1 presented higher values of the dynamic modulus of elasticity.

Table 6. Dynamic modulus of elasticity.

Samples	Density (kg/m^3)	$E_{dynamic}$ (MPa)
T1D1G1	850	42.93
T1D1G2	850	54.66
T1D2G1	900	49.91
T1D2G2	900	59.04
T1D3G1	950	51.00
T1D3G2	950	72.96
T2D1G1	850	42.40
T2D1G2	850	45.12
T2D2G1	900	48.12
T2D2G2	900	52.65
T2D3G1	950	48.76
T2D3G2	950	46.18

Figure 8 shows the graphs of the dynamic modulus of elasticity:

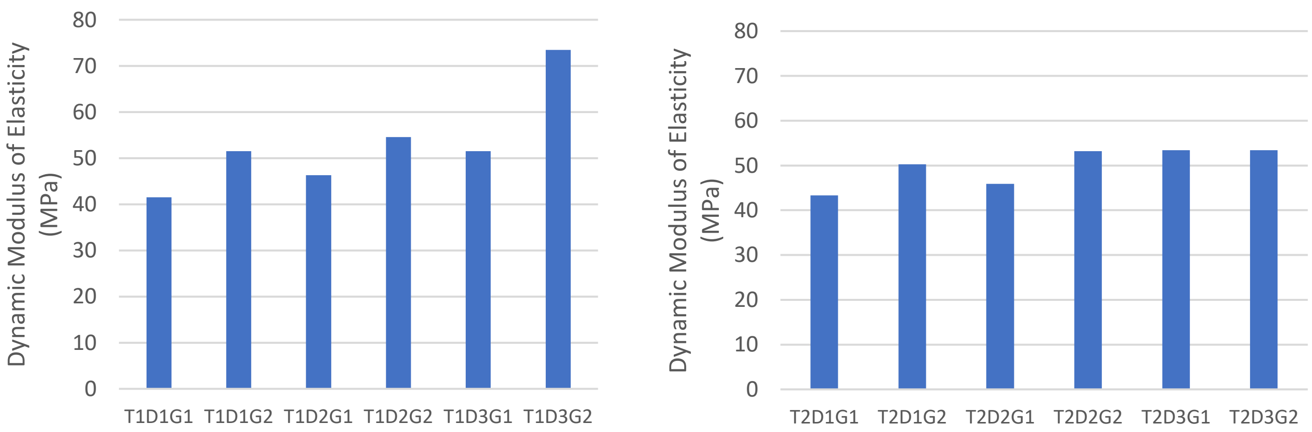

Figure 8. Dynamic modulus of elasticity. Left: thickness T1 samples; right: thickness T2 samples.

4.3. Dynamic Stiffness

Table 7 shows the dynamic stiffness values.

Table 7. Dynamic stiffness results.

Samples	Density (kg/m^3)	S′ (MN/m^3)
T1D1G1	850	36.93
T1D1G2	850	41.48
T1D2G1	900	48.10
T1D2G2	900	37.74
T1D3G1	950	41.05
T1D3G2	950	30.06
T2D1G1	850	37.53
T2D1G2	850	29.16
T2D2G1	900	30.06

Table 7. *Cont.*

Samples	Density (kg/m^3)	S′ (MN/m^3)
T2D2G2	900	42.76
T2D3G1	950	36.33
T2D3G2	950	47.19

These results are compared with the values of ethylene vinyl acetate (EVA), which is the traditional material used in technical flooring with good sound impact absorbing properties [31]. According to this work, an EVA sample of 40 mm thickness and 100 kg/m^3 density presents a dynamic stiffness of 23.3 MN/m^3. This sample can be used as a reference.

Figure 9 shows the graphs with the results of the dynamic stiffness for the samples.

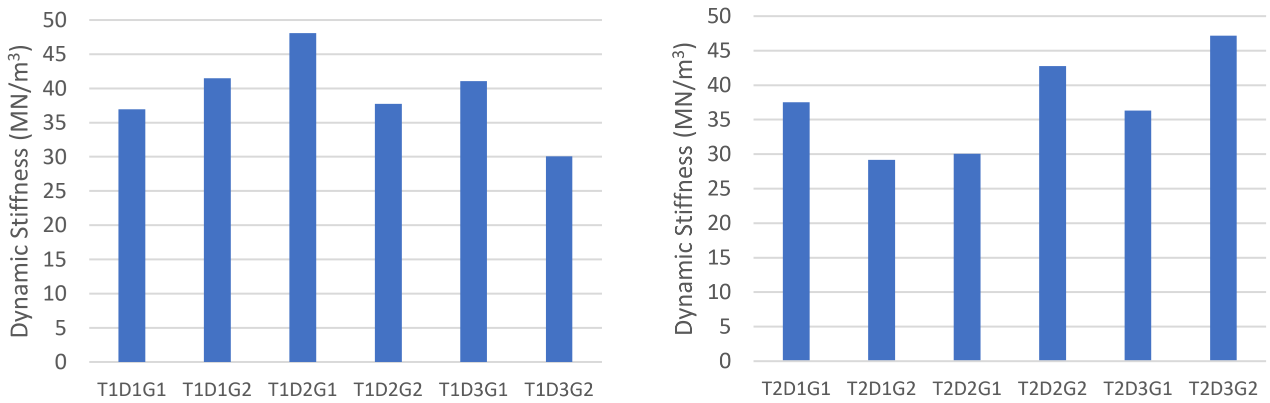

Figure 9. Dynamic stiffness values. Left: thickness T1 samples; right: thickness T2 samples.

4.4. Impact Sound Reduction

From the results of the dynamic stiffness, the impact sound reduction coefficient (ΔL_w) can be determined by Equation (8), given in the Standard ISO 12354-2:2017:

$$\Delta Lw = 18 + 15 \cdot \log\left(\frac{m'}{S'}\right) \quad (8)$$

where m' is the material mass per unit area (kg/m^2) and S' is the dynamic stiffness (MN/m^3). Table 8 shows the results of the impact sound reduction.

As expected, the sample that had the lowest dynamic stiffness presented the highest impact sound insulation value. This sample had a thickness of 22 mm, density of 900 kg/m^3 and granulometry of 4 to 8 mm (T2D2G2). On the other hand, the sample that had the highest dynamic stiffness presented the lowest impact sound insulation value. This sample had a thickness of 20 mm, density of 900 kg/m^3 and granulometry of 1 to 3 mm (T1D2G1).

Table 8. Impact sound reduction.

Samples	Density (kg/m^3)	Thickness (m)	m' (kg/m^2)	S' (MN/m^3)	ΔLw (dB)
T1D1G1	850	0.02	17	36.93	12.95
T1D1G2	850	0.02	17	41.48	12.19
T1D2G1	900	0.02	18	48.10	11.6
T1D2G2	900	0.02	18	37.74	13.18
T1D3G1	950	0.02	19	41.05	12.98
T1D3G2	950	0.02	19	30.06	15.01
T2D1G1	850	0.022	18.7	37.53	13.46

Table 8. *Cont.*

Samples	Density (kg/m^3)	Thickness (m)	m' (kg/m^2)	S' (MN/m^3)	ΔLw (dB)
T2D1G2	850	0.022	18.7	29.16	15.11
T2D2G1	900	0.022	19.8	30.06	15.28
T2D2G2	900	0.022	19.8	42.76	12.98
T2D3G1	950	0.022	20.9	36.33	14.4
T2D3G2	950	0.022	20.9	47.19	12.69

Figure 10 shows the graphs with the results of the impact sound reduction for the samples.

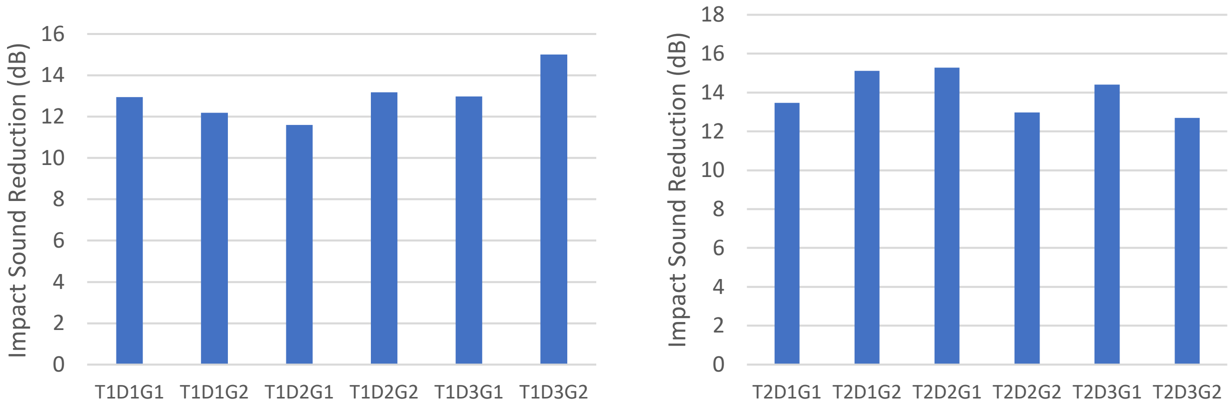

Figure 10. Impact sound insulation values. Left: thickness T1 samples; right: thickness T2 samples.

Table 9 summarizes all the results according to the different tests carried out:

Table 9. Results of the different tests.

Samples	E_{static} (MPa)	$E_{dynamic}$ (MPa)	S' (MN/m^3)	ΔLw (dB)
T1D1G1	49.55	42.93	36.93	12.95
T1D1G2	53.05	54.66	41.48	12.19
T1D2G1	54.99	49.91	48.10	11.6
T1D2G2	57.81	59.04	37.74	13.18
T1D3G1	53.68	51.00	41.05	12.98
T1D3G2	67.30	72.96	30.06	15.01
T2D1G1	48.39	42.40	37.53	13.46
T2D1G2	45.78	45.12	29.16	15.11
T2D2G1	47.71	48.12	30.06	15.28
T2D2G2	56.46	52.65	42.76	12.98
T2D3G1	48.39	48.76	36.33	14.4
T2D3G2	48.39	46.18	47.19	12.69

The comparison between the static and dynamic modulus of elasticity allows us to determine a coefficient or ratio between them (Table 10).

Table 10. Ratio between the static and dynamic modulus.

Samples	E_{static} (MPa)	$E_{dynamic}$ (MPa)	Ratio $E_{static}/E_{dynamic}$
T1D1G1	49.55	42.93	1.154
T1D1G2	53.05	54.66	0.971
T1D2G1	54.99	49.91	1.102
T1D2G2	57.81	59.04	0.979
T1D3G1	53.68	51.00	1.053
T1D3G2	67.30	72.96	0.922
T2D1G1	48.39	42.40	1.141
T2D1G2	45.78	45.12	1.015
T2D2G1	47.71	48.12	0.991
T2D2G2	56.46	52.65	1.072
T2D3G1	48.39	48.76	0.992
T2D3G2	48.39	46.18	1.048

The average ratio between the static and dynamic stiffnesses was 1037, which means that the results were quite similar for the two methods of calculation.

Finally, considering the results of the studied parameters for all the materials, it can be concluded that the composition T1D3G2 is the most suitable for applications where high stiffness is required.

5. Conclusions

The use of recycled rubber in the production of technical flooring can solve the current problems of waste disposal and noise pollution of roads. Among the main advantages of reusing rubber, it costs around half that of natural rubber, conserves non-renewable petroleum products, and generates work in recycling industries.

The results of this research allow us to consider the application of panels manufactured from granular recycled rubber in fitness facilities as an impact sound absorber substituting the most commonly used materials, such as the ethylene vinyl acetate. This is one of the innovative perspectives of using these recycled materials.

Our study has demonstrated that static and dynamic experimental methods produce similar results. In general, there are no noticeable differences in the static and dynamic behaviour among these materials because of their similarities. However, the use of the materials will depend on the fitness application. When the activity requires a more rigid floor, the impact sound reduction will be lower. This is demonstrated by the fact that the samples with the lower dynamic stiffness values presented the highest impact sound reduction values.

Thickness, density and granulometry are the parameters that determine the performance of these rubbery materials. Selection will vary for static or dynamic behaviour, with different materials suitable for different applications. This work shows an approach to choose the best rubbery material for a corresponding room.

Another application for these rubbery materials is their use as sound absorber barriers, as the porosity in their internal structure make these materials suitable for absorption mechanisms.

Further research is under way to develop a model that allows us to predict the optimal configuration in terms of thickness, density and granulometry for a given requirement related to technical flooring.

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