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Integration of Acoustic Metamaterials Made of Plastic to Improve Building Acoustics

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***Abstract* – According to the Waste Management Policy of the European Union, the recycling and reuse of various wastes is considered the most environmentally friendly and advanced waste disposal technology that has the least impact on the environment. By applying the principles of the Circular Economy, plastic waste will extend its life cycle and will be used as secondary materials to create metamaterial structures with improved sound absorption and insulation properties. The aim of this study was to determine plastic potential for use in acoustic structures. Acoustic metamaterial resonators, created from plastic, were measured in an impedance tube according to standards ISO 10534-2 for their sound absorbing and ASTM E2611 for their insulating properties. Two types of plastic, PLA and recycled PET-G, were used in acoustic metamaterial 3D printing process. For sound insulation, combined resonator systems were used to control symmetrical wall sound resonance. Sound absorption of both PLA and PET-G metamaterials were peaking at 1600 Hz with 0.93 and 0.89 sound absorption coefficient, respectfully. The results showed that combined constructions with plastic metamaterials can be integrated into building structures and used as an alternative for improving building acoustics, reducing indoor noise and reverberation time.**

***Keywords* – Circular economy; plastic waste; resonator; sound absorption coefficient; sound transmission loss; waste management.**

Nomenclature

c	Speed of sound	m/s
D_{TL}	Sound transmission loss	dB
f	Frequency	Hz
P	Atmospheric pressure	Pa
R	Sound reflection coefficient	–
t	Temperature	°C
α	Sound absorption coefficient	–
ρ	Air density	kg/m^3
τ	Sound transmission coefficient	–

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1. INTRODUCTION

An acoustic metamaterial is a structured material designed to control, direct, and manipulate sound waves (Fig. 1). In recent years, there has been an increase in research on acoustic metamaterials for noise control and sound absorption improvement to reduce reverberation time in buildings.

Most acoustic metamaterials used for sound absorption and isolation are made of membrane resonators, Helmholtz resonators, quarter-wave resonators, and variations thereof [1].

Plastic acoustic metamaterial is usually designed and manufactured using 3D printing technologies, as it allows to create a reproducible unique material with the desired acoustic parameters.

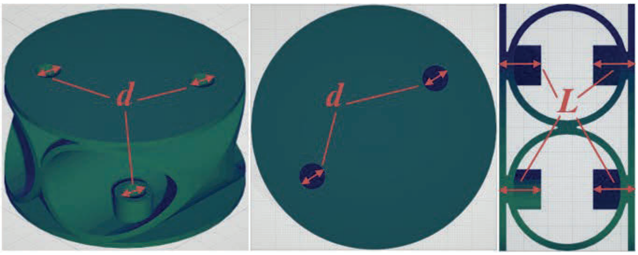


Fig. 1. Example of 3D printed acoustic metamaterial (L3.0_d3.0) resonator, with 3.0 mm neck length (*L*) and 3.0 mm neck diameter (*d*).

The development of functional materials offers increasing opportunities for achieving targeted acoustic properties. Properly crafted acoustic metamaterials possess non-negative characteristics that are frequently challenging to fabricate from natural materials. The increasing interest in acoustic metamaterials and the freedom of their design provided by computer-aided design manufacturing will allow the development of a new generation of acoustic metamaterials in the near future that are smaller and more efficient [2].

Qu *et al.* in their article investigated the value and impact of acoustic metamaterials in room acoustics, especially in small rooms and areas, where there are specific challenges due to the significantly small volume which results in resonant frequencies. To solve this problem, the researchers developed a metamaterial design that simultaneously incorporates multiple acoustic resonators of different frequency lengths to achieve broad-spectrum absorption for the walls of a specific model room. The proposed method of reverse engineering metamaterials, focused on specific acoustic requirements, is widely applicable and has unique advantages in small, confined spaces with high acoustic demands, such as audio recording studios, listening rooms, and transport cabins [3].

In one research paper, the influence of the neck diameter, neck length, and cavity volume of the Helmholtz resonator on its sound transmission reduction was studied: the sound transmission losses of single and multiple Helmholtz resonators were compared, and the sound transmission losses of honeycomb panels and honeycomb-type acoustic metamaterials were analyzed. The results showed that the different peaks of sound transmission reduction are due to the different diameters of the resonator neck. Research shows that the maximum frequency of sound transmission loss gradually changes to higher frequency with increasing neck diameter when the neck diameter of the Helmholtz resonator ranges from 0.2 mm to 1.0 mm [4].

For example, to minimize the area occupied by the building's projected acoustic system, the quarter-wavelength resonators are spirally twisted into the shape of a flat cylinder. The use of resonators and their integration into metamaterial structures is a relatively new and unexplored field, despite the fact that resonators as standalone systems and their working principles are well-known and frequently used in acoustic engineering.

Plastic recycling is highlighted as an important step in the transition to a circular economy to avoid the use of fossil resources and close the plastic recycling cycle [5]. The use of recycled plastic in construction reduces environmental problems, protects the remaining natural resources, and reduces the self-load of buildings. discussed the possibilities of using bricks made from PET bottles and cement in the construction sector. They concluded that plastic bricks are more sustainable than traditional bricks because plastic has better thermal resistance and uses less cement, resulting in lower CO_2 emissions during the manufacturing process. In addition, walls made of bricks and blocks with plastic have good mechanical properties, are brittle, flexible, and resistant to sudden impact loads [6], [7].

Jawaid *et al.* states that the use of polypropylene in buildings has many benefits, including increased energy efficiency and weather resistance, and can be used as a waterproofing material. Polypropylene is widely used in the construction sector in the production of a variety of building materials including films and sheets, air and moisture barrier membranes, industrial tapes and adhesives, pipe and duct components, carpet textiles and insulating building films [8].

As other scientists reviewed [9], since 2020, European Union Green Deal and The Waste Management Policy of states that the recycling and reuse of various wastes is considered the most environmentally friendly and advanced waste disposal technology that has the least impact on our environment [10]. The concept shown in Fig. 2, is that we take plastic waste of various types as raw materials and make secondary materials from them.

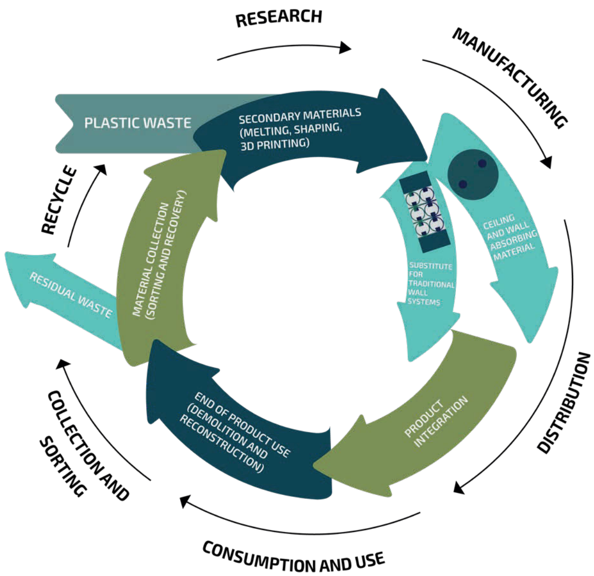


Fig. 2. Plastic waste Circular economy concept for the integration of plastic metamaterials in the construction sector.

Sorted plastic waste can be melted and shaped into desired dimensions or used to make 3D printing filament if we want to make something very specific with precise geometries (metamaterial). In our case, resonating systems for sound insulation and sound absorbing panel systems would be manufactured. At the end of life (consumption and use), we can collect those building structures and parts and recycle them to extend their life cycle. Recycled materials can be used again to make new products for use in building construction or thrown away as residual waste. In order to optimize implementation processes, we need to investigate this field of interest.

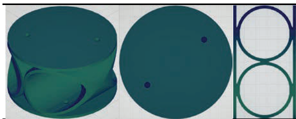
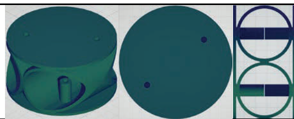
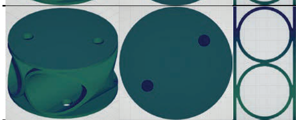
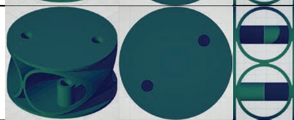
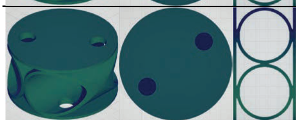
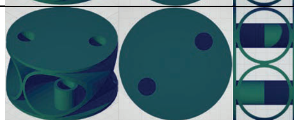
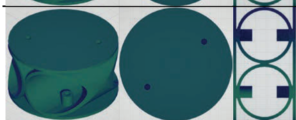
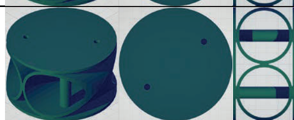
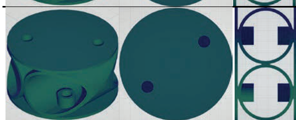
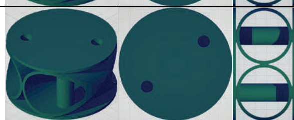
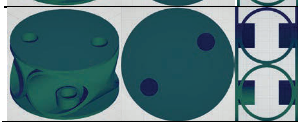
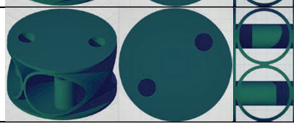
The purpose of this research is not only to create and research metamaterial with good sound insulation and sound absorption properties, but also to implement recycled plastic waste as secondary raw material to circular economy and reduce residual waste in the building construction sector.

2. Samples and Measurement Methodology

2.1. Materials and Samples

For research purposes, we have used 3D printer fused deposition modeling technology with PLA and PET-G plastic filaments in order to create metamaterials from different plastics and investigate their potential in building acoustics. Our acoustic metamaterial made of plastic would be based on the Helmholtz resonator working principle, composed of two filled with air chamber cells with different neck lengths (L) and diameters (d), as presented in Table 1.

TABLE 1. SAMPLE CELL VISUALISATION WITH CODES

Cell axonometry, front and side view	**Code**	**Cell axonometry, front and side view**	**Code**
	L1.5_d1.5		L6.0_d1.5
	L1.5_d3.0		L6.0_d3.0
	L1.5_d4.5		L6.0_d4.5
	L3.0_d1.5		L9.0_d1.5
	L3.0_d3.0		L9.0_d3.0
	L3.0_d4.5		L9.0_d4.5

Overall diameter of samples is 28.3 mm, to be fitted inside plastic cartridge, which is used to ensure no air gaps between impedance tube and the samples. The main passively tunable part is neck of the sample, where neck length (L) is 1.5, 3.0, 6.0 and 9.0 mm long, and neck inlet/outlet diameter (d) is 1.5, 3.0 and 4.5 mm for every neck length. By changing neck geometrical parameters, we can adjust resonant frequency of the sample, by this absorbing sound of that frequency.

The created metamaterial constructions would be used as individual sound-absorbing panel and/or as insulating material to replace existing traditional materials, such as wool.

2.2. Methodology of Sound Absorption Coefficient Measurement with the Impedance Tube

Method of measuring the sound absorption coefficient with impedance tube (Fig. 3) is based on the fact that the complex sound reflection coefficient R can be determined by measuring the transfer function H_{12} between two positions at distances x_1 and x_2 of the test sample [11].

The sound pressure measurement determines the pressure at each frequency by Eq. (1):

$$H_{13} = \frac{p_3}{p_1};\ H_{23} = \frac{p_3}{p_2}, \tag{1}$$

where
H_{13} – transfer function between microphones position no. 1 and position no. 3;
H_{23} – transfer function between microphones position no. 2 and position no. 3;
p_1, p_2, p_3 – pressure recorded by the first, second, and third microphones.

$$H_{\mathrm{I}\,(160\text{–}1000\ \mathrm{Hz})} = e^{-jk_0(x_{12}+x_{23})};\ H_{\mathrm{I}\,(1\text{–}5\ \mathrm{kHz})} = e^{-jk_0(x_{23})}, \tag{2}$$

where
H_{I} – the incident wave transfer function;
k_0 – sound wave number in the air;
j – index of a complex number;
x_{12} – distance between microphones in position no. 1 and position no. 2;
x_{23} – distance between microphones in position no. 2 and position no. 3.

$$H_{\mathrm{R}\,(160\text{–}1000\ \mathrm{Hz})} = e^{jk_0(x_{12}+x_{23})};\ H_{\mathrm{R}\,(1\text{–}5\ \mathrm{kHz})} = e^{jk_0(x_{23})}, \tag{3}$$

where
H_{R} – the transfer function of the reflected wave.

Sound reflection coefficient is calculated at two frequencies bands: for low $R_{(160\text{–}1000\ \mathrm{Hz})}$ and high $R_{(1\text{–}5\ \mathrm{kHz})}$ frequencies. The sound reflection coefficient (R) is calculated according to the following equations:

$$R_{(160\text{–}1000\ \mathrm{Hz})} = \frac{H_{13} - H_{I\,(160\text{–}1000\ \mathrm{Hz})}}{H_{\mathrm{R}\,(160\text{–}1000\ \mathrm{Hz})} - H_{12}} e^{2jk_0(X_{12}+X_{23}+X_{3\mathrm{s}})}; \tag{4a}$$

$$R_{(1\text{–}5\ \mathrm{kHz})} = \frac{H_{23} - H_{\mathrm{I}\,(1\text{–}5\ \mathrm{kHz})}}{H_{\mathrm{R}\,(1\text{–}5\ \mathrm{kHz})} - H_{13}} e^{2jk_0(X_{23}+X_{3\mathrm{s}})}, \tag{4b}$$

where X_{3S} – distance between microphone in the position no. 3 and sample;

After getting sound reflection coefficient, we can finally calculate the absorption coefficient for plane sound waves:

$$\alpha = 1 - |R|^2, \tag{5}$$

where R is a sound reflection coefficient [11].

All sound absorption measurements were done with a 30 mm diameter impedance tube and the results were processed using '*AcoustiStudio*' software.

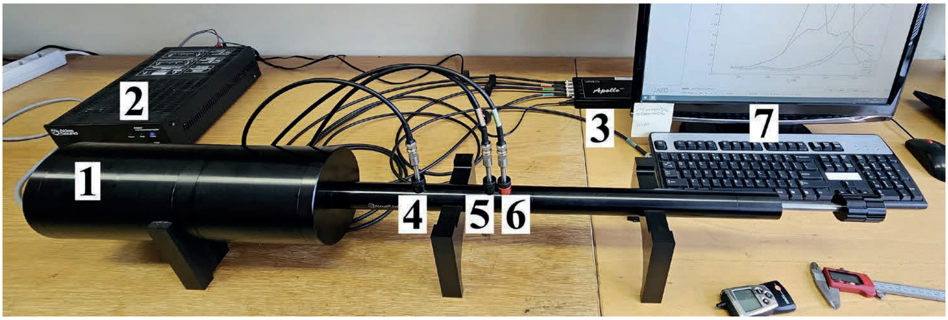


Fig. 3. Setup of the impedance tube and its components for the measurement of sound absorption coefficient (1 – Speaker as a sound source; 2 – sound amplifier; 3 –sound card; 4 – microphone no. 1; 5 – microphone no. 2; 6 – microphone no.3; 7 – data processing software).

2.3. Methodology of Measurement of Sound Transmission Loss with the Impedance Tube

A system of four microphones and one load is used for the study of sound transmission loss [12], the arrangement of the impedance tube and its components for the measurement of transmission loss is presented in Fig. 4.

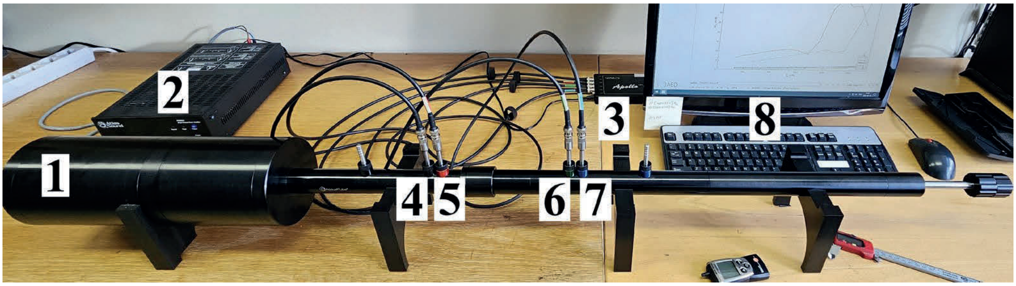


Fig. 4. Setup of the impedance tube and its components for the transmission loss determination (1 – Speaker as a sound source; 2 – sound amplifier; 3 –sound card; 4 – microphone no. 1; 5 – microphone no. 2; 6 – microphone no. 3; 7 – microphone no. 4; 8 – data processing software).

In Fig. 5, the letters *A*, *B*, *C,* and *D* indicate the incident and reflective components of the standing wave field. 1, 2, 3 and 4 mark the measurement positions where the microphones are mounted.

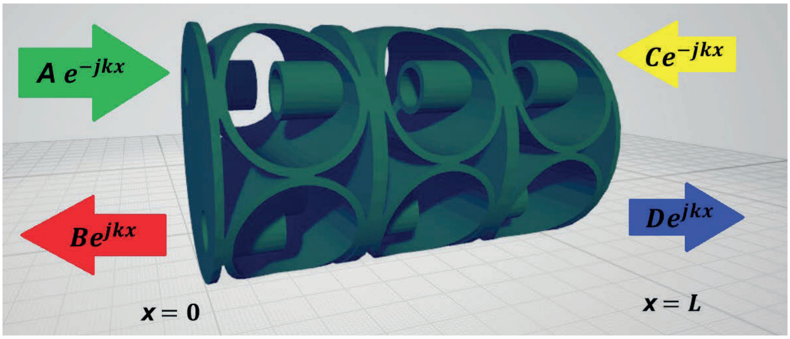


Fig. 5. Principal scheme of the composed in series sample, incident and reflected sound wave components of the standing wave field for the determination of transmission loss in the impedance tube.

The speed of sound (c) and the air density (ρ) must be taken in to account at the beginning of the measurements. The speed of sound (c) is calculated according to the Eq. (6):

$$c = 20.047\sqrt{(273.15 + t)}\ \text{(m/s)}, \tag{6}$$

where t is temperature in the impedance tube, ºC.

The air density (ρ) is calculated according to Eq. (7):

$$\rho = 1.290\left(\frac{P}{101.325}\right)\left(\frac{273.15}{273.15 + t}\right)\ (\text{kg/m}^3), \tag{7}$$

where P is atmospheric pressure, Pa.

The incident and reflective components of the standing wave field are calculated according to Eq. (8)–(11):

$$A = j\frac{H_{11}e^{-jkl_1} - H_{21}e^{-jk(l_1+s_1)}}{2\sin(k\cdot s_1)}; \tag{8}$$

$$B = j\frac{H_{21}e^{+jk(l_1+s_1)} - H_{11}e^{+jkl_1}}{2\sin(k\cdot s_1)}; \tag{9}$$

$$C = j\frac{H_{31}e^{+jk(l_2+s_2)} - H_{41}e^{+jkl_2}}{2\sin(k\cdot s_2)}; \tag{10}$$

$$D = j\frac{H_{41}e^{-jkl_2} - H_{31}e^{-jk(l_2+s_2)}}{2\sin(k\cdot s_2)}, \tag{11}$$

where
H_{11}, H_{21}, H_{31}, H_{41} – transfer function between two microphones, before and after the sample;
k – sound wave number in air, according to Eq. (2);
l_1, l_2 – the distances between the microphones and the sample, m (see Fig. 5);

s_1, s_2 –the distances between the microphone combinations, before and after the sample, m (see Fig. 5).

From this, the sound transmission coefficient (τ) is calculated according to Eq. (12):

$$\tau = \frac{2e^{jkd}}{T_{11} + \left(\frac{T_{12}}{\rho c}\right) + \rho c T_{21} + T_{22}}. \quad (12)$$

In the end, the sample sound transmission loss (*TL*) is calculated from Eq. (13):

$$TL = 20\log_{10}\ (1/\tau). \quad (13)$$

All transmission loss measurements were done with a 30 mm diameter impedance tube and the results were processed using '*AcoustiStudio*' software.

3. Measurement Results

3.1. Sound Absorption Coefficient Measurement Results with the Impedance Tube

For sound absorption measurements PLA and PET-G single cell resonator metamaterials were used. Both PLA and PET-G 3D printed metamaterial constructions showed potential for sound absorption, as presented in Fig. 6 and Fig. 7 graphs. Similar tendencies and sound absorption peaks were achieved with both PLA and PET-G metamaterial, where the highest sound absorption peaks are with (PLA/PET-G) L3.0_d4.5 and (PLA/PET-G) L1.5_d4.5 metamaterial resonators.

From Fig. 6 we can see that highest sound absorption are achieved with bigger diameter resonator neck – 4.5 mm, but only in higher frequencies. Otherwise, lowest sound absorptions were obtained with smaller, 1.5 mm, diameter necks and in lower frequencies. PLA_L1.5_d4.5 metamaterial resonator showed 0.93 sound absorption value at 1630 Hz and PLA_L3.0_d4.5 metamaterial resonator showed 0.92 value at 1250 Hz frequency.

From Fig. 7 we can see similar tendencies and results with PET-G as with PLA. This means, that plastic material has very small impact or does not matter in this situation and main factor for changes in sound absorption is construction geometries.

Same as PLA, PET-G resonators achieved highest sound absorption with wider, 4.5 mm, diameter resonator neck holes, and lowest with narrow, 1.5 mm, diameter neck holes. PET-G_L1.5_d4.5 metamaterial resonator showed 0.89 sound absorption value at 1630 Hz and PLA_L3.0_d4.5 metamaterial resonator showed 0.93 value at 1250 Hz frequency. These results indicate that recycled plastic can be definitely used in building acoustics.

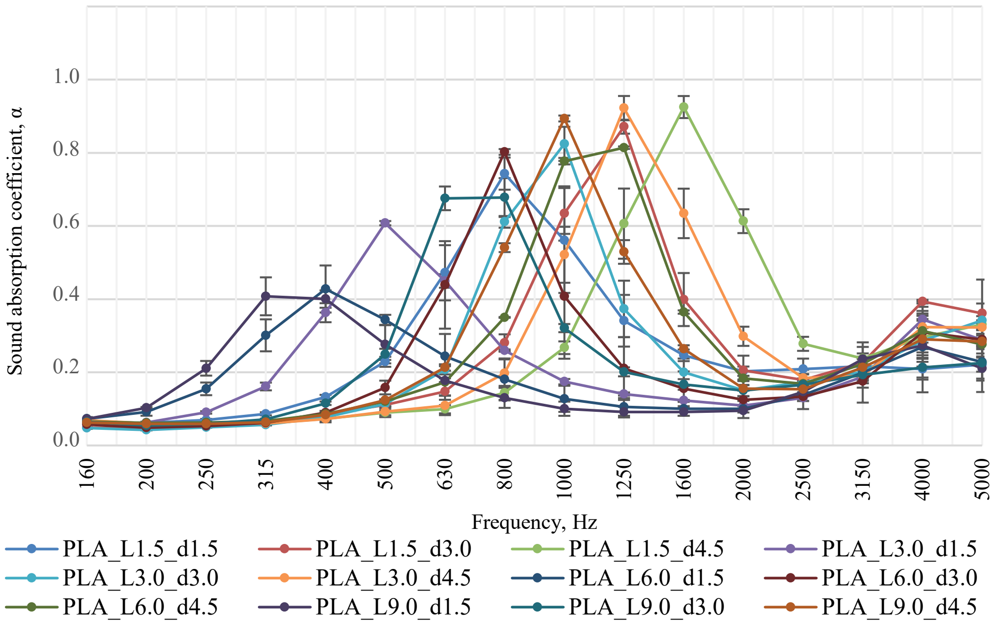


Fig. 6. PLA 3D printed acoustic metamaterials sound absorption coefficient (in 1/3 octave band frequencies).

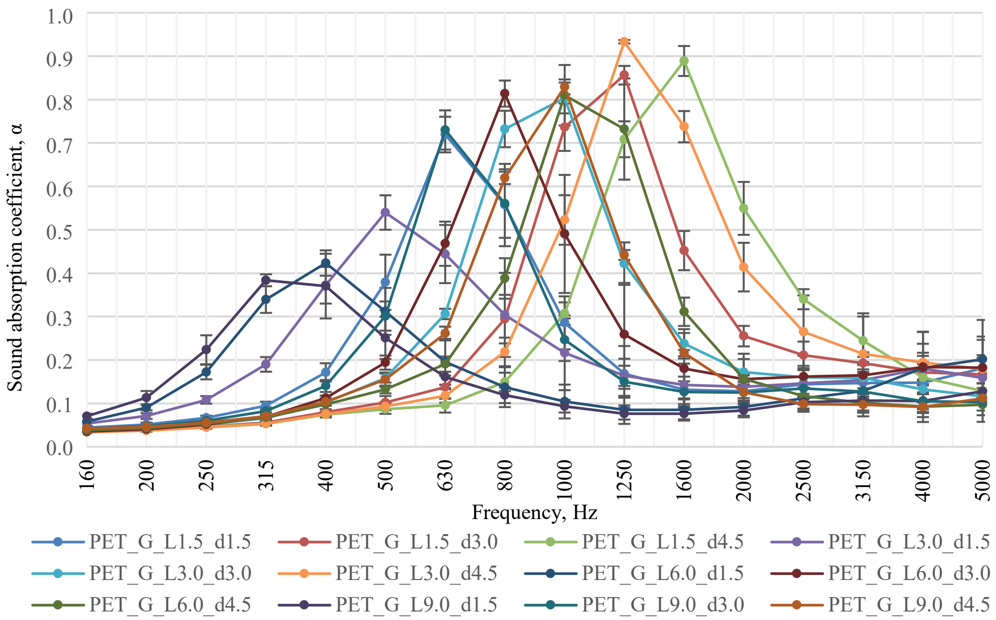


Fig. 7. PET-G 3D printed acoustic metamaterials sound absorption coefficient (in 1/3 octave band frequencies).

3.2. Sound Transmission Loss Measurement Results with the Impedance Tube

For sound transmission loss measurements only PET-G single cell resonator metamaterials were used, because PLA and PET-G showed similar result in sound absorption, and our used PET-G filament is already made from 100 % recycled plastic, which is more beneficial for our concept. Three same sequentially composed resonators are connected in series, to create repetitive metamaterial structures for sound insulation purposes. Later it would be used as sound-absorbing/insulating material in symmetrical wall system to replace traditional materials, such as construction wool. Transmission loss results for composed in series PET-G resonators are presented in Fig. 8.

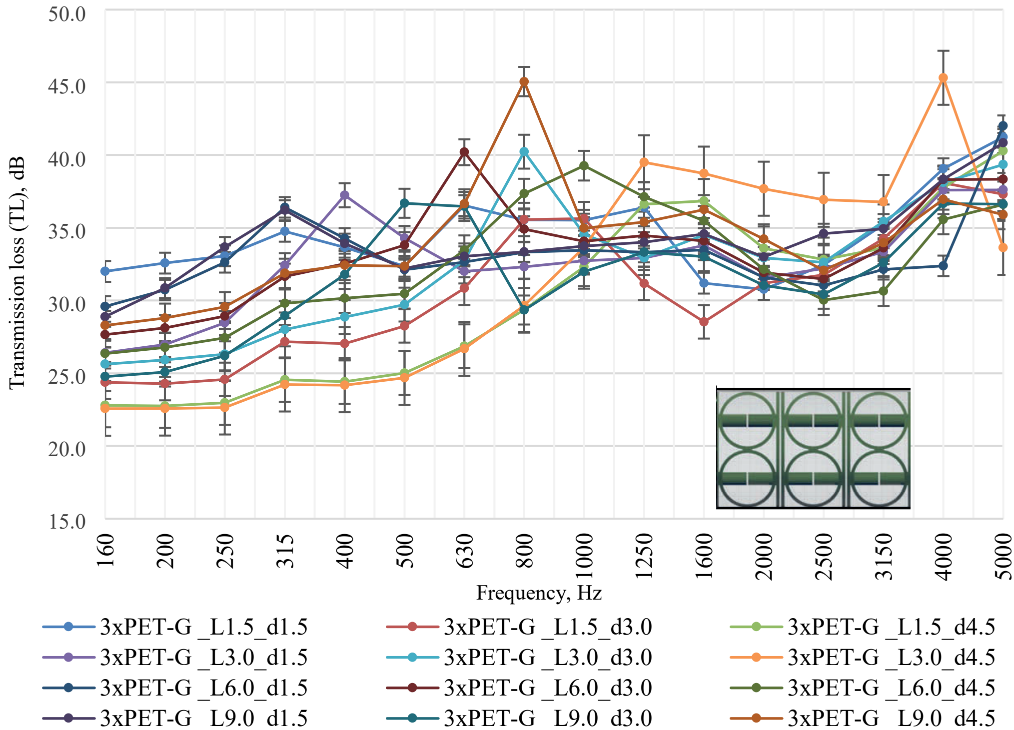


Fig. 8. Composed in series PET-G sound transmission loss (in 1/3 octave band frequencies).

As we can see from Fig. 8 graph, results, from 160 Hz to 500 Hz (at lower frequencies), distributed according to the neck diameter of the resonators. Overall, the smaller the neck diameter, the higher is sound transmission loss. Average sound transmission loss at lower frequencies varies from 23.5 dB to 33.1 dB, where 3xPET-G_L3.0_d4.5 showed worst results and 3xPET-G_L1.5_d1.5 being the best.

From 500 Hz to 1600 Hz (middle frequencies) transmission loss depends on resonator design and air friction (air impedance) that occurs because of sound wave interference. Average sound transmission loss at lower frequencies varies from 31.2 dB to 36.8 dB, where 3xPET-G_L1.5_d4.5 showed worst results and 3xPET-G_L9.0_d4.5 being the best. There is no visible correlation between resonator neck length or hole diameter in these frequencies.

From 1600 Hz to 5000 Hz (higher frequencies) transmission loss depends on resonator design and air friction (air impedance) that occurs because of sound wave interference. Average sound transmission loss at lower frequencies varies from 33.4 dB to 38.2 dB, where 3xPET-G_L9.0_d3.0 showed worst results and 3xPET-G_L3.0_d4.5 being the best. There is no visible correlation between resonator neck length or hole diameter in these frequencies.

Overall, all combinations of neck length and hole diameter showed good sound insulation via transmission loss results. Results are relatively flat from lower frequencies to higher frequencies, which is not typical for light constructions, which shows potential for further investigation.

For thoughtful investigation, symmetrical double leaf system wall with sound-absorbing/insulating material, were measured. Although, for concept proposes 20.0 mm ABS plastic plates were used to as replacement for gypsum (pasteboard) walls and developed metamaterial as replacement for construction wool. Whole wall system thickness is 80 mm, about 50 of which is stacked metamaterial. Transmission loss results and conceptual scheme presented in Fig. 9.

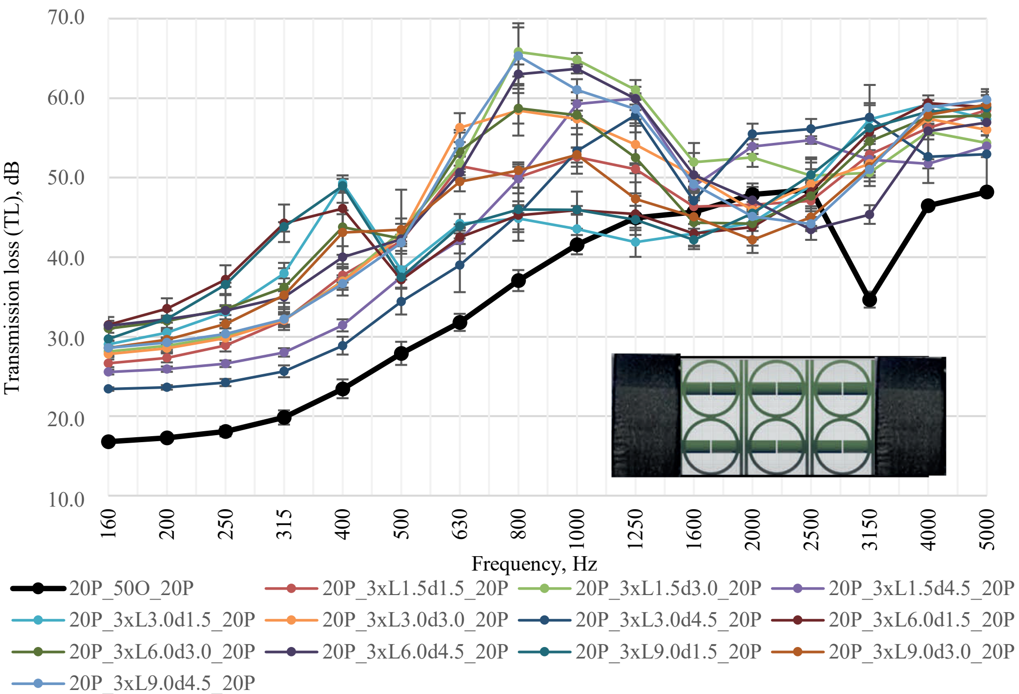


Fig. 9. Sound transmission loss of PET-G acoustic metamaterial systems with 20 mm ABS plastic plates (20P) (in 1/3 octave band frequencies).

First, double leaf wall system without any insulating material (air) between the walls were measured. 20P_50O_20P sample transmission loss results show typical tendencies for these kinds of systems, with sudden decline in sound transmission at 3150 Hz. Sudden decline occurred because of the air space between two partitions and resonance that one system transferred to the other through it. Adding acoustic metamaterial between two partitions improves lower frequency transmission loss (from 160 Hz to 500 Hz) and removes any sudden declines (resonating frequency) in the system, which means system is more stable and more predictable in acoustics. For middle frequencies (from 500 Hz to 2000 Hz) acoustic metamaterial cavities work with wall partitions as mass-spring-mass system. As previous researchers noticed, mass-spring-mass occurs in multilayered systems, and it depends on the gap between the two plates and the density of the medium between them [13]. These means and resonators enhance transmission loss because depending on their geometrical properties if neck length and hole diameter. For this particular system, metamaterial with 1.5 mm neck length and 3.0 mm neck hole diameter works the best, and in some frequencies increase insulation for almost 30 dB, compared to the empty double leaf wall system.

4. Conclusion

1. Sound absorption coefficient measurement results showed, that depending on resonator neck hole diameter and neck length, different frequency sound wave can be absorbed effectively. It can be stated that bigger metamaterial resonator neck hole means higher sound absorption peaks, when longer neck shifts those peaks to the lower frequencies. Depending on the situation neck diameter/length combination should be used for reverberation time improvement in rooms. Typical scenarios could be museum halls, school teaching classes and shopping malls open areas;
2. Sound transmission loss of stacked PET-G acoustic metamaterials systems with double leaf 20 mm plastic plates symmetrical wall systems showed that adding acoustic metamaterial between two partitions improves lower frequency transmission loss and removes any sudden declines in transmission loss, which means system is more stable and more predictable in sound insulation;
3. There is potential for these acoustic metamaterial resonating constructions to be used and to change traditional materials such as gypsum (pasteboard) walls with construction wool. From this study, we can see that the integration of this product in construction sector is possible from building acoustic perspective and can be further conceptualized in the future.

Acknowledgement

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References

[1] Lu Q., Li X., Zhang X., Lu MChen Y. Perspective: Acoustic Metamaterials in Future Engineering. *Engineering* 2022:17:22–30. https://doi.org/10.1016/j.eng.2022.04.020

[2] Arjunan A., Baroutaji A., Robinson J., Wang C. Characteristics of Acoustic Metamaterials. *Encyclopedia of Smart Materials* 2022:3:35–45. https://doi.org/10.1016/B978-0-12-815732-9.00090-5

[3] Qu S., Yang M., Xu Y., Xiao S., Fang N. Reverberation time control by acoustic metamaterials in a small room. *Building and Environment* 2023:244:110753. https://doi.org/10.1016/j.buildenv.2023.110753

[4] Gai X., Guan X., Cai Z., Li X., Hu W., Xing T., Wang F. Acoustic properties of honeycomb like sandwich acoustic metamaterials. *Applied Acoustics* 2022:199:109016. https://doi.org/10.1016/j.apacoust.2022.109016

[5] Eriksen M., Christiansen J., Daugaard A., Astrup T. Closing the loop for PET, PE and PP waste from households: Influence of material properties and product design for plastic recycling. *Waste Management* 2019:96:75–85. https://doi.org/10.1016/j.wasman.2019.07.005

[6] Raut A., Salman Patel M., Jadhwar N., Khan U., Dhengare P. Investigating the Application of Waste Plastic Bottle as a Construction Material-A Review. *Journal of Advance Research in Mechanical and Civil Engineering* 2015:2(3):86–99. https://doi.org/10.53555/nnmce.v2i3.362

[7] Chan L., Aziz Z., Ghazali M. The Performance of Lightweight Concrete with Recycled Polyethylene Terephthalate and Polypropylene as Demising Wall. *Environmental and Climate Technologies* 2022:26:1323–1336. https://doi.org/10.2478/rtuect-2022-0100

[8] Jawaid M., Singh B., Kian L., Zaki S., Radzi A. Processing techniques on plastic waste materials for construction and building applications. *Current Opinion in Green and Sustainable Chemistry* 2023:40:100761. https://doi.org/10.1016/j.cogsc.2023.100761

[9] Ružickij R., Grubliauskas R. Sound Absorption: Dependence of Rubber Particles Impurities in Tyre Textile Fibre. *Environmental and Climate Technologies* 2022:26:331–340. https://doi.org/10.2478/rtuect-2022-0025

[10] European Commission. Circular economy action plan [Online]. [Accessed 05.03.2024]. Available: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

[11] Acoustics – Determination of sound absorption coefficient and impedance in impedance tubes – Part 2: Transfer-function method (LST EN ISO 10534-2:1998).

[12] Standard Test Method for Normal Incidence Determination of Porous Material Acoustical Properties Based on the Transfer Matrix Method (ASTM E2611-19).

[13] Vilniškis T., Januševičius T. Research of Insertion Loss of Multilayered Construction with Devulcanized Waste Rubber. *Environmental and Climate Technologies* 2024:28:120–134. https://doi.org/10.2478/rtuect-2024-0011