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"Modelling and Improvement of Absorbent Materials applied on periodic fitting panels."

TRABAJO FINAL DE MASTER

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Abstract

The challenge of absorption in room acoustics is finding solutions that perform efficiently in most of the acoustic frequency range. While porous or fibrous materials deliver great performance in high frequencies, large membrane or elements creating Helmholtz effect are necessary to reduce the sound energy of lower frequency sound waves.

Thus, there is no element or material that can meet the requirements of all the spectrum, but a combination of elements can lead to an optimum performance.

This work aims to model and compare the absorption behavior of different acoustic materials combined. The learnings will be applied to a commercial absorption solution based on periodic fitting panels.

The designed Mathematical model is defined based on the modification of existing ones (**Delany & Bazley and Dunn&Duvern**), which are based on air-flow resistance property for porous and fibrous materials. The behavior of a low-frequency efficient material is added to the model.

The final model is compared with empirical tests of the materials in plain set up and shaped as fitting panels.

The result is the definition of the most suitable materials for a commercial absorption solution panel that is able to reduce the reverberation in all human voice frequency range.

Keywords: Absorbent Metamaterials, Acoustic absorption. Absorptive fitting panels, Porous Absorption Materials, Fibrous Absorption Materials, Delany & Bazley, Dunn & Duvern

Index

Chapter 1. Introduction and Goals

1.1 Introduction

Nowadays acoustics and noise control play an important role in the comfort conditions of a living space. Its relevance has been increasing as people activities have been developed in crowded spaces.

A key acoustic challenge that occurs in the crowded areas is reverberation: The increase in total noise level in a venue do to the reflections in surfaces of noise created within the same venue. It can be very annoying and can easily get worse: The higher is the final noise level, the louder people tend to speak. This makes the problem hard to solve without corrective actions in the room.

Features that affect the reverberation are volume and geometry of the room, its surfaces and the elements of decoration. To minimize the problem, most efficient solution without affecting the design, is placing elements that are able to absorb total or partial energy of the sound avoiding the increase of total noise level due to reflections. Absorptive corrective elements should be able to mitigate the reverberation problem and add value to the space.

This work aims to model and optimize the absorption behavior of combinations of different acoustic materials. The learnings are applied to commercial absorbent solutions built by fixing periodic fitting panels with attractive design.

1.2 Goals

The goal is to define a **mathematical model** that can **estimate the performance** of a metamaterial **absorber** based on **porous/fibrous material** and **a membrane element**.

The findings will be applied on a complex 3D periodic shaped panel. As a result of the development, a conclusion about which of the analyzed material is the **most suitable for this application** (shaped absorbent materials).

This work will speed up developments based on the same technology, reduce the time-to-market and help saving time and economic resources.

1.3 Methodology

The followed methodology can be summarized in the following 5 steps:

Pre-select materials: Understand the parameters that define the acoustic behavior of an absorbent and narrow down the materials that meet all necessary features for the application.

Define most accurate Mathematical models for these materials: After understanding the key parameters, the most suitable model is chosen based on the nature of the material (fibrous or porous).

Measure key physical property/ies: Measurement of Thickness, Density and Airflow resistance in order to define the input parameters of the Mathematical model.

Calculate the Absorption theoretically and empirically: Obtain the empirical values of the Sound absorption and the theoretical calculations.

Compare model vs real measurement: The model and measurements are adjusted for a proper comparison in order to obtain valuable feedback.

1.4 Content

The work is organized as follows:

Chapter 2. Absorption Efficient Material Definition: After a brief introduction of the Absorption in room acoustics, the key properties for acoustic absorption are explained and most suitable Materials for Acoustic Absorption are summarized in order to define the final material selection.

Chapter 3. Mathematical Model Definition: The most suitable Mathematical model is defined for each of the absorbent materials (fibrous and porous).

Chapter 4. Code Modelling: Code updates over the original methods are presented and commented.

Chapter 5. Empirical Validation: Empirical measurements performed to adjust the defined Mathematical model. (Explanation of the measurements of airflow resistivity and absorption diffusive field measurements).

Chapter 6. Results: Results of the measurements are presented and commented.

Chapter 7. Conclusions and Next Steps: Findings and learnings are commented and explained. They will help propose next steps.

Chapter 2. Absorption Efficient Material Definition

This chapter summarizes the importance of absorption materials and explains which physical features provide proper acoustic properties. This sets the theoretical foundation of the selection of the materials used in the study and development:

2.1 Introduction to Absorption in room Acoustics

As explained formerly, achieving a pleasant environment can be obtained by using techniques that use different elements that absorb the sound. Fibrous, porous and other kinds of materials have been widely accepted as sound absorptive materials for these elements.

When a porous material is exposed to incident sound waves, the air molecules at the surface of the material and within the pores of the material are forced to vibrate. By doing so, they get and dissipate some of their original energy. This is because part of the energy of the air molecules is converted into heat due to thermal and viscous losses at the walls of the interior pores and tunnels within the material. At low frequencies, these changes are isothermal, while at high frequencies, they are adiabatic.

In fibrous materials, much of the energy can also be absorbed by scattering from the fibers and by the vibration caused in the individual fibers. The fibers of the material rub together under the influence of the sound waves. [1]

In order to measure and compare the effective attenuation of the energy and reduction of the reverberation, a coefficient is defined: Sound Absorption Coefficient.

Sound Absorption Coefficient

The Sound Absorption Coefficient indicates the percentage of sound intensity absorbed by the material placed covering a given surface. Values close to 1 show high percentage of absorbed energy while lower values imply that most of the energy is reflected back again in to the venue. This coefficient is proven to be the reference to compare different absorptive elements and materials.

$$\alpha = \frac{I_a}{I_i} \qquad \text{or} \qquad \alpha = 1 - \frac{I_r}{I_i}$$

where

I_a = sound intensity absorbed (W/m^2)

I_i = incident sound intensity (W/m^2)

I_r = reflected sound intensity (W/m^2)

2.2 Key properties for Acoustic Absorption

Absorption is basically the ability of the material to get the energy from the sound wave and damp it transforming it into heat by friction between the fluid (air in most of the cases) and the structure of the material. When sound enters these materials, its amplitude is decreased by friction as the waves try to move through the tortuous passages.

A porous absorbing material should contain cavities, channels or interstices so that the sound waves are able to enter through them, to interact with the structure as much as possible and not get reflected back. On the other side, the material should be able to exchange as much mechanical energy as possible into heat.

Several studies [2][3][4] present models according to Biot's theory (of poroelastic materials consisting of a fluid and a solid phase) to relate behavior of a porous material under acoustic excitation as an equivalent fluid with effective a given effective density and bulk modulus. Thus, the characteristic impedance and the wave number can be defined related to the following properties:

- Air-Flow resistance (σ)
- Porosity (ϕ)
- Tortuosity (α_∞)
- Viscosity: viscous characteristic length (Λ) & dynamic viscosity (η)
- Thermal properties: thermal characteristic length (Λ') & specific heat ration (γ)

$$Z_c = \sqrt{\rho K}$$

$$k = \sqrt{\frac{\rho}{K}}$$

$$\rho = \rho_0 \alpha_\infty \left(1 + \frac{\phi\sigma}{j\omega\rho_0\alpha_\infty} + \left(1 + j\,\frac{4\omega\rho_0\eta\alpha_\infty^2}{\phi^2\sigma^2\Lambda^2} \right)^{\frac{1}{2}} \right)$$

$$K = \frac{P_0\gamma}{\gamma - (\gamma - 1)\left(1 + \frac{8\eta}{j\omega B^2\Lambda'^2\rho_0} + \left(1 + j\,\frac{\omega B^2\Lambda'^2\rho_0}{16\eta} \right)^{\frac{1}{2}} \right)^{-1}}$$

Being B^2 the Prandtl number.

Air-Flow resistance & Air-Flow Resistivity (σ)

It is the ratio between the pressure drop and the velocity. Low values of airflow resistance indicate little resistance for air streaming through the porous material. With little resistance and interaction no exchange of energy and sound waves keep their way and reflect in all surfaces.

On the other side, high values show difficulties of movement through the material, which results in less interaction. That could mean that most of the pores or fibers inside the material are closed. [5]

Flow resistance:

$$\sigma = \frac{\Delta P}{v}$$

$$\sigma = \frac{[Pa]}{[m/s]} = \frac{[Pa]\cdot[s]}{[m]} = \frac{[N/m^2]\cdot[s]}{[m]} = \frac{[N]\cdot[s]}{[m^3]} = \frac{[kg]\cdot[m]\cdot[s]}{[m^3]\cdot[s^2]} = \frac{[kg]}{[m^2]\cdot[s]} = [Rayl]$$

Air Flow Resistivity:

$$R = \frac{\sigma}{espesor} = \frac{\Delta P}{v} \cdot \frac{1}{espesor}$$

$$R = \frac{[Pa]}{[m/s]} \cdot \frac{1}{[m]} = \frac{[Pa] \cdot [s]}{[m^2]} = \frac{[N/m^2] \cdot [s]}{[m^2]} = \frac{[N] \cdot [s]}{[m^4]} = \frac{[kg] \cdot [m] \cdot [s]}{[m^4] \cdot [s^2]} = \frac{[kg]}{[m^3] \cdot [s]} =$$
$$= \frac{[Rayl]}{[m]}$$

Porosity (ϕ)

It is the ratio of the void space within the material to its total displacement volume. It can be expressed as a function of the volumetric densities of the material, ρ_m, and the fibre, ρ_f, as [6]:

$$H = 1 - \frac{\rho_m}{\rho_f}$$

Closed pores are substantially less efficient than open pores in absorbing sound energy. On the other hand, "open" pores have a continuous channel of communication with the external surface of the material, and they have great influence on the absorption of sound.

Tortuosity (α_∞)

It is the elongation of the passage way through the pores, compared to the thickness of the material. Tortuosity describes the influence of the internal structure of a material on its acoustical properties. Also described as a measure of how far the pores deviate from the normal. The measuring methods are very complex and in some cases destructive so is not an easy feature to have.

Viscous Characteristics (Λ & η)

It is the average macroscopic dimensions of the cells related to viscous losses. It may be seen as an average radius of the smaller pores. The viscous characteristic length is similar to this ratio weighted by the velocity in the volume and on the surface for an inviscid fluid.

Thermal Characteristics (Λ' & γ)

It is the thermal properties of the material. They help convert the the energy of the air molecules is converted into heat and dissipate it. As Viscous characteristics, It has little influence on the absorption behaviour. The thermal characteristic length can be obtained by a non-acoustical technique, but it is costly and not very accurate.

Some studies point out that porosity and tortuosity determines the high frequency behavior sound absorbing porous materials [7]. Others, state that tortuosity also affects the location of the quarter-wavelength peaks, whereas porosity and flow resistively affect the height and width of the peaks [8].

Although it has been proved that all have influence on the behavior, **interaction of sound** with a fibrous or open cell material is **mainly defined** by the **flow resistance** of the material [6].

For this reason, and the availability of methods to measure the Airflow Resistance the mathematical models used in this thesis are based on Airflow resistance methods.

2.3 Most suitable Materials for Acoustic Absorption

Based on their microscopic configurations porous absorbent materials can be classified as cellular, fibrous, or granular [9][1]:

Cellular: Materials structured in interconnected open cells. They are commonly known as foams. The airflow resistance per unit thickness of a porous material is proportional to the coefficient of shear viscosity of the fluid involved and inversely proportional to the square of the characteristic pore size of the material. They show a great performance for medium and high frequencies [7].

Fibrous: Materials composed of a set of continuous filaments that trap air between them. They include various materials such as glass, rock wool or polyester fibers. Its performance is defined by the size, orientation and length of the fibers. Absorption coefficient increases with a decrease in fiber diameter as thin fibers can move more easily than thick fibers on sound waves. Other studies show that structural characteristic (characteristic impedance) is inversely proportional to the fiber diameter and to the square root of the frequency [10]. They have a good performance for medium and high frequencies.

Granular: Materials built of macroscopic bodies whose dimensions exceed those of the internal voids by many orders of magnitude. They can be relatively rigid (agglomerates) or loosely packed assemblages of individual particles (aggregates). Examples of them are some kinds of asphalt, porous concrete, granular clays, sands, gravel, and soils. They are mainly used in controlling outdoor sound propagation. [1]

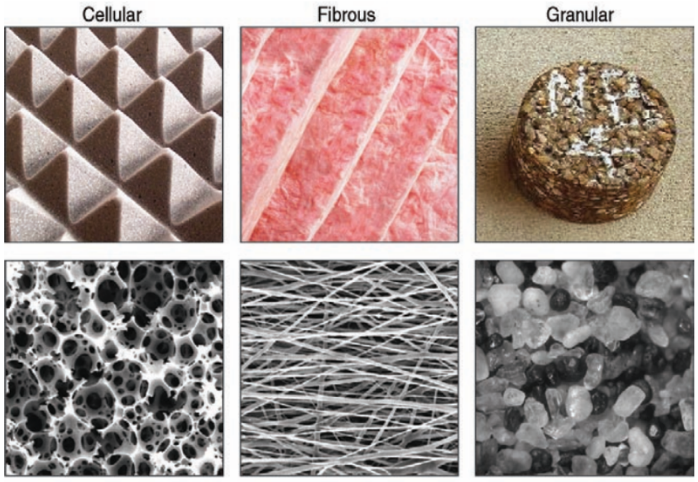


Figure 1. Type of materials according to the inner structure

Another way of absorbing can be achieved by resonating elements. They consist of a mechanical or acoustical oscillation system. When they get excited at their natural frequency, they reach their maximum absorption. Most common are the membrane absorbers:

Membranes: Thin materials that can be elastic or semi-rigid elements of relatively large size. They help damp low frequency high wavelength (thus energy) sound waves by resonating.

2.4 Final Meta-Material selection

In order to provide a good performance for most of the frequency range a combination of porous or fibrous material should be used in combination with a membrane. A perforated membrane spaced away from a solid backing effectively makes up of a large number of individual Helmholtz resonators [1], each consisting of a neck, comprised of the perforated panel and a shared air volume formed by the total volume of air enclosed by the panel and its backing. When the sound waves penetrate the perforated panel, the friction between the moving molecules of air and the internal surface of the perforations dissipates the acoustical energy into heat. The perforations are usually holes or slots, and as with a single resonator, porous material is usually included in the airspace to introduce damping into the system.

Given this configuration to maximize the acoustic performance, the materials are narrowed down to the ones that are able to meet the application requirements: Fire behavior and capability to be and keep a shape.

As the material is to be placed before the walls where the noise and reflections occur, the fire performance must be good enough to stop or at least slow down the propagation of the fire. Absorbent elements that are place either in the wall or in the ceiling as decorative panels must comply with the building code regulation.

Material	**Type**	**Acoustic Performance**			**Fire Behavior**	**Ability to Shape**
		Low	**Mid**	**High**		
Polyurethane Foam	Porous	Poor	Good	Good	Poor	Good
Recycled Polyurethane Foam	Porous	Poor	Good	Good	Poor	Medium
Melamine Foam	**Porous**	**Poor**	**Good**	**Good**	**Good**	**Good**
Latex Foam	Porous	Poor	Good	Good	Poor	Medium
Polyester Fiber	**Fibrous**	**Poor**	**Good**	**Good**	**Good**	**Good**
Cotton Fiber	Fibrous	Poor	Good	Good	Poor	Poor
Polyester Fabric	**Membrane**	**Mid**	**Mid**	**Mid**	**Good**	**Medium**

Table 1. Material Characteristics

According to the fire behavior and ability to shape, the most efficient acoustic materials are narrowed down to one fibrous and one porous material, that are combined with a membrane:

Porous: Melamine Foam

Foam made out of melamine resin. Small sized open porous material with good fire performance properties. Its characteristic feature is its three-dimensional network structure consisting of small and shaped cell network. It has very low density and standard elasticity. Its high nitrogen content makes it highly flame-resistant without the need to use fire retardants. It is a thermoset so it would not melt or produce burning droplets when it comes into contact with flames.

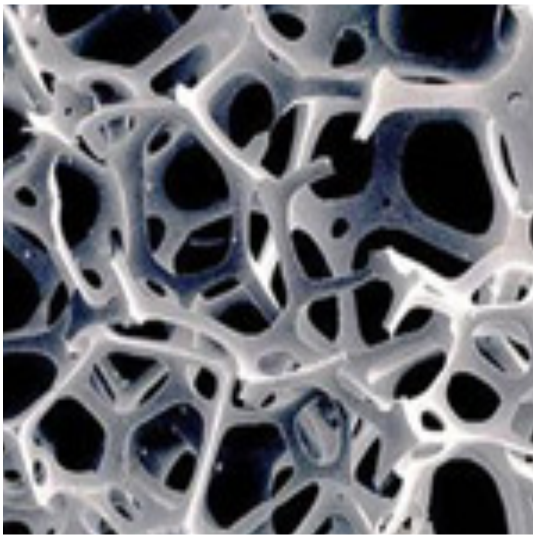


Figure 2. Melamine Foam Structure

Feature	***Value***
Density	11 kg/m^3
Thickness	50mm
Pore Size	10 - 1000 μm

Fibrous: Polyester Fiber

Material made out of recycled Polyester fibers. Small sized long fibers material with good fire performance properties. It has a relatively low density and open structure to help absorb at mid frequencies.

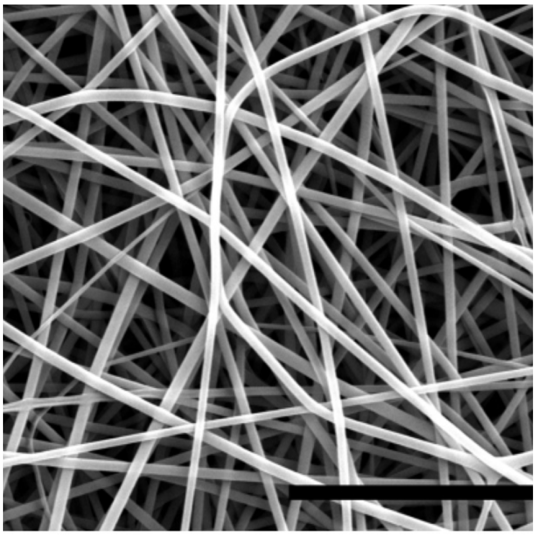


Figure 3. Polyester Fiber Structure

Feature	***Value***
Density	18-20 kg/m^3
Thickness	50 mm
Fiber Size	12-50 um
Fiber Length	45 mm

Membrane: Fabric

Material made out of thick polyester fire-proof fibers. The threads are arranged in a Plain Wave. Thick open fabric with limited flexibility, but enough to be shaped. It acts as a Low-pass filter at the same time that leaves the air to go through the material. Airflow permeability is key to let the absorbent (either porous or fibrous) interact with the wave.

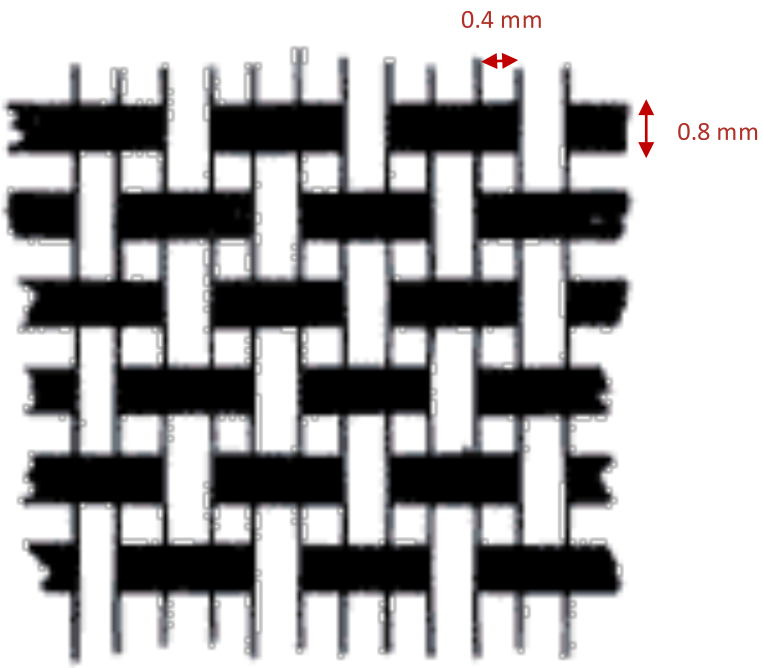


Figure 4. Fabric Structure

Feature	***Value***
Weight (m^2)	0,45 kg/m^2
Weight (m^2)	225 kg/m^3
Thickness	0,7-8 mm
Gap between Threads	0,3-0,4 um

Chapter 3. Mathematical Model Definition

The models defined in the time-domain are useful for studying transient behavior. However, models intended to describe the acoustic behavior of materials as a function of frequency are more common as they are more useful and practical for absorption in room acoustics.

Frequency models are based on obtaining the diffuse field absorption coefficient from the normal absorption coefficient [11]:

$$\alpha_S = \int_0^{\pi/2} \left(1 - \left|\frac{Z_{tot}cos\theta - 1}{Z_{tot}cos\theta + 1}\right|^2\right) \sin 2\theta \, d\theta$$

Being Z_{tot} the normalized closing impedance to the air ($Z_0 = \rho_0 c_0$).

The normal sound absorption coefficient can be obtained from the closing impedance as [12]:

$$\alpha = \frac{4 \cdot Z_{tot} \cdot \rho_0 c_0}{|Z_{tot}|^2 + 2 \cdot \rho_0 c_0 Z_{tot} + (\rho_0 c_0)^2}$$

In our case, as the piece has different layers, each of them acting as different element, a combined model must be used. In order to obtain the Closing Impedance, the behavior of the textile and the inner homogeneous isotropic material must be considered separately:

$$\boldsymbol{Z_{tot}} = Z_{tex} + Z_{him}$$

1. In order to model the textile, model based on perforated membranes must be used. Using a Mixed Mass-Resistance element model (perforated Sheet) [13] the Impedance of the textile can be defined as:

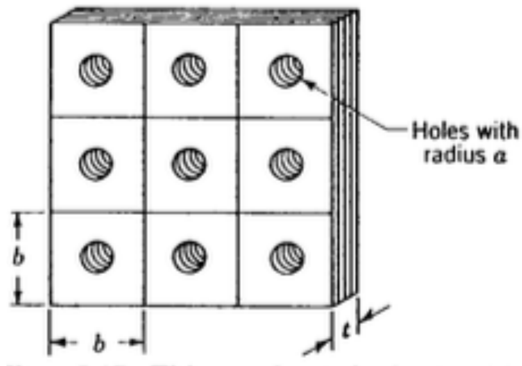


Figure 5. Fabric Modelling

$$Z_{tex} = R_{tex} + jwM_{tex}$$

$$R_{tex} = \frac{1}{\pi a^2}\rho_0\sqrt{2\omega\mu}\left[\frac{t}{a} + 2\left(1 - \frac{A_h}{A_b}\right)\right]$$

$$M_{tex} = \frac{\rho_0}{\pi a^2}\left[t + 1.7a\left(1 - \frac{a}{b}\right)\right]$$

where:

a is the radius of the holes

b is the distance between holes

$A_h = \pi a^2$ is the area of the holes

$A_b = \pi a^2$ is the area of the square of each hole

t is the thickness of the fabric

μ is kinematic coefficient of viscosity

In the case of this study, textile threads will define the area that surrounds the hole, while 2a is the gap between the threads. The thickness of the fabric will define the thickness of the perforated membrane, and the kinematic coefficient of viscosity of the air is $\mu = 1.56 \cdot 10^{-5} m^2/s$.

2.Sound propagation through a homogeneous and isotropic material in the frequency domain is determined by two complex values:

I. The complex propagation constant (Γ):

$$\Gamma = \alpha + j\beta$$

II. Characteristic Wave Impedance (Z):

$$Z = R + jX$$

Given so, the closing impedance is:

$$Z_{him} = Z\cosh(\Gamma \cdot d) = (R + jX)\cosh\big((\alpha + j\beta) \cdot d\big)$$

Where d is the thickness of the inner homogeneous isotropic material.

Models based on the absorbent materials are used to predict the interaction of propagation and sound absorption inside the materials[9]. The following methods allow us to obtain both the characteristic and propagation constant of the medium based on the physical parameters of the material[14]:

Delany & Bazley: For **fibrous** absorbent materials. This model provides good estimations for characteristic impedance and propagation constant for frequencies above 250 Hz, but prediction has significant errors at lower frequencies. Bies & Hansen: extended the lower and upper frequency ranges of validity of this model. [9][15][16][12][17]

Dunn & Davern: Suitable for **foams**. It was observed that the model proposed by Dunn and Davern presents inaccurate predictions of the sound absorption coefficient as the material density is increased. The predicted sound absorption coefficient is lower than the measured value in the low frequency range [9]. Fortunately for this study, the porous material has very low density values.

Pompoli & Garai: Empirical model for textile **fibers**. It is concluded that the new model can predict the basic acoustic properties of common polyester fiber materials with any practical combination of thickness and density [18].

Voronina: Characterize sound absorbing **highly porous** (porosity is greater than 0.7) materials from physical parameters such as tortuosity and structure factor associated either with the fibers or pores layout. This model enables calculation of acoustic parameters, impedance and sound absorption coefficient in terms of a structural characteristic which gives a quantitative estimation of acoustic energy losses in fibrous media. [10]

Kenaf Proposal: Proposed method to estimate the behavior of a fibrous bio-material: the kenaf. [19]

PET Proposal: Empirical method for Polyester (PET) wool. The values of the coefficient back engineered from measured absorption coefficient in normal incidence [15].

The methods based on the air flow resistivity, which are proved to be more accurate for the porous and fibrous materials in a wider range of frequencies, are based on the following formulas and coefficients [16]:

$$\alpha = \left(\frac{2\pi f}{c_0}\right)\left[C_5\left(\frac{\rho_0 \cdot f}{r}\right)^{-C_6}\right]$$

$$\beta = \left(\frac{2\pi f}{c_0}\right)\left[1 + C_7\left(\frac{\rho_0 \cdot f}{r}\right)^{-C_8}\right]$$

$$R = \rho_0 c_0\left[1 + C_1\left(\frac{\rho_0 \cdot f}{r}\right)^{-C_2}\right]$$

$$X = -\rho_0 c_0\left[C_3\left(\frac{\rho_0 \cdot f}{r}\right)^{-C_4}\right]$$

Where r is the airflow resistance per length unit (resistivity) of the homogeneous and isotropic absorbent material.

The European norm EN 12354:2003 [11] recommends the use these formulas for the prediction of the sound absorption of materials. Delany and Bazley [16][20]model in the case of materials made up of fibers whereas the model by Dunn and Davern is the most suitable for foams. [21]

For each of the described methods, the coefficients are:

Method	***C1***	***C2***	***C3***	***C4***	***C5***	***C6***	***C7***	***C8***
Delany & Bazley	0,057	0,754	0,087	0,732	0,189	0,595	0,098	0,700
Dunn & Davern	0,114	0,369	0,099	0,758	0,168	0,715	0,136	0,491
Pompoli & Garai	0,078	0,623	0,074	0,660	0,159	0,571	0,121	0,53
Kenaf Proposal	0,046	0,255	0,112	0,967	0,060	1,256	0,039	0,541
PET Proposal	0,078	0,648	0,082	0,602	0,156	0,629	0,108	0,506

Table 2. Model coeficients

According to ISO10534 and assuming no sound propagation parallel to the surface, the Sound Absorption coefficient in diffusive field can be obtained from the Normalized Impedance as [22]:

$$\alpha_{st} = 8 \cdot \frac{z'}{z'^2 + z''^2}\left[1 - \frac{z'}{z'^2 + z'^2} \cdot \ln(1 + 2z' + z'^2 + z''^2) + \frac{1}{z''} \cdot \frac{z'^2 - z''^2}{z'^2 + z''^2} \cdot \tan^{-1}\frac{z''}{1 + z'}\right]$$

where

$$z' = Re(Z_{tot})$$

$$z'' = Im(Z_{tot})$$

As the diffusive field of the chamber is not ideal. A correction for the theoretical results must be done in order to be able to compare both empirical and theoretical results. According to the the Eyring's formula [23]:

$$\alpha_{Ey} = -\ln 1 - \bar{\alpha} = \bar{\alpha} + \frac{\bar{\alpha}^2}{2} + \cdots + \frac{\bar{\alpha}^n}{n}$$

The theoretical absorption coefficient can be adjusted specifically for this particular reverberation chamber as [24]:

$$\alpha_{Ey} = \bar{\alpha} + \frac{\bar{\alpha}^2}{8}$$

Chapter 4. Code Modelling

The developed mathematical method is implemented in MATLAB code. Explain and comment the Matlab code.

It is divided in 5 parts:

1. Parameters and Absorbent method (Delany & Bazley or Dunn&Davern) definition:

```
%% Parameter Definition
rho=1.2;                %rho= Density (m/s)
c0=343;                         %c0= Speed of Sound in Air at 20ºC (m/s)
f=[0:5000];                     %f= Frequency vector

%% Material Features Definition
r=9.8e3;                % Air-flow Resistivity (Rayls/m)
d=0.05;                         % Espesor del absorbente (m). Espesor total - espesor del tejido

%% Membrane Material Definition
mu=1,56e-5;             % Kinematic coefficient of viscosity of the air (m2/s)
a=0.4;                % Fabric gap between threads (mm)
b=0.8;                % Distance between thread gaps (mm)
Ah=pi()*a.^2;           % Gap area (mm2)
Ab=b.^2;               % surrounding thread Area (mm2)
t=2;                % Espesor del tejido (mm)

%% Method Selection
Met='5';% Metodo a utilizar:
%   1.Delany & Bazley (Fibrous materials f>250Hz)
%   2.Pompoly & Garai (Textile fibres)
%   3.Kenaf (fibrous bio-material)
%   4.PET
%   5.Dunn & Davern (foams)
% ---------------------Model------------------------
switch Met
   case{'1'}
C1=0.057;  C2=0.754;  C3=0.087;  C4=0.732;  C5=0.189;  C6=0.595;  C7=0.098;  C8=0.700;
   case{'2'}
C1=0.078;  C2=0.623;  C3=0.074;  C4=0.66;   C5=0.159;  C6=0.571;  C7=0.121;  C8=0.53;
   case{'3'}
C1=0.046;  C2=0.255;  C3=0.112;  C4=0.967;  C5=0.06;   C6=1.256;  C7=0.039;  C8=0.541;
   case{'4'}
C1=0.078;  C2=0.648;  C3=0.082;  C4=0.602;  C5=0.156;  C6=0.629;  C7=0.108;  C8=0.506;
   case{'5'}
C1=0.114;  C2=0.369;  C3=0.099;  C4=0.758;  C5=0.168;  C6=0.715;  C7=0.136;  C8=0.491;
   otherwise
C1=0;  C2=0;  C3=0;  C4=0;  C5=0.01;   C6=0.01;   C7=0.01;   C8=0.01;
end
```

2. Impedance Calculation based on the method (Propagation constant and Characteristic Impedance):

```
%% Absorbent Impedance
Zb=rho*c0*((1+C1*(rho*f/r).^(-C2))-(j*C3*(rho*f/r).^(-C4)));
Gamma=(j*2*pi()*f/c0).*(1+(C7*(rho*f/r).^(-C8))-j*C5*(rho*f/r).^(-C6));
Zab=Zb.*coth(Gamma.*d);

%% Membrane Impedance
Rftj=rho*sqrt(2*2*pi()*f*mu)*(t/a+2*(1-Ah/Ab));
Xtj=(t+1.7*a*(1-a/b))/1e3;
```

```
Ztj=Rftj+i.*2.*pi().*Xtj.*f;

%% Total Impedance
Ztot=Zab+Ztj;
Rtot=real(Ztot);
Itot=imag(Ztot);
```

3. Standard Absorption Coefficient in diffuse field (Vigran or London):

```
%% Standard Absorption Coefficient (Alfa) London Method ISO10534-2:2002

ZtotNor=Ztot./(rho*c0);
R=real(ZtotNor);
X=imag(ZtotNor);
C1=R./(R.^2+X.^2);
C2=(R.^2-X.^2)./(R.^2+X.^2);
alfast1=(8*C1)-((8*C1.^2).*log(1+2*R+R.^2+X.^2))+(((8*C1.*C2)./X).*atan(X./(1+R)));
```

4. Sabine Correction

```
%% Standard Absorption Coefficient (Alfa) London Method ISO10534-2:2002
alfast1cc=alfast1+alfast1.^2/8;
```

5. Representation

```
fs=[100,125,160,200,250,315,400,500,630,800,1000,1250,1600,2000,2500,3150,4000,5000]'
AL=alfast1cc(fs);
APET=[0.1,0.24,0.3,0.37,0.57,0.67,0.89,0.96,1.05,1.05,1.01,1,0.95,0.91,0.86,0.84,0.83,0.85];
AEM=[0.05,0.16,0.13,0.27,0.38,0.48,0.68,0.8,0.85,0.95,1,1.03,1.02,0.94,0.89,0.85,0.83,0.84];
semilogx(fs,AL,'r',fs,APET,'b');
```

Chapter 5. Empirical Validation

In order to validate the model, empirical measurements are required in order to adjust and confirm the model:

Measurements of Airflow Resistance/Resistivity in the Kundt Tube according to ISO10534 of all 3 materials:

Melamine Foam
Polyester Fiber
Fabric

Measurements of Absorption Coefficient in Reverberation Chamber according to ISO354 of:

Melamine Foam + Fabric
Polyester Fiber + Fabric
Melamine Foam + Fabric in Shaped fitting panels
Polyester Fiber + Fabric in Shaped fitting panels

Air Flow Resistance in Kundt Tube Test

As Airflow resistance is the key parameter that defines the behavior of the material, measures of the resistance of all different materials that are involved in the construction of the piece are performed. The most convenient and accurate method to do it is the Ingard and Dear [6], as it presents closer to the values the ISO standard and less standard deviation[5]. In this method, a sample of the material of thickness is placed in the Kundt tube (closed cylindrical tube with a rigid termination in one end and a loudspeaker on the other end). The tube with the sample should will be excited with a pure tone that meets the condition of $\lambda >> 1.7$ times the Diameter of the tube and total distance from the sample to the rigid termination must be and odd number of quarter wavelength:

$$\lambda \gg 1.7D$$

$$L + d = (2n + 1)\,{}^{\lambda}/_{4}$$

What Ingard & Dear method introduces is the possibility to excite the tube with a broadband stationary random noise, using the absolute value of the imaginary part of the transfer function between the microphone signals:

$$\sigma = \rho c \left| Im\left(\frac{p_1}{p_2}\right) \right|$$

Measuring in tube:

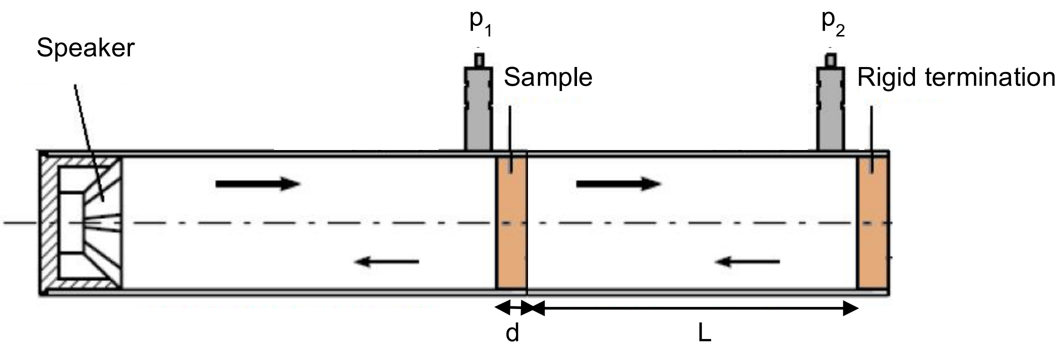


Figure 6. Kundt Tube Set-up

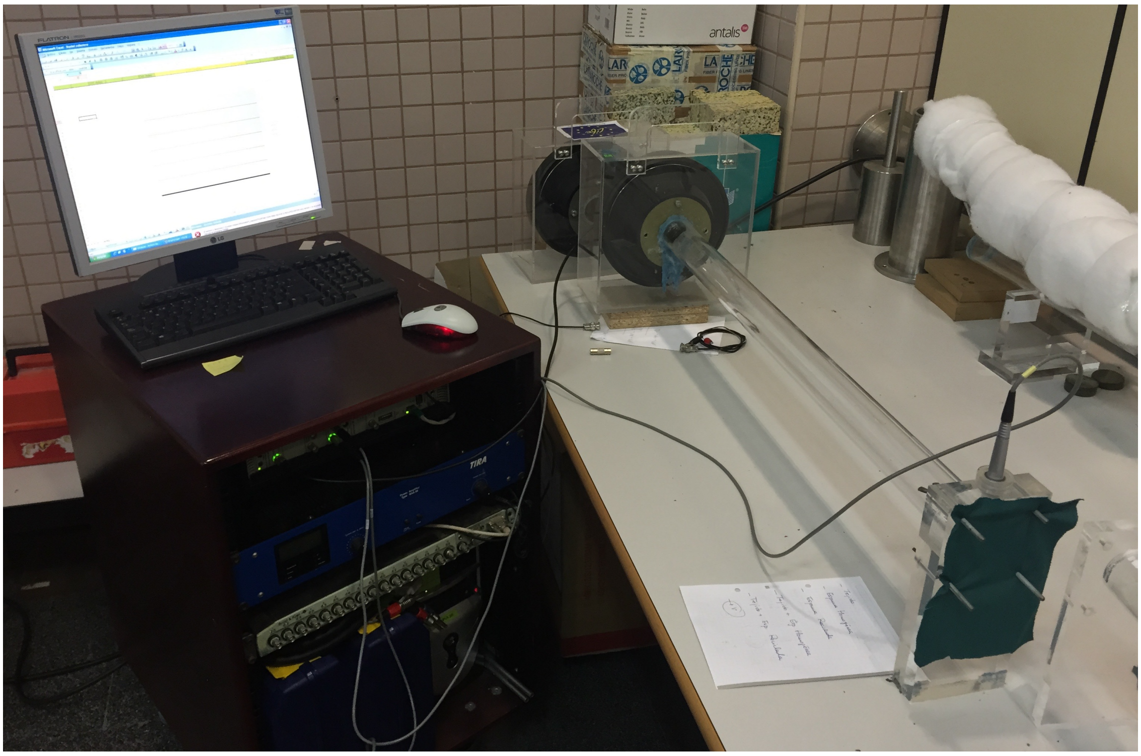


Figure 7. Airflow Resistance measurement Set-up

Material used:

- Loudspeaker Beyma CP 800Ti
- 2 Freefield Microphone B&J4190
- Methacrylate Impedance Tube
- Acquisition System B&J.

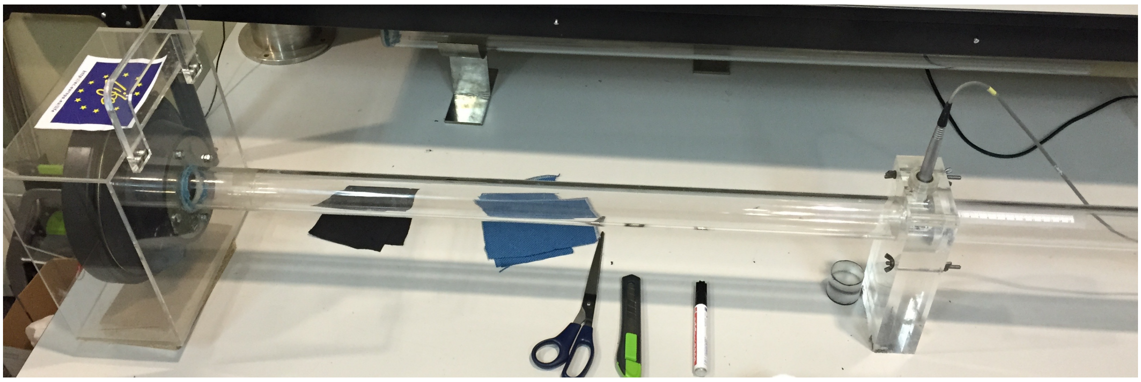
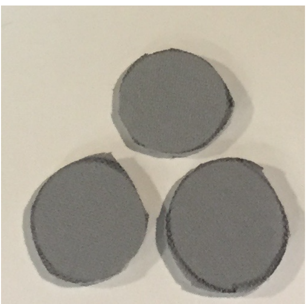


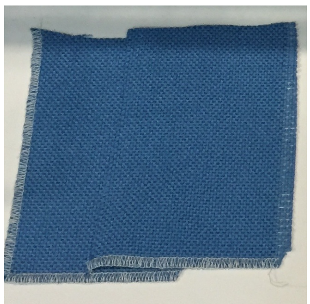
Figure 8. Impedance Tube

Samples to be tested:



a. Melamine Foam

b. Poliester Fiber



c. Fabric

Figure 9. Material Samples

Reverberation Chamber test (under ISO-354 norm)

The ISO 354 norm was defined in order to standardize methods and conditions, delivering an absorption value regardless of the incident angle, and the position of the source in an enclosure. Reverberating sound will depend on the features of the surfaces of the enclosure, so an even distribution of the sound waves must be considered. Sound intensity should also be independent from the position so diffuse field must be achieved to perform the measurements.

Final sound absorption coefficient of the absorbent surface will be obtained from the equivalent absorption area:

$$\alpha = \frac{A_T}{S}$$

where S is the real surface of material and the equivalent absorption area is the incremental absorption equivalent area between the empty chamber A_1 and the chamber with the absorption material A_2:

$$A_T = A_2 - A_1 = 55{,}3 \cdot V\left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1}\right) - 4V(m_2 - m_1)$$

being *m*, the sound attenuation coefficient that depends on the humidity and temperature conditions:

$$m = \frac{\alpha}{10 \cdot \log\, e}$$

and T, the reverberation time of each frequency. It can be measured by three different ways:

Direct: Generating an impulsive source able to excite the whole frequency range.

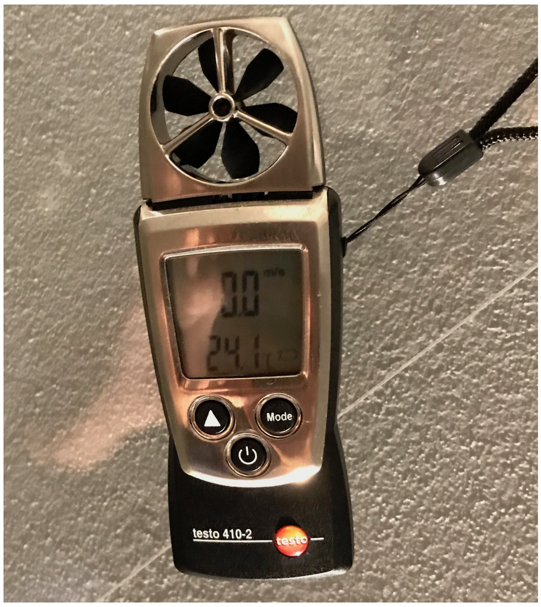
Indirect: Generating special sound signals that can provide an impulsive response after post-processing, such tone swap or pseudo-random noise.

We performed the indirect measurement through pseudo-random noise as it requires less signal-to-noise ratio.

Material used:

- Omnidirectional Loudspeaker Omni Power 4296
- Power Amplifier B&J 2716.
- Prepolarized 1 Freefield Microphone B&J4189
- Sound Level Meter B&J.
- Anemometer Testo 410-2.

a.Amplifier and Sound Level Meter



b.Anemometer and Thermometer

c.Omnidirectional Loudspeaker

d.Microphone

Figure 10. Testing Equipment

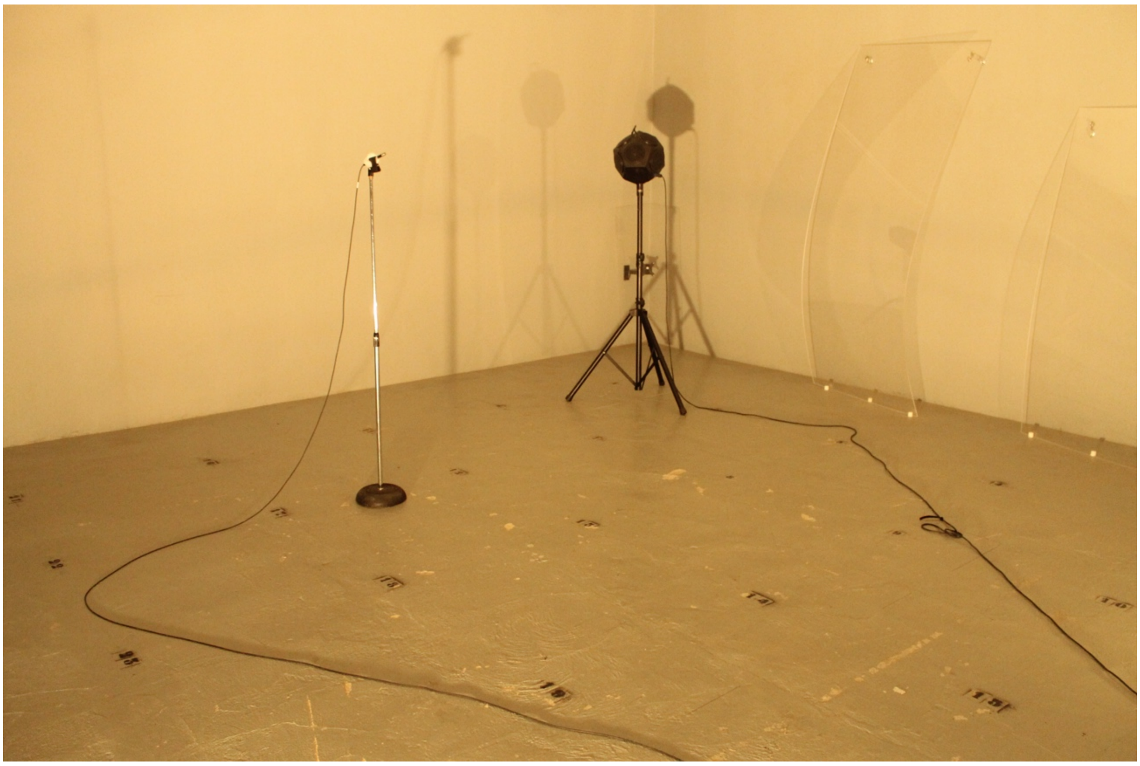


Figure 11. Empty Chamber set-up

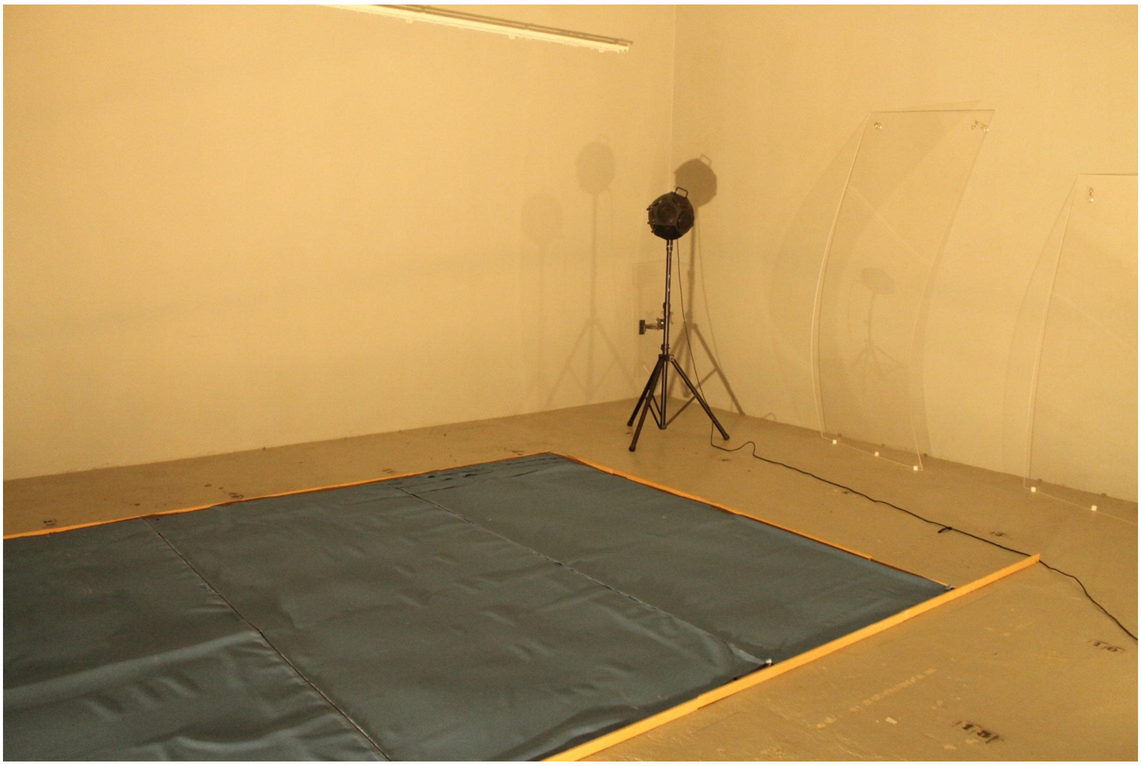


Figure 12. Melamine Foam + Fabric set up

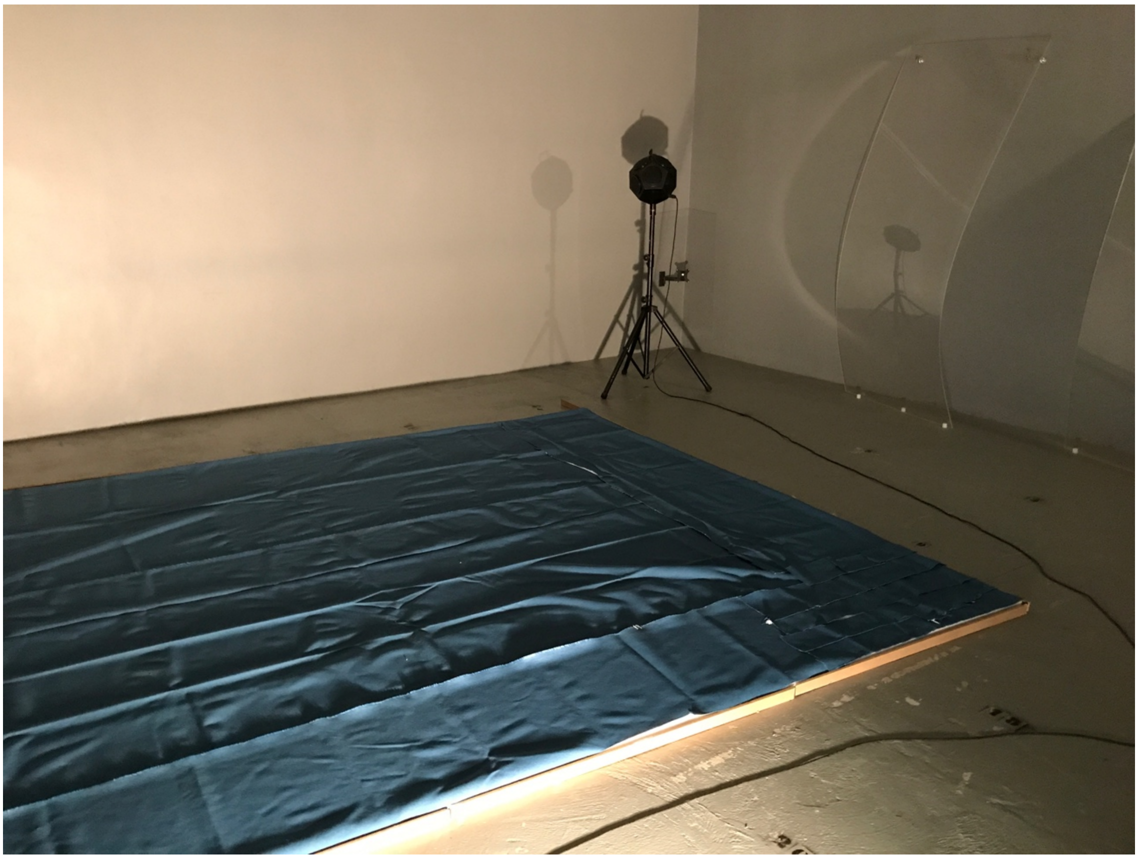


Figure 13. Polyester Fiber + Fabric set up

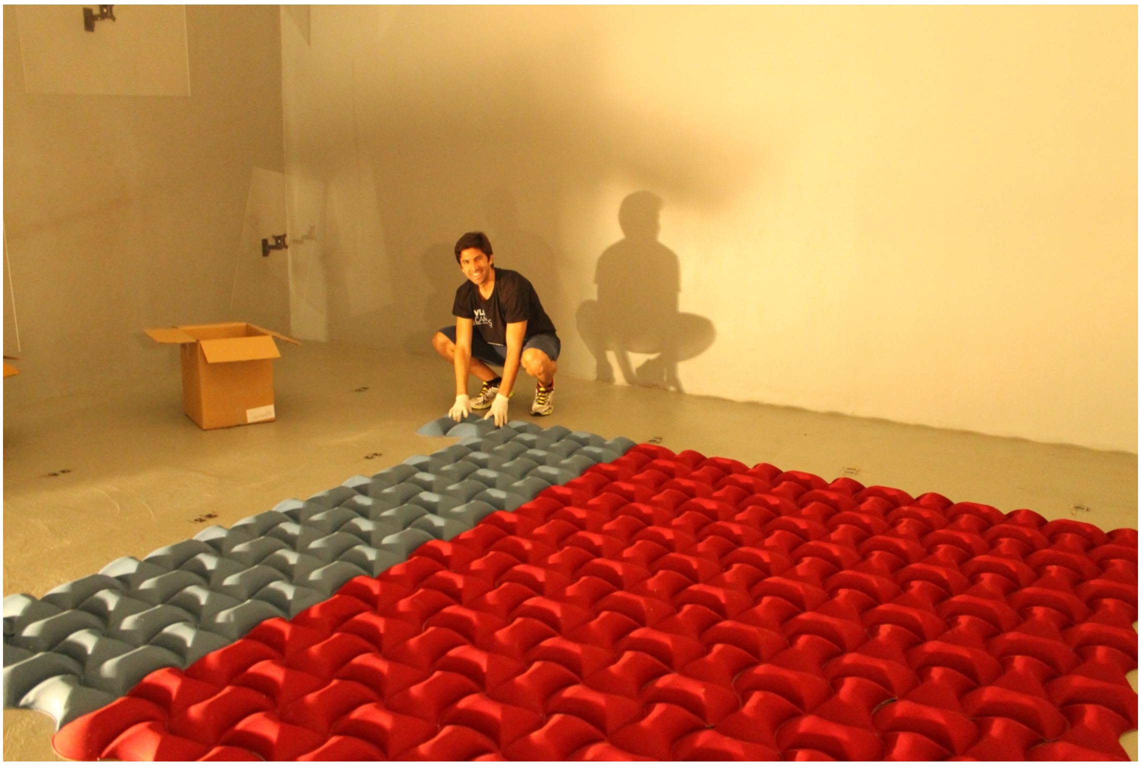


Figure 14. Melamine Foam + Fabric in Shaped fitting panels set up

Figure 15. Polyester Fiber + Fabric in Shaped fitting panels set up

Chapter 6. Results

6.1. Results of the Airflow Resistivity:

Sample	***Resistivity (Pa·s/m2)***	***Std Dev***
Polyester Fibre	1.877	103
Melamine Foam	8.763	149

Table 3. Air-flow resistance results

6.2. Results of the Sound Absorption Coefficient:

6.2.1. Absorption Coefficient of Melamine Foam + Fabric: Empirical vs Model

f (Hz)	*Melamine Foam Model*	*Melamine Foam Measured*
100 Hz	0,09	0,05
125 Hz	0,16	0,16
160 Hz	0,25	0,13
200 Hz	0,36	0,27
250 Hz	0,49	0,38
315 Hz	0,63	0,48
400 Hz	0,76	0,68
500 Hz	0,86	0,80
630 Hz	0,94	0,85
800 Hz	0,98	0,95
1000 Hz	0,99	1,00
1250 Hz	0,98	1,03
1600 Hz	0,95	1,02
2000 Hz	0,89	0,94
2500 Hz	0,83	0,89
3150 Hz	0,82	0,85
4000 Hz	0,83	0,83
5000 Hz	0,78	0,84

Table 4. Absorption Coefficients Melamine Foam

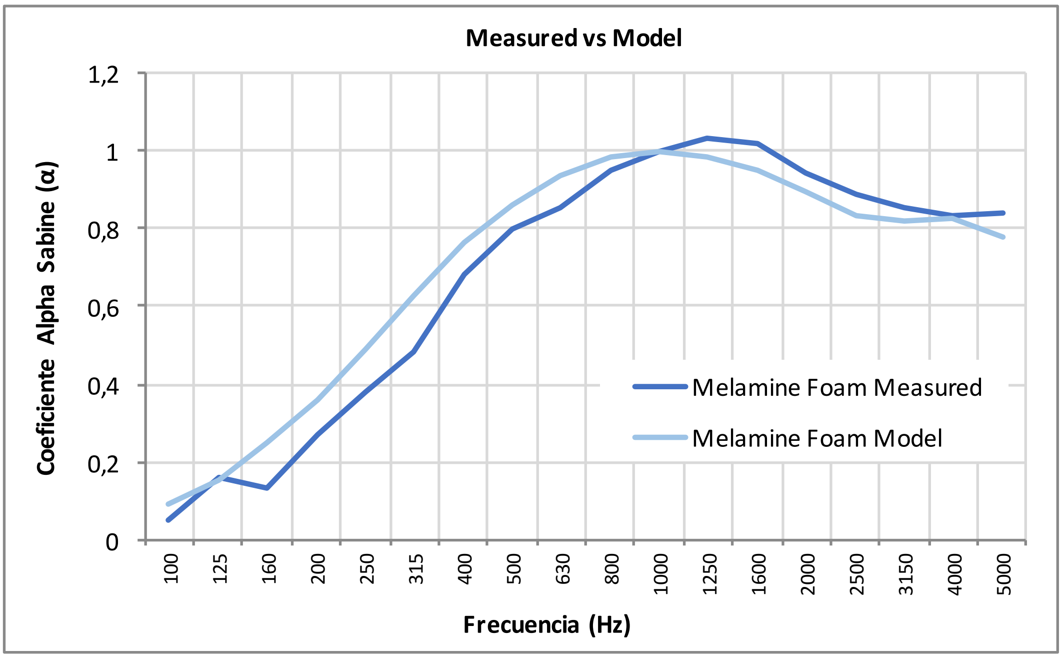


Figure 16. Absorption Coefficient Melamine Foam

6.2.2. Absorption Coefficient of Polyester Fiber + Fabric: Empirical vs Model

f (Hz)	*PET Model*	*PET Measured*
100 Hz	0,13	0,10
125 Hz	0,18	0,24
160 Hz	0,25	0,30
200 Hz	0,34	0,37
250 Hz	0,44	0,57
315 Hz	0,57	0,67
400 Hz	0,70	0,89
500 Hz	0,82	0,96
630 Hz	0,91	1,05
800 Hz	0,97	1,05
1000 Hz	1,00	1,01
1250 Hz	1,00	1,00
1600 Hz	0,97	0,95
2000 Hz	0,93	0,91
2500 Hz	0,84	0,86
3150 Hz	0,68	0,84
4000 Hz	0,79	0,83
5000 Hz	0,78	0,85

Table 5. Absorption Coefficients PET Fiber

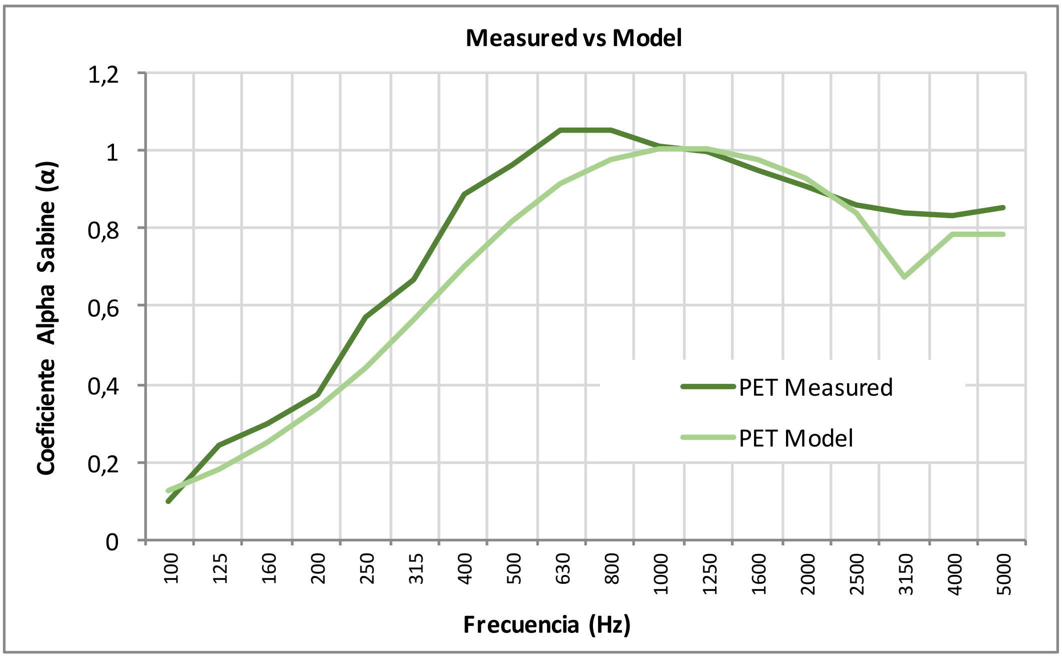


Figure 17. Absorption Coefficient PET Fiber

6.2.3. Absorption Coefficient of Materials: Melamine Foam vs PET

f (Hz)	***Melamine Foam Measured***	***PET Measured***
100	0,05	0,10
125	0,16	0,24
160	0,13	0,30
200	0,27	0,37
250	0,38	0,57
315	0,48	0,67
400	0,68	0,89
500	0,80	0,96
630	0,85	1,05
800	0,95	1,05
1000	1,00	1,01
1250	1,03	1,00
1600	1,02	0,95
2000	0,94	0,91
2500	0,89	0,86
3150	0,85	0,84
4000	0,83	0,83
5000	0,84	0,85

Table 5. Absorption Coefficient Melamine Foam vs PET Fiber

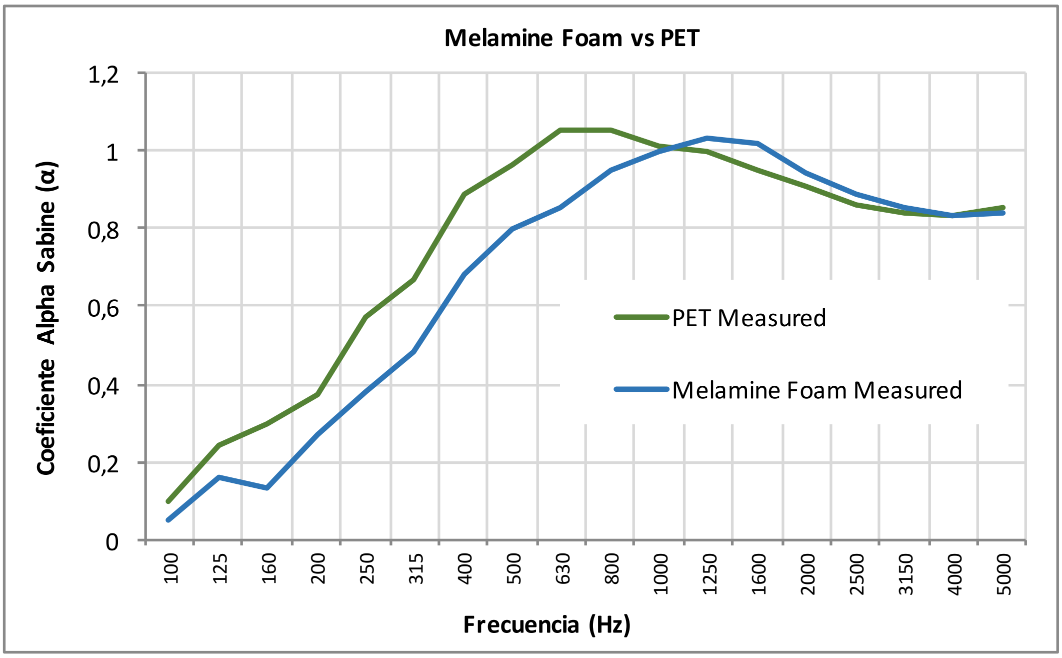


Figure 18. Absorption Coefficient Melamine Foam vs PET Fiber

6.2.4. Absorption Coefficient of Melamine Foam: Plain vs Shaped

f (Hz)	*α Material*	*α Panels*
100	0,07	0,08
125	0,14	0,16
160	0,13	0,18
200	0,25	0,27
250	0,41	0,42
315	0,51	0,58
400	0,67	0,82
500	0,79	1,02
630	0,88	1,13
800	0,97	1,14
1000	1,02	1,14
1250	1,04	1,12
1600	1,00	1,09
2000	0,96	1,08
2500	0,90	1,08
3150	0,86	1,04
4000	0,83	1,04
5000	0,83	1,02

Table 6. Absorption Coefficient Melamine Foam Plain vs Shaped

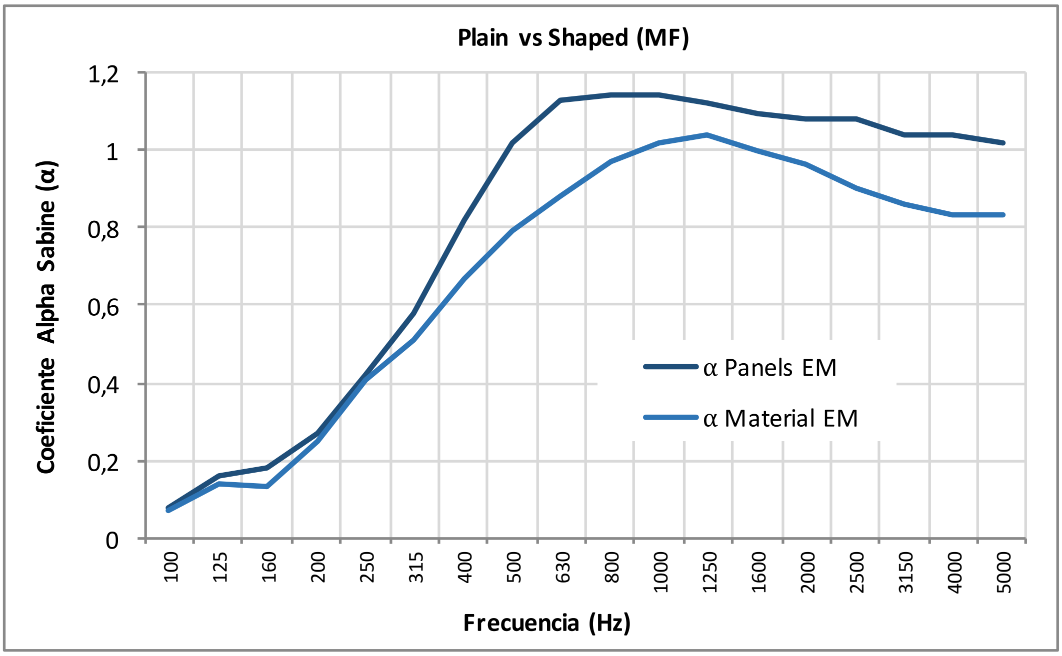


Figure 19. Absorption Coefficient Melamine Foam Plain vs Shaped

6.2.5. Absorption Coefficient of PET: Plain vs Shaped

f (Hz)	*α Material*	*α Panels*
100	0,10	0,06
125	0,24	0,14
160	0,30	0,14
200	0,37	0,20
250	0,57	0,40
315	0,67	0,55
400	0,89	0,76
500	0,96	0,95
630	1,05	1,05
800	1,05	1,08
1000	1,01	1,10
1250	1,00	1,08
1600	0,95	1,10
2000	0,91	1,09
2500	0,86	1,06
3150	0,84	1,07
4000	0,83	1,03
5000	0,85	1,03

Table 7. Absorption Coefficient PET Fiber Plain vs Shaped

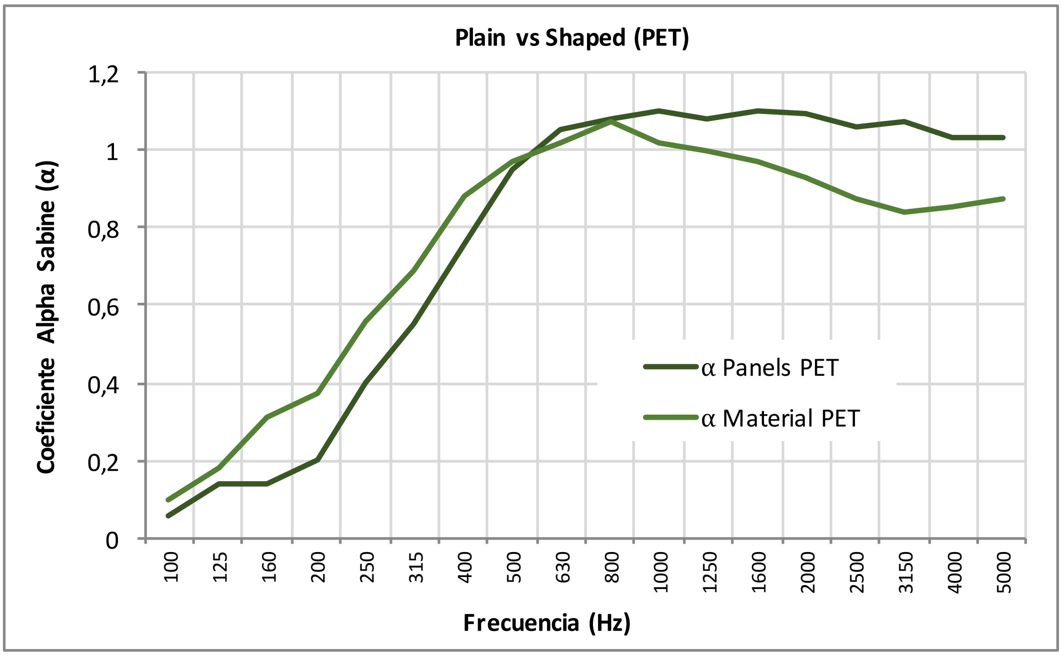


Figure 20. Absorption Coefficient PET Fiber Plain vs Shaped

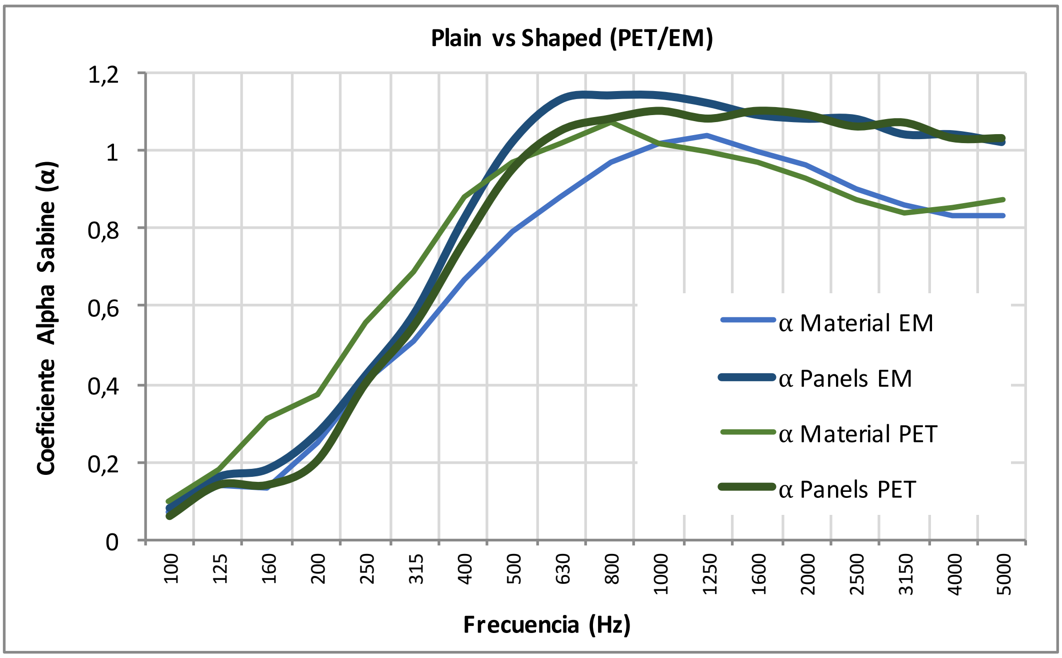


Figure 19. Absorption Coefficient Melamine Foam and PET Fiber Plain vs Shaped

Chapter 7. Conclusions and Next Steps

7.1 Conclusions

Model:

The study shows that the model estimates reasonably well the behaviour of the absorbent with the frequency. It can be also stated that Airflow resistance is a valid parameter upon which base absorbent material modelling.

The model, for higher frequencies, delivers conservatives values for both materials. For low frequencies model values are conservative for fibrous absorbent while optimistic for porous. This could be due to the **imperfections** (airgaps between the textile and the absorbent) on one side. On the other side, is important to consider that the model does not include the effects of the **elasticity of the material** nor the textile.

Thus, it is clear that further tests with different elasticity materials must be perform in order to identify the impact on the performance.

Material:

Regarding the performance of the two materials, better results can be found for the Polyester Fiber Material (PET) for low and mid frequencies (f < 1KHz). Achieving up to 20% more energy absorbed (300Hz -400Hz). Presumably due to the higher elasticity of the PET compared to the Melamine Foam (MF). It might allow the textile to vibrate easily and act as a real vibrating membrane. For high frequencies, both materials perform similarly, dropping their absorption progressively with frequency from 1 down to 0.8. It shows that theoretically PET would be a better suited material for this purpose.

Shaped fitting panels:

The results of the fitting panel configuration show a performance dominated by the geometry for both materials. In the case of the PET, the low frequency performance has got worse. It can be due to the shaping process, which causes the compression of the PET. With lower thickness, higher density and thus higher airflow resistance, the performance is similar to the fabric. This might be causing impedances coupling. This together with an increase of the rigidity can be causing the worsening of the performance at low frequencies. For high frequencies (f > 900Hz) shaping increases the absorption performance.

The MF, on the other side, undergoes a significant improvement. Shaped panel outperforms plain material for all frequency range. For low frequencies, the resonance frequencies of the shape (600Hz and 1000Hz) define the behaviour of the absorbent. For high frequencies, there is also an improvement, as occurred with the PET, caused by diffusion.

Finally, it has been demonstrated that the interface of different materials improves the performance of the final solution if the right combination of features (low and high frequencies) is made. According to the theoretical and empirical results, both technologies are equally suitable for the purpose. Thus, the decision should be made according to other considerations (fire resistance and cost).

7.2 Next Steps

Further work is necessary to understand the impact of the elasticity of the vibrating membrane in the model before it can be adjusted. In order to do so, similar empirical tests must be done with different elasticity (keeping thread size and pattern).

On the other side, once the model is adjusted, interesting work lies ahead trying to model the behavior of the sound wave inside the panel. It can be demonstrated that the behavior depends on the shape and fundamental frequency of it, but a model would help to estimate the effect of diffusion/scattering. In plane configuration is not that relevant, but it is in shaped fitting panels.

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