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Acoustic Properties of Recycled Polyurethane Foam Waste and Polyvinyl Acetate Composites

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***Abstract* – According to a European Commission report, around 675 000 tons of polyurethane foam waste is generated in Europe annually. Only 11 % of this waste is recycled, and the rest goes to landfills or is incinerated, so it is worth looking for new ways to treat or recycle it. This article examines the possibilities of recycling such waste into sound-absorbing materials. With this paper, an alternative way to recycle polyurethane foam is proposed. The purpose of this study is to evaluate the acoustic properties of various polyurethane foam waste scraps in the production of mattresses, pillows, and other products and to assess whether such waste can be used as a basis for creating a sound-absorbing composite material. Research was performed using standard transfer function (ISO 10534-2) and transfer matrix (ASTM E2611) methods. Samples were formed in 3 different thicknesses: 1 cm, 3 cm and 5 cm. Polyurethane (PU) foam waste was used as the main material of the composite. The samples were bound using polyvinyl acetate. Measured parameters: normal incidence sound transmission loss and sound absorption. Sound absorption coefficient (SAC) values of different thickness composite samples reached up to 0.9 in frequencies higher than 1000 Hz (depending on thickness). Sound transmission loss (STL) values increase with thickness and reach 20 dB (5 cm thickness sample). Sound absorption results show that binding material quantity in the composite does not affect sound absorption and sound transmission loss negatively. The aim of this paper is to understand the binding material influence on acoustic properties of PU foam – polyvinyl acetate (PVA) composites.**

***Keywords* – Impedance tube measurements; noise control sound absorption; sound transmission loss; acoustic materials.**

1. INTRODUCTION

One of the biggest problems in the modern world is the noise emitted by production companies, vehicles, and other types of transport. It not only harms people in the cities but also wildlife and its overall well-being, by causing stress [1]. It has been well known that strong noise waves can directly damage people's hearing or do long-term damage to their mental abilities. Noise control is an active strategy to deal with the problems that have arisen from the ever-increasing levels of noise pollution around the world. The main focus of noise

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control is to reduce noise emitted from main areas: transport, railways and roads, industrial machinery, and urbanization [2].

Sound-absorbing materials is one of the tools used in noise control for urban areas. When sound waves hit the material, three types of different events happen for the sound energy: it gets reflected, absorbed, or it gets transmitted. The full sound energy can be viewed as the total sum of energy reflection, absorption and transmission [3]. Porous sound-absorbing materials have different types of channels, cracks, or cavities that allow the sound waves to enter the materials. Sound energy then dissipates due to thermal loss caused by air molecules that interact with the pore walls [3].

The latest trends in material science are dictated by the circular economy and the green deal principles. This legislation led to scientists shifting their focus to natural materials. Natural materials consist of olive tree leaves, hemp, flax, kenaf fibres [4]–[6]. Such materials showed sound absorption values 0.833–0.900 at frequencies 600–800 Hz. Such results show a great potential for natural materials to be used in the future.

Another way to make materials fit into the principles of circular economy is material recycling. Scientists are looking for new ways to recycle materials, often using waste as the main material of composite materials. Various wastes, such as paper sludge, tyre textile, plastics, and other textiles, are researched as potential materials for applications for sound absorption or insulation applications [7]–[11]. Such materials show sound absorption values that range from 0.7 to even perfect sound absorption.

According to a report by the European Commission, around 675 000 tonnes of polyurethane waste is generated annually in Europe [12]. The disposal of waste can have a significant impact on the environment, particularly if the waste is not managed properly. This can include the release of harmful chemicals or gases into the air, water, or soil, as well as the creation of nonbiodegradable waste that can persist in the environment for many years.

The most popular type of foam in the industry is polyurethane foam, which also results in waste generation. Other authors proposed to transform polyurethane foam back into polyol and to make polyurethane foam again [13]. This approach encourages the 'enclosing' of the circular economy, making polyurethane foam more sustainable. Another way to recycle foam is to mechanically grind the foam and reuse it in construction or other sectors as wall fillers or acoustic construction fillers or as thermal insulation materials [14], [15].

In this paper, we propose the use of polyurethane foam scraps without additional mechanical grinding or chemical treatment. Polyurethane foam scraps bonded with biodegradable polyvinyl acetate. The aim of this paper is to characterise the acoustic properties of polyurethane foam (PU) and polyvinyl acetate (PVA) composites and to gain knowledge of the influence of quantity binding material on acoustic properties of the composite material. The paper is divided into 4 main sections and is organised as follows: Section 2 research methodology, Section 3 results and discussion, and Section 4 conclusions.

2. METHODOLOGY

In this section the sample preparation method is presented. For the acoustic material characterization standard methods ISO 10534-2 and ASTM E2611-19 was used. In this section of the paper, the methods used in this study are presented.

2.1. Sample Preparation Method

Samples were prepared using foam rubber waste scraps (Fig. 1) from the production line of mattresses, pillows and other products. Chosen sizes for samples were 10 mm, 30 mm and 50 mm thickness.

Fig. 1. PU foam waste scraps.

The scrap was mixed inside of the bag and then picked for sampling using the envelope method. Composite samples with polyvinyl acetate (PVA) were formed in the 3D printed cylinder shape frame. The PU foam was kept to fill mould with density of 33 kg/m^3 Then the PU foam scraps were mixed with polyvinyl acetate in 6 different proportions: 1:1; 1:2; 1:0.5; 1:3; 1:2.5 and 1:1.5 (Fig. 2). The composite material was placed in the corresponding moulds (height 10 mm; 30 mm; 50 mm) and then introduced with mass pressure to stay within the mould limits and left to dry. The drying was done at room temperature the drying time was 24 hours.

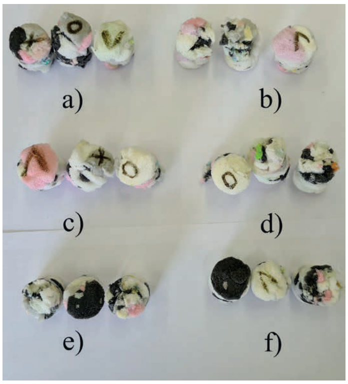

Fig. 2. Examples of 30 mm thickness samples: a) 1:1 samples; b) 1:2 samples; c) 1:0.5 samples; d) 1:3 samples; e) 1:2.5 samples; f) 1:1.5 samples.

For each proportion a total of 3 samples were made. In total, 18 samples were produced. After sample production, the acoustic properties of the materials were investigated using methods presented in Section 2.2.

2.2. Determination of Acoustic Properties of Porous Materials by Transfer Matrix and Transfer Function Methods Using an Impedance Tube

The normal incidence sound absorption and transmission loss was determined using an impedance tube (Fig. 3). The measurement system consists of 7 main components: 30 mm diameter Tube (AED AcoustiTube); free field 6.35 mm microphones (Microtech gefell type M370); data acquisition device (Sinus "Apollo lite"); sound source (integrated into tube); software (AED AcoustiStudio); signal amplifier (Atlas Sound PA 604); acoustic calibrator (Larson Davis CAL 200).

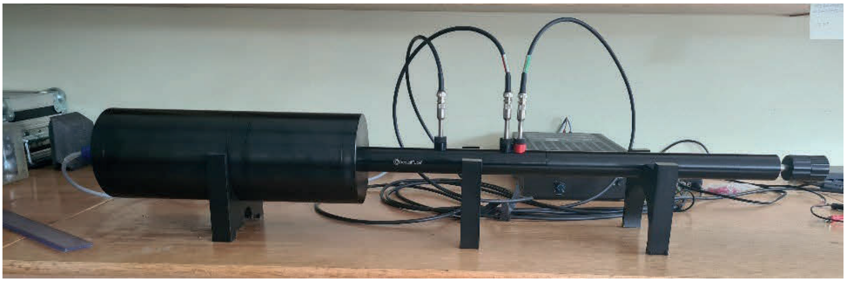

Fig. 3. AcoustiTube impedance tube.

2.2.1. Method of Material Sound Absorption Coefficient (SAC) Characterisation

The method for determining sound absorption with an impedance tube (ISO 10534-2) is based on the fact that only plane and reflected waves are transmitted in the test stand, the amplitude of which is constant at any moment in all planes of the tube, perpendicular to a fixed direction, harmonic in time, and having a frequency. To perform sound absorption calculations, it is assumed that the sound waves in the tube are not damped because of the viscosity of air.

The material to be measured is firmly placed in the sample holder of the impedance tube, which is covered with a reflective surface without an air gap. At the other end of the tube is a built-in speaker that excites the sample with white noise [16].

After performing the sound pressure measurement, the pressure is determined at each frequency:

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

where

H_{13} transfer function between microphones no. 1 and no. 3;

p_3 pressure recorded by the third microphone;

p_2 pressure recorded by the second microphone;

p_1 pressure recorded by the first microphone; f is the frequency [16].

$$k_0 = \frac{2\pi f}{c_0}, \tag{2}$$

where k_0 is sound wave number in air; f is frequency; c_0 is the speed of sound in air.

$$H_{\mathrm{I}\,(160\text{–}1000\ \mathrm{Hz})} = \frac{p_{3\mathrm{I}}}{p_{1\mathrm{I}}} = e^{-jk_0(x_{12}+x_{23})}; H_{\mathrm{I}\,(1\text{–}5\ \mathrm{kHz})} = \frac{p_{3\mathrm{I}}}{p_{2\mathrm{I}}} = e^{-jk_0(x_{23})}, \tag{3}$$

where

H_{I} transmission function of the incident wave;
k_0 wave number in air;
j index of a complex number;
x_{12} distance between Microphones no. 1 and no. 2;
x_{23} distance between Microphones no. 2 and no. 3 [(ISO 10534-2)].

$$H_{\mathrm{R}\,(160\text{–}1000\ \mathrm{Hz})} = \frac{p_{3\mathrm{R}}}{p_{1\mathrm{R}}} = e^{jk_0(x_{12}+x_{23})}; H_{\mathrm{R}\,(1\text{–}5\ \mathrm{kHz})} = \frac{p_{3\mathrm{R}}}{p_{2\mathrm{R}}} = e^{jk_0(x_{23})}, \tag{4}$$

where H_{R} is the transfer function of the reflected wave; j is the index of a complex number [16].

The reflection coefficient (R) is calculated according to the formula:

$$R_{(160\text{–}1000\ Hz)} = \frac{H_{13} - H_{I\,(160\text{–}1000\ Hz)}}{H_{R\,(160\text{–}1000\ Hz)} - H_{12}} e^{2jk_0(X_{12}+X_{23}+X_{3s})}, \tag{5}$$

$$R_{(1\text{–}5\ \mathrm{kHz})} = \frac{H_{23} - H_{\mathrm{I}\,(1\text{–}5\ \mathrm{kHz})}}{H_{\mathrm{R}\,(1\text{–}5\ \mathrm{kHz})} - H_{13}} e^{2jk_0(X_{23}+X_{3s})}, \tag{6}$$

where

H_{13} transfer function between microphones no. 1 and no, 3;
H_{23} transfer function between microphones no. 2 and no. 3;
H_{I} incident wave transfer function;
H_{R} reflected wave transfer function;
k_0 wave number in air;
$x_{3\mathrm{S}}$ distance between microphone no. 3 and sample;
j the index of a complex number [16].

Finally, SAC of the material for plane waves is determined by the formula:

$$\alpha = 1 - |R|^2, \tag{7}$$

where R is the reflection coefficient [16].

2.2.2. Method of Sound Transmission Loss (STL) Characterisation

This method is commonly referred to as the four-microphone method, where two microphones are mounted in front of the subject and the other two microphones are behind the subject. A system of 4 microphones and one load is used for the study of sound transmission reduction; the scheme is presented in Fig. 4. The methodology was prepared based on the standard ASTM E2611-19 'Standard test method for normal incidence determination of porous material acoustical properties based on the transfer matrix method' [17].

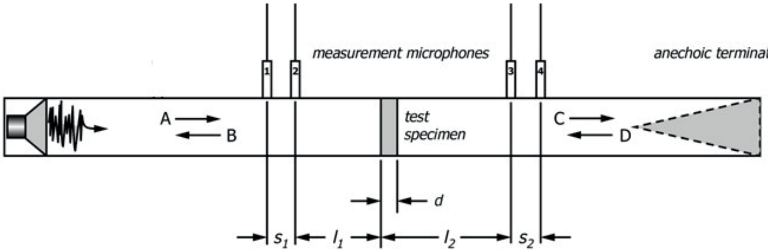

Fig. 4. Schematic of two-tube, four-microphone method [17].

In the scheme, the letters A, B, C, and D indicate the outgoing and returning waves. 1, 2, 3 and 4 mark the measurement positions where the microphones are installed.

The speed of sound (c) and air density (ρ) must be calculated before measurement. The speed of sound (c) is calculated according to the formula:

$$c = 20.047\sqrt{273.15 + t}\ , \tag{8}$$

where t is the temperature in the laboratory, °C.

Air density (ρ) is calculated according to formula:

$$\rho = 1.290\left(\frac{P}{101.325}\right)\left(\frac{273.15}{273.15 + t}\right), \tag{9}$$

where t is room temperature, °C; P is atmospheric pressure, Pa.

Outgoing and returning waves are calculated according to formulas:

$$A = j\frac{H_{11}e^{-jkl_1} - H_{21}e^{-jk(l_1+s_1)}}{2\sin(k\cdot s_1)}, \tag{10}$$

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

$$C = j\frac{H_{31}e^{+jk(l_2+s_2)} - H_{41}e^{+jkl_2}}{2\sin(k\cdot s_2)}, \tag{12}$$

$$D = j\frac{H_{41}e^{-jkl_2} - H_{31}e^{-jk(l_2+s_2)}}{2\sin(k\cdot s_2)}, \tag{13}$$

where

j index of a complex number;

k wave number in air, which is equal to $2\pi f/c$ (f – frequency; c – speed of sound);

f frequency, Hz;

H_{11}, H_{21}, etc. transmission function between two microphones;

l_1 and l_2 distances between the microphones and the sample, m;

s_1 and $s_2$distances between microphones, m.

Next, the pressure and velocity of the air particles on both sides of the sample under the influence of the sound wave (x = 0 and x = d) are calculated:

$$p_0 = A + B \tag{14}$$

$$u_0 = \frac{A + B}{\rho c} \tag{15}$$

$$p_d = Ce^{-jkd} + De^{+jkd} \tag{16}$$

$$u_d = \frac{Ce^{-jkd} - De^{+jkd}}{\rho c} \tag{17}$$

Next, matrix is made:

$$T = \begin{bmatrix} \dfrac{p_d u_d + p_0 u_0}{p_0 u_d + p_d u_0} & \dfrac{{p_0}^2 - {p_d}^2}{p_0 u_d + p_d u_0} \\ \dfrac{{u_0}^2 - {u_d}^2}{p_0 u_d + p_d u_0} & \dfrac{p_d u_d + p_0 u_0}{p_0 u_d + p_d u_0} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \tag{18}$$

The formed matrix must satisfy the conditions: $T_{11} = T_{22}$ and $T_{11}T_{22} - T_{12}T_{21} = 1$.

The sound transmission coefficient (τ) is calculated according to the formula (19):

$$\tau = \frac{2e^{jkd}}{T_{11} + \left(\dfrac{T_{12}}{\rho c}\right) + \rho c T_{21} + T_{22}} \tag{19}$$

Sound transmission loss (STL) is calculated according to the formula (20):

$$TL = 20\log\left(\frac{1}{\tau}\right) \tag{20}$$

The increase of sound transmission loss characterises the material's ability to isolate sound.

3. Results and Discussion

In this section SAC and STL experimental results are presented.

Sound absorption results for 10, 30 and 50 mm thickness samples are presented in Fig. 5. Looking at the results, the lowest sound absorption was achieved in the frequency range 160–1000 Hz for 10 mm samples.

Sound absorption coefficient of 10 mm thickness samples at lower frequency range varied between 0.06 and 0.18. At frequencies over 1000 Hz, sound absorption increases with frequency and peaks at 4000 Hz with sound absorption reaching 0.94. The composition of the samples does not influence sound absorption drastically, but 1:2.5 and 1:3 slightly higher sound absorption values at the peak.

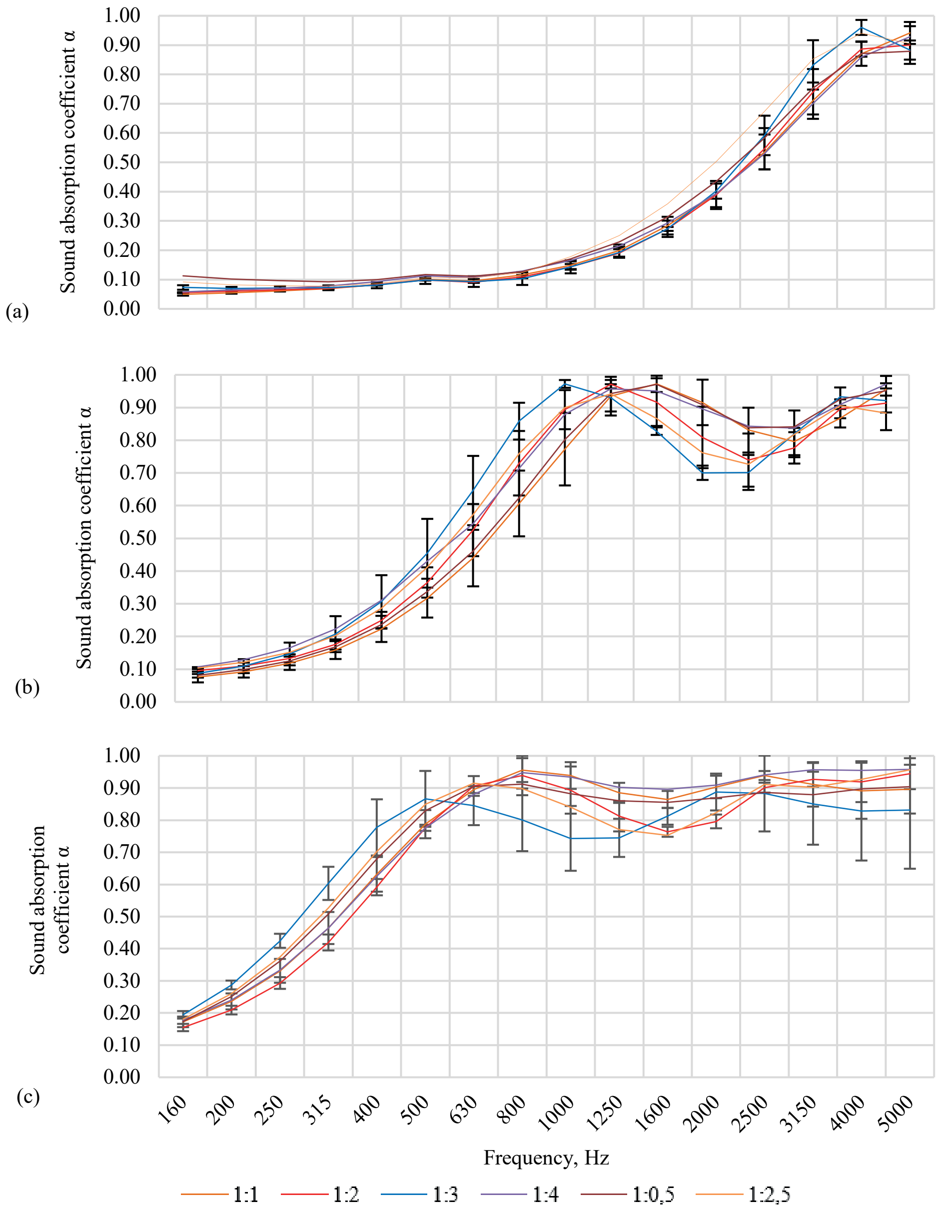

Fig. 5. Sound absorption coefficient of different foam waste – PVA composites: (a) – thickness 10 mm; (b) – thickness 30 mm; (c) – thickness 50 mm.

The results of 30 mm samples are quite similar, low frequencies (from 160 to 400 Hz) are similar to 10 mm samples, reaching 0.29 sound absorption. Sound absorption peaks and maxes out at 0.97 at 1000 Hz for 1:3 ratio and at 1600 Hz for 1:1 and 1:1.5 ratios.

Unlike 10- and 30-mm samples, 50 mm samples show sound absorption at low frequency range reach up to 0.2. In all cases, the peak values of 1:3 composition samples are in lower frequency band. The peak sound absorption values were found at 500 Hz and reached 0.78

while in other cases the peak frequency was 800 Hz. The acoustic behaviour of the materials was similar and the sound absorption values reached 0.95 at 800 Hz. It was found that the sound absorption peak shifts to a lower frequency with thickness. A similar influence of the peak shift was found in other studies, such behaviour of the materials was also found in [6], [7].

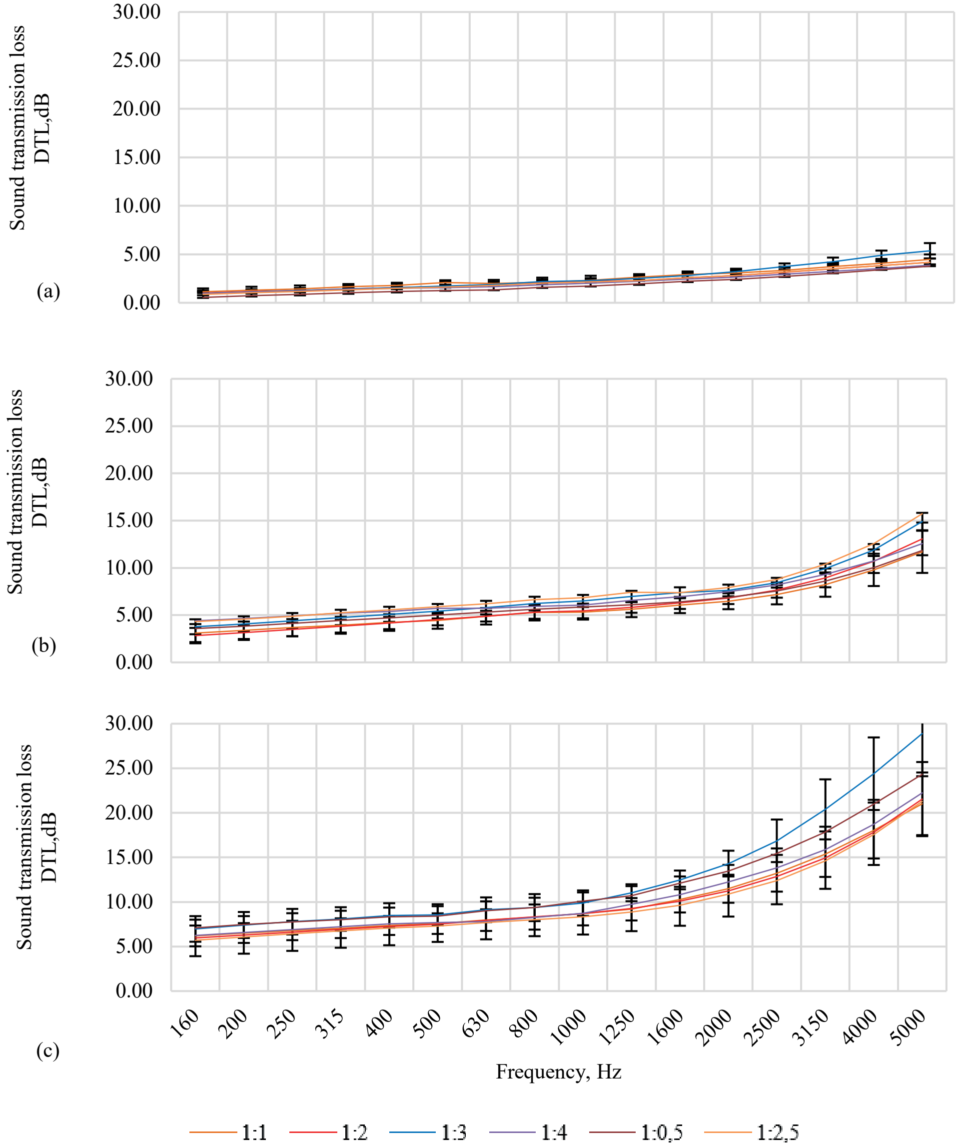

Fig. 6. Sound transmission loss of PU foam – PVA composites: (a) – thickness 10 mm; (b) – thickness 30 mm; (c) – thickness 50 mm.

As seen in Fig. 6, 10 mm, 30 mm and 50 mm thickness samples results of sound transmission loss are presented. In all cases it was found that sound transmission loss increases with frequency. Such results indicate that material is highly porous and tortuosity is high values as in [18]. The

1:1.5 sample ratio of 10 mm thickness reached 0.74 dB in 160 Hz frequency. Other composition samples sound transmission loss values also increase with frequency and peaks at 5.36 dB for 5000 Hz for 1:3 ratio sample. 30 mm thickness samples show slightly higher sound transmission loss results, starting 3.14 dB in 160 Hz and doing the same steady increase towards 5000 Hz, where it peaks at 15.72 dB for 1:2.5 sample. All of different ratio samples showed similar values of sound transmission loss, although 1:2.5 and 1:3 showing a bit higher values. The overall value increase is mostly influenced by the thickness of the materials.

Lastly, 50 mm thickness samples showed the highest values of sound transmission loss. Same as in other cases, sound transmission loss increases with frequency. The samples of ratio 1:3 and 1:1.5 showed the highest values of sound transmission loss peaking at 28.9 and 24.33 dB respectively.

Few studies reported similar results using naturals fibres, flax, wood or polyesters. Authors in their work achieved very similar results using flax fibres and biodegradable polylactide fibre composites. Produced composite material showed sound absorption coefficient that reached 0.7 in high frequencies over 4500 Hz [19]. In [20] natural fibres and wood composite material was tested. Authors reported very similar results to sound absorption to PU foam and PVA composite, peaking above 0.9 sound absorption in higher frequencies. Other studies explored the sound absorption of electrospun fibrous composite materials. Using flexible microperforated membranes they reached perfect (equal to 1) sound absorption in around 2000 Hz frequency [21].

Other colleagues explored acoustic properties of waste tyre textile fibres with paper sludge using PVA glue as a binder. The scientists manage to reach over 0.9 sound absorption in frequencies over 2000 Hz and very similar results to PU foam and PVA samples in sound transmission loss [22].

4. CONCLUSIONS

In this paper the alternative way to recycle PU foam was proposed. To test the influence of binding material on acoustic properties of recycled PU foam waste and polyvinyl acetate composites a set of samples with different ratios were created. The gained results show the potential of PU foam waste to be recycled into sound absorbing material.

It was found that peak sound absorption shifts to lower frequency range when thickness of the material sample was increased. Sound absorption coefficient of 10 mm thickness samples reached 0.94 at 4000 Hz. Sound absorption of 30 mm samples reached 0.97 at frequency of 1000 Hz. Lastly, 50 mm samples showed the best results, consistently staying above 0.7 sound absorption in frequency range from 500 Hz to 5000 Hz.

Transmission loss of 10 and 30 mm samples showed lower results compared with the same composites of 50 mm thickness. Sound transmission loss reached 5.36 dB for 10 mm samples and 15.72 dB for 30 mm. 50 mm sample showed higher sound transmission loss and reached 28.90 dB at 5000 Hz frequency.

The results of this study show that the quantity of binding material in the composite material does not have a significant impact on the absorption and sound transmission loss properties of the composite material. This could be linked due to the fact that foam materials are usually highly porous and the binding material did not completely fill the pores unlike in [8].

In this study, we were able to measure sound absorption and transmission loss in the frequency range 160–5000 Hz. Other limitations include that in the prototyping phase we only characterised the acoustic properties of materials.

Future studies will include a more detail analysis of the non-acoustic properties of recycled PU foam composites. It is very important to characterise such materials' porosity and airflow resistivity, and mechanical properties in the future. Such data would help us to analyse the sound absorption results in more detail manner.

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