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ACOUSTIC PROPERTIES OF HIGHLY ELASTIC POLYURETHANE FOAM VAPEN HR 3744

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Abstract: *Within this research, testing of the acoustic properties of polyurethane foam samples was conducted. The measurement of the absorption coefficient was performed using the transfer function method in an impedance tube, according to the SRPS EN ISO 10534-2:2008 standard. The tested samples represent highly elastic polyurethane foam of low density, with sample thickness ranging from 10 mm to 100 mm. The research results indicate the potential application of polyurethane foam in areas that require efficient sound insulation or noise control, particularly in the mid-frequency range. Therefore, polyurethane foam can be considered an excellent material with acoustic properties that exceed expectations within the given frequency range.*
Keywords: *polyurethane foam, sound absorption coefficient, passive noise protection*

Akustička svojstva visokoelastične poliuretanske vapen pene HR 3744. *U okviru ovog istraživanja, sprovedeno je testiranje akustičkih svojstava uzoraka od poliuretanske pene. Merenje koeficijenta apsorpcije izvršeno je primenom metode transfer funkcije u impedansnoj cevi, prema standardu SRPS EN ISO 10534-2:2008. Uzorci koji su ispitani, predstavljaju visokoelastičnu poliuretansku penu male gustine sa debljinom uzorka od 10 mm do 100 mm. Rezultati istraživanja ukazuju na potencijalnu primenu poliuretanske pene u oblastima koje zahtevaju efikasnu zvučnu izolaciju ili kontrolu buke, posebno u srednjem frekvencijskom opsegu. Prema tome, poliuretanska pena se može smatrati odličnim materijalom sa akustičkim svojstvima koja prevazilaze očekivanja u datom frekvencijskom području.*
Ključne reči: *poliuretanske pene, koeficijent apsorpcije zvuka, pasivna zaštita od buke*

1. INTRODUCTION

The acoustic characteristics of materials are of great importance in the construction industry, especially when it comes to achieving the best possible sound insulation and absorption in different spaces. Periodic sound control is of most importance in various environments such as residential and office spaces, healthcare, and educational facilities, all of which aim to provide adequate comfort and user productivity.

There is a wide range of different materials used for the production of porous foams. Due to this diversity, establishing a general approach for studying the acoustic properties of foams is challenging [1]. However, polyurethane (PU) foams stand out for their characteristics such as elasticity, relatively low weight, various hardness levels, and resistance to mechanical loads, which have expanded their application across a wide range of industries, including automotive, furniture, textile, packaging and construction industries [2].

PU foams have an open-cell structure, which facilitates sound absorption by creating internal friction and dispersing sound waves. PU foams are produced in various densities and thicknesses, allowing for a wide range of applications in the mentioned industries and noise protection systems. They are increasingly being used as substitutes for mineral and stone wool, which can be harmful to human health [3,4].

There has been extensive research demonstrating the exceptional sound absorbing abilities of PU foams over a wide frequency range. Due to their open-cell structure, high density, and elasticity, they reduce sound wave reflection and provide effective sound insulation. Research has also demonstrated that the acoustic characteristics of PU foams are influenced by factors such as thickness, density, porosity, and material composition. Kino, Nakano, and Suzuki [5] investigated the acoustic and non-acoustic properties of crosslinked and partially crosslinked PU foams. The focus of their research was on studying the structural factors and their dependence on temperature. Pompoli and Bonfiglio [6] conducted research on PU foams with open-cell structures. It was observed that these materials show different acoustic performances, mainly due to the inhomogeneity of the tested samples. Vulović et al. [7] mentioned in their work that changing the composition of reactants and polymer synthesis conditions allows for obtaining polyurethanes for various applications, such as coatings, fibers, rigid and flexible foams, crosslinked elastomers, and linear thermoplastic elastomers. Lauriks et al. [8] presented a theory of sound absorption that assumes the propagation of a single wave in a fibrous absorber. This theory has been confirmed only in highly porous elastic foams with an open-cell structure. Rey et al. [9] modeled the acoustic behavior of recycled PU foam from two different perspectives. Firstly, the airflow resistance was used as a simple parameter to describe the properties of the recycled foam material, while on the other hand, the porosity and average pore diameter of the recycled foam were observed as two simple parameters. Both models provided good predictions of the sound absorption of recycled foam.

Taking into account previous research, this paper aims to present the results of research on the acoustic properties of high-elastic polyurethane Vapen foam HR 3744. By combining experimental measurements and numerical simulations, it is anticipated that comprehensive data on the sound absorption coefficient will be obtained, thus uncovering potential uses of PU foam in noise reduction.

2. RESEARCH PLAN

Within the research plan, the goal is to study the acoustic properties of high-elastic PU foam HR 3744 in the frequency range from 125 Hz to 1600 Hz. Additionally, the research will include analyzing the dependency of the sound absorption coefficient on the thickness of the material sample.

2.1 Material

PU foams of low density are a type of material characterized by low density and high elasticity and are made from polyol, isocyanate, water and usually have a low density, less than 100 kg/m^3. These foams are subject to research on acoustic properties and can be divided into four groups, depending on the method of production and application. The first group consists of standard foams (S), the second group consists of foams with increased elasticity (ES), the third group consists of foams with increased hardness (T), while the fourth group includes high-elastic foams (HR) [10].

S foams are produced with an open-cell structure, which allows sound to pass through the foam pores. ES foams also have an open-cell structure, but have greater elasticity, making them suitable for certain acoustic applications. T foams have a similar open-cell structure, but are characterized by a greater hardness of the material.

HR foams, as the last group, are produced with a closed-cell structure. However, under the influence of pressure, cell membranes rupture, thereby opening the way for sound to pass through the foam pores. This means that these foams, although initially closed, can be considered foams with an open-cell structure when exposed to the pressure force.

This classification of PU foams allows researchers and industries to choose the appropriate foam type according to specific acoustic performance requirements.

2.2 Sample preparation

In order to produce soft PU foam, two different processes are used: discontinuous (block by block) and continuous. In the discontinuous process, blocks are poured into molds of appropriate dimensions, whereas in the continuous process, raw materials are continuously fed into a mixer where the liquid reaction mixture is poured onto a moving conveyor. The foam expands and forms a continuous stream of foam, which is then cut into smaller blocks of the appropriate size. [11]

For the research, samples of PU foam were used, which were provided by the company "Vapeks d.o.o." from Čačak. The testing samples were cut from continuously produced PU foam blocks. The samples were cut from a foam block with a width of 2 m, an average height of 1 m, and a length of 1 m. Three cylinders with a diameter of 102 mm were cut out along the entire length of the block. From each cylinder, samples of different thickness from 10 mm to 100 mm were further cut. In this way, three samples were obtained for each of the 10 different material thicknesses (Figure 1).

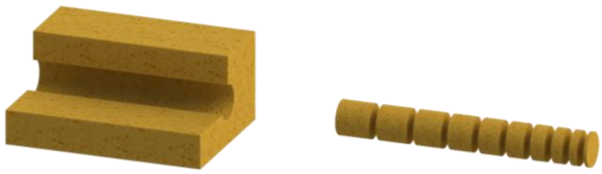

Fig. 1. Procedure of cutting samples from PU foam block

The basic mechanical characteristics of HR foam are presented in Table 1.

PU foam type	Sample group label	Density [kg/m3]	Hardness (SLD) [kPa]	Tensile strength [kPa]	Elongation at break [%]	Permanent deformation [%]	Elasticity [%]
		ISO 745	ISO 3386	ISO 1798	ISO 1798	ISO 1856	ISO 8307
Highly elastic foams (HR)	HR_1	25.8	1.4	159	85	2.9	51
	HR_2	35.0	3.9	168	95	2.0	54
	HR_3	37.0	4.6	161	82	2.1	50
	HR_4	39.4	3.5	165	100	3.2	50

Table 1. The values of the mechanical characteristics of standard PU foam [12]

3. METHOD AND EQUIPMENT

The measurement of sound absorption coefficient of high-elastic PU foam was carried out using the impedance tube method - the transfer function method between two microphones, described by the standard SRPS EN ISO 10534-2:2008 [13] in the Laboratory for Acoustics at the Faculty of Electrical Engineering, University of Belgrade.

The transfer function method is based on the decomposition of a standing wave that forms in the tube while recording signals with two microphones, and calculating their transfer function. Based on this transfer function, the reflection coefficient is calculated, which is then used to determine the absorption coefficient at normal incidence. Measurements are made in a specific frequency range determined by the physical dimensions of the tube and the distance between the microphones. The transfer function method allows for fast measurements at normal incidence and can be applied to small samples. This means that the acoustic properties of materials can be effectively evaluated with minimal sample requirements.

For an impedance tube with two microphones, the reflection coefficient is calculated according to Eq.1 [14]:

$$R = \frac{H - e^{-jks}}{e^{jks} - H} e^{j2k(l+s)} \qquad (1)$$

where is:

- H – the corrected transfer function,
- s – the distance between microphones,
- l – the distance of the closer microphone from the sample, and
- k – the wave number.

The absorption coefficient is determined through the calculated reflection coefficient, Eq.2:

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

The impedance tube method has numerous advantages and disadvantages, which are described in the standard SRPS EN ISO 354:2008 [15].

4. RESULTS AND DISCUSSION

4.1 Experimental results

Experimental values of absorption coefficients for various material thicknesses obtained through impedance tube measurements are presented in Table 2 and Figure 2.

	Material thickness (cm)									
f_c(Hz)	1	2	3	4	5	6	7	8	9	10
125	0.078945	0.052273	0.078038	0.091768	0.095615	0.099378	0.14166	0.14739	0.1988	0.23425
160	0.07159	0.064579	0.088787	0.095501	0.1163	0.13339	0.17142	0.1915	0.23306	0.28444
200	0.067147	0.071539	0.095544	0.1082	0.13866	0.16303	0.21552	0.26369	0.29383	0.36679
250	0.062784	0.081199	0.10469	0.12844	0.16959	0.20025	0.26771	0.3203	0.37254	0.47083
315	0.060061	0.082818	0.11674	0.15397	0.20809	0.24824	0.34862	0.41372	0.44536	0.56428
400	0.061533	0.088451	0.13883	0.19781	0.26972	0.31781	0.44411	0.49926	0.59604	0.73095
500	0.062915	0.10462	0.17202	0.25435	0.324	0.38727	0.55493	0.66397	0.75279	0.88024
630	0.07125	0.12535	0.22696	0.3171	0.44179	0.52143	0.74253	0.82768	0.8864	0.96609
800	0.086209	0.15796	0.29957	0.44704	0.59085	0.67178	0.88578	0.93204	0.94498	0.9434
1000	0.089769	0.19083	0.40787	0.5967	0.74673	0.80233	0.92326	0.92662	0.90819	0.8601
1250	0.1146	0.24294	0.56195	0.75699	0.84916	0.8587	0.86797	0.85938	0.83806	0.82517
1600	0.073466	0.30496	0.74481	0.86448	0.85371	0.84389	0.77397	0.80167	0.80959	0.90507
α_w	0.05	0.15	0.25	0.3(M)	0.35(M)	0.4(M)	0.55(M)	0.6(M)	0.65	0.75
f_c(Hz)	α_p									
250	0.063331	0.078519	0.105658	0.130203	0.172113	0.20384	0.277283	0.33257	0.370577	0.4673
500	0.065233	0.10614	0.17927	0.25642	0.34517	0.408837	0.580523	0.663637	0.745077	0.859093
1000	0.096859	0.197243	0.42313	0.600243	0.728913	0.777603	0.892337	0.906013	0.897077	0.876223

Table 2. Absorption coefficient values for HR 3744 foam [11]

From table 2 and image 2, the following can be observed:

- At low frequencies up to 400 Hz, PU foam does not have significant absorption properties, and the absorption coefficient ranges from 0.05 for a thickness of 10 mm to 0.31 for a thickness of 60 mm. As the thickness of the material increases, the absorption coefficient at low frequencies also increases. For a thickness of 100 mm at frequencies up to 400 Hz, the absorption coefficient is 0.73.
- At high frequencies up to 1600 Hz, PU foam has good absorption properties. For a material thickness of 40 mm to 60 mm, the maximum absorption coefficient value occurs at a frequency of 1600 Hz, where d=40 mm α=0.86, d=50 mm α=0.85, d=60 mm α=0.84, and d=100 mm α=0.9.
- For a thickness of 100 mm, the absorption coefficient of PU foam is α=0.96 at a frequency of 630 Hz. However, this value decreases at higher and lower frequencies.
- The highest efficiency of PU foam is achieved in the range of 500 Hz to 1600 Hz, where the absorption coefficient ranges from 0.6 to 0.96.

The absorption coefficient of PU foam shows a tendency to increase with increasing material thickness but at the same time, its peak shifts to lower frequencies, up to 630 Hz.

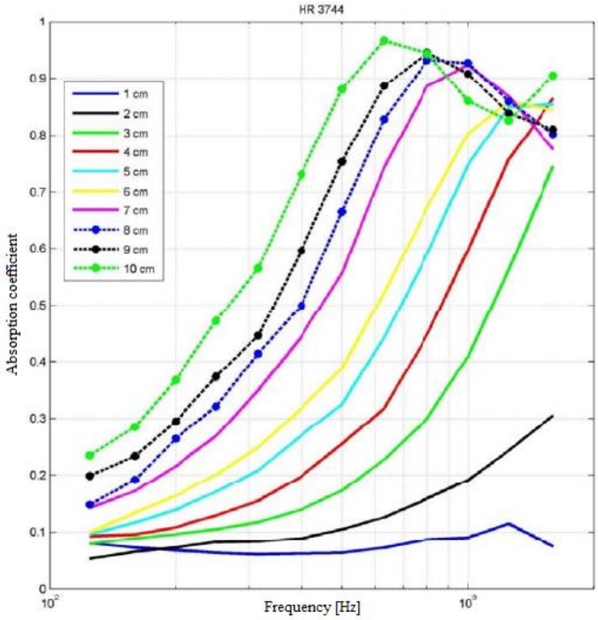

Fig. 2. Absorption coefficient value for HR 3744 foam [11]

4.2 Procession and analysis of the experimental results

In order to apply the regression analysis method and select an appropriate regression model after choosing an experimental plan and carrying out measurements, the following phases (figure 3) [11] must be completed:

- Input of experimental data,
- Summary statistics of possible mathematical models,
- Selection of a stochastic model,
- ANOVA analysis - determination of model significance,
- Assessment of model adequacy,
- Determination of the confidence interval of model parameters,
- Model diagnostics and, if necessary, model transformation and repeating the cycle of selecting and evaluating the transformed model,
- Determination of the confidence interval of the regression function, and
- Graphical interpretation and explanation of the model.

For generating and analyzing stochastic models, the software package Design Expert v9.0.6.2 was used. The choice of regression model depends primarily on the available number of experimental points. However, even when there are enough experimental points, it does not necessarily mean that the highest degree model will be the best. The models were shaped in the form of an nth-degree polynomial. Among the mathematical models available, 5th and 6th-degree models were proposed (Table 3) [11].

A summary statistical analysis [16, 17] is used to select the stochastic model, comparing possible models based on the standard deviation, coefficient of determination (R-Squared), adjusted coefficient of determination (Adjusted R-Squared), predicted coefficient of determination (Predicted R-Squared), and PRESS statistic (Prediction Sum of Squares Statistic). It is recommended that a model with a higher value of the predicted multiple determination coefficient (Predicted R-Squared) be selected.

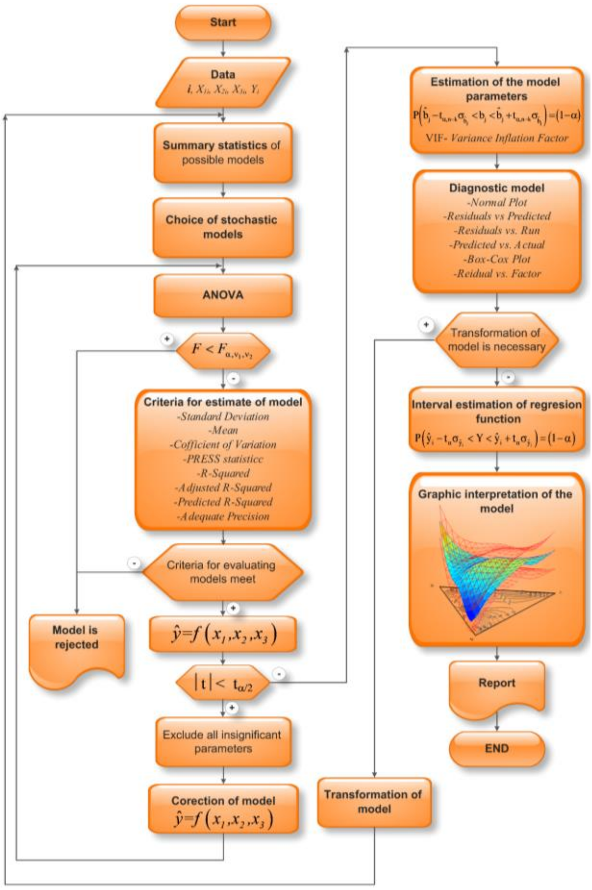

Fig. 3. Algorithm for selecting the optimal stochastic model [11]

Model Summary Statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.41	0.8060	0.8027	0.7922	20.56	
2FI	0.41	0.8061	0.8011	0.7785	21.92	
Quadratic	0.27	0.9148	0.9111	0.8981	10.08	
Cubic	0.17	0.9670	0.9643	0.9470	5.24	
Quartic	0.097	0.9899	0.9886	0.9843	1.56	
Fifth	0.085	0.9927	0.9912	0.9871	1.27	Suggested
Sixth	0.071	0.9953	0.9940	0.9847	1.51	Suggested

Table 3. Summary statistics table for HR 3744 foam

The 5th-degree model was adopted. In order to improve the results of the analysis, it was necessary to perform a transformation of the response function using the natural logarithm (Natural Log, k=0, λ=0). After reducing the non-significant terms from the proposed model, an analysis of variance (ANOVA) was performed, which is shown in table 4.

The high F-value of the model (F=749.66) and low probability value (p<0.0001) indicate that the model is significant. The coefficient of determination (R-Squared) and other statistics after the ANOVA analysis (Table 5) have good values, confirming the validity of the chosen mathematical model.

The regression coefficient values of the mathematical model, standard errors, 95% confidence intervals, and variance inflation factors (VIF) of the regression coefficient are shown in Table 6.

Response 1 HR3744
Transform: Natural Log Constant: 0
ANOVA for Response Surface Reduced Fifth model
Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	98.20	18	5.46	749.66	< 0.0001	significant
A-d	0.35	1	0.35	48.03	< 0.0001	
B-f	0.88	1	0.88	120.44	< 0.0001	
AB	2.04	1	2.04	280.54	< 0.0001	
A^2	0.43	1	0.43	59.50	< 0.0001	
B^2	0.27	1	0.27	36.49	< 0.0001	
A^2B	0.014	1	0.014	1.95	0.1656	
AB^2	0.25	1	0.25	34.33	< 0.0001	
A^3	0.29	1	0.29	40.06	< 0.0001	
B^3	2.846E-005	1	2.846E-005	3.910E-003	0.9503	
A^2B^2	0.36	1	0.36	49.00	< 0.0001	
A^3B	1.05	1	1.05	143.87	< 0.0001	
AB^3	0.87	1	0.87	119.69	< 0.0001	
A^4	0.035	1	0.035	4.75	0.0317	
B^4	1.857E-003	1	1.857E-003	0.26	0.6145	
A^3B^2	0.028	1	0.028	3.89	0.0512	
A^4B	0.10	1	0.10	14.00	0.0003	
A^5	0.13	1	0.13	17.28	< 0.0001	
B^5	5.789E-003	1	5.789E-003	0.80	0.3746	
Residual	0.74	101	7.278E-003			
Cor Total	98.94	119				

Table 4. ANOVA report for HR 3744 foam

Std. Dev.	0.085	R-Squared	0.9926
Mean	-1.26	Adj R-Squared	0.9912
C.V. %	6.75	Pred R-Squared	0.9882
PRESS	1.17	Adeq Precision	81.300

Table 5. Computational values of statistics for the assessment of the mathematical model

The final equation of the mathematical model that adequately describes the dependence of HR 3744 foam absorption coefficient on frequency and material thickness is shown Eq.:

$$
\begin{aligned}
\mathbf{Ln}(\alpha_{\mathbf{HR3744}}) = & -1.63817 - 154.21661*d \\
& -2.80518E-003*f + 0.32484*d*f \\
& +6387.80998*d\wedge 2 - 1.07210E-006*f\wedge 2 \\
& -4.38184*d\wedge 2*f - 1.30302E-004*d*f\wedge 2 \\
& -1.22214E+005*d\wedge 3 + 5.56533E-009*f\wedge 3 \\
& -3.67750E-004*d\wedge 2*f\wedge 2 \\
& +39.08242*d\wedge 3*f + 4.12341E-008*d*f\wedge 3 \\
& +1.09656E+006*d\wedge 4 - 4.31711E-012*f\wedge 4 \\
& +4.64308E-003*d\wedge 3*f\wedge 2 \\
& -158.68298*d\wedge 4*f - 3.66516E+006*d\wedge 5 \\
& +9.55248E-016*f\wedge 5
\end{aligned} \tag{3}
$$

For graphical interpolation of the mathematical model, three-dimensional and two-dimensional contour diagrams are available. The graphical representation of the mathematical model described by equation (3) is shown in Figures 4 and 5.

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	-0.32	1	0.027	-0.37	-0.26	
A-d	0.52	1	0.074	0.37	0.66	37.22
B-f	0.81	1	0.074	0.67	0.96	34.09
AB	-1.26	1	0.075	-1.41	-1.11	19.00
A^2	-0.77	1	0.099	-0.96	-0.57	20.91
B^2	-0.79	1	0.13	-1.05	-0.53	36.25
A^2B	-0.19	1	0.13	-0.46	0.079	38.10
AB^2	-0.54	1	0.092	-0.72	-0.35	21.39
A^3	1.39	1	0.22	0.95	1.82	198.05
B^3	0.018	1	0.29	-0.56	0.59	372.04
A^2B^2	0.44	1	0.063	0.31	0.56	4.55
A^3B	0.82	1	0.068	0.68	0.95	9.63
AB^3	0.74	1	0.068	0.61	0.88	10.01
A^4	-0.20	1	0.091	-0.38	-0.018	19.25
B^4	-0.058	1	0.12	-0.29	0.17	31.74
A^3B^2	0.23	1	0.12	-1.207E-003	0.46	21.31
A^4B	-0.48	1	0.13	-0.73	-0.23	28.12
A^5	-0.68	1	0.16	-1.00	-0.35	94.63
B^5	0.21	1	0.23	-0.26	0.67	211.28

Table 6. The values of the mathematical model coefficients and confidence intervals

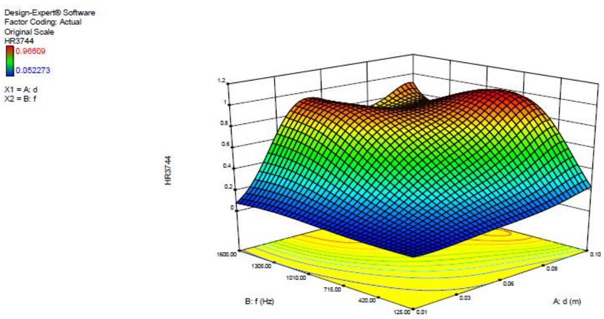

Fig. 4. 3D Graphical representation of the mathematical model for HR 3744 foam

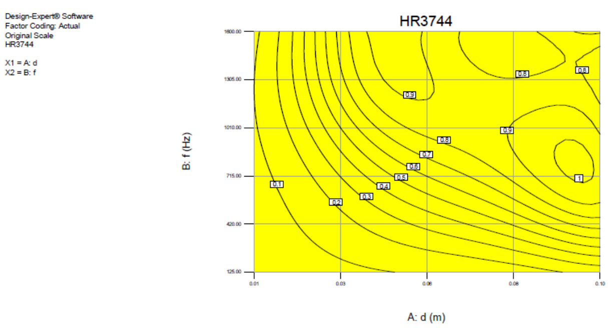

Fig. 5. Contour 2D representation of the mathematical model for HR 3744 foam

5. CONCLUSION

Based on experimental results, it was observed that the absorption coefficient of PU foam increases with increasing frequency up to 630 Hz, after which it decreases. The best possible absorption coefficient values are obtained in the range of 500 Hz to 1000 Hz.

Regarding material thickness, it was observed that increasing thickness has a positive impact up to 80 mm, after which the absorption coefficient decreases. These results explain why the testing was conducted on samples with thicknesses up to 100 mm.

Based on these findings, it can be concluded that these materials exhibit a high level of sound absorption in the mid-frequency range, which is an unusual characteristic compared to most absorption materials. Therefore, these materials can find applications in areas that require effective sound insulation or noise control.

6. REFERENCES

[1] Wang, N., Torng, H.: *Experimental study of the absorption characteristics of some porous fibrous materials*, Appl. Acoust., Vol. 62(4), p.p. 447–459, 2001.

[2] Eaves, D.: *Handbook of Polymer Foams*, Rapra Technology Limited, Rapra Technology Limited, Shawbury, 2004.

[3] Yamashita, T., Suzuki, K., Adachi, H., Nishino, S., Tomota, Y.: *Effect of Microscopic Internal Structure on Sound Absorption Properties of Polyurethane Foam by X-ray Computed Tomography Observations*, Mater. Trans., Vol. 50(2), p.p. 373–380, 2009.

[4] Joshi, P., Shravage, P., Jain, K., Karanth, V.: A *Comparative Study on Flow Resistivity for Different Polyurethane Foam Samples*, J. Acoust. Soc. India, Vol. 38(4), p.p. 153–157, 2011.

[5] Kino, N., Nakano, G., Suzuki, Y.: *Non-acoustical and acoustical properties of reticulated and partially reticulated polyurethane foams*, Appl. Acoust., Elsevier Ltd, Vol. 73(2), p.p. 95–108, 2012.

[6] Pompoli, F., Bonfiglio, P.: *Acoustical properties of polyurethane open cells materials*: Experimental investigation and theoretical models, ICSV14, p.p. 2140-2147, Australia, Cairns, 2007.

[7] Vuković, J., Pergal, M., Jovanović, S., Vodnik, V.: *Umreženi poliuretani na bazi hiperrazgranatih polimera*, Hem. Ind., Vol. 62(6), p.p. 353–359, 2008.

[8] Lauriks, W., Cops, A., Verhaegen, C.: *Acoustical properties of elastic porous materials*, J. Sound Vib., Vol. 131(1), p.p. 143–156, 1989.

[9] Rey, R., Alba, J., Arenas, J., Sanchis, V.: *Sound absorbing materials made of recycled polyurethane foam*, 40th International Congress and Exposition on Noise Control Engineering p.p. 2058-2063, Osaka, Japan, 2011.

[10] Pajović, S., Bjelic, M., Grković, V., Perić, J.: *Acoustic properties of standard low density polyurethane lime foam S 2535*, INTERNATIONAL Conference Noise and

Vibration, p.p. 137-142, Serbia, Niš, 2022.

[11] Radičević, B.: *Development of a decision-making model for the selection of the optimal mixture of sound absorbing materials*, PhD Thesis, Fakultet za mašinstvo i građevinarstvo u Kraljevu, Univerzitet u Kragujevcu, Kraljevo, Srbija, 2016.

[12] Vapeks d.o.o.; [Electronic resource], URL: http://www.vapeks.rs/en (accessed: 04.02.2016), 2015.

[13] EN ISO 10534-2:2001, Acoustics. Determination of sound absorption coefficient and impedance in impedance tubes Transfer-function method.

[14] Ristanović, I., Mijić, M.: *Jedna realizacija sistema za merenje koeficijenta apsorpcije sa impedansnom cevi*, 58. ETRAN, p.p. 1-6, Serbia, Vrnjačka Banja, 2014.

[15] SRPS EN ISO 354:2008, Akustika - Merenje zvučne apsorpcije u reverberacionoj komori.

[16] Montgomery, D.: *Design and Analysis of Experiments*, Ninth Edition, Wiley, 2017.

[17] Myers, R., Mongomery, D., Anderson-Cook ,C.: *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*, Fourth Edition, Wiley, 2016.

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