RUBBER CRUMB AS GRANULAR ABSORPTIVE ACOUSTIC MATERIAL

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Pfretzschner Jaime
Instituto de Acústica
Serrano 144
28006 Madrid
Spain
Tel: 34.91. 5 61 88 06
Fax: 34 91 4 11 76 51
E-mail: iacjp36@ia.cetef.csic.es

ABSTRACT

We have developed a research project on the use of scrap tyres as absorbers in acoustic noise barriers for highways. This project is based on the aims for the period 2000-2006 of the Scrap Tyres Working Group of the EU concerning the discovery of new uses and tyre processing technologies to reduce the percentage of waste tyre crumbs and thus minimise the environmental pollution produced by this type of waste.

Besides reducing the noise in neighbouring residential areas, such a barrier would also act as an elastic wall for crashes. The paper describes the theoretical basis (under the phenomenological behaviour of the material) of the acoustic absorption process inside the granular material. Experimental results are given, followed by the optimisation of the shape and dimensions of an acoustic wall, in order to achieve the maximum absorption compatible with a controlled volume of consumed rubber crumb.

INTRODUCTION

During recent years in the Environmental Acoustic Department of our Institute, several research programmes have been developed on Acoustic Noise Barriers against noise traffic. Amongst the various noise screens we have dealt with, there are two general groups: absorptive and reflectance screens.

The need to use absorptive barriers is well known, especially in the case where parallel barriers are installed on both sides of a street or highway. Normally the absorptive characteristics of this type of screen are attained through the use of fibrous materials. At the same time the world environmental pollution departments are concerned about the huge amounts of scrap tyres from vehicles. In Europe there is a Directive recommending that associate members establish national plans in order to recycle used car tyres.

The idea of employing used tyres in the construction of barriers against traffic noise can be found in old USA patents in which large pieces of cut tyres served to fill the screens. Consequently, there was no chance of them acting as an acoustic absorber.

In 1996 we patented a self-standing acoustical absorbent noise screen using rubber crumbs. The idea arose when we studied the outdoor-sound propagation and the influence of the soil impedance in the reflection properties of the ground. Many authors demonstrated the relationship between the acoustic impedance of a sandy terrain and the effective flow resistivity.

The description of the acoustic impedance of granular material in accordance with the empirical relationship proposed by Delany and Bazley [1] conduces generally to a poor correlation between theory and experimental results. Attenborough in 1983 [2] demonstrated the necessity for additional parameters, so that the acoustic impedance is influenced by the tortuosity, porosity and dynamic shape factor of the ground surface as well as by its dc flow resistivity.

During the last two decades, many available models have been established under the micro-structural approach based on the Zwikker and Kosten theories [3] and on Biot´s approximations [4]. These approaches include viscous and thermal effects in tortuous pores of different sizes and geometry in a sound field.

Under all these assumptions concerning rigid frame porous media, the theoretical proposals of Bérengier et al [5] can be mentioned for porous road pavements, and the model of Allard [6] implies the knowledge of characteristic viscous and thermal lengths. On the other hand, the models of Attenborough, Champoux, Stinson et al [7, 8, 9,10], involve empirical shape factors whose values had to be adjusted to fit experimental data.

Recently, the model proposed by Horoshenkov and Swift [11] is able to predict the acoustic properties of a porous granular media, starting from the above-mentioned intrinsic parameters with some assumed pore geometry and the pore size distribution close to log-normal.

ABSORPTION CHARACTERISTICS OF RUBBER CRUMB

In relation to the traffic noise there are two main "acoustical applications" for the re-utilisation of rubber, consisting in its use in pavements, as modified asphalt with increased elasticity, crack resistance and lower emission levels. Noise reduction can be achieved by a porous road, through partial absorption of the acoustic energy at the road surface, reducing the noise which propagates close to its surface. Due to the necessary constitution of this type of asphalt (compatible with its mechanical performances), its absorption spectrum has narrow band characteristics, centred in 1200 Hz. Nevertheless, and taking into account that this frequency band corresponds to the most sensitive frequency range of the human ear, the absorption sensation can reach between 3 and 5 A weighted dB for this kind of new surface.

The possibility of reducing traffic noise by using porous road surfaces is nowadays well known, but the physical explanation of the acoustical performances remains rather empirical (it depends on the size and distribution of the aggregates, the type of binder, layer thickness, etc.).

Another application is based on the use of rubber crumbs in the construction of absorbing sound barriers along highways to reduce noise in neighbouring residential areas. In this case, the acoustical design of any new material should be made in such a way that its absorption characteristics should be broadband and adequate to the energy band spectrum of the pollutant source; this means that the highest absorption bands of the material designed should coincide with those of maximum emission bands of the noise source. In this way, noise can be considerably reduced.

In the beginning of our research, we made an extensive experimental study of the absorption of rubber crumbs, with different granulometries, in standing wave tube.

In order to design acoustic material adequate to the characteristics of an incident noise (e.g. traffic noise), it is appropriate to elaborate a physico-mathematical model to predict the acoustical absorption in accordance with the frequency; in this way, empirical solutions can be avoided, saving time and a lot of experimental testing.

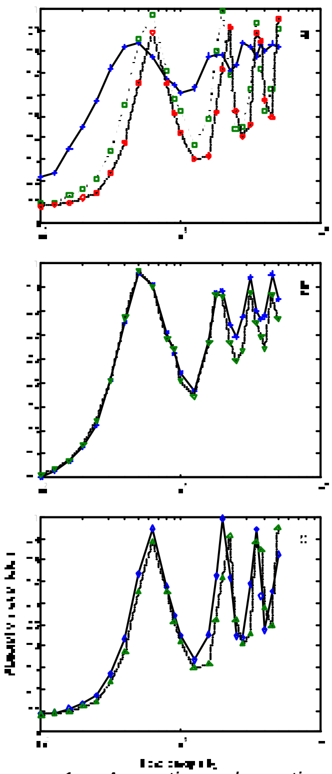

Figure 1 Acoustic absorption coefficients versus frequency for the following types of samples (thickness 9 cm): a) s1 (+), s4 (...□), and s6 (o); b) s2 (—), and s3 (...D); c) s7 (--o) and s6 (...D).*

From the previously mentioned theoretical proposals, we used those of Champoux and Stinson [8] because we found in them the best approximations between experimental and theoretical results. This theoretical model describes the propagation of sound through pores whose cross -sectional area and shape change along the course of each pore. The models require two different shape factors related to thermal and viscous effects which should be adjusted with well-controlled experimental results, so as to predict the acoustical characteristics. On the other hand the intrinsic characteristics of the granular material: porosity, tortuosity, and air flux resistivity, should be measured in advance because they are involved in the algorithms that describe the internal acoustical process [9].

In the general case of common porous materials (such as rubber crumbs), the key question is to find an expression for the characteristic acoustic impedance of the material under study, that is the function of the frequency-dependent dynamic density, *r(w)* and the bulk modulus, *K(w)* of the material:

$$Z_C(w) = \frac{p}{U} = \sqrt{r(w) \cdot K(w)} \qquad (1)$$

The dynamic density and the bulk modulus can be calculated using the well-known expressions given by Biot and Zwikker [9]. Having *r* and *K*, the specific impedance of the granular material can be evaluated in accordance with the test frequency, (eq. 1).

It is well known [6] that the relationship between the surface impedance of a layer of porous material with a thickness *d*, for normal incidence sound waves, considering rigid backing, is:

$$Z(w) = -jZ_C(w)\cot(kd) \qquad (2)$$

k being the wave number in the material : $k = \sqrt{r(w)/K(w)}$.

Finally, the acoustic reflection and absorption coefficients of the material are:

$$R(w) = \frac{Z(w) - r_0 c}{Z(w) + r_0 c} \qquad a(w) = 1 - |R(w)|^2 \qquad (3)$$

where r_0c is the air impedance at standard conditions $r_0c = 415\ Nsm^{-4}$.

ABSORPTION PROPERTIES IN ACCORDANCE WITH THE SIZE OF THE GRAIN PARTICLES

As has been observed in preceding paragraphs, the acoustic absorption behaviour of a sample depends on the intrinsic characteristics of the pore sizes and on the thickness of the layer.
The tested samples correspond to rubber crumbs obtained from waste tyres (without metallic and textile residues) with granulometries in the range of *1.4* to *7 mm*.
The following types of rubber crumbs have been studied and subjected to experiment:

sample	s1	s2	s3	S4	s5	s6	s7
size(ϕ)	ϕ=1.4	ϕ<3.5	1<ϕ<3	3<ϕ<5	ϕ=3.5	5<ϕ<7	ϕ<7

f being the size of the rubber crumbs in *mm*. The samples *s2* and *s7* include any size of grain (from powder to the limiting size of the mesh), and a content of about *70%* of samples *s3* and *s4* respectively has been found.
For a given sample thickness, the absorption coefficient increases when the diameter of the grains decreases. In this way, figure 1a shows, for a layer of *9 cm*, the measured absorption curves in accordance with the frequency for rubber crumb samples: *s1* (+), *s4* (□), and *s7* (○). In order to check the influence of small sized components, in figure 1b the absorption of the polidisperse sample *s2(---✳)* with the monodisperse *s3 (...Δ)* is shown comparatively. Figure 1c

shows analogous curves for the samples *s7(--◊)* and *s6(....Δ)*. The influence of the small sized components inside the polidisperse samples in the high frequency range can be observed. Analogous results have been found for other thicknesses of the samples studied.

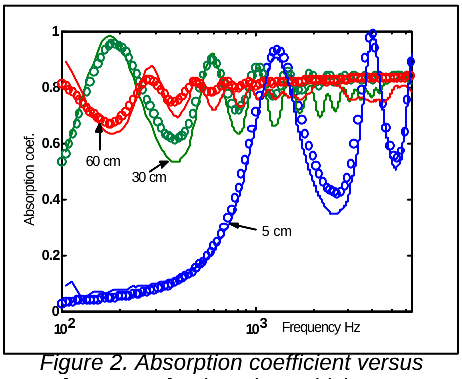

Figure 2. Absorption coefficient versus frequency for three layer thickness

In order to demonstrate the behaviour of the material in relation to the size of the sample, in figure 2 the variation of the absorption coefficient for several thicknesses can be seen. Continuos curves correspond to experimental data obtained with a two microphone impedance measurement tube, and with circles, the corresponding analytical values calculated in accordance with the eq. (3). In this case the material was loose rubber crumb with grain sizes of between 1 and 3 mm.

It can be observed that for the lower thickness experimented, there is a principal maximum of absorption at 1.1 kHz, due to the composition of the incident and the reflected wave on the hard backing of the tube. This maximum halves its frequency value (descending one octave) when the thickness doubles in size. The amplitude of the maxima and minima are related with the energy absorption of the incident acoustic wave (poor for low frequencies). As the frequency increases, the size of the extremals decreases. In the figure only three of the eleven curves have been represented, steeped every 5 cm in thickness.

In comparison with fibrous materials, the behaviour of the granular absorptive materials is quite different. In the previous one there is a “critical thickness” characterised by a certain attenuation of the sound wave, which limits the absorbing properties of the material. Experimentally it can be observed through the asymptotical behaviour of the absorption coefficient versus the width of the sample. Above this thickness $\alpha(f)$ does not change noticeably and a progressive increase of the layer thickness only means an unnecessary waste of acoustic material [12].

In fibrous materials the absorption asymptote tends to unity value, yet for granular materials it takes 0.8. In general, for fibrous materials the critical thickness can be attained with a few centimetres of the layer (depending on the sigma value) and for the granular ones this quantity is much larger.

Based on this property a nomogram can be made for the calculation of the best layer thickness for a given granular absorbing material in accordance with the lowest frequency to be absorbed, as we have described for fibrous materials [12].

If the crumb is agglomerated with a binder product, like cement, asphalt, polyurethane, etc, its acoustical characteristics can change, and in this case experimental measurements should be made in order to infer its empirical behaviour. Even though the acoustical characteristics are similar, the mechanical ones are very different because the former is very rigid while the latter has a good elasticity, which is very useful against crashes.

In order to protect motorcyclists, the advantages of this second case are evident when used in noise barriers very close to roads.

IMPROVEMENTS OF THE ABSORBENT ACOUSTICAL LAYERS

As we have shown in previous paragraphs, when a limited layer thickness of granular materials has been used, a controlled number of maxima and minima can be found in the curve of the absorption coefficient versus frequency. The reason for this unevenness in the curve is due to the insufficient absorption of the acoustic energy inside the material, giving as a consequence, a noticeable energy reflection on the hard backing surface of the layer. Mathematically this maxima and minima are related to the behaviour of cot(kd) in eq.(2), and, as a consequence, have remarkable maxima and minima in the curve of the absorption coefficient versus frequency.

In order to increase the absorption of the sample, an alternative, maintaining the total volume of the material constant, consists in distributing the exposed surface of the sample with different depths; in doing so, the respective maxima and minima are shifted and thus the sum of the reflected waves presents a smoother curve.

A classical way of improving acoustical absorption performances of porous materials is the use of corrugated surfaces (a specific case are wedges); with this use, lower cut-off frequencies can be obtained and also the overall absorption over a wide frequency range is improved.

Analytical theories have been developed which can explain the wave propagation throughout the material, but their solutions become very complex for surfaces which are not planar. In the present work the problem is overcome by approximating the wedge by a series of steps. For each step an analytical calculation of the reflection coefficient is then possible. The reflection coefficient of every step is obtained and will contribute to the net reflection coefficient. The use of a special weighted averaging of all the reflection coefficients then approaches the value of the continuous wedge.

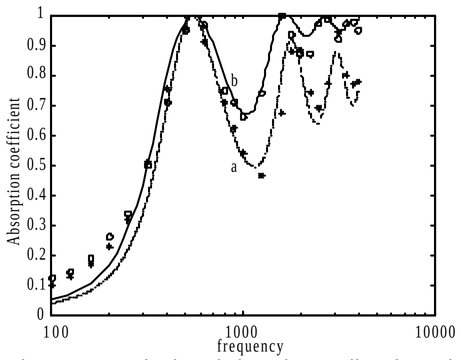

Figure 3. Calculated (continuos lines) and measured absorption of a cylinder and a wedge of granular material with identical volume.

As stated above, the study will be carried out on a sample obtained from the material, which includes a representative portion of its surface. The sample has two symmetrical slopes and a bevel. The formal description below corresponds to one slope only and the bevel; under these assumptions the depth of the sample varies continuously from b_{min} to b_{max}. We will assume this variation is linear, but another kind of dependence could be applied. The slope will also be considered, divided into N equal steps, so that the surface impedance of each step is:

$$Z_{S,n} = -j\frac{Z_c}{\Omega}\cot(k_c b_n) \qquad n = 1,\dots N \qquad (4)$$

where k_c is the wave number inside the test material, $W$and Z_c the porosity and characteristic impedance of the acoustic material respectively, and b_n the distance of the considered step surface to the bottom.

Every step will have its own $Z_{S,n}$ and therefore its own pressure reflection coefficient R_n; in the same way the bevel will have its own R_n, which will be considered the N+1 element. Now it will be assumed that the quantity measured in a standing wave tube, R_T is an average of all the R_n. Every term of the average will be weighted by the surface of nth step s_n , which coincides with the normal to the front wave getting over that part of the surface. In our case the area of the steps is calculated as a difference between two adjacent circular segments:

$$R_T = \sum_{n=1}^{N+1} R_n s_n \Big/ \sum_{n=1}^{N+1} s_n \qquad (5)$$

Every R_n must be obtained from the acoustic impedance Z_n on the same reference plane normal to the tube axis, and, in our case, located at the top of the sample

$$Z_n = Z_0 \frac{-jZ_{S,n}\cot(k_0 l_n) + Z_0}{Z_{S,n} - jZ_0\cot(k_0 l_n)} \qquad (6)$$

where k_0 is the wave number in the air, l_n the distance of the considered step to the reference plane, Z_0 the air impedance, ρ*c*, and $Z_{S,n}$ as defined in Eq. (1); R_n will be:

$$R_n = \frac{Z_n - Z_o}{Z_n + Z_o} \qquad (7)$$

Finally the absorption coefficient can be calculated by the expression: $a = 1 - |R_T|^2$ (8)

Fig. 3 corresponds to rubber crumb samples. Curve (a) shows the acoustical absorption coefficient of a test specimen with plane external surface (cylinder); in this case, a series of maxima and minima can be observed due to the interference between incident and hard–

backed reflected rays. Curve (b) corresponds to the absorption of a wedge with the same volume as sample (a). In this case, oscillations have smoothed giving better absorption performances, due to the out-of-phase interference among the reflected rays.

CONCLUSIONS

It has been observed that rubber crumbs, especially sorted and prepared, can be good acoustic material with a broadband absorption spectrum.

The physico-mathematical algorithms developed give a good correlation with the experimental values obtained through Kundt's tube. These algorithms constitute a valuable tool for designing a new absorption granular material, adequate to the noise spectrum of a pollutant source.

On the other hand, a simplified mathematical analysis, which can be used to model acoustic treatment for absorbent noise screens has been presented. The analysis can also be applied to model wedges of small dimensions. The proposed calculus is a good tool for designing ridged absorbent panels. Good compatibility between the proposed algorithms and the experimental results can be demonstrated.

The use of this kind of material in noise barriers on emplacements exposed to climatic atmospheric agents (especially rain) is advantageous compared to the classical ones (glass or rock wool fibres), because its performance is not affected when impregnated with water, and it is not put out of action by dust. On the other hand, it can be painted with appropriate colours and cleaned easily.

For all these reasons, its use is encouraged outdoors as an excellent alternative to the current absorbent screens used for protection against traffic noise. At the same time, it contributes to the elimination of scrap tyres.

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