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EXPERIMENTAL STUDIES AND NUMERICAL VALIDATION OF SOUND INSULATION OF PLASTIC ACOUSTIC METAMATERIAL COMPOSED OF PERFORATED LAYERS AND RESONATORS

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Abstract. Noise – messy loud noises of different frequencies, which have various types of pressure, which can be felt as air vibrations or sounds that interfere with human comfort. This kind of noise can be transferred through building construction and/or directly to the human ear. To prevent or minimise noise transfer, sound insulation of considerate construction should be improved. The accumulation of plastic waste and the lack of proper disposal methods has created a critical and unprecedented problem where plastic waste enters our water resources, overflows landfills, leaches into the soil, and enters the air, polluting all natural objects and other resources in our environment. In this research, plastics would be used as secondary raw material to create a better sound insulation solution than what is currently available on the market, such as plasterboard. By applying Circular Economy principles, plastic waste will extend its life cycle and be used as secondary raw material to create metamaterial structures with good sound insulation properties. Numerical validation of metamaterial acoustic characteristics will be compared to the experimental study using an impedance tube.

Keywords: acoustic metamaterial, sound insulation, transmission loss, plastic, circular economy.

Introduction

Plastic is one of the most important elements of modern life and is widely used in all regions and areas. Every year more than 300 million tons of plastic materials are produced, however, after use most of it is thrown into the ocean, buried in landfills, or simply burnt polluting our air (Sezgin et al., 2021). Some research shows that by 2050 a total of 700 million tons of plastic waste will be produced annually, with Asia, North America and Europe being the higher producers with 50, 10 and 16% of the future supply, respectively (Almohana et al., 2022). As an example, the production of plastic materials has rapidly increased because they exhibit several advantages over other materials such as being light weight, high flexibility, resilience, resistance to corrosion, excellent chemical resistance, durability, transparency, and ease of processing, easy transportation, and cost-effectiveness. These characteristics make plastics otherwise very useful materials (Jamnongkan et al., 2022; Lamba et al., 2021). However, there is an overconsumption of plastics that is creating havoc on the planet. There are many sectors where we can use plastic waste, as example construction materials for acoustics application, we just need to investigate the field of interest and how to convert it to secondary raw material for proper use and application. Scientists are now encouraged to come up with innovative discoveries that would further help control the circulation of plastics, as a review on sustainable plastic waste management of Babaremu et al. states that plastics are now used in concrete aggregates, structural walls and structural columns, filament materials in 3D printing or manufacturing technologies (Babaremu et al., 2022).

Most of the materials currently used in the building construction sector for sound insulation, such as glass wool and foam, are toxic and cause serious environmental and health problems (Sailesh et al., 2022). These materials include fiberglass (used in glass wool and continuous glass filaments), rock or stone wool, slag wool, and refractory ceramic fiber. They are widely applied for thermal and sound insulation, and to a lesser extent for other purposes. Earlier Robert et al. stated that these products are potentially hazardous to human health due to the release of respirable fibers during their manufacture, use and disposal (Baan & Grosse, 2004). Some materials, such as plasterboard, that are very popular and widely used in building construction, are not recyclable and are basically thrown away at the end of their usage.

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Islam et al. studied and developed insulation materials using 3D printing technology that allows for more precise control of advanced insulation materials. The lowest thermal conductivity obtained is 0.037 W/mK with a porosity of 0.71 and a density of 366.46 kg/m^3, which is significantly lower than that of commonly used thermal insulation materials, glass wool (0.04 W/mK). The maximum sound transmission loss obtained is 28.0 dB (average value from 125 Hz to 2500 Hz) at a porosity of 0.43 and a density of 721.26 kg/m^3, which is significantly higher than the sound transmission loss of plasterboard. This indicates that the developed materials have very good potential for commercial use as building insulation materials and may also replace plasterboard or tiles of building walls (Islam et al., 2023). Researchers believe that there is a possibility to replace traditional sound insulation solutions with recycled, more environmentally friendly product. As example, in some cases, thermal and acoustic insulation materials produced from waste textiles show much better results than the currently available products in the market (Islam & Bhat, 2019). One of the most important challenges for the buildings of the future is the reduction of energy consumption at all stages of their life, from construction to demolition. Asdrubali et al. review on of unconventional sustainable building insulation materials showed, that recycled plastic can be used as sound insulating material in building construction sector and prolong their life cycle as product. Although the market is currently dominated by several categories of thermoacoustic insulators such as mineral wool, extruded polystyrene and expanded polystyrene, the push towards environmentally friendly buildings shows the possibilities of developing new sustainable materials (Asdrubali et al., 2015).

When it comes to room reverberation, noise control is one of the most important problems faced in high-volume crowded spaces such as shopping malls, residences, hospitals and factories. Porous materials are often used in the design of such congested areas to reduce background noise, but often also reduce acoustic quality and speech transmission index. We think that integrating proper acoustic metamaterial in those scenarios would allow one to manipulate sound wave and improve sound insulation and sound absorption, which would lead to an overall improved sound quality in the room. As an example, previous research presented the design of a micro-helix metamaterial supporting a high sound absorption characteristic by 3D printing. The sample structures were made of polylactide (PLA) material, and many micro-helixes were arranged in periodic arrays in the X-Y plane. The results of the experimental measurements show that different geometric dimensions of the spiral entrance and the depth of the cavity have a significant influence on the sound absorption coefficient. It was found that as the depth of the cavity with air continues to increase, the increase in the sound absorption coefficient would also increase (Gao & Hou, 2018). Another example is plate-type acoustic metamaterials (PAMs) consisting of a thin film with periodically added masses made by Langfeldt et al. These metamaterials can be designed to be very light and have narrow low-frequency bands and high sound transmission loss values that can be greater than the corresponding mass law. The basic principle behind this design is that the Helmholtz resonance creates an additional peak in the transmission loss spectrum that can be tuned to increase the bandwidth of the PAM. Measurements were carried out for the configurations with open Helmholtz resonators (HR) (PAM with HR) and closed resonators (PAM). For PAM with closed Helmholtz resonators, the first antiresonance can be clearly seen at 600 Hz for sound transmission loss values above 25 dB. When the Helmholtz resonators are open (PAM with HR), this antiresonance remains at about the same frequency, but the peak STL value is reduced by about 5 dB (Langfeldt et al., 2022). As an artificial composite structure for low-frequency absorption and isolation, acoustic metamaterials have received a lot of attention due to their ability to handle and manipulate large wavelengths within their small dimensions (Li & Yan, 2023).

According to the waste management policy of the European Union (EU), the recycling and reuse of various wastes is considered the most ecological and advanced waste disposal principle, which has the least negative impact on the environment. The EU Circular Economy Action Plan aims to reduce the amount of waste that goes to landfills and extend the useful life of products and raw materials (European Commission, 2023). In this work, by applying principles of Circular Economy, plastic waste will extend its life cycle and be used as secondary raw materials to create acoustic metamaterial structures with potentially good sound insulation and/or absorption properties. The use of plastic in various spheres has already been studied by other scientists and researchers, but little attention has been paid to its use in building acoustics, especially as an alternative to plasterboard walls and other building partitions. We would not discuss plastic recycling technologies in this work and focus on sound insulation results and its numerical validation.

1. Material, samples and methodology

For research purposes, we have used 3D printer technology and PLA plastic filament in order to investigate how plastic behaves in different scenarios and shapes. Our, made of plastic, acoustic metamaterial would be based on the resonator working principle, composed of different cells (see Table 1).

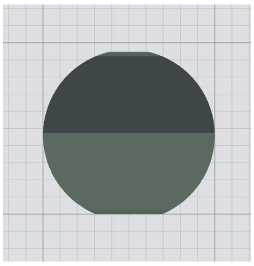
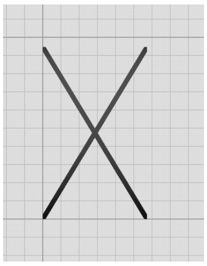
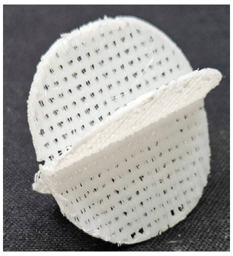
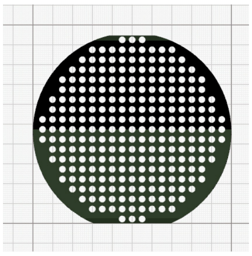
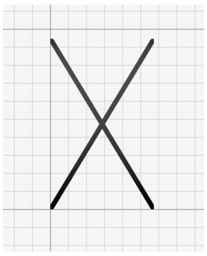
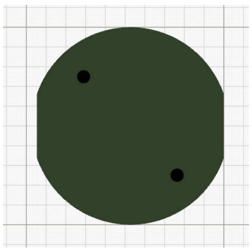
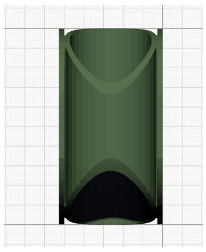
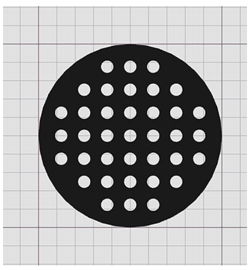
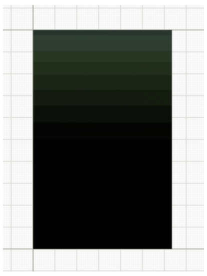
The first stage is to design the samples using "AutoCad" drafting and 3D design software. Taking into account the reviewed literature and the experience of other scientists in creating sound-insulating and absorbing structures, the geometry, thicknesses and lengths of the components of the samples are carefully planned. The samples are circular in shape about 29 mm in diameter to fit in the impedance tube of the "AED" manufacturer. The final sample (acoustic metamaterial) consists of four parts: plates with 2.0 mm perforation with an air gap in front of (L) and behind (R) the resonator, resonator cells of different geometries (X, Xp, O) and properties, and a 50 mm long combined resonator holder.

The second stage is the 3D printing and preparation of the samples before the measurements. A "Creality CR 10s" 3D printer is used for 3D printing of the samples, which prints using the fused deposition modeling method. The technology behind this method works with specialized 3D printers and production-grade thermoplastics (ABS, TPU, PLA, etc.) to create strong, durable and dimensionally stable parts with the best accuracy and repeatability of any 3D printing technology. For 3D printing we have used "Devildesign" PLA thermoplastic. After the 3D printing process, the sample components are particularly inspected, all irregularities and small printing defects are removed with sandpaper, and the perforation, if necessary, is refined with a needle to the required size.

"AcoustiStudio" software developed by "AED" specifically for their impedance tube will be used for data processing and code written in "MATLAB" for displaying the results.

Transmission loss determination method is commonly referred to as the four-microphone method, where two microphones are mounted in front of the sample and the other two are behind the sample. A system of four microphones and one load is used for the study of sound transmission loss, the arrangement of the impedance tube and its components for the transmission loss measurement is presented in Figure 1.

Table 1. 3D printed cell samples with codes used for combinations and their description

Photographs of the sample	2D front and side view of the sample		Code name	Description of the sample
			X	Cell with spring-like effect. Adds stiffness to whole construction and dampens vibrations. Designed with intentions to absorb lower frequency waves when combined, improve transmission loss.
			Xp	Perforated cell with spring-like effect. Less stiff, because of microperforation. Designed with intentions to absorb higher frequency waves. Improves overall sound absorption.
			O	Combined cell with air gaps. Designed with intentions to work like a Helmholtz resonator. Have two holes (necks) on each side, which leads to longer (lower frequency) wave absorption.
			L, R	Perforated cell with air gap before (R) and after (L) plate. The air gap with the air mass, after the perforated plate combined with the resonators, acts as an additional absorption layer. Additional air gap after the perforated plate should increase sound absorption at lower frequencies.

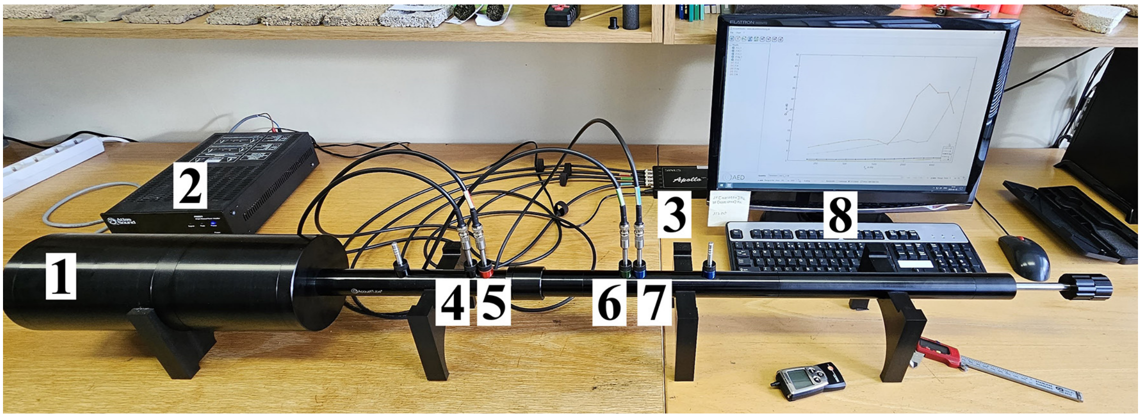


Figure 1. Arrangement of the impedance tube and its components for the transmission loss determination: 1 – sound source; 2 – amplifier; 3 – data processing system (sound card); 4 – microphone no. 1; 5 – microphone no. 2; 6 – microphone no. 3; 7 – microphone no. 4; 8 – data processing system ("AcoustiStudio" software)

The decrease in sound transmission characterizes the material's ability to isolate sound waves, specifies the characteristics of the material in terms of its porosity, ability to reflect and absorb sound waves (American Society for Testing and Materials [ASTM] E2611-19).

Recently, many authors proposed numerical validation methods, based on transfer matrix function. Based on correctly selected material type (porous material, resonator, plate and etc.), we can configure correct transfer matrix from components T_{11}, T_{12}, T_{21} and T_{22}. As example, Dogra et al. proposed method for calculating acoustical properties of Helmholtz resonator-based metamaterial plate. Two-load boundary condition method has been used to calculate the pressure and particle velocities (Dogra & Gupta, 2021). Laly et al. proposed a transfer matrix approach that combines with finite element calculations to characterize homogeneous and non-homogeneous acoustic absorbing materials (Laly et al., 2022a). Another group of scientists modelled acoustic metamaterial sound insulator using transfer matrix method approach. One of their proposed methods can be used to obtain the equivalent transfer matrix of an inhomogeneous material that may contain complex inclusions (Laly et al., 2022b).

For numerical calculations purposes we would use measured unit Cell complex surface impedance (Z) and the complex wave number (k). Then, the following acoustic properties at the surface for symmetrical non-homogeneous material, when $x = 0$, would be calculated from the transfer matrix coefficients; sound transmission coefficient:

$$\tau = \frac{2e^{jkd}}{T_{11} + \left(\frac{T_{12}}{Z}\right) + ZT_{21} + T_{22}}, \quad (1)$$

where: j – index of a complex number; T_{11}, T_{12}, T_{21}, T_{22} – transfer matrix components; k – complex sound wave number in air; d – sample thickness, m; Z – complex surface impedance (Lietuvos standartizacijos departamentas, 1998).

Then from this we can calculate sound transmission loss:

$$TL = 10\log_{10}\left(\frac{1}{\tau}\right). \quad (2)$$

In this paper, for validation purpose, we would numerically and experimentally verify only symmetrical cell units (presented in Table 1). Based on Cell results we can then calculate whole structure acoustic properties, using transfer matrix method.

2. Results of experimental studies and numerical validation

2.1. Results of sound transmission loss measurement with the impedance tube

Results of transmission loss for all combined acoustic metamaterials are presented in Figure 2 and are categorized in three categories: without perforated layers, with one perforated layer and with two perforated layers.

As we can see from Figure 2 there is no big transmission loss difference in lower frequencies when using additional perforated plates with metamaterials. Although, when combined metamaterial consist X cell, slightly better results achieved with one additional perforated layer. But, in all scenarios constructions with OXO and XOX metamaterials showed better transmission loss results. Lowest transmission loss achieved in all scenarios with XpOXp metamaterial, with practically no difference with or without additional perforated plates. These is because of a perforation level of structure, which results in lower mass of a whole system. And, because of a symmetrical system when using two perforated layers, resonators transfer sound wave energy to other side (after them), which mean lower transmission loss.

More detailed view on transmission loss of each system is presented in Figure 3 and Figure 4, where graphs distributed according to acoustic metamaterial design.

OXpO metamaterial is similar to OOO, with similar sound transmission loss in all scenarios, although, from 2500 Hz it starts to differ for metamaterial with two additional perforated plates.

With XOX metamaterial we can see difference in constructions transmission loss from the lowest frequencies. Overall, slightly better transmission loss is achieved with system with one additional perforated layer. This metamaterial has better overall transmission loss in all scenarios, however, when compared to sound absorption, these systems performed the worst.

As we can see from Figure 3 OOO metamaterial transmission loss is similar in all scenarios, although, from 2000 Hz it starts to differ for metamaterial with two additional perforated plates.

For OXO metamaterial we can see significantly better results with one addition perforated layer. Up to 2000 Hz there is average 10 dB difference in sound transmission

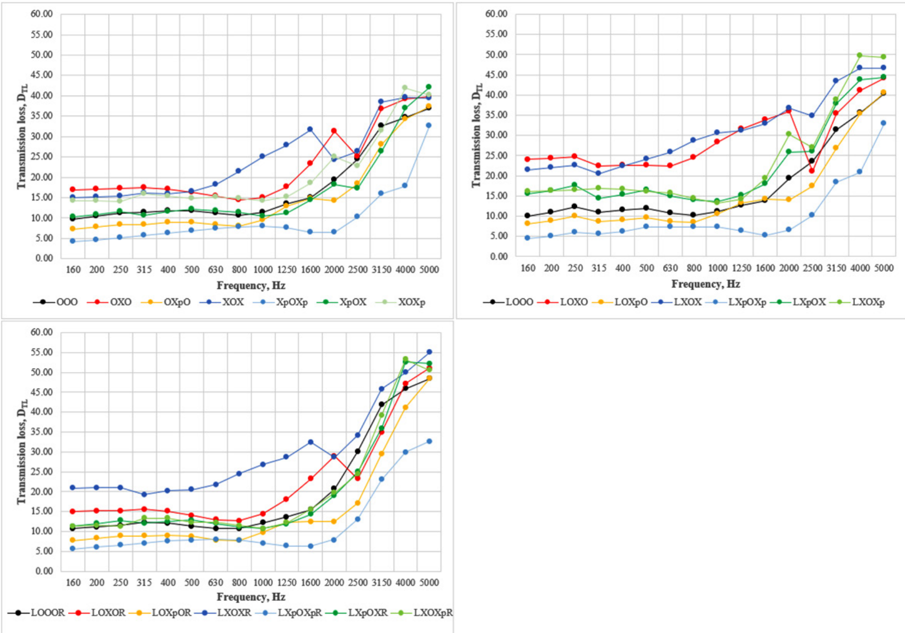


Figure 2. Transmission loss of all combined acoustic metamaterials (without perforated layers, with one perforated layer and with two perforated layers) at different frequencies

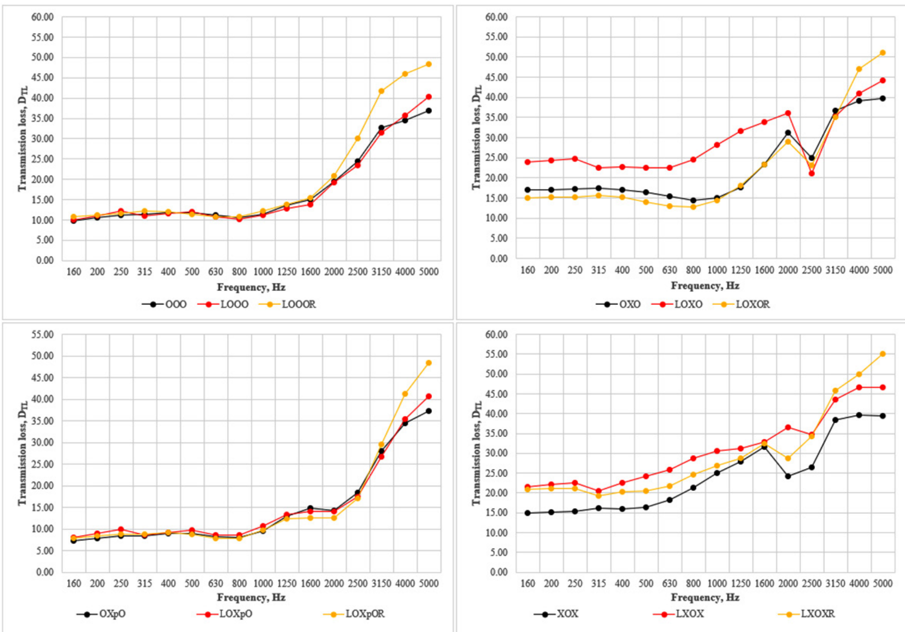


Figure 3. Transmission loss of combined OOO, OXO, OXpO and XOX acoustic metamaterials (without perforated layers, with one perforated layer and with two perforated layers) at different frequencies

loss between system with one perforated layer and others systems. In 2500 Hz we can see sudden drop in all scenarios, which indicates resonance and sound wave energy transfer in other side.

As we can see from Figure 4 XpOXp metamaterial transmission loss is similar in all scenarios, although, from 2000 Hz it starts to differ for metamaterial with two additional perforated plates.

For XpOX metamaterial we can see significantly better results with one addition perforated layer. Up to 2000 Hz there is average 5 dB difference in sound transmission loss between system with one perforated layer and others systems. There is no correlation with sound absorption coefficient of the same metamaterial.

XOXp metamaterial is similar to XpOXp, with similar sound transmission loss in all scenarios, although, from 1600 Hz it starts to differ for metamaterial with one additional perforated plate.

All metamaterials and their combinations showed same tendencies. On low frequencies there is no big difference in transmission loss between without, with one and with two perforated layers, but in high and 5000 Hz cut-off frequency all metamaterials performed the same. Without perforated layers systems have lowest transmission loss, with one additional perforated layer in the middle and with two additional perforated layers being the best.

2.2. Numerical validation of transmission loss based on transfer matrix method

Transmission loss of three Cell units were numerical calculated: O, X and Xp. These metamaterials are symmetrical, because of that we can meet the condition of transfer matrix were $T_{11}=T_{22}$. Next, transmission loss of experimental and numerical calculations will be presented in Figure 5.

As we can see from Figure 10, tendencies of calculated and measured metamaterials are the same. Comparing O measured and calculated metamaterial results, there similarity in higher frequencies (from 1250 Hz), but in lower – calculated results showed much better transmission loss of selected metamaterial. These differences occurred, because our numerical validation model is based on porous–elastic material, where our O metamaterial is based on Helmholtz resonator.

Comparing X measured and calculated metamaterial results, there similarity in lower and higher frequencies (from 2000 Hz), but from 800 to 1600 Hz – measured results showed much better transmission loss of selected metamaterial. These differences occurred, because our numerical validation model is based on porous–elastic material, where our X metamaterial is based on resonator.

Comparing Xp measured and calculated metamaterial results, there similarity in all frequencies but sudden drop in 4000 Hz. Measured results are steadier and more stable, with no peak or drops of transmission loss. This method suits this metamaterial better, because it is fairly elastic and porous on if we take to the account microperforation on the material surfaces.

Overall, calculated values and measured values of selected metamaterials showed same tendencies on transmission loss, and from this we can calculate whole structure acoustic properties, by combining Cell transfer matrix, as long as it symmetrical.

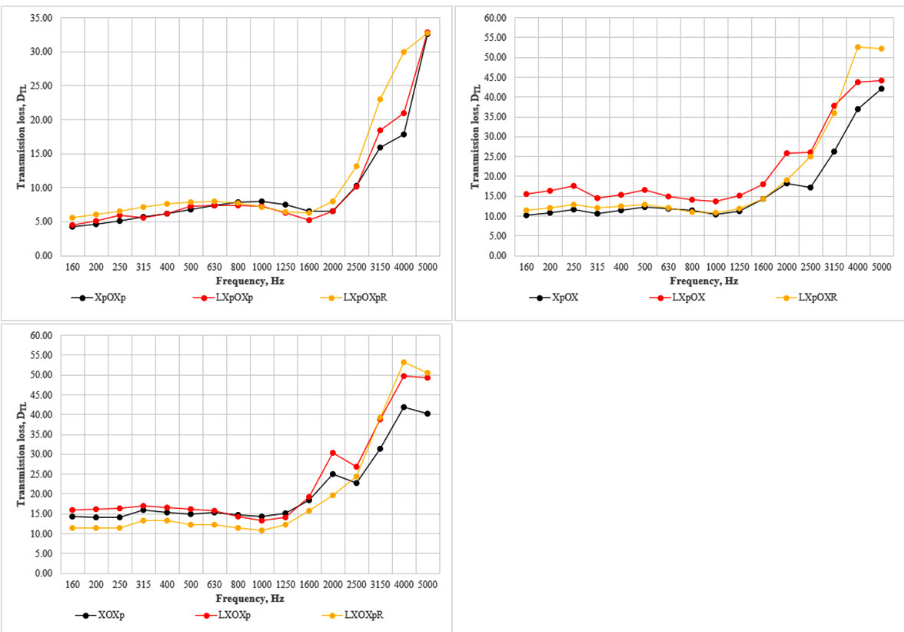


Figure 4. Transmission loss of combined XpOXp, XpOX and XOXp acoustic metamaterials (without perforated layers, with one perforated layer and with two perforated layers) at different frequencies

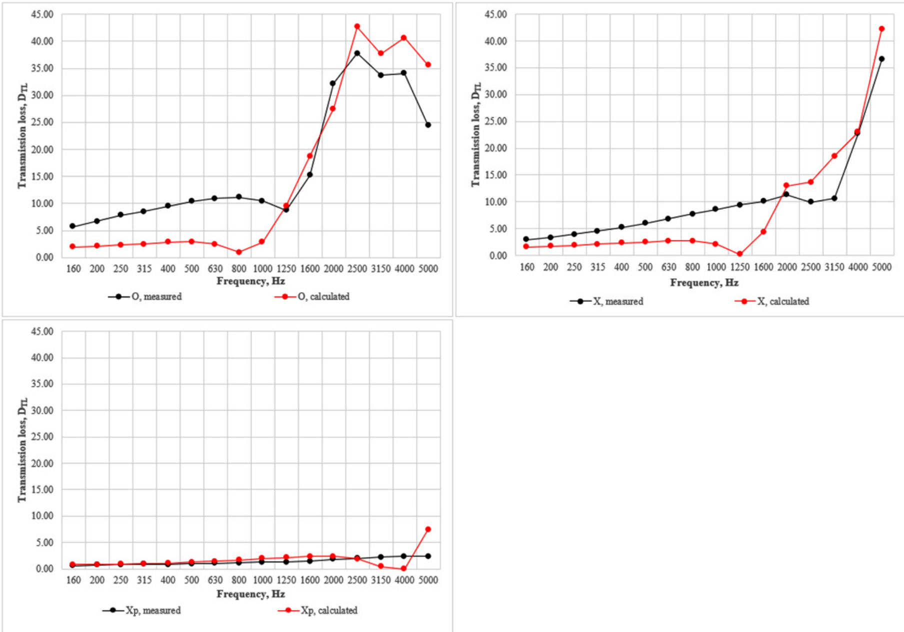


Figure 5. Measured and numerically calculated transmission loss of O, X and Xp acoustic metamaterials at different frequencies

3. Discussion

By integrating this product into the building and construction sector, plastic waste would extend their life cycle. Combined construction with plastic perforated panels, plastic acoustic metamaterial based on resonators would be a good alternative to existing solutions in building construction. With correct geometric parameters these constructions should provide better sound absorption than traditional solutions as wall panels.

It would be interesting to manufacture a real scale wall panel from recycled plastic and investigate its acoustic parameters. Then to recycle its component, sort them and manufacture the same panel again. The comparison between these two panels would show how good this concept would work and what recycle technologies are the best for this kind of plastic wall panels with metamaterial resonators.

Conclusions

All metamaterials and their combinations showed same tendencies in transmission loss. On low frequencies there is no big difference in transmission loss between without, with one and with two perforated layers, but in high and 5000 Hz cut-off frequency all metamaterials performed the same. Without perforated layers systems have lowest transmission loss, with one additional perforated layer in the middle and with two additional perforated layers being the best.

Calculated values and measured values of selected O, X, Xp metamaterials showed same tendencies on transmission loss depending on the frequency, although, selected model is based on porous–elastic materials, because of that, we can see some differences in some situations. Model for resonator would be more suitable for this application.

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Contribution

Conceptualization, A.N.; methodology, T.J. and A.N.; software, A.N.; validation, A.N.; formal analysis, A.N and T.J.; investigation, A.N.; resources, T.J.; data curation, T.J.; writing – original draft preparation, A.N.; writing – review and editing, T.J.; visualization, A.N.; supervision, T.J.; project administration, T.J.; funding acquisition, T.J.

Disclosure statement

Authors declare that they have no financial, professional, or personal interests that relate to the research described in this paper.

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