Polyamide Waste Thermal and Acoustic Properties: Experimental and Numerical Investigation on Possible Reuse for Indoor Comfort Improvement

Manuela Neri – University of Brescia, Italy – manuela.neri@unibs.it
Eva Cuerva – Universitat Politècnica de Catalunya, Italy – eva.cuerva@upc.edu
Alfredo Zabaleta – Universitat Politècnica de Catalunya, Spain – alfredo.guardo-zabaleta@upc.edu
Pablo Pujadas – Universitat Politècnica de Catalunya; Spain – pablo.pujadas@upc.edu
Elisa Levi – University of Brescia; Italy – elisa.levi@unibs.it
Ondrej Sikula – Brno University of Technology, Czech Republic – sikula.o@vutbr.cz

Abstract

Referring to the circular economy model, end-of-life household materials (EoLHM), such as packaging and clothes, could be converted into building elements with thermal and acoustic properties; for example, they could be converted into panels to be installed indoors for building refurbishment. Given the high availability almost anywhere, panels made of EoLHM would represent an alternative to commercial insulating materials that, even though relatively cheap, cannot be afforded by disadvantaged people. This paper presents a multidisciplinary analysis aimed at the characterization of polyamide 6.6, obtained as a waste from the production of non-surgical face masks. The research focuses on the thermal and acoustic properties of the material. The properties have been determined experimentally through the guarded hot plate method hot and the impedance tube technique. Then, the influence of the panel's position on the indoor operative temperature and the reverberation time has been analyzed through numerical simulations. 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 fire resistance and the containment of the material need further investigation.

1. Introduction

Living in dwellings characterized by inadequate 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 relatively high price of commercial insulating materials. By 2030, the United Nations aim to make cities inclusive, safe, resilient, and sustainable, and to promote the circular economy model (Carnemolla et al., 2021; United Nations, 2015).

An alternative to commercial insulating materials is insulating elements realized by reusing end-of-life household materials (EoLHM) such as packaging and clothes. In the literature, several studies investigated the properties of EoLHM, but a comprehensive and systematic analysis is still missing (Drochytka et al., 2017; Ibrahim & Meawad, 2018; Kudzal et al., 2018; Mansour & Ali, 2015; Neri et al., 2021a and 2021b; Secchi et al., 2015).

The aim of this paper is the thermal and acoustic characterization of polyamide 6.6 waste (henceforth polyamide) obtained from the production of non-surgical face masks. Firstly, polyamide's thermal and acoustic properties have been determined experimentally. Then, the improvement of the building's indoor condition due to the installation of panels made of polyamide has been assessed through numerical simulations. These panels are intended installed indoors to allow for easy and fast building refurbishment interventions and also by unskilled people.

Part of
Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2023. Building simulation applications BSA 2022. bu,press.
https://doi.org/10.13124/9788860461919

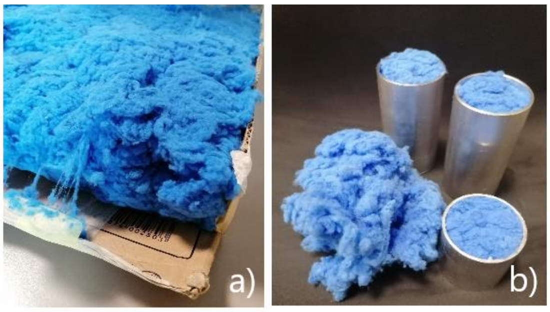

Fig. 1 – Test specimens for the thermal test a), and for acoustic tests b). For the thermal test, the material has been confined in a cardboard case. For the acoustic tests, the material in the samples was contained between two glass tissue discs to ensure that the front surface was normal to the axis of the tube

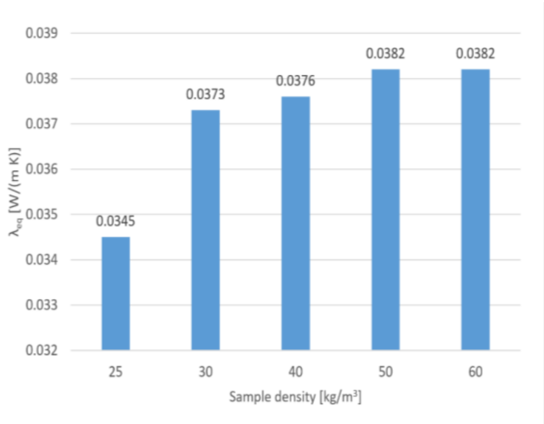

Fig. 2 – Measured equivalent thermal conductivity of polyamide

Indoor comfort embraces several aspects, such as thermal and acoustic comfort, which are the two aspects analyzed in this paper. Under steady-state conditions, heat transfer through a wall is described by the relationship:

$$q = A \cdot \Delta T / (\Sigma\ (s/\lambda)) \qquad (1)$$

where q is the heat flux through the wall, A, s, λ are the surface, thickness, and thermal conductivity of the wall. ΔT is the difference in temperature measured on the panel surfaces. Conversely, under unsteady conditions, the heat flux q depends also on the wall heat capacity and position of the layers. In this study, the thermal conductivity of samples realized with polyamide at different densities has been measured employing the hot plate method with the guard ring.
When dealing with indoor acoustic comfort, one of the aspects to be evaluated is the reverberation time *TR*, which is related to the indoor sound quality in terms of echo effect and, consequently, vocal message intelligibility. Optimal *TR* values depend on the ambient' intended use, and reference values are specified in the UNI 11367 (UNI, 2010). *TR* is the time lapse in which the sound energy density decreases by 60 dB. It is determined by suddenly switching off a sound source and measuring the sound energy level variation. *TR* can be estimated according to the Sabins formula:

$$TR=0.16\ V/S \qquad (2)$$

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

$$1=\eta+\tau+\alpha \qquad (3)$$

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

$$\alpha=1-|TL|^2 \qquad (4)$$

where TL is the sound transmission loss, that is generally determined experimentally and is a function of τ according to:

$$TL=10\cdot\log10(1/\tau) \qquad (5)$$

In this paper, the sound absorption coefficient α and transmission loss TL have been determined by means of the impedance tube technique. This technique is suitable for R&D analysis but considers only waves that impinge the sample surface normally.

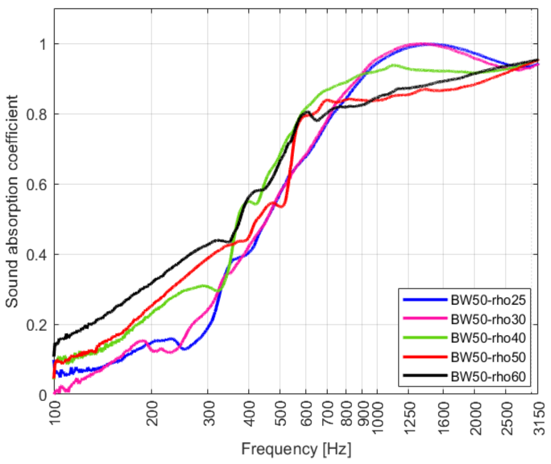

Fig. 3 – Sound absorption coefficient of the 50-mm-thick samples

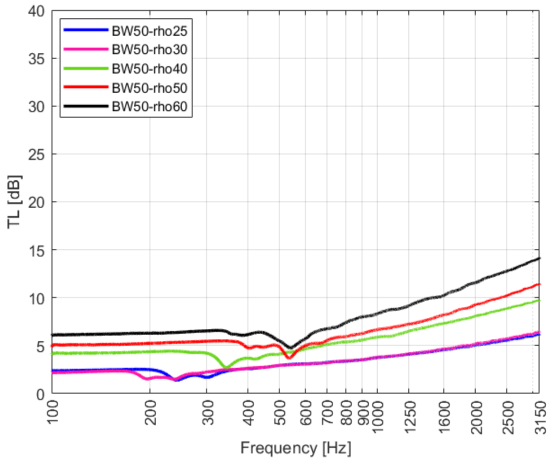

Fig. 5 – Sound transmission loss of the 50-mm-thick samples

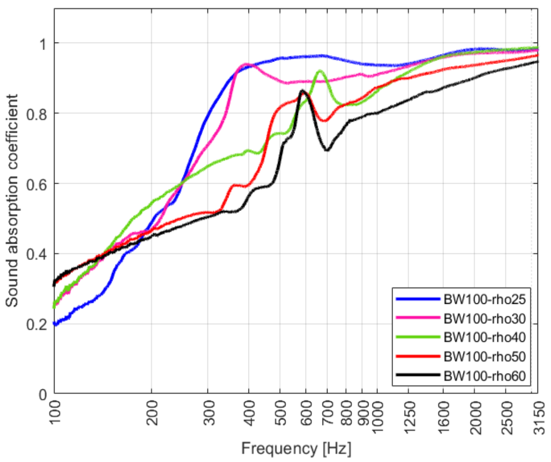

Fig. 4 – Sound absorption coefficient of the 100-mm-thick samples

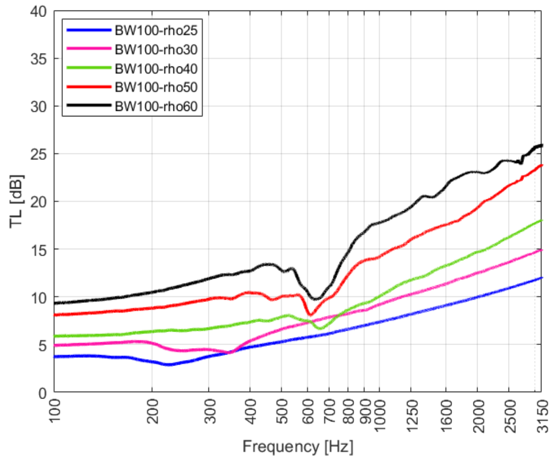

Fig. 6 – Sound transmission loss of the 100-mm-thick samples

2. Experimental Campaign

Since polyamide is a soft and porous material (see Fig. 1), its density depends on the packing degree, which is 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 through the guarded hot plate method.

The test consisted in measuring the heat flow q obtained under a predefined temperature difference ΔT, and λ_{eq} is determined as:

$$\lambda_{eq} = (q \cdot s) / (A \cdot \Delta T) \quad (6)$$

where A and s are the surface and thickness of the same. Results are shown in Fig. 2.

Samples of different densities 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 of two tubes 4.6 cm in diameter connected to a test sample holder. Two microphones are placed on either side of the specimen (45 mm from each other). A source emitting a pink noise is placed at one end of the tube. A multi-channel Fast Fourier Transform (FFT) analyzer acquires the signals captured by the microphones.

The pressure and particle velocity of the travelling and reflected waves are determined by a MATLAB script implemented according to the E2611 ASTM standard (ASTM E2611, 2019). To assess the influence of the specimen's thickness, samples 50-mm and 100-mm thick have been realized and tested. The frequency range is between 100 Hz and 3150 Hz, according to the characteristics of the test apparatus.

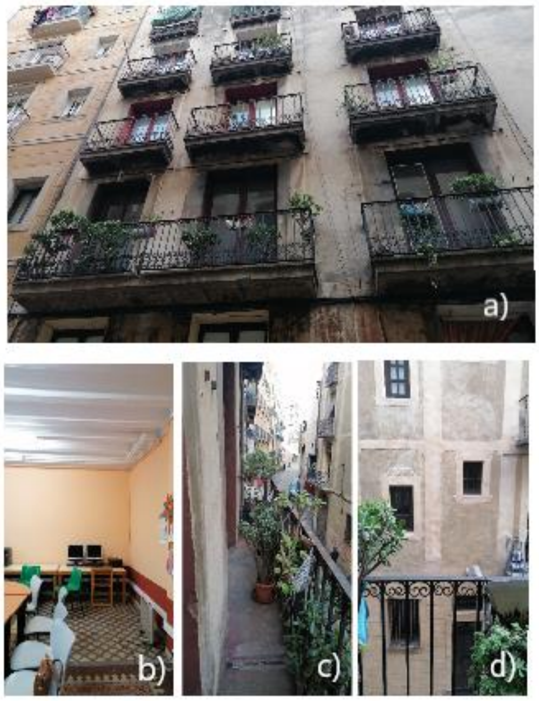

Fig. 7 – The real case study, a classroom in the Raval neighbourhood in Barcelona: **a**) façade, **b**) interior with furniture, **c**) view from the balcony, and **d**) view of the opposite building

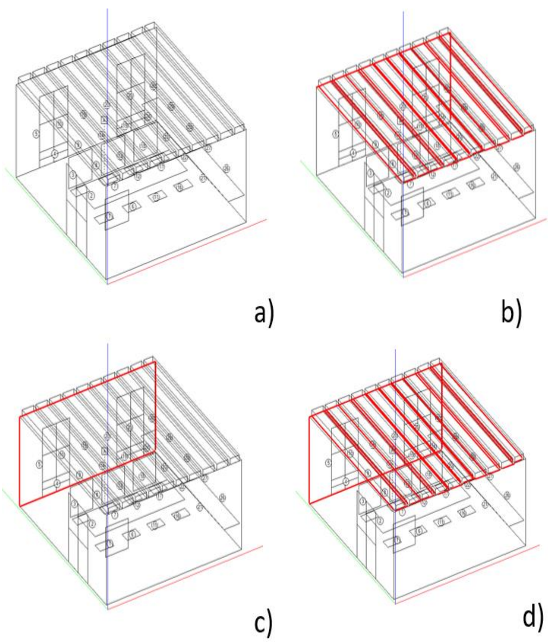

Fig. 8 – Scenarios considered in the numerical analysis: **a)** current configuration without panels (*Case00*), **b)** panels installed on the ceiling (*Case01*), **c)** panels installed indoors on the façade (*Case02*), **d)** panels installed indoors on both the façade and the ceiling (*Case03*)

Table 1 – Wall layers set in the numerical model defined with Energy+

Structure	Layer 1	Layer 2	Layer 3	Layer 4
Roof	T	XPS	HR	P
Internal wall	P	DIW	P	
Facade	P	DIW	P	
Basement	CLS_B	CLS_S	CLSM	T
Floor	P	HF	CLSM	T
Ceiling	T	CLSM	HF	P

Table 2 – Material properties set in the numerical model defined with Energy+

Material	s [m]	λ [W/(m K)]	ϱ [kg/m^3]	c [kJ/(kg K)]
Plaster	0.015	0.8	1600	1
Hollow bricks_R	0.5	0.24	800	1
Hollow bricks_F	0.3	0.24	800	1
CLS_S	0.1	0.9	1800	0.88
Dolomite_IW	0.15	1.75	2872	0.91
XPS	0.08	0.035	30	1.5
Tiles	0.01	0.208	530	1
CLS_M	0.05	1.1	1000	0.88
Dolomite_F	0.35	1.75	2872	0.91
CLS_B	0.3	2.4	2400	1

The lower and the upper working frequencies are determined according to:

$$fu<0.586 * c_{air} /d \quad (7)$$

$$d<0.586* c_{air} /fu \quad (8)$$

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

3. Numerical Simulations

To assess how the panel made of polyamide and installed indoors on the walls and the ceiling affects indoor conditions, an acoustic and a thermal numerical model were set. Two open-source software solutions, Energy+ and Ramsete, were used.

In the numerical simulations, the panel is 10-cm thick, made of polyamide at 25 kg/m³ confined between two glass veil layers.

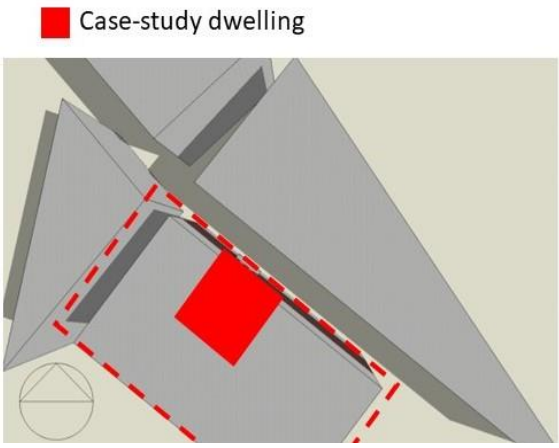

Fig. 9 – Model defined in Energy+. The building is modelled as a single thermal zone which includes another thermal zone related to the classroom. The other buildings participate in the shading effect

The models represent a classroom in the Raval neighborhood in Barcelona (see Fig. 7), where thermal and acoustic measurements were taken. The classroom is on the second floor of a building and is 5.1 x 5.8 x 3.0 m in dimension. The façade is 17 m² with two windows 2.6 x 1.1 m in dimensions. The ceiling is a typical Catalan structure with 30-cm-wide vaults. In the acoustic model (see Fig. 8), also the furniture is modeled, as it may affect the sound wave reflection and, in turn, the reverberation time.
Materials properties are listed in Tab. 1 and Tab. 2: some properties have been hypothesized, while the building owner provided others. The material vapor diffusion factor equal to 180 was chosen. The polyamide vapor diffusion factor equal to 1.254 according to CIBSE Guide A (CISBE, 2015) was chosen. The occupancy level is 0.38 persons/m², and air natural infiltration is considered.
Numerical simulations were performed for different scenarios in which the panel's position varied according to Fig. 8. Scenario *Case00* is representative of the current configuration without pan els. In contrast, panels are installed in the other scenarios: the panels are placed in the ceiling vaults in *Case01*, on the façade in *Case02*, and on both the ceiling and façade in *Case03*. The wall surface covered with panels varies according to the scenario: 29 m² for *Case01*, 17 m² for *Case02*, and 47 m² for *Case03*.

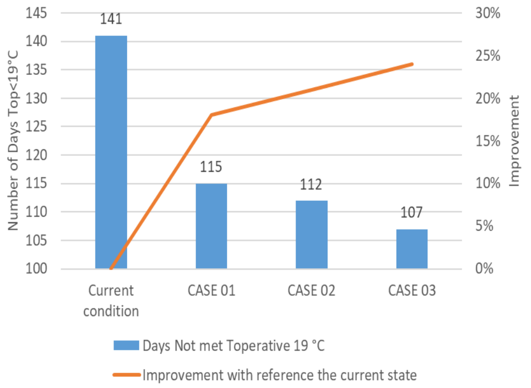

Fig 10 – Number of days when the indoor temperature is lower than 19°C, and improvement of the indoor operative temperature as a function of the panels' position. The panels are intended installed indoors

The model defined in Energy+ includes the building where the classroom is located (considered as two thermal zones) and the surrounding buildings that contribute to shading (see Fig.9). Results in Fig. 10 show the number of days when the indoor temperature is lower than 19 °C, and a heating system would be necessary to maintain an adequate indoor temperature.

Ramsete software is based on the Pyramid Tracing algorithm, and it can analyze problems in large enclosures or outdoors. It considers specular reflections over sound-absorbing surfaces. In the acoustic model, an omnidirectional sound speaker and 30 sound receivers uniformly distributed in the room have been set. In the acoustic analysis, polyamide is considered confined between two layers of glass veil - a very light material that does not affect the thermal and acoustic properties of the panel. Material-sound-absorbing coefficients are reported in Tab. 3, and they have been selected from the database of the software. For polyamide experimental data presented in this paper has been used.

In the classroom, acoustic tests were performed according to the ISO 16283-3:2016 standard (ISO 16283:2016) through the loudspeaker method. The indoor sound pressure level wasmeasured by a sound pressure meter LD-831-C fulfilling the standard IEC 60942 (IEC 60942:2017). Experimental data were used to verify whether the numerical model can predict the acoustic conditions in the classroom correctly. Measured and estimated reverberation time *TR* are shown in Fig. 11, while the reverberation time estimated for the different panels' positions is reported in Fig. 12.

Table 3 – Sound absorption coefficients α of the materials set in the numerical model defined with Ramsete. Polyamide sound absorption coefficients relate to incident sound waves only

Material	31 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Plaster (walls)	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
Window - slighlty open	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
Polyam.- 25 kg/m^3 - 10 cm	0.03	0.1	0.26	0.62	0.96	0.94	0.98	0.9

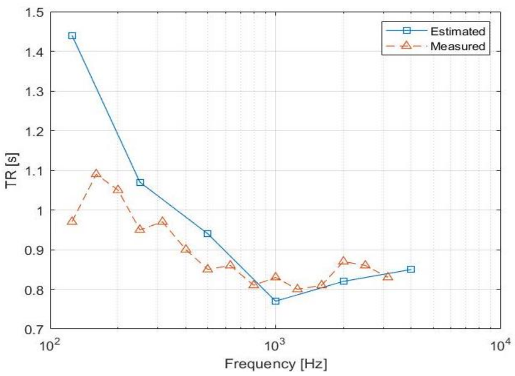

Fig. 11 – Comparison between estimated and measured reverberation time *TR* in the test case in Barcelona

4. Discussion

Through the analysis of experimental and numerical data, an assessment of whether polyamide is suitable for the realization of panels destined for building refurbishment was performed.

4.1 Experimental Results

Fig. 2 shows the measured equivalent thermal conductivity of polyamide as a function of density. Density does not affect the material's thermal properties significantly, and measured values are comparable to those of commercial insulation materials such as mineral wool. However, the best performance was shown by the lightest panel.

According to Fig. 3 and Fig. 4, density affects the material's acoustic properties in the low-middle frequency range. The typical trend for porous materials, with low values at low frequencies and high values in the high-frequency range, is detected. According to Fig. 3, lower sound absorption coefficients are measured for higher density values; indeed, compact wool behaves as a stiff spring that reflects the sound energy. Fig. 4 refers to samples 10-cm thick and shows an overall performance improvement in the low-frequency region for all the tested samples thanks to the greater thickness.

Fig. 5 and Fig. 6 show the sound transmission loss *TL* results. In Fig. 5, all five samples feature a similar trend, and higher panel density entails lower *TL*: high-density samples reflect the sound energy backwards, thus reducing the sound transmitted component.

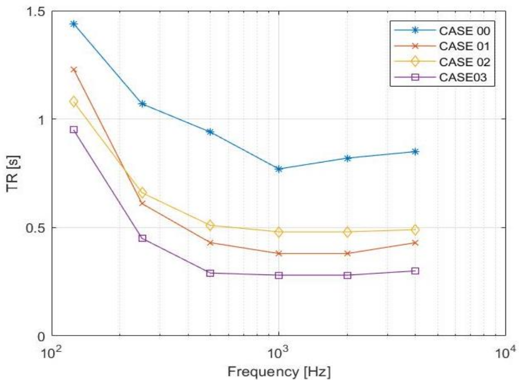

Fig. 12 – Reverberation time *TR* estimated in the different scenarios for the test case in Barcelona

In Fig. 6, the sound absorption performance is better throughout the entire frequency range thanks to the sample thickness of 100 mm, and the five plots are more distant from each other.

4.2 Numerical Results

As regards the numerical analysis, Fig. 10 shows that the presence of panels installed indoors 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, i.e., *CASE01* and *CASE02*, the best condition is represented by the panel installed on the façade; indeed, this is the only wall facing the external environment. The more significant improvement belongs to scenario *CASE03* with panels installed on both the façade and the ceiling, and this is an expected result since a wider surface is treated. However, a weak point is possible water condensation in the wall, and this requires the installation of a vapor barrier.

As the numerical and measured results in Fig. 11 are comparable, the numerical model defined in Ramsete can be used to design interventions for improving indoor acoustic comfort. Fig. 12 shows that when the panels are installed indoors, *TR* is lower than 0.62 s, which corresponds to the optimal reverberation time for environments destined for speech and sports activities suggested by the UNI 11367 (UNI, 2010). The greatest improvement is detected between 200 and 1200 Hz, where *TR* reduces by 0.5 s. Results are comparable for *CASE01* and *CASE02*, but panels installed on the ceiling are more effective at 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 detected for *CASE03*, with panels installed both on walls and ceiling, and it is coherent with the theory. However, sound-absorption improvement is expected when considering polyamide properties for diffuse sound, but this data is obtainable only by tests performed in the sound reverberation room.

5. Conclusion

The study investigated experimentally and numerically the thermal and acoustic properties of polyamide 6.6. Experimental results have shown that polyamide has interesting properties, which are comparable to commercial insulating materials. Therefore, it could be used for realizing building elements. Results show that density influences sound properties significantly: low-density panels show better thermal insulation (λ_{eq} between 0.034 and 0.0382 W/(m K)) and sound insulation properties (α higher than 0.9 for frequency higher than 400 Hz), while high-density panels show better sound insulation properties which depend also on thickness.

Numerical results show that the panels when installed indoors on the walls and ceiling increase the indoor operative temperature in winter and reduce the reverberation time. Therefore, this material is suitable for building thermal and acoustic refurbishment. However, further analysis is needed to evaluate the thermal performance in summer, sound performance related to the diffuse sound field, material containment, and fire resistance.

Acknowledgement

The contribution has been supported by TAČR NCK CAMEB nr. TN01000056/06, and by the Department of Mechanical and Industrial Engineering of the University of Brescia through the MetATer PRD project.

Nomenclature

A	surface (m^2)
c	specific heat (J/(kg K))
c_{air}	sound speed in air (m/s)
d	distance between microphones (m)
f_l	lower working frequency (Hz)
FFT	Fast Fourier Transform
f_u	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)
α	sound absorption coefficient (-)
λ	thermal conductivity (W/(m K))
λ_{eq}	equivalent thermal conductivity (W/(m K))
η	sound reflection coefficient (-)
ϱ	density (kg/m^3)
τ	sound transmission coefficient (-)

References

ASTM. 2019. "ASTM E2611 Standard Test Method for Normal Incidence Determination of Porous Material Acoustical Properties Based on the Transfer Matrix Method."

BSI. 2016. "BS EN ISO 16283-3:2016 Acoustics — Field measurement of sound insulation in buildings and of building elements — Part 3: Façade sound insulation."

Carnemolla, P; S. Robinson, and K. Lay. 2021. "Towards inclusive cities and social sustainability: A scoping review of initiatives to support the inclusion of people with intellectual disability in civic and social activities." *City, Culture and Society* 25: 100398. doi: https://doi.org/10.1016/j.ccs.2021.100398

CIBSE. 2015. "CIBSE - Guide A - Environmental design."

Drochytka, R., M. Dvorakova, and J. Hodna. 2017. "Performance Evaluation and Research of Alternative Thermal Insulation Based on Waste Polyester Fibers." *Procedia Engineering* 195: 236–243. doi: https://doi.org/10.1016/j.proeng.2017.04.549

González-Eguino, M. 2015. "Energy poverty: An overview." *Renewable and Sustainable Energy Reviews* 47: 377-385. doi: https://doi.org/10.1016/j.rser.2015.03.013

Ibrahim, S., and A. Meawad. 2018. "Assessment of waste packaging glass bottles as supplementary cementitious materials." *Construction and Building Materials* 182: 451–458. doi: https://doi.org/10.1016/j.conbuildmat.2018.06.119

IEC. 2017. "IEC 60942:2017 - Electroacoustics – Sound calibrators"

Kudzal, A., S. Pliestic, D. Filipovic, I. Kovacev, K. Copec, Z. Janjecic, and D. Bedekovic. 2018. "Mechanical properties of ten-egg boxes made of different materials." *Journal of Food Science and Technology* 55: 1325–1330. doi: https://doi.org/10.1007/s13197-018-3043-z

Mansour, A., and S. Ali. 2015. "Reusing waste plastic bottles as an alternative sustainable building material." *Energy for Sustainable Development* 24: 79–85. doi: https://doi.org/10.1016/j.esd.2014.11.001

Neri, M., M. Pilotelli, M. Traversi, E. Levi, E. A. Piana, M. Bannò, E. Cuerva, P. Pujadas, and A. Guardo. 2021a. "Conversion of end-of-life household materials into building insulating low-cost solutions for the development of vulnerable contexts: Review and outlook towards a circular and sustainable economy." *Sustainability* 13(8): 4397. doi: https://doi.org/10.3390/su13084397

Neri, M., E. Levi, E. Cuerva, F. Pardo-Bosch, A. G. Zabaleta, and P. Pujadas. 2021b. "Sound absorbing and insulating low-cost panels from end-of-life household materials for the development of vulnerable contexts in circular economy perspective." *Applied Sciences* 11(12): 5372. doi: https://doi.org/10.3390/app11125372

Polyamide 6.6 characteristics. Available at https://designerdata.nl/materials/plastics/thermo-plastics/polyamide-6.6. Accessed on the 15th of April 2022.

Secchi, S., F. Asdrubali, G. Cellai, E. Nannipieri, A. Rotili, and I. Vannucchi. 2015. "Experimental and environmental analysis of new sound-absorbing and insulating elements in recycled cardboard." *Journal of Building Engineering* 5: 1–12. doi: https://doi.org/10.1016/j.jobe.2015.10.005

United Nations. 2015. "Transforming Our World: The 2030 Agenda for Sustainable Development."

UNI. 2010. "UNI 11367:2010 Acoustic classification of building units - procedure for evaluation and verification in situ."