REBONDED POLYURETHANE FLEXIBLE FOAM AS SOUND ABSORBING MATERIAL

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Polyurethane (PU) foams are highly established material in noise control engineering, but also in other remarkably versatile domains. Unfortunately, this increases the amount of PU waste disposal in the landfills. Concerning the new strategies for sustainable and green polyurethanes, this study investigates the sound absorption properties of Rebonded PolyUrethane (RPU) foam.

Measurements of sound absorption coefficient, α, under normal incidence were made using an impedance (Kundt) tube for RPU foam samples with two different densities (40 kg/m^3±15% and 60 kg/m^3±15%) and three different thicknesses (45 mm, 70 mm and 95 mm). The airflow resistivity was also measured for the same samples.

The Transfer Matrix Method (TMM) was employed to simulate the sound absorption phenomenon for normal and diffuse sound incidence of unbounded poro-elastic RPU layer with hard wall termination. The visco-inertial dissipative effects inside the porous layer were described with Johnson-Champoux-Allard (JCA) model.

Keywords: sound absorption coefficient, airflow resistivity, impedance tube, transfer matrix method, rebounded polyurethane foam

1. INTRODUCTION

Polyurethane production reached a total of 22.3 million tons and grew at a rate of 4.0 % during 2016, while the estimated global polyurethane production for 2020 was 28.2 million tons, with an annual production growth rate of 5,2 % [1]. PU production is constantly increasing due to their diverse application, which leads to an increase in the amount of polyurethane waste in the environment.

Polyurethanes are group of polymers, produced using petroleum-based polyols and diisocyanate and they are generally very resistant to biodegradation. The methods for PU recycling can be categorized into three groups: mechanical recycling, chemical recycling and energy recovery. Mechanical recycling consists of grinding/shredding the polyurethane waste and then, reprocessing. With chemical recycling the PU is chemically degraded, while energy recovery considers combustion of polyurethane foam waste to recover energy. Regarding costs, applied temperature and additional substrates, chemical recycling is very demanding process and only two chemical recycling methods are implemented on a large scale (glycolysis and gasification), while others are still in the research stage, [2]. Mechanical recycling is, so far, the most effective and economic route for recycling.

Flexible and rigid foams are the two main types of polyurethanes. Rebonded PU foams are mechanically recycled polyurethane foams, manufactured form grinded foam, pressed and bonded with binder. Rebonded polyurethane foam is a very convenient way to reuse PU foam waste.

There are many research studies dedicated to acoustic characterization of PU foams, but there is a vast research area for the recycled PU foams that has yet to be addressed. Del Rey et al., [3], [4], studied the acoustic properties of recycled foams developed from grinded polyurethane foam waste with different internal composition. Tiuc et al., [5], research the sound absorption of recycled PU foams developed by using grinded rigid PU foam waste as a raw material. Sabbagh and Elkhateeb, [6], investigate the absorption coefficients of rebonded PU foam in the reverberation chamber. Bougdah and Hall, [7], performed field measurements and Nering et al., [8], measured the dynamic stiffness, and critical damping coefficient in order to investigate the possibility of using rebonded PU foam for impact sound insulation. Parikh et al., [9], study the absorption properties of rebonded polyurethane foam and possibility to use it as underpad for reduction of automotive interior noise.

Despite the fact that rebonded PU has been used for a long time, its potential has not been extensively explored. Therefore, this paper focuses on acoustic characterization of rebonded PU flexible foams with different densities and thicknesses. Sound absorption coefficients are measured using impedance tube and airflow resistivity is also measured for the same specimens. Based on the obtained experimental results, transfer matrix method was employed for extended research.

2. MATERIALS & METHODS

Rebonded polyurethane foam specimens were produced from shredded polyurethane waste combined with binder and then exposed to pressure. This type of mechanical recycling technology creates non-homogenous distribution of the volume weight in the produced foam block. Specification of the volume weight is based on measuring and weighing the entire block.

Two different densities were produced by a local PU flexible foam manufacturer: 40 kg/m^3±15% and 60 kg/m^3±15%, Figure 1. For each density, 3x3 cylindrical samples with thicknesses: 45 mm, 70 mm and 95 mm, were cut out, each with diameter of 100 mm.

a) 

b) 

Figure 1. Rebonded polyurethane foam specimens: a) ρ=40 kg/m^3, b) ρ=60 kg/m^3

For acoustic characterization of the RPU foam, airflow and impedance (Kundt) tube measurements were performed on the same samples. From the measurements, the airflow resistivity, R_1, and the sound absorption coefficients, α, were obtained. The measurements were conducted in the laboratory facilities of University of Campania "Luigi Vanvitelli", Department of Architecture and Industrial design.

The airflow resistivity (flow resistance per unit thickness) is very important acoustic parameter that is associated with the absorption capacity of the material. For the selected rebonded foam specimens, the airflow resistivity was measured according the ISO 9053, [10], following the alternating airflow method, using the measuring device SCS9023, Figure 2, [11]. The airflow resistivity, R_1, is obtained from Equation 1, under alternate air flow generated with a piston at a frequency of 2.0 Hz.

$$R_1 = \frac{\Delta p}{v \cdot \Delta x}\ [Rayl/m] \qquad (1)$$

where Δp is pressure difference, v is air velocity and Δx is the thickness of the specimen, in the direction of the flow, in metres.

Figure 2. Airflow resistivity measuring device SCS9023

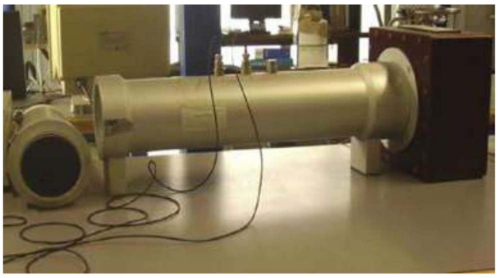

Figure 3. Impedance tube SCS9020

The normal incidence sound absorption coefficients of the RPU specimens were measured with SCS9020 impedance (Kundt) tube, Figure 3, [11], in accordance with ISO 10534-2, [12].

On the one end of the tube there is a noise source that generates plane waves and on the other end, the test sample is mounted. The impedance tube has internal diameter of 100 mm and length of 570 mm and provides satisfactory results for the absorption coefficients in the frequency range 250 Hz – 2000 Hz. The sound absorption coefficients are obtained from the acoustic transfer functions measured with the two microphones.

By using the transfer matrix method, unbounded poro-elastic layer with hard wall termination on one side and semi-infinite fluid on the other side was modeled, considering plane wave propagation, Figure 4.

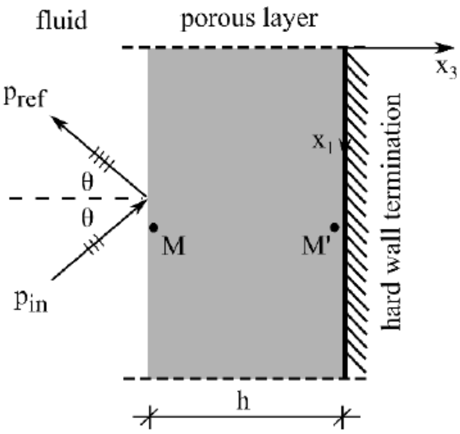

Figure 4. Unbounded poro-elastic layer backed with hard wall for transfer matrix calculation

Transfer matrix method is simple but powerful method widely used in many fields of physics among which the field of acoustics. It is used to calculate the wave propagation in a layered system where each layer within the system is defined by a transfer matrix. The size of the matrix depends on the type of the layer. For elastic-solid layer is 4x4, for elastic-porous layer is 6x6, for stationary fluid layer is 4x4 etc., [13]. This depends on the number of quantities that describe the acoustic field in the layer. For example, for a porous layer, 6 quantities describe the acoustic field: two velocity components of the porous frame (v_1 and v_3), one velocity component of the fluid (v_3), two components of the stress tensor of the porous frame (σ_{33} and σ_{13}) and one in the fluid (σ_{33}). The surface impedance, Zs, is obtained directly from the transfer matrix for given boundary conditions. Hence, reflection, absorption, transmission and other phenomena can be easily studied.

The transfer matrices relate the variables V that describes the acoustic field of the medium on both sides:

$$V(M) = [T]V(M') \qquad (2)$$

where M and M' are points near the forward and backward face of the layer.

The considered porous layer, on one side, interacts with semi-infinite fluid so the continuity condition for fluid-porous interface was applied. On the other side, hard wall termination condition was imposed (infinite impedance). Next, the surface impedance of the medium is determined, the reflection coefficient and then the absorption coefficient.

The visco-inertial and thermal dissipative effects occurring in the porous medium were described with Johnson-Champoux-Allard (JCA) model. For this model, besides air flow resistivity *R*1, that is measured, several other parameters are needed: porosity ϕ, tortuosity a_∞, viscous characteristic length *Λ* and thermal characteristic length, for which the following dependency is adopted: *Λ*'=2*Λ*. Porosity is estimated from the Equation 3, while the other parameters are obtained by fitting the measured curves. Same values per density were adopted.

$$\phi = 1 - \frac{\rho_{bulk}}{\rho_{solid}} \tag{3}$$

After obtaining the intrinsic parameters for the two densities, the sound absorption coefficient for diffuse sound incidence was calculated with TMM through integration:

$$\alpha_{diff} = \int_0^{\pi/2} \alpha(\theta) sin2\theta d\theta \tag{4}$$

The Noise Reduction Coefficient, *NRC,* was also calculated. *NRC* is a single-number rating of sound absorption and is widely used as a parameter to characterize and compare sound-absorbing materials. NRC is the arithmetic mean of the absorption coefficients for 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, [14]:

$$NRC = \frac{\alpha_{250}+\alpha_{500}+\alpha_{1000}+\alpha_{2000}}{4} \tag{5}$$

3. ANALYSIS & RESULTS

The measured airflow resistivity for the two considered densities are shown in Table 1. The airflow resistivity influences the sound absorption properties and is one of the parameters of the JCA model.

Table 1. Airflow resistivity

Density [kg/m³]	R_1 [Rayl/m]
40	3800
60	5000

The normal incidence sound absorption coefficients measured with the impedance tube are presented in Figure 5. It can be seen that by increasing the thickness the low to mid frequency absorption coefficients are improved. For example, for 500 Hz and ρ=40 kg/m³ the absorption coefficient increases for 81% when increasing the thickness from 45 mm to 70 mm, and 43% when increasing the thickness from 70 mm to 95 mm. For 500 Hz and ρ=60 kg/m³, the absorption coefficient increases for 76% when increasing the thickness from 45 mm to 70 mm, and 23% when increasing the thickness from 70 mm to 95 mm. As expected, the efficiency of the RPU foams for high frequencies is significant i.e., α>0.7.

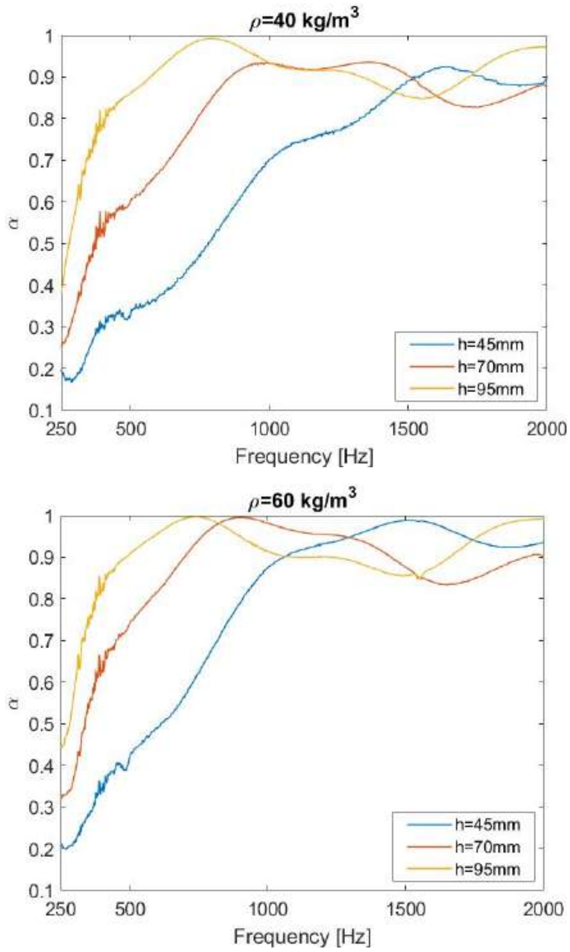

Figure 5. Sound absorption coefficients measured in impedance tube

For normal incidence, *θ*=0°, the comparison between the experimental results and transfer matrix method is shown in Figure 6. The predicted result compares well with the experimental results with expected small discrepancies. One of the main reasons for the differences is the inhomogeneity and anisotropy of the RPU foam. Furthermore, the experimental testing was performed on samples with finite dimensions, while the calculation is based on infinite models. Also, the diffraction at the edges of finite porous samples causes constructive as well as destructive interference, [15].

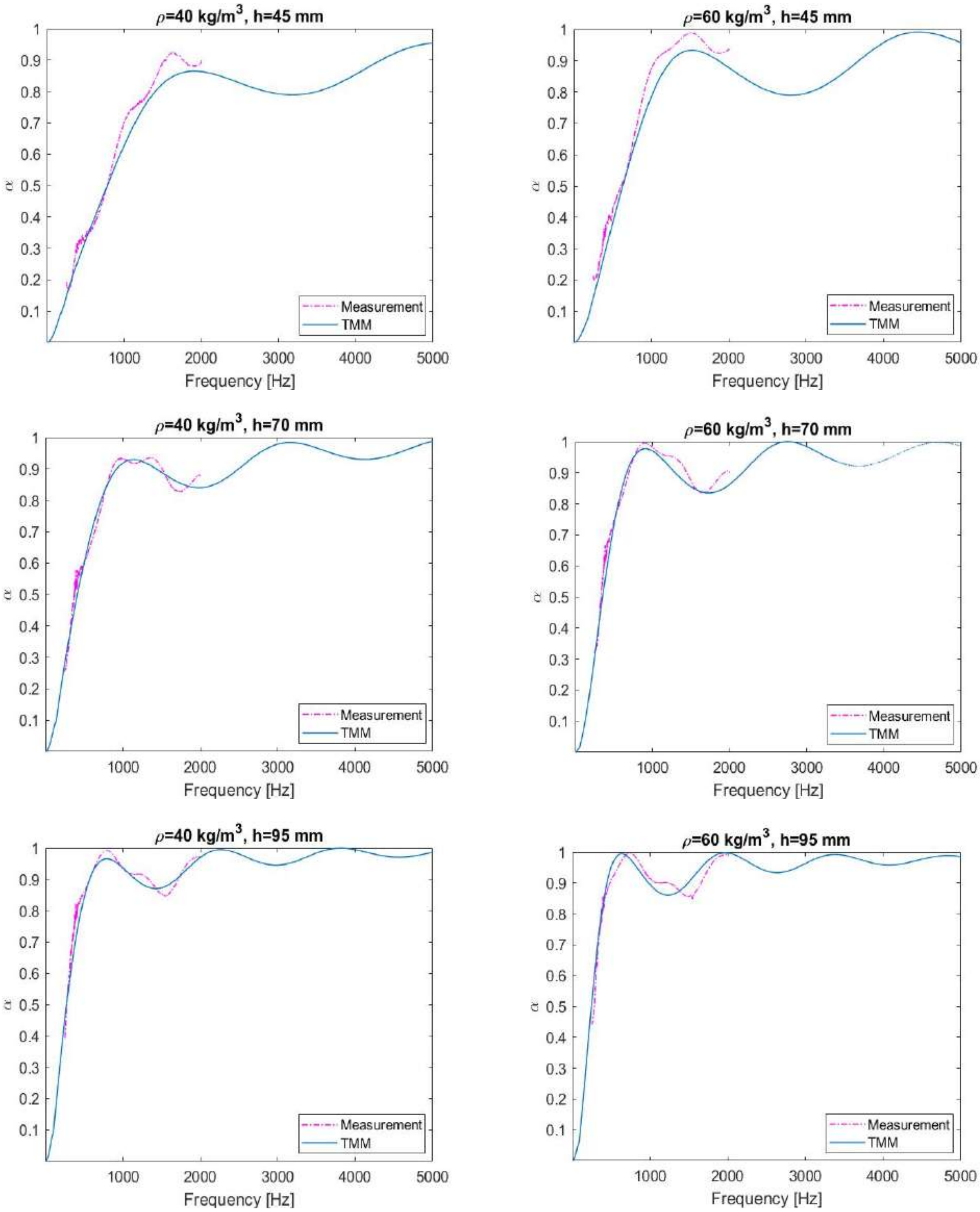

Figure 6. Sound absorption coefficients for normal incidence, θ=0°

By using the transfer matrix method and estimated parameters from the measurements, the sound absorption coefficients for diffuse sound field are predicted. The results are shown in Figure 7. The calculated sound absorption coefficients for diffuse sound incidence are higher for low to medium frequencies than the one for normal incidence while in the high frequency region, the diffuse sound absorption curve is smoother.

The Noise Reduction Coefficient, *NRC,* for the calculated and experimentally obtained sound absorption coefficients are shown in Table 2. The calculated *NRC* values for θ=0° are close to the one obtained with measurements. The differences between the experiment and TMM simulation for *NRC* is in the range 1-10%. It can be seen that with increasing the thickness, *NRC* also increases. The same applies for the density, the specimens with higher density perform better. The obtained values for NRC for the diffuse sound filed are higher than for normal incidence, except for ρ=40 kg/m^3 and h=45 mm. *NRC* value of 0.70 and above is considered as good sound absorption. For the diffuse field calculation, *NRC* above 0.7, can be achieved with the thicknesses 70 mm and 95 mm.

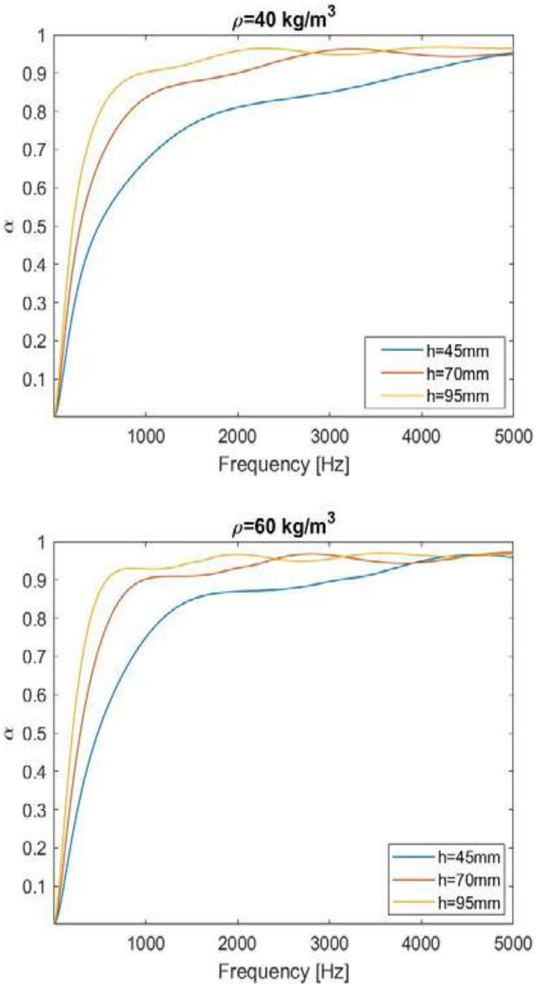

Figure 7. Absorption coefficients calculated with transfer matrix method for diffuse sound field

Table 2. *NRC* for the RPU foams

Density [kg/m^3]	*h* [mm]	*NRC* Exp θ=0°	*NRC* Calc θ=0°	*NRC* Calc diff
40	45	0.53	0.49	0.58
40	70	0.67	0.66	0.71
40	95	0.79	0.80	0.81
60	45	0.61	0.55	0.60
60	70	0.73	0.72	0.75
60	95	0.81	0.84	0.84

4. CONCLUSIONS

From the obtained results it can be seen that for RPU foams NRC values greater than 0.7 can be achieved. Regarding the low frequencies, which are usually a challenge when designing acoustic treatments, adequate absorption can be obtained by choosing appropriate thickness and density.

Although there are materials and products on the market with better absorption abilities, rebonded polyurethane foams, with their price and with their good relationship with the environment can be one possible solution for various noise treatment applications. One of the main challenges is to achieve a reliable and stable production process of elements with, as much as possible, uniform characteristics.

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