Polyamide waste thermal and acoustic properties: experimental and numerical investigation on possible reuse for indoor comfort improvement

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Abstract

Referring to the circular economy model, end-of-life household materials (EoLHM) such as packaging, and clothes, could be converted into building elements – for example panels - with thermal and acoustic properties. Given the high availability almost anywhere, EoLHM represents an alternative to commercial insulating materials that, even though relatively cheap, cannot be afforded by disadvantaged people. The panels are intended for the refurbishment of existing buildings and, therefore, to be installed indoor. This paper presents a multidisciplinary analysis aimed at the characterization of polyamide 6.6 waste from the production of non-surgical face masks. The analysis focuses on thermal and acoustic aspects that have determined experimentally by means of the hot plate with guard ring test, and the impedance tube technique respectively. Then, the influence of the panel position on the indoor operative temperature and the reverberation time has been analysed numerically. Results show that, from the thermal and acoustic point of view, this waste is suitable for the realization of building panels and the performance depends on the density and the thickness of the material. However, aspects such as the fire-resistance and the containment of the material need further investigation.

1. Introduction

Living in dwellings characterized by not adequate indoor temperature and poor air quality is called ‘energy poverty’, a condition affecting 1 in 3 Europeans, and linked to 100000 premature deaths each year (European Parliament and Council of the European Union, 2018, González-Eguino, 2015). People living in disadvantaged contexts cannot refurbish their dwellings because of the relative high price of commercial insulating materials. Since by the 2030, the United Nations aim at making cities inclusive, safe, resilient, sustainable, and at promoting a circular economy model (United Nations, 2015), an alternative to commercial insulating materials may be insulating elements realized by reusing end-of-life household materials (EoLHM) such as packaging, clothes, bottles, etc. In the literature, several studies investigated the properties of EoLHM but a comprehensive and systematic analysis is still missing (Drochytka et al., 2017, Secchi et al.,2015, Ibrahim et al., 2018, Kudzal et al., 2018, Mansour et al., 2015, Neri et al., 2021).

The aim of this paper is the thermal and acoustic characterization of polyamide 6.6 waste (in the following called polyamide) obtained from the production of non-surgical face masks. Firstly, the thermal and the acoustic properties of polyamide have been experimentally determined. Then, by means of numerical simulations, the improvement of the building indoor condition determined by the presence of panels of polyamide is assessed. In this preliminary study, the panels are made of polyamide confined between two layers of glass veil - a very light material that does not affect the thermal and acoustic properties of the system. These panels are intended to be installed indoor on the internal wall surfaces to allow easy and fast building refurbishment interventions also by unskilled people.

In this study, the thermal conductivity of samples realized with polyamide at different densities has been measured by means of the hot plate with guard ring test. Indoor comfort embraces several aspects such as thermal and acoustic comfort, that are the aspect analyzed in this paper. Under steady-state conditions, heat transfer through a wall is described by the relationship

$q = A \cdot \Delta T / (\Sigma\ s/\lambda)$

where q is the heat flux through the wall, A, s, λ are the surface, the thickness and the thermal conductivity of the wall. ΔT is the difference in temperature on the two sides. Under unsteady conditions, the heat flux q depends on the wall heat capacity and layers position too.

When dealing with indoor acoustic comfort, one of the aspects to be evaluated is the reverberation time TR that gives information on the indoor sound quality in terms of echo effect and, consequently, vocal messages intelligibility and listening conditions. Optimal TR values depend on the intended use of the room and reference values are specified in UNI 11367 (UNI 11367:2010). Measurement the TR consists in determining the time lapse in which the sound energy density decreases of 60 dB and is determined by suddenly switching off a sound source and in measuring the sound energy level variation. TR can be estimated according to the Sabins formula

$TR=0.16\ V/S$

where V is the volume of the room, S is the room total absorption defined as $S=\Sigma(\alpha \cdot A)$, where A is the surfaces extension and α the sound absorption coefficient of the surface. The sound energy balance on a surface impinged by sound power leads to

$1=\eta+\tau+\alpha$

where η is the sound reflection coefficient, τ is the sound transmission coefficient and α is the sound absorption coefficient. In general, for porous material such as the one investigated in this paper, the higher the density, the lower α, and greater thickness entails higher α. The absorption coefficient for a hard backed element is defined as

$\alpha=1-|TL|^2$

where TL is the sound transmission loss a properties function of τ:

$TL=10\cdot\log_{10}(1/\tau)$

In this paper, the sound absorption coefficient, and sound transmission loss coefficient have been determined experimentally by means of impedance tube technique.

2. Experimental campaign

Since polyamide is a soft and porous material (see Fig.1), its density depends on the packing degree- an important aspect in view of panel self-realization. To evaluate this aspect, the equivalent thermal conductivity λ_{eq} as a function of the density has been determined by means of the hot plate with guard ring test. The test consists in measuring the heat flow q through a sample under a predefined temperature difference ΔT, and λ_{eq} is determined as

$\lambda_{eq} = (q \cdot s) / (A \cdot \Delta T)$

where A and s are the sample surface and thickness respectively. Results are shown in Figure 2.

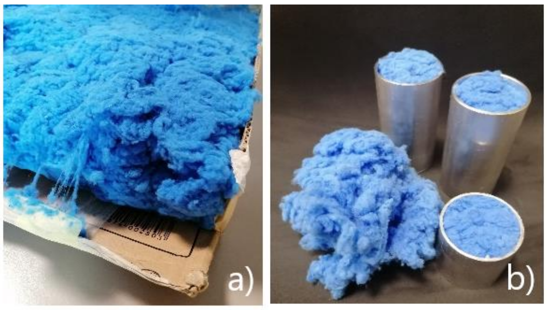

Figure 1 – Test specimens for the hot plate with guard ring test a) and for the impedance test b). For the acoustic tests, the material in the samples has been contained between two glass tissue discs at either ends to ensure that the front surface was normal to the axis of the tube.

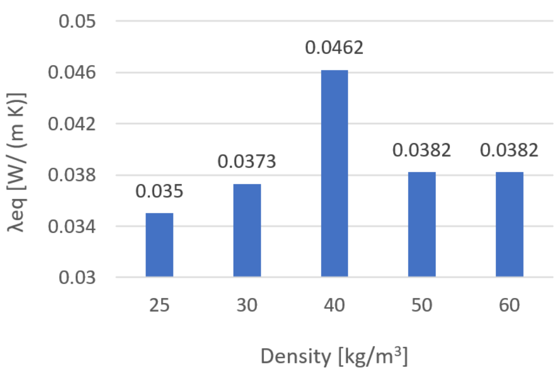

Figure 2. Measured equivalent thermal conductivity of polyamide.

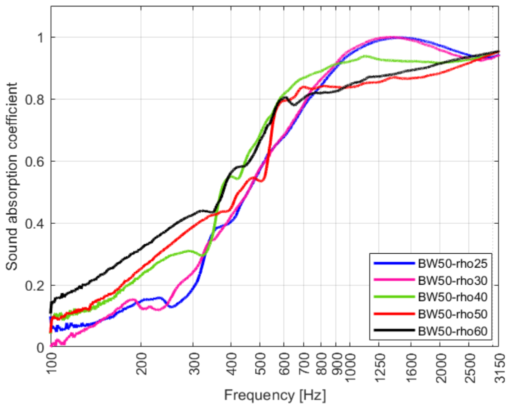

Figure 3. Sound absorption coefficient of the 50 mm thick samples.

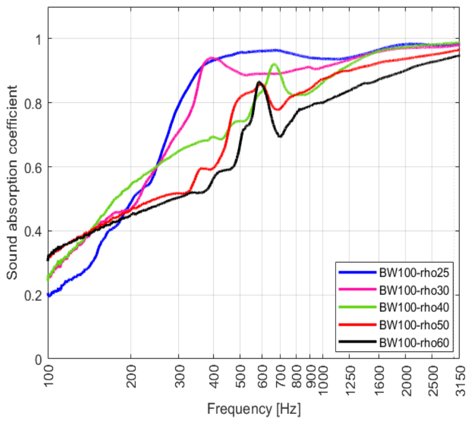

Figure 4. Sound absorption coefficient of the 100 mm thick samples.

Samples with the same density have been realized and tested in the impedance tube apparatus to determine the polyamide sound absorption coefficient α, and the sound transmission loss TL. The test apparatus consists in two tubes 4.6 cm in diameter connected to a test sample holder. On either side of the specimen two microphones are placed (45 mm from each other), and at one end of the tube a source emitting a pink noise is placed. A multi-channel Fast Fourier Transform (FFT) analyzer acquires the signals captured by the microphones. Pressure and particle velocity of the traveling waves and of reflected waves are determined by means of a MATLAB script implemented according to the E2611 ASTM standard (ASTM E2611, 2019). To assess the influence of the specimen's thickness, samples 50

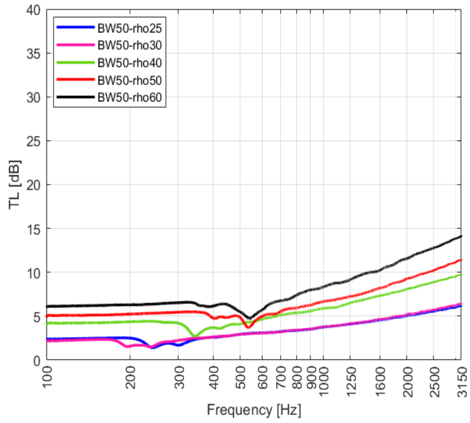

Figure 5. Transmission loss of the 50 mm thick samples.

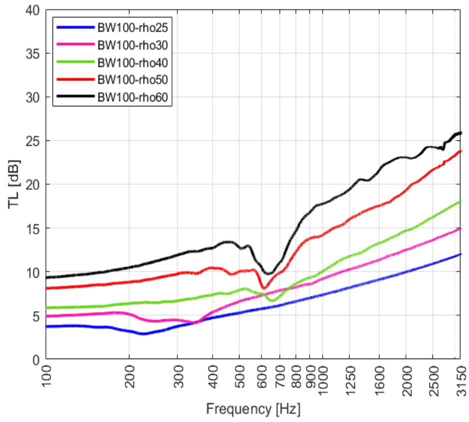

Figure 6. Transmission loss of the 100 mm thick samples.

mm and 100 mm thick have been realized and tested in the frequency range from 100 Hz to 3150 Hz. The working frequency range is related to the test apparatus characteristics; in particular, the lower and the upper working frequency have been respectively determined according to:

$fu<0.586 * c_{air} /d$

$d<0.586* c_{air} /fu$

where c_{air} is the speed of sound in the tube, and *d* is the tube diameter. Results are shown in Figure 3 – Figure 6.

3. Numerical simulations

To assess how the presence of panels made of polyamide affects the indoor conditions when installed indoor (directly on the internal surface of

Figure 7. Facade of the case study in Raval neighborhood in Barcelona a) interior, b) view from the balcony, and c) opposite building.

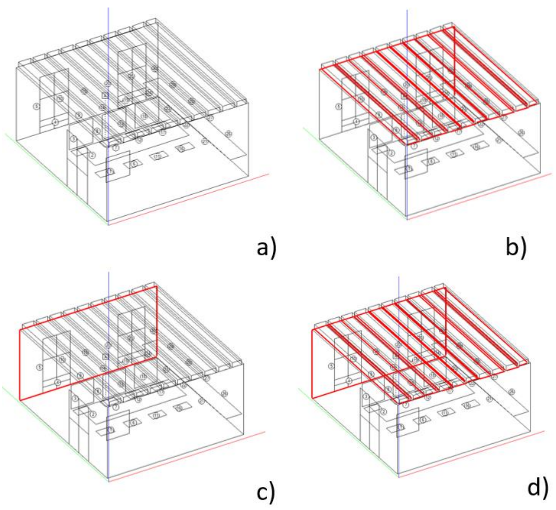

Figure 8. Panel positions considered in the numerical analysis: a) current configuration without panels (Case00), b) panels installed on the ceiling (Case01), c) panels installed internally on the façade (Case02), d) panels installed on both the façade and the ceiling (Case03).

the walls and/or ceiling), both acoustic and thermal numerical models have been set by means of the EnergyPlus and Ramsete opensource software. At this stage, the panel is considered 10 cm thick and realized with polyamide at 25 kg/m3 confined

Table 1. Wall layers details.

Windows	Roof	Internal wall	Façade
Glass	Tiles	Plaster	Plaster
	XPS	Dolomite IW	Dolomite F
	Hollow bricks R	Plaster	Plaster
	Plaster		
Basement	**Floor**	**Ceiling**	
CLS_B	Plaster	Tiles	
CLS_S	Hollow bricks F	CLS_M	
CLS_M	CLS_M	Hollow brick F	
Tiles	Tiles	Plaster	

between two glass veil layers.

The models have been defined referring to a dwelling (a classroom) located in the Raval neighborhood in Barcelona (see Fig.7) where thermal and acoustic measurements have been taken and, then, used to verify the numerical models. The classroom is on the second floor of a building, and it is 5.1 x 5.8 x 3.0 m in dimensions. The external wall (façade) is 17 m^2 and occupied by two windows 2.6 x 1.1 m. The ceiling is a typical Catalan structure with volts 30 cm large. Materials properties are listed in Table 1 and Table 2: some of them have been supposed while others have been provided by the building owner. The materials diffusion vapor factor is 180 except for Polyamide that, according CIBSE Guide A (CISBE Guide, 2015) has been chosen equal to 1.2543. The occupancy level is 0.38 persons/m^2 and natural air infiltration is considered. The geometry of the model is shown in Figure 8: also the furniture has been included as it may affect the sound waves reflection and, in turns, the reverberation time.

Numerical simulations have been performed for different scenarios where the position of the panels has been varied according to Figure 9: Case00 is representative of the current configuration without any panel, while panels are installed in the ceiling vaults in Case01, on the internal side of the façade in Case02, and both on the ceiling and on the internal side of the façade in Case03.

The model defined in EnergyPlus includes the entire building (considered as a single thermal

Table 2. Material properties used in the thermal numerical model defined with EnergyPlus.

Material	Plaster	Hollow bricks_R	Hollow bricks_F
s	0.015	0.5	0.3
λ	0.8	0.24	0.24
ρ	1600	800	800
c	1000	1000	1000
Material	**CLS_M**	**Dolomite_F**	**Dolomite_IW**
s	0.05	0.35	0.15
λ	1.1	1.75	1.75
ρ	1000	2872	2872
c	880	910	910
Material	**XPS**	**Tiles**	**CLS_B**
s	0.08	0.01	0.3
λ	0.035	0.208	2.4
ρ	30	530	2400
c	1500	1000	1000
Material	**CLS_S**		
s	0.1		
λ	0.9		
ρ	1800		
c	880		

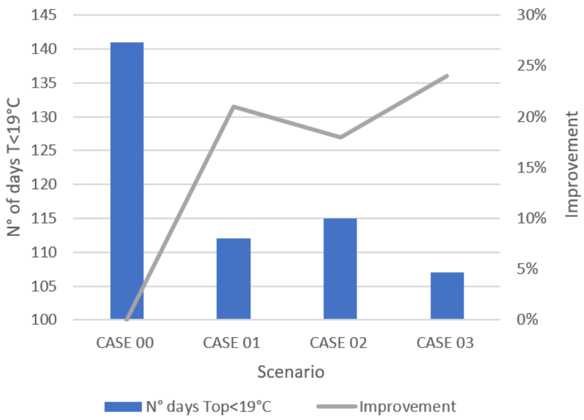

Table 3zone) and the surrounding buildings that contribute to shading. Results are reported in Figure 9 that shows the number of days when the indoor temperature is lower than 19°C and, then, a heating system would be necessary.

The software Ramsete is based on the Pyramid Tracing algorithm able to solve problems in large

Table 3. Sound absorption coefficients α of the materials set in the numerical model defined with Ramsete software. As regards the Polyamide, only the normal incident properties have been considered.

	31 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Plaster (walls)	0.005	0.005	0.01	0.01	0.01	0.02	0.02	0.02
Open window	0.4	0.8	0.8	0.8	0.8	0.8	0.9	0.99
Glass (windows)	0.21	0.42	0.35	0.25	0.18	0.12	0.07	0.04
Floor	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.04
Wood (window)	0.06	0.12	0.17	0.2	0.21	0.22	0.18	0.12
Painted wood (ceiling)	0.06	0.11	0.11	0.12	0.12	0.12	0.1	0.1
Plaster on wood (ceiling)	0.02	0.03	0.04	0.05	0.06	0.07	0.07	0.06
Chairs	0.08	0.1	0.15	0.74	0.82	0.9	0.9	0.78
Polyamide 6.6 - 25 kg/m3 - 10 cm	0.026	0.097	0.255	0.617	0.955	0.938	0.982	0.9

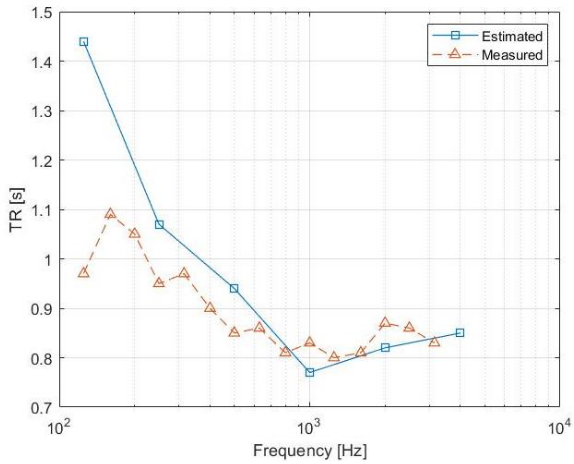

Figure 9. Comparison between estimated and measured reverberation time TR in the test case dwelling in Barcelona.

enclosures or outdoors. It considers specular reflections over sound absorbing surfaces. In the acoustic model, an omnidirectional sound speaker and 30 sound receivers uniformly distributes in the room have been set. Materials sound absorbing coefficients are reported in Table 3and they have been selected from the database of the software except for Polyamide for which experimental data presented in this paper has been used. Measured and estimated reverberation time are shown in Figure 9, while the reverberation time estimated for the different panels positions are reported in Figure 10.

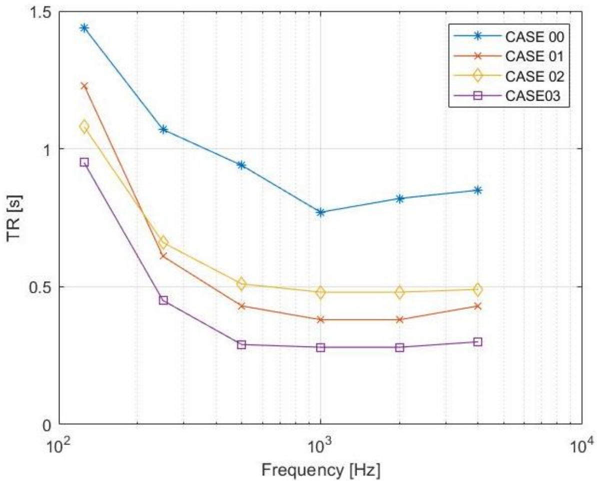

Figure 10. Reverberation time TR estimated in the different scenarios for the test case dwelling in Barcelona.

4. Discussion

Through the analysis of experimental and numerical data it is possible to assess whether polyamide presents properties suitable for the realization of panels destined to building refurbishment. Figure 2 shows the measured thermal conductivity of polyamide as a function of density, and it emerges that it does not affect the thermal properties of the material strongly. Moreover, it can be seen that measured values are comparable to those of commercial insulation materials such as mineral wools.

According to Figure 3 and Figure 4 that show the sound absorption coefficient for test specimens 50 mm and 100 mm thick, the specimen density does influence the acoustic properties of the material. In Fig. 3 the typical trend for porous materials can be identified, with low values at low frequencies and high values in the high frequency range. The specimens BW50-rho25 and BW50-rho30, in the low frequency region, show the lowest values of sound absorption among the five specimens, and for higher density values lower sound absorption coefficients are measured. This is due to that such compact wool behaves as a too stiff spring and reflects the sound energy. Fig. 4 shows the sound absorption coefficient of the same five specimens but with doubled thickness, that is 100 mm. It can be noticed an overall improvement of the performance in the low frequency region for all the tested samples thanks to the higher thickness, and this is coherent with theory. In general, the higher the density, the lower the absorption, due to the higher flow resistivity attributable to the higher density. Fig.5 and Fig.6 display the sound transmission loss results. In Fig.5 it can be noticed that all the five samples feature a similar trend, and the higher the density, the better the TL: the higher density, and related higher flow resistivity, reflect backward the sound energy, thus reducing the transmitted portion. On the contrary, in Fig.6, thanks to the sample thickness of 100 mm, the performances are better throughout the entire frequency range of interest and the five plots are more defined and distant from each other.

As regards the numerical analysis, Table 4 shows that the presence of panels installed indoor improves the operative temperature: the number of days when the indoor operative temperature is lower than 19°C decreases depending on the panel position. When considering panels installed only on a surface, that is CASE 01 and CASE 02, the best condition is represented by the panel installed on the internal side of the façade: this is the only wall that separates the dwelling from the external environment and, for this, is the most affected by external ambient conditions. However, by comparing all the scenarios, it emerges that the greater improvement belongs to the one with panels installed on both the façade and the ceiling (CASE03) and this is an expected result since a greater surface is treated.

According to Figure 10, it can be said that the numerical model defined in Ramsete can be used in a preliminary analysis to design interventions for the improvement of the indoor acoustic indoor comfort as numerical and measured results are comparable. Figure 11 shows that in all the scenarios with panels, TR is lower than 0.62 s, that is, the optimal reverberation time indicated by the UNI 11367 (UNI11367:2010) for environments destined to speech and sports activities. In particular, the presence of the panels reduces the reverberation time of about 0.5 s especially in the middle-low frequency (200 Hz -1200 Hz). By comparing CASE01 and CASE02, the improvement is comparable, but the presence of the panel on the ceiling is more effective for low frequency, while the panel on the internal surface of the façade is more effective in the middle-high frequency range. The best improvement is related to CASE03 with panels installed on both the vertical walls and the ceiling; this coherent with the theory and the Sabins formula.

Results show that this material has interesting acoustic and thermal properties; however, aspects such as the fire resistance must be investigated. Another important aspect is the containment method of the material.

5. Conclusion

The study investigated experimentally and numerically the thermal and acoustic properties of polyamide 6.6 waste to assess whether this material is suitable to be reused for the realization of building elements. Experimental results have shown that polyamide has interesting acoustic and thermal properties comparable to those of commercial insulating materials. In particular, it is emerged that density influence the sound properties significantly, while the thermal conductivity of the material is less influenced. Preliminary results from numerical simulations have shown that the presence panels made of polyamide installed indoor (directly on the walls and the ceiling) increases the indoor operative temperature in winter and reduces the reverberation time, thus, improving the indoor conditions. Further analysis is needed to evaluate the thermal performance in summer of the material, and the sound performance related to diffuse sound. Fire resistance is another important aspect that need to be investigated.

6. Acknowledgement

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7. Nomenclature

A	surface (m^2)
c	specific heat (J/kg K)
c_{air}	sound speed in air (m/s)
d	distance between microphones (m)
fl	lower working frequency (Hz)
FFT	Fast Fourier Transform
fu	Upper working frequency (Hz)
q	heat flux (W)
R	thermal resistance (m^2K/W)
s	thickness (m)
S	total absorption surface (m^2)
T	temperature (°C)
TL	sound transmission loss (-)
Top	Indoor operative temperature (°C)
TR	reverberation time (s)
V	volume (m^3)

Greek letters

α	sound absorption coefficient (-)
λ	thermal conductivity (W/mK)
λ_{eq}	equivalent thermal conductivity (W/mK)
η	sound reflection coefficient (-)
ϱ	density (kg/m^3)
τ	sound transmission coefficient (-)

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