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SOUND ABSORPTION OF POLYIMIDE FOAMS, AN EXPERIMENTAL STUDY

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Polyimide foam panels have emerged as advanced solutions in naval, nautical, aeronautical, and railway industries, overcoming limitations associated with the high densities and thicknesses of traditional thermal and acoustic insulation materials. This study aims to experimentally characterize the sound absorption coefficient of both standard and mechanically crushed polyimide foams within the 200-4300 Hz frequency range, utilizing the Standing Wave method with three microphones. Thermally cut samples, designed for thermal insulation, show significant absorption in high-frequency ranges but are less effective at lower frequencies. Remarkably, the mechanical compression of these samples transforms closed pores into open and interconnected structures, substantially enhancing absorption at lower frequencies. This phenomenon is also observed in acoustically cut samples. Polyimide foam shows tuneable sound absorption, with the degree of enhancement dependent on variables such as the number of compression cycles, the applied force magnitude and rotational forces (not evaluated in this paper). Further investigation into these mechanical influences promises insights into optimizing the acoustic performance of polyimide-based solutions.

Keywords: Polyimide foams, Mechanical reticulation, Mechanical compression, Sound absorption

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1. Introduction

Polyimide foams, in comparison with other foams such as polyurethane ones, exhibit excellent behaviour in terms of thermal resistance, high working temperatures, fire resistance, low smoke and no toxic gas emissions [1]. Different investigations through scanning electron microscopes (SEM) concerning the microstructure of the polyimide foam show that their structure can be considered as interlinked struts forming packing of cells interconnected to others through pores. Based on their microstructure composition, polyimide foams can be characterized by closed cells which make them rigid and a good material to be used as a thermal insulator (due to their capacity to snare the air passing through it), or by open cell (partially or fully reticulated) structures which usually are less rigid and good sound absorbers [2]. This depends on the fabrication process or other subsequent applied processes.

Over the years, different fabrication processes have been developed such as the powdered foaming method [3], polycondensation method [4], closed mold foaming method [5], freeze-drying method [6], [7] and 3D printing method [8]. Using the powder forming method it is possible to obtain polyimide foams with high densities and nonuniform structures. On the other hand, closed mold forming permits obtaining low-density foams with a uniform structure. The polycondensation method remains the most widely used due to the low costs of production. Freeze-drying has the advantage of producing foams with integral 3D structures and adjustable shapes. Moreover, 3D printing allows to create arbitrary shapes but with high costs [9]. Thanks to their high mechanical strength, fire resistance, heat resistance, sound absorption, etc., polyimide foams are emerging in different fields such as naval, nautical, aeronautical, and railway industries, so that many studies are conducted in order to characterize and improve their properties. It is known that sound absorption of the foams is directly affected by the foam microstructure and the service environment. An increase in thickness leads to an increase of the sound absorption in the low frequency range, whereas a decrease in density leads to increase of the sound absorption. Moreover, as cell size decreases, the interfacial area between the solid frame and the fluid resistance increases, so that the viscosity dissipation of sound wave increases and the value of the sound absorption coefficient (α from now on) increases in the mid and low frequency region. The ambient temperature increase causes a decrease in α [10]. On the contrary, the increase of the slurry temperature from 0ºC to 40ºC leads to the increase of the opening rate from 6.85% to 58.46%, with a double increase of the sound absorption coefficient and even more for the frequency range over 1 kHz [11].

Producing closed-cell foams is generally cheaper and simpler than open-cell foams. The airflow resistivity of these foams is thus high and must be decreased to an acceptable level to have proper sound absorption. For this reason, further optimization methods are needed, such as thermal or chemical reticulating methods which consists in the destruction of the membranes and obtaining fully or partially reticulated materials. Chemical reticulation means that the destruction of the membranes is reached by using chemical agent. It ensures higher absorption coefficients such as 0.6 at 2 kHz and 0.8 at 4 kHz, but air flow resistivity and tortuosity are greatly decreased [12].

Instead, mechanical reticulation or mechanical compression makes possible to obtain a sound absorption coefficient of about 0.9 at 2 kHz, but it decreases above 2 kHz to reach 0.6 at 4 kHz [12]. Also in other studies, the mechanical compression from 20-90% of the original thickness of the polyimide foams lead to a relevant increase in sound absorption performance. Furthermore, the measurement of double wall sound transmission loss application of mechanically crushed polyimide was consistent with the prediction of the poroelastic material model simulated by Statistical Energy Analysis (SEA) software [13]. Shock wave treatment is another method to remove the membranes closing the pore cells and though to improve the absorption performance of the polyimide foams. By increasing the shock wave amplitude with Mach number $M_s<1.58$ the amount of the destroyed membranes increases and consequently, the sound absorption increases as well. For $1.53<M_s<1.73$ the sound absorption decreases after a plateau due to the increase of the plastic deformation and is followed by a strong increase of the airflow resistivity [14].

This paper is focused on acoustical characterization, based on the standard methodology outlined in ISO 10534-2, of the standard and mechanically crushed polyimide foams in the frequency range of 200-4300 Hz.

The first round of measurements consists in the measurement of the sound absorption coefficient of the 8 samples of ‘Soliboard’ material, made by expanded polyimide already studied in a previous paper by means of the Standing Wave Ratio method in the frequency range of 160-1000 Hz [15].

The second round of measurement deals with mechanically reticulated samples corresponding to 10%, 20% and 40% decrease of their original thickness. Higher mechanical compression led to lower absorption in frequency range 200-700 Hz and a relevant increase 700-1700 Hz with α close to 1, but again lower in high frequencies if compared to the α of the standard non-crushed samples.

2. Materials and Method

As already mentioned, the present study is focused on the experimental characterization of the standard polyimide foam samples and mechanically compressed ones. In Figure 1, the images of different samples of polyimide foams treated in this study are represented.

Uncoated polyimide foam

Polyimide foam with RMW coating layer

Polyimide foam with VBD coating layer

Figure 1. Images of polyimide samples with and without covering layers

The non-crushed samples S1 to S8 differ from each other in thickness (25 cm and 50 cm), coating layer (naked, RMW or VBD) and microstructure (based on the production process they can be with open or closed cell structures). Some of them are designed as thermal insulation materials and the remaining ones as sound-absorbing materials. Based on their use, the Soliboard panels can be reinforced with polyester film (RMW) which provides a barrier to vapours and chemical agents used in machineries and living spaces in ships, or with fiberglass scrim and aluminized polyester film (VBD) which provides a vapour barrier as well that is also highly fire resistant. These polyimide foams are mostly used in air conditioning ducts on ships. Polyimide foams reinforced with the aluminized film are used also in the commercial buildings sector as duct liners as they satisfy the requirements about fire resistance, thermal and acoustical performance, resistance to mold growth, etc. [16].

Table 1. Samples tested

Sample ID	Thickness [mm]	Cut	Surface finish
S1	25	Thermal	-
S2	25	Thermal	RMW
S3	25	Thermal	VBD
S4	50	Thermal	RMW
S5	25	Acoustic	-
S6	25	Acoustic	RMW
S7	25	Thermal	RMW
S8	50	Acoustic	RMW

Mechanical compression is then applied to two samples, the S1 uncoated polyimide foam (25 mm thick) and the S4 polyimide foam sample with RMW coating (50 mm thick), causing a decrease of their original thickness of about 10%, 20% and 40%.

Original sample

10% thickness reduction

20% thickness reduction

40% thickness reduction

Figure 2. Example of the mechanically compressed samples

As already mentioned, the compression led to the crushing of the membranes interlinking the pores which led the samples to become partially open-cell. The sample ID and their thicknesses are presented in the following Table 2.

Table 2. Mechanically reticulated samples

Original sample	Sample ID	Thickness [mm]	Surface finish
S4	SC9	45	RMW
	SC10	40	RMW
	SC11	30	RMW
S1	SC12	22.5	-
	SC13	20	-
	SC14	15	-

The experimental setup consists in a standing wave tube based on the standard methodology outlined in ISO 10534-2. The impedance tube used is suitable for measurements in the frequency range from 200 Hz to 4300 Hz. The apparatus consists in an aluminium tube with an internal diameter of 45 mm, three PCB Piezotronics 378C10 microphones, and a NI USB 4431 data acquisition system. All the measurements are conducted by maintaining a rigid end.

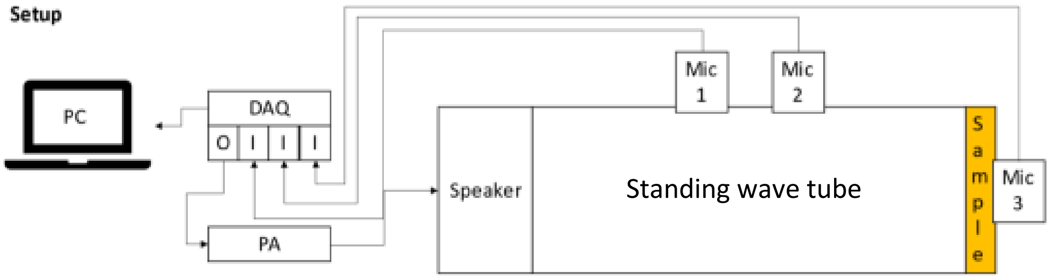

Figure 3. Experimental set-up

3. Results and Discussion

The results of the measurements for the samples S1 to S8 are summarized in Figure 4 and Figure 2. The sample S1, designed as a thermal insulation material without any covering layer presents a considerable absorption, reaching a peak of the absorption coefficient between 2900 Hz and 3200 Hz. A shift towards the 2600 Hz - 2900 Hz range is observed for sample S7 reaching an absorption coefficient close to 1 and a second peak with lower absorption at about 3800 Hz. Instead, the samples S2 and S3, both with surface finishings, provide lower absorption if compared to sample S1. A shift of sound absorption towards lower frequencies is noticed for sample S4 (50 mm thick), having two peaks with α around 0.9 in the frequency range between 1300 Hz and 1500 Hz, and the second peak covering a very wide frequency range from 2400 Hz to 4300 Hz.

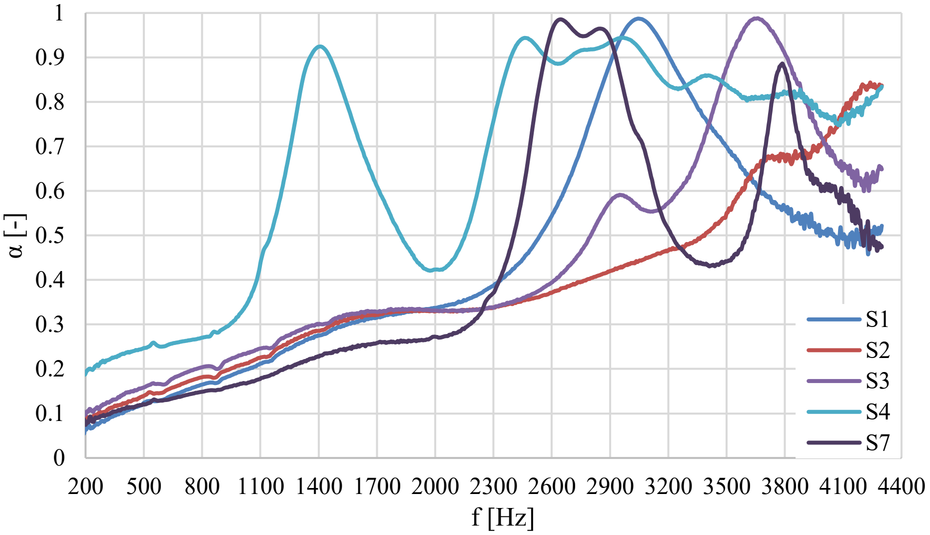

Figure 4. Sound absorption coefficient of the thermal samples S1 to S4 and S7

The samples designed as sound absorption materials show higher absorption as expected, having an open porous structure. The uncoated S5 sample reaches a coefficient of about 0.4 at 1200 Hz and of about 0.9 around 2400 Hz.

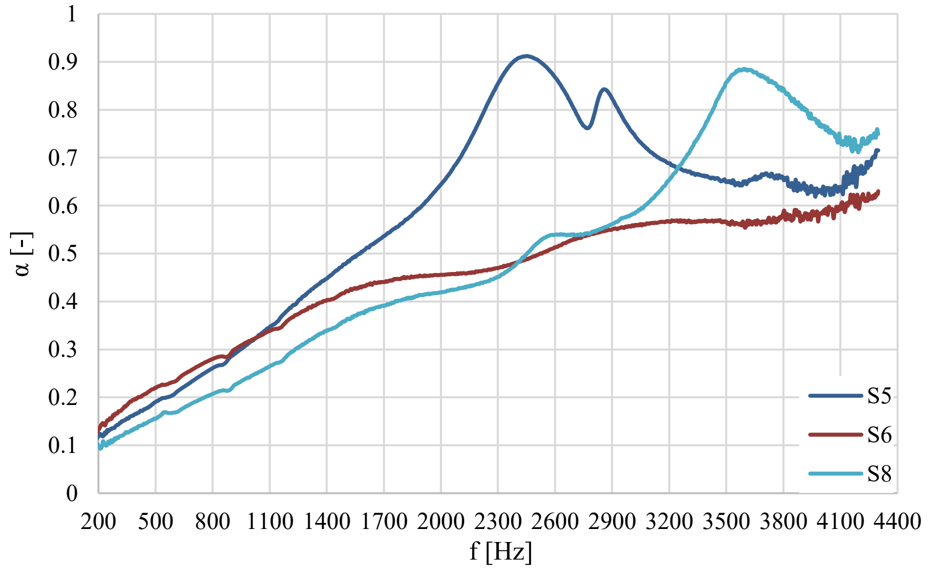

Figure 5. Sound absorption coefficient of the acoustic samples S5, S6 and S8

On the other hand, sample S6 which has a reinforced RMW layer but is of the same thickness as the S5, shows lower absorption. The increase in thickness of sample S8 from 25 mm to 50 mm led to a slight increase in absorption for higher frequencies ranges over 3000 Hz.

After mechanically crushing the samples by applying compression cycles to them, as expected and witnessed in different studies [13], [14], the sound absorption was greatly improved. With just a 10%

reduction of the original thickness, i.e. the SC9 sample, it can be observed that the absorption is tuned and shifted towards lower frequencies but with a slight decrease of the peak from about 0.9 to 0.85. The increase of compression reaching the 20% of the original thickness (sample SC10) highlights more this effect. Furthermore, sample SC11 being compressed and having a reduction of the original length of 40% led to further shift towards lower frequencies, increase of the first peak and extension in wide frequency range. Instead, a decrease of the absorption in higher frequencies is obtained for such compression.

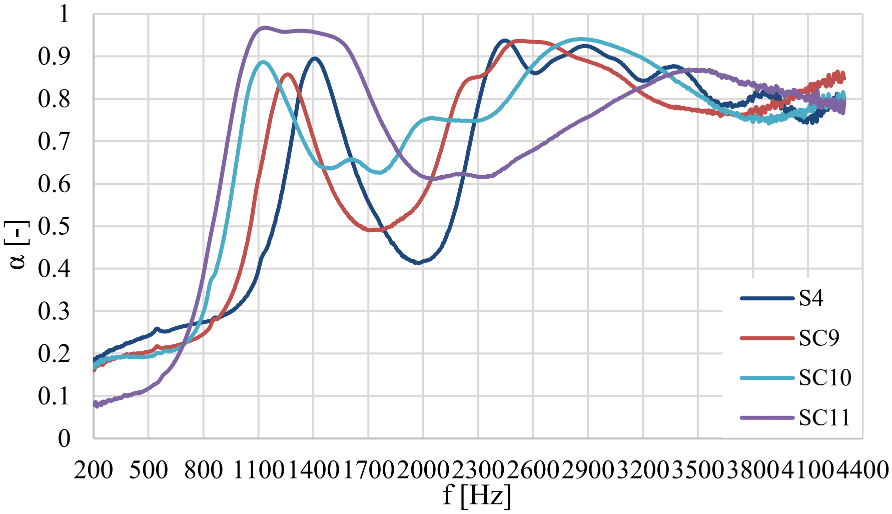

Figure 6. Sound absorption coefficient of mechanically compressed samples S9 to S11 and the original S4

Referring to the sample S1, after 10% reduction of its original thickness (sample SC12), the sound absorption enhances having two peaks where the first one is shifted towards lower frequency ranges, but the peak is lower if compared to the peak reached by S1 sample (see Figure 7).

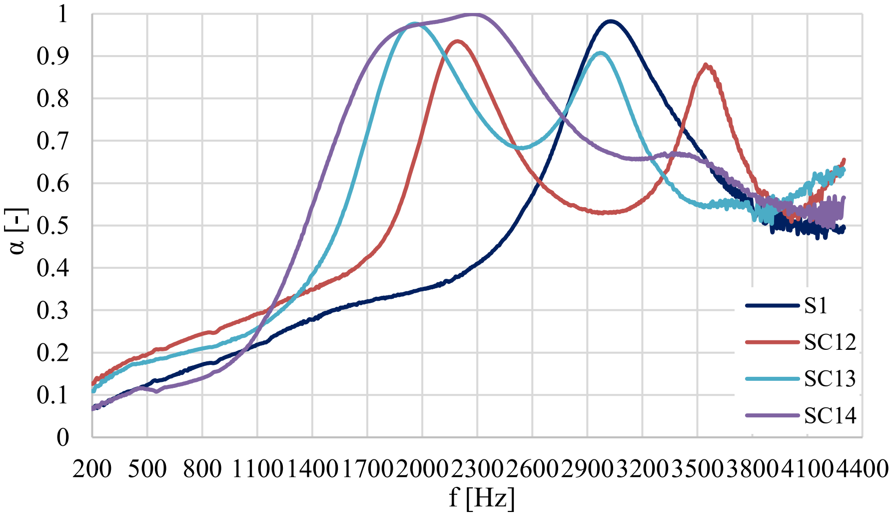

Figure 7. Sound absorption coefficient of mechanically compressed samples S12 to S14 and the original S1

By increasing the compression cycles, passing from 10% to 20% reduction of the original thickness, the progression is the same of sample SC12 but with higher peaks and displaced towards lower frequencies. After 40% reduction of the thickness, the absorption is increased and spread in a wide frequency range.

The mechanically crushed samples at the beginning reduce their thickness, but after one day it is observed that the samples tend to return to their initial shape by increasing their thickness of at least 2 mm up to 5 mm, as showed in **Errore. L'origine riferimento non è stata trovata.**.

Table 3. Samples thickness after 1 day

Sample ID	Thickness [mm]	Thickness after 1 day [mm]	Surface finish
SC9	45	47	RMW
SC10	40	44	RMW
SC11	30	35	RMW
SC12	22.5	25	-
SC13	20	24	-
SC14	15	19	-

4. Conclusions

This paper is focused on the acoustical characterization of polyimide foams based on the standard methodology outlined in ISO 10534-2. This study consists in two rounds of measurements. The first round was aimed to the measurement of the sound absorption coefficients of the samples already treated in a previous study, but in a more extended frequency range. The second round of measurements was aimed to the α measurement of mechanically reticulated (crushed) samples. This consisted in applying different cycles of compression to the polyimide foam samples to obtain a reduction of 10%, 20% and 40% of their original thickness, causing a crushing of the cell membranes. Then, a cutting machine was used to cut samples with diameters of 45 mm. The samples tended to recover their thickness after one day. Higher mechanical compression led to lower absorption in low frequency ranges but a relevant increase from 700 Hz to 1700 Hz.

From this study the following aspects were observed:

1. for most of the samples from 100Hz to 2000 Hz the sound absorption coefficient increases linearly with the increase of the frequency. But after that each one presents different behaviors with different peaks achieved at different frequencies. The uncoated samples present better behavior than the ones with RMW or VBD surface finish, reaching peaks of α close to 1 and covering more frequencies, for both thermal and acoustic designed samples.
2. Higher mechanical compression led to a relevant absorption increase from 700 Hz to 1700 Hz, whereas it decreases at higher frequencies if compared to the α of the non-crushed one.
3. The samples tend to recover their initial thickness one day after the mechanical compression.

Further research is needed to explore optimization strategies for compression parameters and investigate long-term stability post-compression.

Acknowledgements

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