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POSSIBILITY OF USING POLYURETHANE MATERIALS TO REDUCE VIBRATIONS AND NOISE IN THE WORKING ENVIRONMENT

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Noise and vibrations are physical factors, the impact of which on the employee may negatively affect their health. Therefore, it is extremely important to effectively reduce the negative impact of these factors by implementing solutions that reduce the risk. In the article the possibility of using selected porous materials (layer systems) in the frequency range from f = 100 Hz to f = 2500 Hz, is presented. In order to assess the suitability of the application of the developed layer system, tests were carried out to determine the physical sound absorption coefficient (Kundt's tube), as well as to assess the effectiveness of vibration damping by polyurethane materials in the form of a layer system. It was found that the developed layer system can be used to reduce vibrations and noise. The developed layer system was characterized by the desired sound absorption properties αfśr > 0.6, in addition to damping efficiency above 50%, especially in the range of f = 315 Hz - 2500 Hz. The developed layered system took into account the frequency ranges characterized by the highest αf values (f = 1000-2500 Hz) as well as the effectiveness, aimed at a permanent reduction in physical factors (noise, vibrations) in the case of design solutions focused on limiting the negative impact of these factors on employees' health.

Keywords: noise, vibrations, polyurethane materials, testing of sound-absorbing properties

INTRODUCTION

The issue of reducing the negative impact of noise and vibration is an important issue for both employers and employees. Effective protection comes down to eliminating sources of noise or vibration in the work environment. In the literature on the issue of reducing noise and vibrations in the work environment, attention is paid to technical, legal, organizational and administrative means and methods [1–2]. This study analyzes technical methods relating to the possibility of using polyurethane materials to protect workers against noise and vibrations.

Vibrations are physical phenomena characterized by alternating movements of material points relative to the state of equilibrium, propagating in gaseous, liquid and solid media. The concept of vibration in the literature is sometimes put on an equal footing with the concept of oscillations and is defined as vibrations occurring in mechanical systems that have a harmful effect on the structure, people or the environment [1, 3, 4]. Vibrations constitute a nuisance or harmful hazard that appears in most industrial processes. The sources of mechanical vibrations in industry are most often various machines [5].

Mechanical vibrations penetrate from the source to the elements of the employee's body who are in constant contact with the vibrating elements of devices, machines or entire structures. The impact of vibrations on the human body depends on several aspects, i.e. the values of the basic parameters characterizing vibrations – frequency, speed acceleration, course; the time of exposure to vibrations and the direction of their action; the place and method of transmitting vibrations to the human body and the positions in which they are perceived; the individual psychophysiological characteristics of the employee; the current state of physical and mental health [3, 6].

In order to minimize the undesirable impact of mechanical vibrations on people during work, the following methods of counteracting vibrations are most often employed: preventing the causes of vibrations, modifying workstations, or damping vibrations. [4, 7–9].

Vibration damping is a physical phenomenon whose essence is the dissipation of mechanical energy. Internal damping in metals, which are the main sources of vibrations, is insignificant [10–12]. Therefore, in order to reduce vibration emission, it is recommended to use additional damping layers (single or layered). Thanks to this, the amplitude of vibration displacements is reduced, free vibrations disappear more quickly and the waves propagating in the elastic elements are damped. Recommended damping layers include: organic glass, polymers, felt, rubber, elastomers and various bituminous materials. For these materials to fulfill their purpose, they must have the following properties: a low specific weight, non-flammability, durability, high damping ability, a lack of corrosive activity, and low hygroscopicity, [1, 2, 13–15].

Vibration dampening structures in the form of plates are made of a number of materials. The most commonly used ones are shown in Fig. 1.

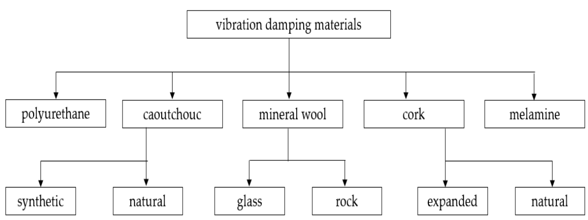

Fig. 1. Materials used to build sound-absorbing and vibration-absorbing structures

In order to effectively reduce the acceleration of mechanical vibrations, plates, mats and layered structures made of various materials are recommended as the best technical solutions [16–18]. Moreover, additional surface layers are also used, having protective, aesthetic or insulating functions. The most common supporting materials in the construction of layered systems are:

- aluminum foil designed to protect against dirt, high temperature, grease, liquids and mechanical damage. Aluminum foil is sometimes reinforced with e.g. glass fiber
- carbon nonwoven fabric that protects the main material against moisture
- fabrics, utilized only for decorative purposes, by adding additional properties, e.g. mechanical
- synthetic leather with damping and protective properties
- glass, creating a layer with a high light reflection coefficient, stable enough to use the material as additional acoustic insulation [13, 15].

Adhesive is also an auxiliary or additional layer in damping layer systems. Depending on the glued material, manufacturer and additional requirements, e.g. fire resistance, increased system stiffness, waterproofness, etc., among others, acrylic, methacrylic, cyanoacrylate, epoxy, anaerobic, polyurethane or polymer glue can be used [13, 19–24].

Many commercially available layered structures and innovative composites are being tested on a laboratory scale. These include, among others: glass-epoxy, steel-polyurethane, metal-polystyrene, cotton-phenolic, chipboard-polyisocyanurate, resin-based composites, glass-silicone, gypsum-polyurethane, cotton-melamine, glass-melamine, glass-polyester, cork-based boards, boards reinforced with various natural fibers, etc. [2, 13, 16–18, 25–36].

Table 1 presents an overview of materials with sound-absorbing properties. The physical quantity enabling the description of these properties was physical sound absorption coefficient α, which describes the degree of sound absorption by the tested material. It is determined by means of the standing wave method [37] or the reverberation method in so-called reverberation chambers [2, 36]. α_f coefficient values range from 0 to 1. The higher the α_f coefficient value, the better the material's ability to absorb sound [38]. For the purposes of the study, an analysis was carried out, which included a review of materials employed in noise protection, for which the physical sound absorption coefficient was determined (as the adopted analysis criterion). The materials for which the physical sound absorption coefficient was determined were granular and granulated materials [38–40], honeycomb-structured materials [41], fibrous and textile materials [42–49], composite materials [50–52], wood materials [53–56] and polyurethane materials [57].

Table 1. Materials used in noise protection

Authors, year of publication	Journal	Materials subjected to sound-absorbing tests
Sikora, J. (2007) [38]	Technical Journal – Mechanics. Krakow University of Technology Publishing House	Granular materials: polypropylene, polystyrene, expanded clay, quartz sand
Turkierwicz, (2007) [41]		Honeycomb material
Turkiewicz, J.; Sikora, J. (2009) [42]		Fibrous materials: uncombed fibers, combed fibers, fine wood chips, bark, mineral wool
Ducourneau, J.; Planeau, V.; Chatillon, J.; Nejade, A. (2009) [43]	Applied Acoustics	Mineral wool, glass wool
Turkiewicz, J.; Sikora, J. (2011) [50]	Technical Journal – Mechanics. Krakow University of Technology Publishing House	Composite materials – expanded clay concrete (granulate)
Na, Y.; Agnhage, T.; Cho, G. (2012) [44]	Fibers and Polymers	Textile materials, microfiber knits
Fudalej, P.; Najduchowska, M.; Pichnirczyk, P. (2014) [39]	Works of the Institute of Ceramics and Building Materials	Glass-crystalline aggregate
Bratu, M.; Dumitrescu, O.; Vasile, O.; Constantin, A.; Muntean, M.; (2014) [51]	Romanian Journal of Materials	Polymer composites: formaldehyde resin – ground glass waste, formaldehyde resin –- wood waste, formaldehyde resin – polypropylene waste
Berardi U., Iannace G. (2015) [53]	Building and Environment	Materials such as: kenaf, hemp, coconut, cork, reed, wood, cardboard and sheep's wool
Małysa, T.; Nowacki, K.; Wieczorek, J. (2016) [57]	Composites Theory and Practice	Polyurethane materials (foams and layer systems)
Nandanwar A., Kiran M.C., Varadarajulu K.CH. (2017) [54]	Open Journal of Acoustics	Fiberboard
Dunne, R.; Desai, D.; Sadiku, R. (2017) [45]	Acoustics Australia	Fiber materials: coconut, kenaf, hemp, sheep wool
Zunaidi, N.H. et al., (2017) [46]	Journal of Physics: Conference Series	Natural fibers: kenaf fiber, rice straw fiber
Berardi, U.; Iannace, G. (2017) [55]	Applied Acoustics	Materials include: wood, hemp, coconut, straw and reed, single animal fiber, sheep wool, recycled cardboard, granulated cork and kenaf

Authors, year of publication	Journal	Materials subjected to sound-absorbing tests
Mamtaz, H., Fouladi, M.H., et al. (2017) [52]	Applied Acoustics	Fiber-granular composite
Oancea, I.; Bujoreanu, C.; Budescu, M., et al. (2018) [40]	Journal of Cleaner Production	Recycled materials, including polystyrene pellets, PET pellets, recycled corn cobs, sunflower stalks, and sheep wool balls
Zhang, J.; Shen, Y.; Jiang, B.; Li, Y. (2018) [47]	Aerospace	Natural fiber – linen, balsa wood (layered systems)
Tudor, E. M.; Dettendorfer A., et al. (2020) [56]	Polymers	Spruce and larch bark
Yang, T.; Hu, L.; Xiong, X., et al. (2020) [48]	Sustainability	Glass fiber, sisal fiber, sugar cane, coconut fiber, sugar cane + resin, flax + polyester, hemp fiber, pineapple leaf fiber, kapok fiber
Jeon, J.H.; Yang, S.S.; Kang, Y.J., (2020) [49]	Applied Acoustics	Polyester fiber felt (PET) – layered systems

MATERIALS AND METHOD

Polyurethane materials – characteristics of the material being the subject of the study

Due to their porous structure, a wide group of polymer materials is utilized in the construction of solutions that reduce noise and vibration in the working environment. The properties of polymeric materials, which include polyurethane materials, depend on the conditions of their production in technological processes and are produced as flexible, rigid and integral foams [58, 59].

Polyurethane materials, which are the subject of this study, belong to the group of polymeric materials and are defined as materials that are not plastics, but polymers with a different composition and structure. Polyurethanes may contain ester, urethane or urea groups, depending on the type of raw materials used and the reaction conditions. Their physical properties are diverse, as they are on the border between elastomers and plastomers. They are known primarily as flexible foams of various densities, construction materials, paints, adhesives, and elasticizing agents employed for other plastics as fibers [58].

Polyurethane foams are widely used in many industries, including for the construction of solutions that reduce physical factors such as vibrations and noise. Flexible foams are obtained from linear or slightly branched polyesters or polyethers. Among them, soft foams are characterized by open pores and, under the influence of pressure, show low resistance to deformation. Flexible foams can be produced in the form of plates, blocks or shapes [58, 60]. Rigid foams are most often obtained from a polyol with a high degree of branching. Depending on the application, flame retardant components are also added [58]. Rigid foams, on the other hand, are characterized by high resistance to deformation under the influence of pressure; their main property is low thermal conductivity owing to gases located in closed pores [1, 36]. Because of their diversity, the above-mentioned materials can be employed in a wide range, i.e. from applications in household appliances [61] to solutions implemented in noise protection [57].

Testing sound-absorbing properties

When assessing the suitability of the material for the construction of solutions reducing noise and vibrations in the work environment, tests were carried out to determine the physical sound absorption coefficient α_f. The sound absorption properties were tested by measuring the physical sound absorption coefficient αf by means of the standing wave method in accordance with ISO 10534-1:2001 [37]. The measurement of the physical sound absorption coefficient was carried out in a so-called Kundt tube. The measuring device consists of a long smooth tube to which a loudspeaker is attached, and at the other end of the tube the material is placed, which is subjected to testing. Inside there is a thin, sliding connected tube, which is connected to a microphone. This system is a probe that allows the pressures in the nodes and arrows of the standing wave to be determined [1, 36, 37]. If we assume that there is no significant attenuation of sound waves in the pipe, then based on the measurements of the acoustic pressures at the shot (p_{max}) and the node (p_{min}) of the standing wave, which are proportional to the voltage value on the microphone amplifier, the sound absorption coefficient can be determined with the mathematical relationship in Eq. 1 [1, 36].

$$\alpha_f = 1 - \left[\frac{p_{max} - p_{min}}{p_{max} + p_{min}}\right]^2 = 1 - \left[\frac{U_{max} - U_{min}}{U_{max} + U_{min}}\right]^2 \qquad (1)$$

where: p_{max} – max. sound pressure of a standing wave [Pa]; p_{min} – min. sound pressure of a standing wave [Pa]; U_{max} –maximum voltage value read on the measuring amplifier [mV]; U_{min} – minimum voltage value read on the measuring amplifier [mV].

The physical sound absorption coefficient was tested for a layered system consisting of two polyurethane foams with an apparent density of 220 kg/m^3 and the thickness of each foam creating a layered system of 20 mm. The polyurethane foams were joined with a layer of one-component adhesive designed to join polyurethane materials. In order to carry out the tests in an impedance tube, samples corresponding to the diameters of impedance tubes, i.e. 30 mm and 100 mm, were prepared. For the prepared layered system, α_f was determined in the range of f = 100 Hz – 2500 Hz (center frequencies 1/3 octave), and the resonance frequency was determined in the frequency range provided for in the tests.

Mechanical vibration testing

Mechanical vibration measurements were carried out on a test stand, which was a steel cube-shaped structure with the dimensions 500 x 500 mm (Fig. 3). In the structure, the four walls are a solid surface, while the two opposite sides are left empty. This structure provides direct access to each of the four walls of the cube, both for performing vibration measurements and for attaching vibration damping systems. The structures were placed on an even and stable base, and all causes of measurement disturbances, including those related to the operation of the construction were eliminated. The entire structure stands on four steel legs with rubber vibration isolators. During the measurements, the vibration transducer (magnetic) was placed on the upper surface of the cube, at the intersection of the symmetry axis of the test stand. Mechanical vibrations were generated impulsively by a steel weight (Fig. 2) hitting the side wall of the structure.

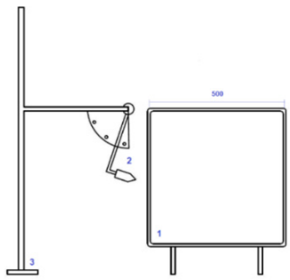

Fig. 2. Diagram of testing station: 1 – steel cube, 2 – steel weight (vibration exciter), 3 – stand [authors' own work]

Vibration acceleration measurements were carried out for systems magnetically attached to the walls of the structure. A The arrangement of the systems is illustrated in Fig. 3. In the next step, the weight was released and measurements were made of the maximum acceleration of vibrations, the source of which was the steel weight hitting the wall. The measurement was carried out for 10 seconds.

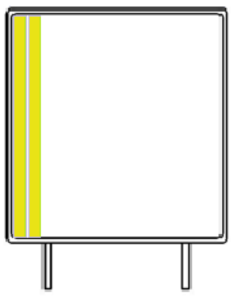

Fig. 3. Arrangement of single- and multi-layer polyurethane systems [authors' own work]

Measurements of the acceleration of mechanical vibrations were made utilizing a four-channel, digital SVAN 958 meter. It enabled narrowband analysis and analysis in one-third octave bands. The measurements were carried out employing a three-axis acceleration transducer dedicated to measuring local and general vibrations in the work environment. The analysis of the measured values was performed in the SvanPC++ program, ver. 3.2.8. Vibration acceleration values in the range of one-third octave frequencies from 100 to 2500 Hz were analyzed. For each frequency, the arithmetic mean of 10 measurements was determined.

The vibration damping efficiency was determined according to Eq. 2. For comparative purposes, the difference between the average of the measurement of vibration accelerations of the unloaded structure (without layer systems) and the average of the measurements of the loaded structure are presented. The statement “damping effectiveness” should be understood as the percentage of reduction in vibration acceleration.

$$S_{TD} = (1 - (\frac{X_{OBC}}{X_{BEZ}})) * 100\% \qquad (2)$$

where: STD – vibration damping efficiency; XOBC - arithmetic mean of the results of vibration acceleration measurements using a damping mat; XBEZ - arithmetic mean of vibration accelerations of the unloaded structure.

The tested layer systems were mats made of 2 and 3 layers of polyurethane foam, connected with a single-component adhesive constituting a sound-insulating layer. In order to attach the systems to the steel structure, a 0.5 mm thick magnetic foil was attached to the adhesive. Therefore, for example, the single-layer systems consisted of alternating layers of magnetic foil, glue and PU foam, while the three-layer systems consisted of magnetic foil, glue, foam, glue, foam, glue and PU foam. Post-foamed polyurethane foams with thicknesses of 20, 40 and 60 mm were utilized to construct the layer systems. The vibration attenuation values were determined for the tested samples in the range of third octave bands from 100 to 2500 Hz.

RESULTS

Mechanical vibration testing

The results of vibration damping of the steel structure by systems consisting of one layer of foam with a thickness of 20, 40 and 60 mm are presented graphically in Figs. 4 and 5. The average values obtained for each of the samples with a thickness of 20 mm indicate that the damping of vibrations at the frequency of one-third octave bands 100 – 250 Hz is in the range of 32 – 44% (average 37.8%), while for the frequency 315 – 2500 Hz it is in the range of 46 – 71% (average 59.0%). In the case of the 4 cm thick foams, for frequencies of 100-160 Hz, the attenuation was in the range of 29 – 37% (average 34.3%), while for higher ones it was in the range of 36 – 66% (average 55.7%). Vibration damping by 60 mm thick foams was in the range of 50 – 70% (average 62.3%), but in the case of this thickness there is a noticeable decrease in vibration damping properties with increasing frequency. The collective analysis of the results obtained for the three foam thicknesses, presented in Fig. 5, shows that there is a rising tendency in the damping capacity with an increase in the thickness of foams with a density of 220 g/cm3.

The results of vibration damping of the steel structure by the single-, double- and three-layer systems with thicknesses of 20, 40 and 60 mm are presented graphically in Figs. 6 and 7.

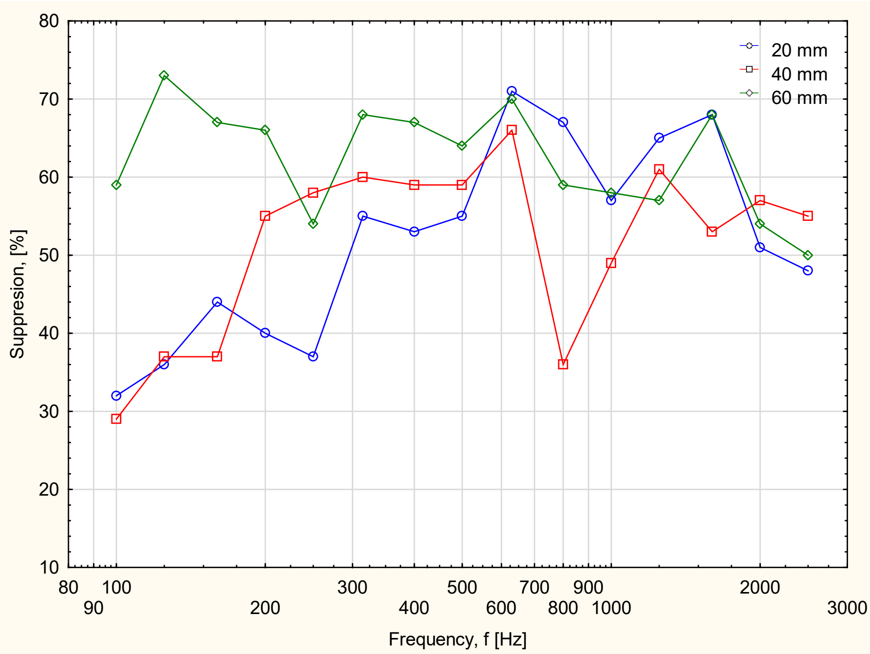

Fig. 4. Vibration damping by 220 kg/m3 PU foams with thicknesses of 20, 40 and 60 mm in one-third bands of f = 100 – 2500 Hz

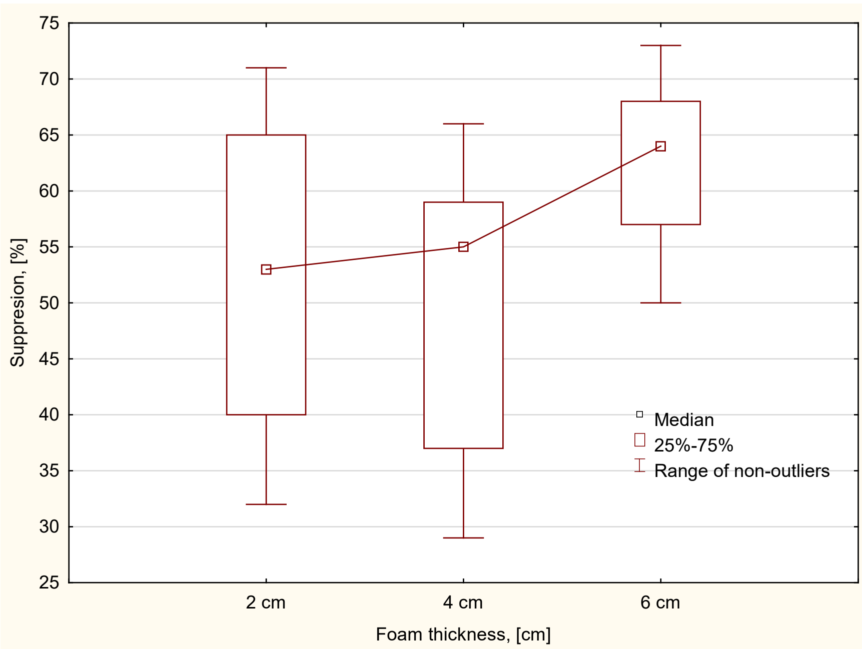

Fig. 5. Vibration damping by PU foams 220 kg/m3 with thicknesses of 20, 40 and 60 mm (f = 100 – 2500 Hz)

The average values obtained for each of the single-layer samples are described above in the case of the samples with a thickness 20 mm. In the case of the two-layer systems for the frequencies of 100-160 Hz, the attenuation was in the range of 25–43% (average 32.0%), while for higher frequencies it was in the range of 55–79% (average 65.4%). The damping of vibrations by the three-layer systems at frequencies 100–125 Hz was in the range of 20–22% (average 21.0%), while for higher frequencies it was in the range of 25–74% (average 56.5%). The collective analysis of the results obtained for the layered systems of PU foams, presented in Fig. 7, indicates slight differences in the obtained results, with the best damping properties being characterized by the two-layer systems.

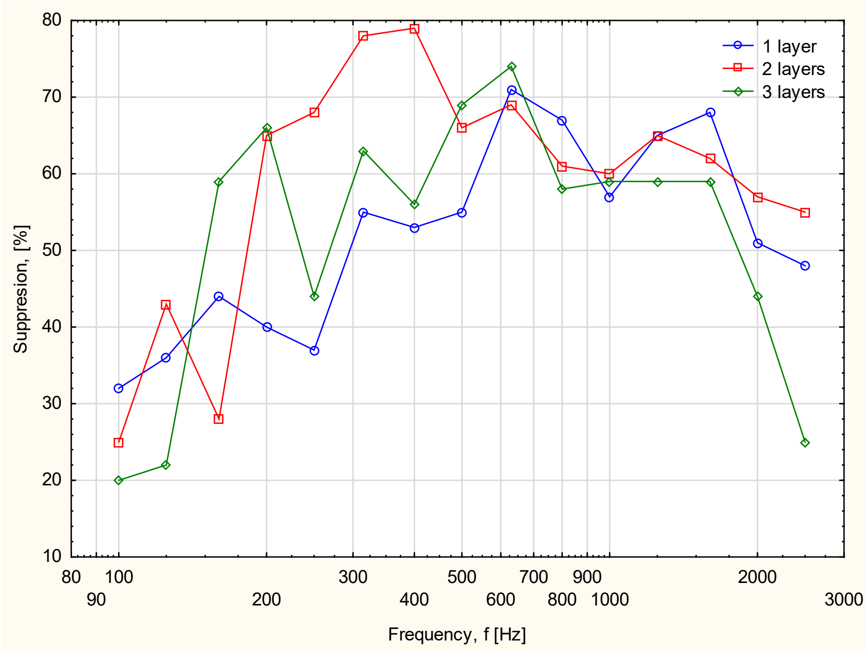

Fig. 6. Vibration damping by single-, double- and three-layer systems of 220 kg/m3 PU foam with thicknesses of 20, 40 and 60 mm in one-third bands f = 100 – 2500 Hz

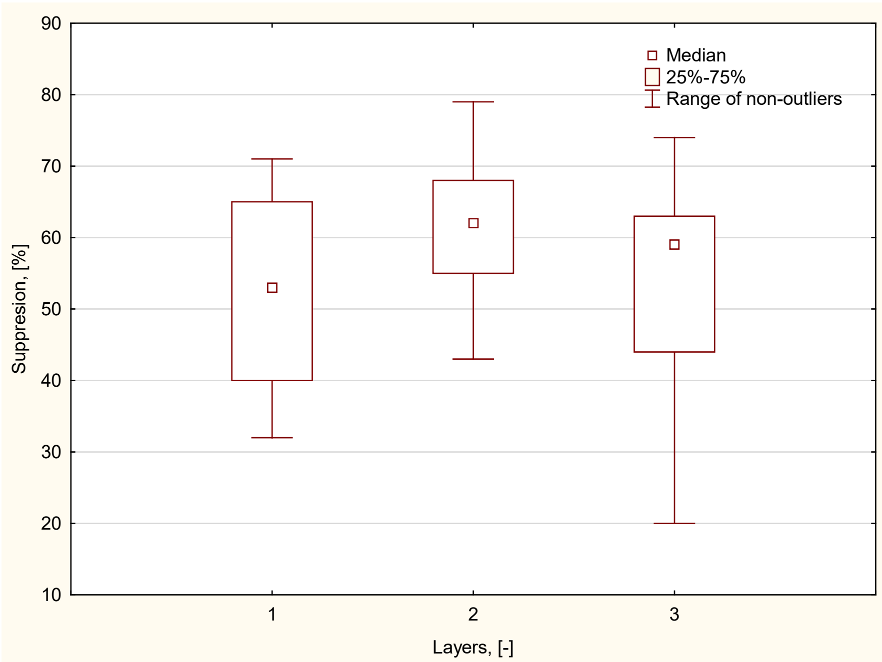

Fig. 7. Vibration damping by single-, double- and three-layer systems of 220 kg/m3 PU foam with thicknesses of 20, 40 and 60 mm (f = 100 – 2500 Hz)

Assessment of layered systems in terms of sound absorption properties

The sound absorption properties were tested for a layered system, which was developed using 20 mm thick PU foams with an apparent density of 220 kg/m^3. The material sample prepared for testing was 40 mm thick, and a layer of polyurethane adhesive was placed between the foams, creating both an insulating layer and connecting both samples with each other. The material prepared in this way was tested to determine its sound absorption properties (α_f).

A sample of the sandwich system, was tested in an impedance tube in the frequency range f = 100 Hz – 2500 Hz. The resonance frequency was determined for the tested material sample, i.e. the frequency for which the tested sample showed the highest value of αf = 0.93 (f = 2500 Hz). The α_f values in the 1/3 octave bands for the layered system are graphically presented in Fig. 8.

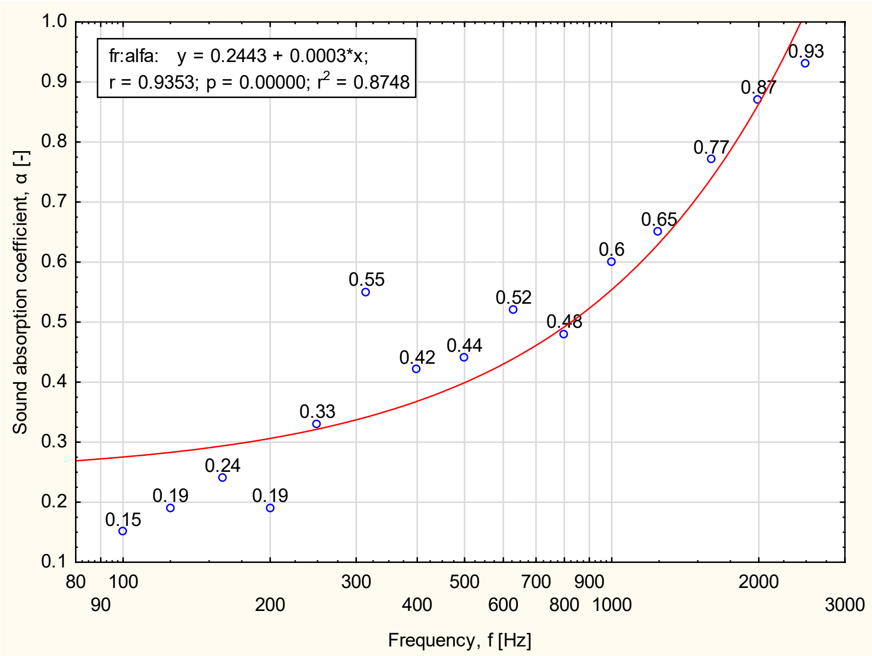

Fig. 8. Physical sound absorption coefficient values of 40 mm thick layered system in frequency range f = 100 Hz - 2500 Hz

Based on the conducted tests, it was found that the tested layered system is characterized by sound-absorbing properties. The desired sound-absorbing properties of the layered system are recorded in the f range from 1000 Hz to 2500 Hz, where the α_f values reach values above 0.6. Therefore, especially in the range of these frequencies, it is recommended to use this layered system as a solution intended for the construction of anti-noise solutions.

DISCUSSION OF RESULTS

A wide group of materials with sound-absorbing properties are used in noise protection. Conducted research [38-61] indicates the possibility of adapting materials that differ in structure, i.e. porous, fibrous, honeycomb, and granular materials. The tested materials [38-61] were characterized by different values of the physical sound absorption coefficient ($\alpha_{f\,sr}$), which allowed them to be classified as acoustically useful materials in accordance with the literature assumptions of $\alpha_f = 0.60$. In the study, the analysis of the conducted research was supplemented with layered foam systems with an apparent density of 220 kg/m^3. The developed layered system as an anti-noise solution can be implemented in the frequency range of f = 1000 Hz to 2500 Hz, where $\alpha > 0.6$. With the increase in frequency, in the case of the layered system, growth in its sound-absorbing properties was recorded.

The vibration-insulating properties of materials depend on their structure and thickness. The mechanical wave propagating in them at each interface is dispersed due to multiple reflections, which in turn reduces its energy. The tests carried out on the single-layer systems made of PU foams with thicknesses of 20, 40 and 60 mm as well as the 1, 2 and 3-layer systems have shown their usefulness in isolating vibrations propagating in steel structures. The studies have shown that in the range of low one-third octave frequencies (up to approx. 250 Hz), the effectiveness of vibration damping is relatively low (approx. 25%), while 60 mm thick PU demonstrates satisfactory effectiveness of mechanical vibration damping already in the above-mentioned frequency range. At one-third octave frequencies of 315 Hz and higher, all the investigated layered systems have the ability to damp mechanical vibrations by more than 50%. In the case of the single-layer systems, it has been proven that their damping properties grow with increasing thickness. In analyzing the damping properties of the 60 mm thick PU, it was found that they were 11 percentage points higher than those of the 20 mm thick PU and 9 percentage points higher than those of the 40 mm thick PU. The layered systems demonstrated 9 percentage points higher mechanical vibration damping properties than the single-layer system. However, in the case of the conducted analyses, no statistically significant differences were recorded between the damping properties of the two- and three-layer systems.

CONCLUSIONS

The issue of protection against noise and vibrations is important when implementing technical solutions that limit the impact of these factors on the health of employees. The conducted research allowed assessment of the usefulness of layered systems made of 20 mm thick foam materials, each layer with an apparent density of 220 kg/m3. The developed layered system was assessed in terms of its usefulness for the construction of solutions that limit noise in the range of f = 100 Hz – 2500 Hz.

Based on the tests carried out in the Kundt's impedance tube, it was found that the desired sound absorption properties ($\alpha > 0.6$) for the tested samples are recorded in the range of f = 1000 Hz 2500 Hz. In the lower frequency range, the prepared samples were characterized by fluctuations of the recorded αf values from αf = 0.15 (f = 100 Hz) to αf = 0.55 (f = 315 Hz). Above the frequency of f = 1000 Hz, a linear increase in the value of the physical coefficient was recorded. The resonance frequency for the tested samples was recorded at f = 2500 Hz, where αf = 0.93 (the highest value of the physical sound absorption coefficient).

Based on the tests carried out on the test stand, it was found that the desired vibration insulation properties (damping above 50%) for the systems under consideration were recorded for resonance frequencies from 315 Hz to 2500 Hz. In the lower frequency range, the prepared samples had a damping capacity of about 25%. A rise in the vibration insulation properties of the tested samples was also recorded with the increase in their thickness, especially for the samples with the thickness of 60 mm.

The conducted tests of sound-absorbing and vibration-insulating properties of the single- and multi-layer systems based on polyurethane foams have shown their suitability for industrial applications. In connection with the above, it can be stated that for frequencies from 1 kHz, the investigated materials have the desired properties in terms of both noise and vibration protection.

Conflict of Interest

The authors declare that there is no conflict of interest.

REFERENCES

[1] Engel Z. Zawieska W.M., Hałas i drgania w procesach pracy. Wydawnictwo CIOP-BIP, Published: Warszawa, 2010.

[2] Sikora J., Warstwy gumowe w rozwiązaniach zabezpieczeń wibroakustycznych, Wydawnictwo AGH, Published: Kraków, 2011.

[3] Koradecka D. (red.), Bezpieczeństwo i higiena pracy, Wyd. Centralny Instytut Ochrony Pracy – Państwowy Instytut Badawczy, Warszawa, 2008.

[4] Uzarczyk A., Czynniki szkodliwe i uciążliwe w środowisku pracy, Wyd. ODDK, Gdańsk, 2006.

[5] Łakomy K., Nowacki K., Lis T., Ocena bezpieczeństwa pracy przy użytkowaniu pras hydraulicznych. Innowacje w zarządzaniu i inżynierii produkcji. T. 2. pod red. Ryszarda Knosali, Wyd. Oficyna Wydawnicza

Polskiego Towarzystwa Zarządzania Produkcją, Opole. 2017, 467–478.
[6] Kardas-Cinal, E. Metody oceny komfortu wibracyjnego, Prace naukowe Politechniki Warszawskiej, z. 112 Transport 2016, 165–174.
[7] Maciejewski I., Krzyżyński T., Uogólniony model układu redukcji drgań stosowanego do ochrony operatorów maszyn roboczych. Technika transportu szynowego 2015, 12, 982–986.
[8] Gvozdkova S.I., Shvartsburg L., Analysis of Sources and Methods for Reducing Noise by Minimizing Vibrations of Engineering Technological Processes, International Conference on Industrial Engineering ICIE 2017. Procedia Engineering 2017, 216, 958–964.
[9] Pandaa K.C., Dealing with Noise and Vibration in Automotive Industry, 12th International Conference on Vibration Problems ICOVP 2015. Procedia Engineering 2016, 144, 1167–1174.
[10] Indulski J. (red), Higiena pracy, tom II, Wyd. Instytut Medycyny Pracy, Łódź 1999.
[11] Malburet F., Krysinski T., Mechanical Vibrations Active and Passive Control, Wyd. ISTE Ltd, London 2007.
[12] Mayer D., Militzer J., Bein M., Integrated Solutions for Noise and Vibration Control in Vehicles. SAE. 2014, 01, 2048–2043.
[13] Sikora J., Katalog nowych materiałów dźwiękochłonnych przydatnych w projektowaniu zabezpieczeń wibroakustycznych, Wyd. AGH, Kraków 2013.
[14] Kraśkiewicz G., Lipko C., Oleksiewicz W., Zbiciak A., Parametry charakteryzujące wibroizolacyjne maty podpłytowe stosowane w konstrukcji dróg szynowych i metody ich badania, Zeszyty Naukowo-Techniczne SITK RP, oddział w Krakowie 2015, 2, 106, 89–113.
[15] Kaczmarska A., Engel Z., Sikora J., Dobór warstwowych zabezpieczeń przeciwhałasowych – wytyczne dla projektantów, Bezpieczeństwo pracy 2005, 6, 10–13.
[16] Swinarew, B., Poliuretany – nowoczesne wszechstronne materiały, Część II – pianki poliuretanowe. Przetwórstwo Tworzyw. 2014, 3, 252–259.
[17] Renedo C.M.C., Díaz I.M., García-Palacios J.H., Gallegos-Calderón C., Structural Optimization of Lightweight Composite Floors with Integrated Constrained Layer Damping for Vibration Control. Actuators 2023, 12, 7.
[18] Akande I.G., Fajobi M.A., Odunlami O.A., Oluwole O.O., Exploitation of composite materials as vibration isolator and damper in machine tools and other mechanical systems: A review. Materials Today-Proceedings 2021, 43, 1465–1470.
[19] Havaldar S., Ramesh S., Experimental investigation of dynamic characteristics of multilayer PU foam Sandwich panels. Journal of Minerals and Materials Characterization and Engineering 2013, 1, 201–206.
[20] Datta J., Haponiuk J., Głowińska E., Durczak Ł., Badanie wytrzymałości warstwowych połączeń elementów poliuretanowo stalowych. Polimery 2012, 57, 11–12, 846–851.
[21] Osiński Z. (red.), Tłumienie drgań, Wyd. Naukowe PWN, Warszawa 1997.
[22] Dragan K., Bieniaś J., Leski A., Czulak A., Hufenbach, W. Metody badania włóknistych kompozytów metalowych (FML) dla oceny kontroli jakości w konstrukcjach lotniczych. Composites Teory and Practices 2012, 14, 2, 272–278.
[23] Muc A., Nogowczyk W., Formy zniszczenia konstrukcji sandwiczowych z okładzinami wykonanymi z kompozytów. Kompozyty (Composites) 2005, 4, 31–36.
[24] Damm J., Albiez M., Ummenhofer T., Goeddecke J., Meschut G., Koetz F., Matzenmiller A., Experimental and numerical investigation of the damping properties of adhesively bonded tubular steel joints. Journal of adhesion. 2023, 99, 15, 2191–2221.
[25] Cho K.H., Joo J.H., Kim M.G., Kam D.H., Kim J., Joining Strength of Self-Piercing Riveted Vibration-Damping Steel and Dissimilar Materials. Journal of manufacturing and materials processing 2023, 7, 2.
[26] Dacol V., Caetano E., Correia J.R., Comparative Study of Damping on Pultruded GFRP and Steel Beams. Polymers 2021, 13,13.
[27] Vijayakumar K.R., Jayaseelan J., Ethiraj N., Prabhahar M., Bhaskar K., Jayabalakrishnan D., Sendilvelan S., Krishnamoorthi S., Investigation on aluminium/mild steel plates bonded polyurethane sheets to control vibration. Materials Today-Proceedings 2021, 45, 7, 5860–5867.
[28] Han S., Yu W.R., Effect of interfacial properties on the damping performance of steel-polymer sandwich cantilever beam composites. Journal of vibration and control 2021, 29, 1–2, 400–410.
[29] Dannemann M., Siwek S., Modler N., Wagenfuhr A., Tietze J., Damping Behavior of Thermoplastic Organic Sheets with Continuous Natural Fiber-Reinforcement. Vibration 2021, 4, 2, 529–536.
[30] Rahman M.Z., Mechanical and damping performances of flax fibre composites – A review. Composites Part C 2021, 4.
[31] Higuchi R., Yokozeki T., Matsuhashi M., Imaoku A., Yamamoto T., Ohnishi Y., Sakakibara T., Numerical investigation into vibration damping in woven composite structures. Composite Structures 2023, 324.
[32] Kam M., Saruhan H., Ipekçi A., Experimental investigation of vibration damping capabilities of 3D printed metal/polymer composite sleeve bearings. Journal of thermoplastic composite materials 2023, 36, 6, 2505–2522.
[33] Karpenko M., Nugaras J., Vibration damping characteristics of the cork-based composite material in line with frequency analysis. Journal of theoretical and applied mechanics 2022, 60, 4, 593–602.
[34] Parvez Y.A., Abuthakeer S.S., Damping research in fibre reinforced composites? A review. Materials Today-Proceedings. 2021, 44, 1794–1799.
[35] Yun Y.M., Lee J.H., Choi M.C., Kim J.W., Kang H.M., Bae J.W., A Study on the Effect of Petroleum Resin on Vibration Damping Characteristics of Natural Rubber Composites. Elastomers and Composites 2022, 56, 4, 201–208.
[36] Povolo M., Maccaferri E., Cocchi D., Brugo T.M., Mazzocchetti L., Giorgini L., Zucchelli A., Damping

and mechanical behaviour of composite laminates interleaved with rubbery nanofibers. Composite structures 2021, Volume 272.

[37] Standard: ISO 10534-1:2001 Acoustics – Determination of sound absorption coefficient and impedance in impedance tubes. Part 1: Method using standing wave ratio.

[38] Sikora J., Badanie współczynnika pochłaniania dźwięku materiałów ziarnistych, Czasopismo Techniczne – Mechanika 2007, 1-M, 79–88.

[39] Fudalej P., Najduchowska M., Pichniarczyk P., Otrzymywanie oraz możliwości zastosowania kruszywa szklano – krystalicznego do wytwarzania materiałów pochłaniających dźwięk, Prace Instytutu Ceramiki i Materiałów Budowlanych 2014, 19, 15–33.

[40] Oancea I., Bujoreanu C., Budescu M., Benchea M., Grădinaru C.M., Considerations on sound absorption coefficient of sustainable concrete with different waste replacements, Journal of Cleaner Production 2018, 203 (1), 301–312.

[41] Turkiewicz J., Właściwości dźwiękochłonne struktur warstwowych z materiałem typu „plaster miodu", Czasopismo Techniczne – Mechanika 2007, 1-M, 105–114.

[42] Turkiewicz J., Sikora J., Doświadczalne wyznaczanie współczynnika pochłaniania dźwięku materiałów włóknistych i wiórowych będących odpadami produkcyjnymi, Czasopismo Techniczne – Mechanika 2009, 12, 109–120.

[43] Ducourneau J., Planeau V., Chatillon J., Nejade A., Measurement of sound absorption coefficients of flat surface in a workshop, Applied Acoustics 2009, 70, 710–721.

[44] Na Y., Agnhage T., Cho G., Sound absorption of multiple layers of nanofiber webs and the comparison of measuring methods for absorption coefficients, Fibers and Polymers 2012, 13 (10), 1348–1352.

[45] Dunne R., Desai D., Sadiku R., A review of the factors that influence sound absorption and the available empirical models for fibrous materials, Acoustics Australian 2017, 45 (2), 453–469.

[46] Zunaidi N.H., Wei H.T., Abdul Majid M.S., Lim E.A., Effect of physical properties of natural fibre on the sound absorption coefficient, Journal of Physics: Conference Series 2017, 908, 012023.

[47] Zhang J., Shen Y., Jiang B., Li Y., Sound Absorption Characterization of Natural Materials and Sandwich Structure Composites. Aerospace 2018, 5, 75.

[48] Yang T., Hu L., Xiong X., Petrů M., Noman M.T., Mishra R., Militký J., Sound Absorption Properties of Natural Fibers: A Review. Sustainability 2020, 12, 8477.

[49] Jeon J.H., Yang S.S., Kang Y.J., Estimation of sound absorption coefficient of layered fibrous materials using artificial neural networks, Applied Acoustics 2020, 169, 107476.

[50] Turkiewicz J., Sikora J., Badanie współczynnika pochłaniania dźwięku materiałów kompozytowych, Czasopismo Naukowe – Mechanika 2011, 15, 113–122.

[51] Bratu M., Dumitrescu O., Vasile O., Constantin A., Muntean M., Research on the sound-absorbing properties of new composite materials with some wastes, Romanian Journal Materials 2014, 44, 160–168.

[52] Mamtaz H, Fouladi M.H., Nuawi M.Z., Namasivayam S.N., Ghassem M., Al-Atabi, M. Acoustic absorption of fibro-granular composite with cylindrical grains, Applied Acoustics 2017, 126, 58–67.

[53] Berardi U., Iannace G., Acoustic characterization of natural fibers for sound absorption applications, Building and Environment 2015, 1045, 94, pp. 840–852.

[54] Nandanwar A., Kiran M.C., Varadarajulu K.Ch., Influence of density on sound absorption coefficient of fibre board, Open Journal of Acoustics 2017, 7, 1–9.

[55] Berardi U.G., Iannace G., Predicting the sound absorption of natural materials: best-fit inverse laws for the acoustic impedance and the propagation constant, Applied Acoustics 2017, 115, 131–138.

[56] Tudor E.M., Dettendorfer A., Kain G., Barbu M.C., Réh R., Krišt'ák L., Sound-absorption coefficient of ark-based insulation panels, Polymers 2020, 12, 1012.

[57] Małysa T., Nowacki K., Wieczorek J., Assessment of sound absorbing properties of polyurethane sandwich system, Composites Theory and Practice 2016, 16 (4), 244–248.

[58] Żuchowska D., Polimery konstrukcyjne, Wydawnictwo Naukowo-Techniczne, Published: Warszawa, 2020, 20, 224–225.

[59] Szlezyngier W., Brzozowski Z.K., Tworzywa sztuczne – środki pomocnicze i specjalne zastosowanie polimerów, Tom 3, Wydawnictwo Oświatowe FOSZE, Published: Warszawa, 2012, 129–134.

[60] Seachting H., Tworzywa sztuczne – Poradnik, Wydawnictwo Naukowo Techniczne, Published: Warszawa, 2000, 497–510.

[61] Żukowska W., Kosmela P., Wojtasz P., Szczepański M., Piasecki A., Barczewski R., Barczewski M., Hejna A., Comprehensive Enhancement of Prepolymer-Based Flexible Polyurethane Foams' Performance by Introduction of Cost-Effective Waste-Based Ground Tire Rubber Particles. Materials, 2022, 15, 5728.

