Sound absorbing properties of materials made of rubber crumbs

F. Asdrubali, F. D'Alessandro and S. Schiavoni

Università degli studi di Perugia, Via G. Duranti 67, 06125 Perugia, Italy
fasdruba@unipg.it

Recycled tyre granules can be used for manufacturing acoustic insulating and absorbing materials, with applications in buildings and road barriers. Therefore, the production of these materials is a valid alternative to the disposal into landfill or incineration of used tyres. This paper presents the results of sound absorbing coefficient measurements of several samples manufactured at the Acoustics Laboratory of the University of Perugia. The sound absorbing panels were produced by mixing rubber crumbs and an adequate binder in a proper proportion and then by compacting the obtained mix. The methodology used to evaluate the coefficient of absorption coefficient is indicated in ISO 10534-2 standard, thanks to an impedance tube. The influence on the absorption performance of granules size, binder concentration, thickness and compaction ratio of the samples was investigated and an optimization process was carried out, in order to produce a sample with satisfying acoustical performance.

1 Introduction

Used tyres represent an enormous amount of material to be disposed. Around 2.500.000 tons of used tyres per year have been produced in the last years in the European Union; this number grows to 3.250.000 tons in the United States. This situation causes obvious problems related to management costs and environmental impact.

The European Directive 1999/31/CE on the landfill of waste establishes that from the year 2003 whole tyres cannot be disposed into landfill and from the year 2006 also ground tyres are banned.

So new solutions for their re-use are urgently required. The development of novel acoustic materials created from ground tyres can possibly be one of these solutions.

Materials made of rubber crumbs usually have high porosity and consequently good sound absorbing properties. However the grains alone show no mechanical strength, so it is necessary to mix them with an adequate binder and to consolidate the compound in order to create a solid structure.

The parameters that mainly influence the properties of this kind of materials are:

- grain size;
- binder type and concentration (binder weight/total weight);
- compaction ratio (volume decrease after compaction/initial volume);
- final thickness.

All these characteristics have different impacts on the acoustic (absorption coefficient) and non acoustic (pore size, flow resistivity, porosity, tortuosity) properties; the goal of the present paper is to analyze the influence of such parameters on the normal incidence absorption coefficient of several prototypes measured by means of the impedance tube technique in order to create materials with optimized acoustic performance.

2 Preliminary measurements

Several samples were manufactured at the Acoustics Laboratory of the University of Perugia, in order to evaluate the influence of constructive parameters (grain size, compaction, thickness) on the coefficient of absorption values [1]. The normal incidence coefficient of absorption was measured by means of a 2-microphone impedance tube (Brüel & Kjær, model 4206) using the transfer function method and cylindrical samples with diameters of 29 mm and 100 mm (combined frequency from 50 to 6400Hz), according to ISO 10534-2 standard [2].

Samples were produced following these steps:

- definition of binder concentration, weight of the rubber granules and weight of the binder by means of a digital precision balance in order to obtain the required concentration;
- mechanical mixing of rubber granules and binder;
- compaction of the mix;
- drying of the sample (at least 24 hours);
- cutting of the cylindrical samples to be tested in the impedance tube.

The rubber granules derive from the chipping and winnowing of used tyres: different grain sizes are available (from a thin powder to bigger pieces, fig. 1), but only two of them have been considered suitable for the required applications: a "small" size (average diameter of the granules = 1 mm) and a "medium" size (average diameter of the granules = 3 mm).

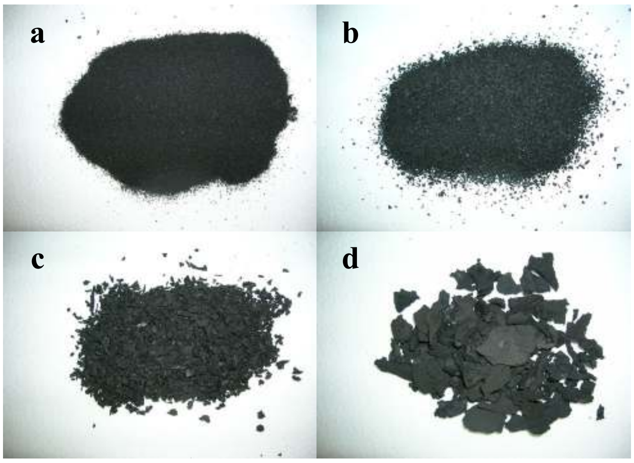

Fig. 1 Available grain sizes: a) powder (Ø < 1 mm); b) small size (Ø = 1 mm); c) medium size (Ø = 3 mm); d) large size (Ø > 10 mm).

Both grain sizes were used for the first samples, but later only the small size was used because of its higher absorptive performance. However it has to be taken into account that the smaller the grains are the higher is their cost.

Three binders were used for samples production: a double-component polyurethane resin (PB), a double-component epoxy resin (EB) and a single-component epoxy resin (EM)

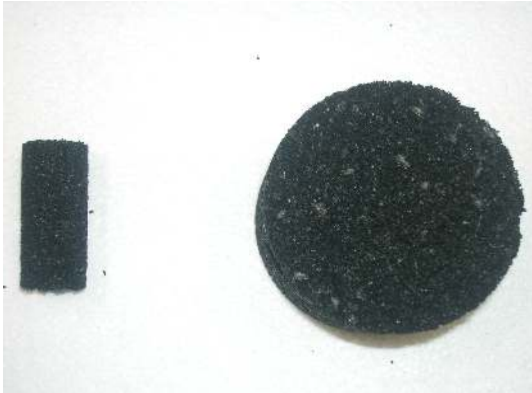

Fig. 2 Sample for the measurement of the absorption coefficient in the impedance tube; left: side view of the sample for the 29 mm tube; right: front view of the sample for the 100 mm tube

The first binder used for the preparation of the samples was the double-component polyurethane resin (PB): because of its viscosity, it is difficult to mix the rubber grains with the binder efficiently; moreover, a huge binder concentration (20-50 %) is needed in order to have a solid sample. It is clear that high binder concentrations are negative in terms of performance (reduced porosity) and costs (the cost of the binder is more than the one of rubber granules). For these reasons another binder with lower viscosity was chosen (EB) in order to reach an adequate percentage of binder (10-15 %).

The second stage of the research aimed at taking into account also fire resistance of the samples. A single-component epoxy resin (EM) added with fire retardants was purposely developed by a partner chemical company.

For the first samples a compaction ratio = 0 was used, but it soon seemed clear that a certain compaction is needed to achieve adequate mechanical characteristics.

Table 1 reports the characteristics and the constructive parameters of the produced samples; the type of binder used is identified by the initials in the ID code column (for example PB indicates a sample made of rubber and double-component polyurethane resin). The average values of the coefficient of absorption of the samples between 100 and 5000 Hz are also reported in Table 1. Figure 3 reports the absorption coefficient spectra for the best performing samples.

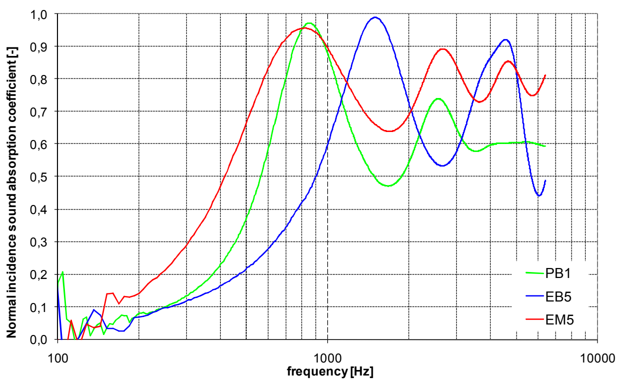

Fig.3 Sound absorption coefficient spectra of the best performing samples

As stated before, three types of binders were used. The first one is a double component polyurethane binder (PB); because of its high viscosity, the binder was mixed with water in order to make it a more fluid solution. The reaction between water and binder releases carbon dioxide, and creates a foam in the interstices between the granules. In this way good values of absorption can be achieved (for example PB1, fig. 3), but the binder concentration is still unacceptable (> 25%). Then, a double component epoxy binder (EB) with lower viscosity was used: lower values of the binder concentration can be reached (about 13 %), along with good acoustic performance (for example EB5, fig. 3). Moreover, samples containing the epoxy resin show better structural properties than those containing the polyurethane binder. Binders added with flame retardant also show good properties (for example EM5, fig. 3); samples containing single component polyurethane and epoxy binders show comparable acoustic properties and the optimal binder concentration (about 10 %) seems to be the same.

n.	ID code	thickness (mm)	grain size	BC (%)	CR (%)	Notes	$\alpha_{average}$
1	0	19	-	-	-	external origin	0.517
2	PB1	48	medium	48	0	binder mixed with water (25%)	0.593
3	PB2	21	medium	42	0	binder mixed with water (20%)	0.413
4	PB3	21	small	43	0	binder mixed with water (20%)	0.479
5	PB4	49	50% small+ 50% medium	47	0		0.514
6	PB5	20	small	25	0		0.545
7	PB6	25	small	33	0		0.521
8	PB7	18	small	27	0	binder mixed with water (15%)	0.533
9	EB1	18	small	33	0		0.477
10	EB2	20	medium	27	0		0.349
11	EB3	22	small	13	0		0.601
12	EB4	21	medium	7	0		0.388
13	EB5	38	small	13	19		0.676
14	EB6	28	50% small+ 50% medium	10	30		0.549
15	EM1	33	small	13	23		0.578
16	EM2	48	small	10	20		0.674
17	EM3	45	small	9	17		0.692
18	EM4	60	small	9	17		0.698
19	EM5	62	small	11	13		0.754

Table 1 Characteristics and normal incidence average coefficient of absorption of the tested samples.

Concerning the compaction ratio, an optimal value seems to be about 10-15 %. This is an important parameter, because it influences mainly the tortuosity (and consequently the position of the peak of the absorption coefficient) and the samples' structural characteristics. In order to have the best performance for noise barriers applications (high values of the coefficient of absorption in the frequency range 500-2000 Hz), a thickness of 60 mm or more should be used (fig. 4).

Concerning rubber grains size, figure 5 reports a comparison between samples EB3 (small size), EB4 (medium size) and EB6 (50 % small + 50 % medium): even if the thickness is the same (except for EB6), the coefficient of absorption of the sample made from small sized grains is definitely higher. The mixture of two different grain sizes causes an increase of the tortuosity value and a consequent sensible shift of the maxima towards lower frequencies.

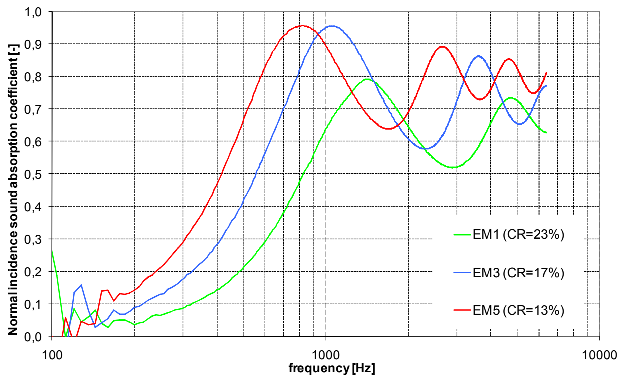

Fig. 4 Sound absorption coefficient spectra of samples EM1, EM3 and EM5.

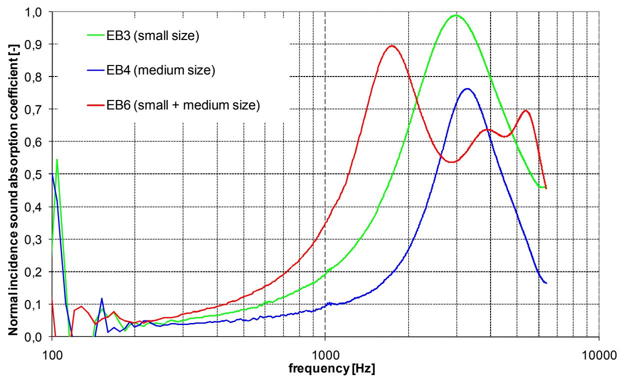

Fig. 5 Sound absorption coefficient spectra of samples EB3, EB4 and EB6.

The results of the preliminary measurements campaign suggest the following consideration:

- The best absorption coefficients are achieved with the small sized grains;
- The viscosity of the binder has to be as low as possible in order to obtain an optimal mixing with the grains;
- The optimal binder concentration (BC) seems to be around 10 %.
- The optimal consolidation ratio (CR) seems to be around 10-15 %.

Taking into account the results acquired in this preliminary experimental campaign and others coming from similar researches [3, 4, 5], a new phase of the work has been planned in order to create a prototype with optimized acoustic characteristics and also to better study and understand the influence of the constructive parameters on the final acoustic performance.

3 Optimization stage

The first step of this stage has concerned the development of an adequate binder added with a fire retardant. The efficiency of fire retardants depends on the binder concentration, i.e. on their quantity in the sample: some tests showed that the single-component epoxy resin (EM) was not suitable for the concentrations required in our applications. For these reasons a new low viscosity polyurethane resin added with fire retardants (PM) was developed and used for producing the samples.

Table 2 reports the main characteristics of the samples tested in this stage of the research. Samples with binder concentrations lower than 15 % crumble very easily even with strong compaction ratios. For this reason all the samples were produced using a binder concentration equal to 15%. Furthermore, as stated in section 2, only small sized grains (average diameter ≈ 1 mm) were used, since they allow to obtain the best acoustic performance.

ID code	CR (%)	Thickness(cm)
PM1	20	6
PM2	20	7.2
PM3	20	8
PM4	20	9.4
PM5	28	6
PM6	28	7.2
PM7	40	6
PM8	20	3
PM9	40	3

Table 2 Characteristics of the samples tested in the optimization stage.

The measurement results are reported in the following paragraphs, together with the analysis of the influence of the various parameters on the absorption coefficient.

3.1 Influence of the compaction ratio

Three samples were produced with different compaction ratios (20, 28 and 40%) and with the same binder concentration (15%) and thickness (6 cm) (samples PM1, PM5 and PM7); the results of the measurements carried out on these samples are reported in figure 6.

With increasing values of the compaction ratio the maxima of the absorption coefficient shift towards lower frequencies and their amplitude is lower and also the minima are deeper.

This is due to the fact that the increase of the compaction ratio has two main effects:

- increase of the tortuosity;
- decrease of the porosity.

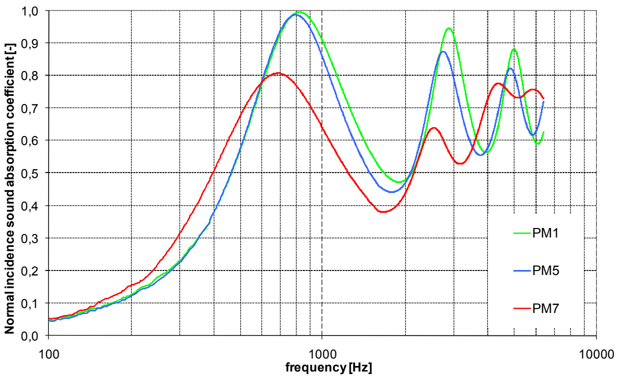

Fig. 6 Sound absorption coefficient spectra of samples PM1, PM5 and PM7: comparison between different compaction ratios.

As stated before, the first phenomenon makes the maxima of the absorption coefficient shift towards lower frequencies. Instead, lower quantities of air are included inside the interstices of the solid matrix because of the reduction of porosity and, consequently, this allows less interactions between the two phases. This interaction is the main responsible for the dissipation of sound energy.

Thus, as it can be clearly seen in figure 6, less consolidated materials have better acoustic performance. Moreover low compaction ratios allow to use lower quantities of rubber crumbs and binder to produce a sample with a specified thickness. However a certain compaction is needed to achieve adequate mechanical characteristics.

3.2 Influence of the thickness

Four samples were produced with different thicknesses (6, 7.2, 8 and 9.4 cm) and with the same binder concentration (15%) and compaction ratio (20%) (PM1, PM2, PM3 and PM4); the results of the measurements carried out on these samples are reported in figure 7.

It can be noticed that with increasing thicknesses:

- maxima shift towards lower frequencies;
- the amplitude between the first maxima and the minima decreases so that the trend of the curve is flatter.

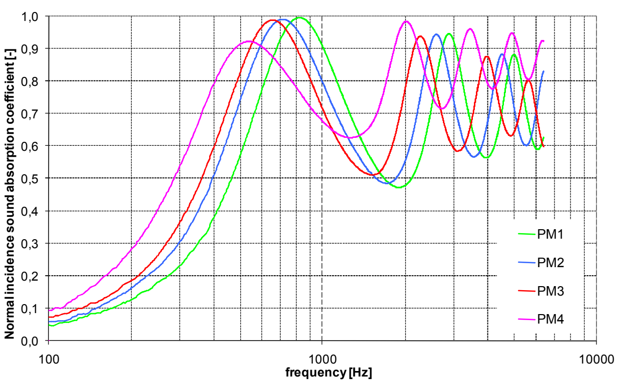

Fig. 7 Sound absorption coefficient spectra of samples PM1, PM2, PM3 and PM4: comparison between different thicknesses.

The shift of the maxima agrees with the results obtained in previous researches found in the Literature.

This phenomenon is caused by the fact that sound absorption grows with increasing values of the speed of the air particles. The speed tends to zero near a rigid surface while it reaches the highest levels at a distance between 1/4 and 1/8 of the wavelength of the sound wave from the surface.

For this reason, the choice of the thickness is strictly connected with the fields of application and not always its increase results in better acoustic performance. On the contrary the optimal thickness is the one that has the highest values of the absorption coefficient in the desired frequency range.

Since the scope of the present research is to have the best performance for noise barriers applications (high values of the coefficient of absorption in the frequency range 500-2000 Hz), the most appropriate sample is PM4 (CR = 20%, thickness = 9.4 cm). For this sample the absorption coefficient reaches the highest amplitude by the second maximum (α=0,98 a 2000 Hz) while the first peak is placed by 550 Hz (α=0,92). The prototype has absorption coefficient values higher than 0.6 for frequencies over 330 Hz and higher than 0.7 in the frequency range between 360-960 Hz.

Another test was executed to evaluate the effects of an air gap between the absorbing sample and the reflecting back plate of the impedance tube.

To that end sample PM1 (thickness = 6 cm) was tested with an air gap of 2 cm and then the results were compared with those obtained for sample PM3 which has the same thickness of sample PM1 plus the air gap (the other constructive parameters are the same for the two samples). The results are reported in figure 8.

It can be noticed that under 1000 Hz the spectra of the absorption coefficient are almost superimposable while at higher frequencies the effect of the decrease of the thickness of the porous material becomes preponderant.

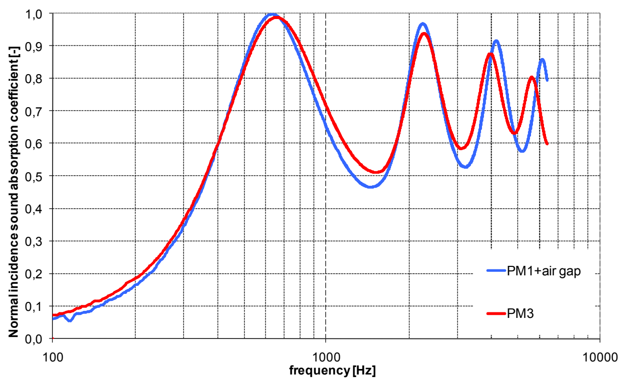

Fig. 8 Sound absorption coefficient spectra of samples PM1 + air gap and PM3.

3.3 Analysis of the performance of double-compaction ratio panels

Materials constituted by coupling two materials with different compaction ratios were also tested. To that end two cylindrical samples having the same constructive parameters of samples PM1 and PM7 and thickness equal to 3 cm were manufactured in order to obtain a composite sample with a total thickness of 6 cm. These samples are identified as sample PM8 and PM9 in Table 2.

Figure 9 reports the spectra of the absorption coefficient of the following samples:

- PM1 (thickness 6 cm, CR = 20%);
- PM7 (thickness 6 cm, CR = 40%);
- PM8 [front] (thickness 3 cm, CR = 20%) + PM9 [back] (thickness 3 cm, CR = 40%);
- PM9 [front] (thickness 3 cm, CR = 40%) + PM8 [back] (thickness 3 cm, CR = 20%).

As expected, the best acoustic performance can be achieved with the composite panel having the more consolidated layer (PM9) on the back side and the softer one (PM8) on the front side. As a matter of fact the absorption coefficient of this sample is on average higher than those of the single layer samples PM1 and PM7.

This effect is even more evident at medium-high frequencies; in this range the trend of the curve is similar to the one of the more consolidated sample but with a vertical shift towards higher values.

This kind of solution allows to combine the positive aspects of both the samples PM1 and PM7 (and consequently of the different compaction ratios):

- High amplitude of the maxima of absorption coefficient of the softer materials;
- Flatter spectra of the absorption coefficient of the more consolidated materials.

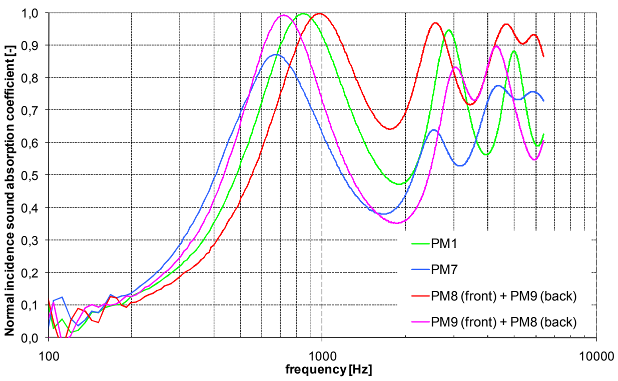

Fig. 9 Sound absorption coefficient spectra of samples PM1, PM7 and of the two composite samples.

4 Conclusions

Various measurements were executed on several prototypes of sound absorbers made of rubber crumbs from end of life tyres, using the impedance tube technique, in order to highlight the relationships between the normal incidence sound absorption coefficient and the constructive characteristics.

As far as the grain sizes, highest values of the absorption coefficient can be achieved using grain sizes between 1 and 2 mm. Smaller sizes lead to a too compact material while bigger sizes lead to low values of flow resistivity (which is inversely proportional to grain size) and consequently of absorption coefficient.

Also the effects of the thickness and of the compaction ratio were analyzed.

With increasing values of the thickness not only the absorption properties improve, but also the maxima of the absorption coefficient spectra shift towards lower frequencies. For this reason the thickness of this materials should be chosen taking into consideration the range of frequencies to be absorbed. Furthermore it is worth noting that obviously a thicker material is heavier and more expensive so there is the need to come to a compromise between costs and acoustic performance.

The compaction ratio determines the position and the amplitude of the maxima of the absorption coefficient spectra. An increase of tortuosity and a decrease of porosity correspond to an increase of compaction ratio. The first effect causes a shift of the maxima towards lower frequencies while the second causes a remarkable decrease of the absorption coefficient in the entire frequency range of interest, because of the lower strength of the dissipative effects between the external surface of the grains and the air included in the interstices.

From the results of these analysis various prototypes with optimized acoustic properties were produced, using only small sized grains (average diameter around 1 mm) and a purposely developed single-component polyurethane resin added with fire retardants (PM) with a concentration equal to 15%. In particular the best performing sample is the one with a compaction ratio equal to 20% and a final thickness equal to 9.4 cm.

Measurements on samples constituted by coupling two materials with different compaction ratios (20 % and 40%) were also executed and the results compared with those obtained from samples with the same thickness and a single compaction ratio. The double-layer panels show higher and flatter trends of the absorption coefficient.

In conclusion the results obtained from the experimental campaign are satisfying thus encouraging the development of a full scale noise barrier prototype and the testing of the absorption coefficient in diffuse sound field (reverberating chamber).

The research will therefore continue with the production and testing of larger samples, together with the evaluation of further important non-acoustical parameters such as inflammability and durability.

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