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TESTING OF MECHANICAL AND ACOUSTICAL PARAMETERS OF POLYURETHANE MATERIALS WITH DESIRABLE PROPERTIES

BADANIA WŁAŚCIWOŚCI MECHANICZNYCH I AKUSTYCZNYCH MATERIAŁÓW POLIURETANOWYCH O WYMAGANYCH WŁAŚCIWOŚCIACH

A b s t r a c t

This paper summarises the results of the testing of the mechanical and acoustical behaviour of polyurethane materials with desirable properties. Testing was performed on several samples of materials which were modified during the manufacturing processes. Tests of mechanical parameters included, among other things, the Young modulus and the energy dissipation rate. Tests were conducted on the model 43 MTS Criterion hydraulic testing machine. In the framework of the acoustic research, sound absorption coefficient measurements were conducted. The sound absorption coefficient was measured with the type 4002 Bruel & Kjaer standing wave apparatus. Characteristics of the tested materials are provided.

Keywords: polyurethane materials, measurements mechanical and acoustical properties

S t r e s z c z e n i e

W artykule przedstawiono wyniki pomiarów właściwości mechanicznych i akustycznych materiałów poliuretanowych o oczekiwanych właściwościach. Badania przeprowadzono na kilku próbkach materiałów, które w procesie wytwarzania poddane zostały różnym modyfikacjom. Badania parametrów mechanicznych obejmowały m.in. określenie modułu Younga oraz zmian energii dyssypacji w pierwszych pętlach histerezy. Badania przeprowadzono na hydraulicznym urządzeniu MTS Criterion Model 43. W ramach badań akustycznych przeprowadzono pomiary współczynnika pochłaniania dźwięku. Pomiary przeprowadzono za pomocą rury impedancyjnej na stanowisku Bruel & Kjaer 4002. Przeprowadzono charakterystykę materiałów poddanych badaniom.

Słowa kluczowe: materiały poliuretanowe, pomiary właściwości mechanicznych i akustycznych

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1. Introduction

Elastomers have a number of engineering applications – some types of plastic materials are successfully used as energy damping elements. Porous materials, such as polyurethane foams, perform well in acoustical and mechanical energy dissipation processes.

The work by Domka, Malicka & Stachowiak [1] summarises the results of testing performed on a polyethylene-based composite material with kaolin fillers to determine its mechanical properties. This data can be further utilised to determine the acoustical properties of such structures. The paper by Dziechciowski [2] investigates methods to determine the sound insulation behaviour of multi-layered structures based on the mathematical model proposed by Sharp [3], which requires that mechanical parameters of component materials be first established. Reports in the literature provide the results of extensive testing conducted on polyurethane foams. More information about the composition of tested materials can be found in the paper by Gayathri, Vasanthakumari & Padmanabhan [4]. The research program summarised in this publication involved the measurements of the sound absorption coefficient. Acoustical measurements summarised in the work by Ekici, Kentli & Küçük [5] were taken on polyurethane foams filled with tea leaves as organic filler.

Cracow University of Technology has been engaged in research work relating to the design, manufacture and testing of polyurethane foams with predetermined parameters. It is expected that foams will soon be made from renewable materials, such as vegetable oils or natural fibres used as fillers.

2. The characterization of the research object

2.1. Applications of polyurethanes [6, 7]

Polyurethanes (PUR) are a group of polymers with versatile properties and thus have a wide range of industrial applications. They include foams, elastomers, coatings and adhesives, fibres and synthetic leather. Depending on their actual properties, they can be applied in many areas of life. Flexible polyurethane foams are used in the furniture industry, in automotive and aerospace engineering and in the manufacturing of air filters, liners, seals, packaging and toys. Rigid foams are used in the construction sector, in the manufacturing of walls, structure-reinforcing elements, and in heat insulating materials. Rigid polyurethane foam systems are also used in sealing and in the structural components of aircraft. Another group includes elastomers used to make shoe soles, heels and gears. Polyurethane systems are employed to provide excellent protective coatings for metal, wood and concrete as well as flexible coatings for leather, rubber or other materials. Polyurethane-based adhesives and fibres are another group of promising materials displaying specific properties which are demanded for many industrial applications.

2.2. Tested materials

Polyurethane foams were obtained using two component systems (A and B). Component A (so-called polyol premix) consist of polyols, catalysts, surfactant, water (as a chemical blowing agent) and fillers. Component B was 4.4'-methylenediphenyl diisocyanate. Foams were formed in a closed mould measuring 120 mm × 100 mm × 20 mm by the one shot method. The final products were flexible foams. Their properties were similar to those displayed by visco-elastic materials. Such foams slowly return to their initial shape after deformation.

In order to estimate the influence of isocyanate on foam properties, 10 different foams were prepared. The quantitative ratio between components A and B and the apparent densities of the foams are shown in Table 1.

Table 1

Parameters of investigated foams (POL/ISO ratio and density ρ)

	Sample designations									
	POL/ISO ratio-fixed					POL/ISO ratio-varied				
	1n	5n	2n	4n	3n	1f	2f	3f	4f	5f
POL/IZO	2.67:1	2.67:1	2.67:1	2.67:1	2.67:1	2:1	2.25:1	2.5:1	2.75:1	3:1
ρ [kg/m^3]	126	142	156	170	197	166*	166*	166*	166*	166*

* Density range: 160–170 kg/m^3

The samples were divided into two groups – samples characterised by the constant ratio of polyol POL to isocyanate ISO (hereinafter designated as 'POL/ISO') and variable density (indicated by the letter 'n') and those having a constant density and variable POL/ISO ratio (indicated by the letter 'f').

In order to obtain porous materials with different apparent densities, varied amounts of component of polyurethane foam systems was poured into the mould. Tests described in this study were performed on polyurethane foams with apparent densities ranging from 126 to 197 kg/m^3. Measurements were taken of the acoustical and mechanical parameters of each foam. The density was determined by an approximate method involving weighing, measuring the foams' dimensions and computing their densities expressed as the ratio of the components' mass to the mould volume of the manufactured foam.

3. Testing the mechanical parameters and energy dissipation performance

3.1. Methodology

The procedure involved conducting static tension tests, compression tests and dynamic compression tests. The measurements were performed according to specifications laid out in documents PN-EN ISO 527-2 and PN-EN ISO 604 [8, 9]. Tests were conducted with the model 43 MTS Criterion electromechanical tester, supported by the TestWorks 4 software.

The application of time-variant loads lead to material wearing. There are two fundamental mechanisms leading to fatigue failure of polymer composites, these are crack propagation (being the consequence of micro-sized defects) and viscoelastic heating. On account of the viscoelastic behaviour of polymer materials, during its deformation the compression and tension stresses acting on the material are not in phase, but they appear with a certain delay. In the consequence, a hysteresis loop is formed. A hysteresis loop is incurred through the heat energy dissipation. This process is responsible for the accumulation of internal energy and an increase of the self-excited temperature of the material leading to thermal fatigue failure.

To enable a preliminary assessment of the viscoelastic properties of foam materials, their energy dissipation capability and the effects of the loading rate on foam properties, the dynamic test involved fifty compression cycles with large amplitudes. Dynamic compression tests of polyurethane foams were performed at a sampling frequency of 0.14 Hz and a strain rate of 200 mm/min. A kinematic load was applied to the sample during the test (displacement control) and the maximal rate of applied displacement in the loops was 10 mm, which accounted for 50% displacement of the original sample thickness.

3.2. Measurement results

Table 2 summarises the results of elongation tests. The registered parameters included the maximal breaking force F_{max}, the modulus of elasticity E_e and the maximal elongation of foam samples. All foam samples subjected to elongation tests broke beside the clamps. The test proved the variety of foam properties. The module of elasticity of the investigated foams was in the range of 57 to 167 kPa – for samples indicated with ‘n’ and from 40 to 345 kPa for samples denoted by ‘f’. It appears that there is no straightforward relationship between the modulus of elasticity and the value of breaking force, as we observe in the case of samples 2n and 5n. The sample elongation was in the range of 20 to 60 mm.

Table 2

Maximal breaking force F_{max}, modulus of elasticity E_e and elongation at break of tensioned samples Δl

	Sample designation									
	1n	5n	2n	4n	3n	1f	2f	3f	4f	5f
F_{max} [N]	33	43	101	123	71	188	116	90	73	60
E_e [kPa]	57	78	84	100	167	345	145	90	47	40
Δl [mm]	60	52	28	29	35	20	30	32	42	37
ρ [kg/m^3]	126	142	156	170	197	166*	166*	166*	166*	166*

* Density range: 160–170 kg/m^3

Table 3 summarises the force value registered during the sample displacement (25%) and the Young modulus E_c obtained from the static compression test. For the sake of comparison, the values of the elasticity modulus at elongation E_c are also provided. The compression test was interrupted when the displacement approached 50%. The values of the elasticity moduli of the investigated foams fell across a very broad range (34–870 kPa). Forces determined for a 5 mm displacement fall in the range of 9.7 N to 136.8 N. In the case of the compression tests, the relationship between the applied compression force and the modulus of elasticity is fairly proportional and thus, easier to compare. The Young modulus in the samples subjected to larger compression loads also increased. The actual ratio POL/IZO was found to have a major influence on the mechanical behaviour of the investigated samples.

Table 3

Force registered during the sample 5 mm displacement (25%), ($F_{5\,mm}$) and Young modulus during the compression tests

	Sample designation									
	1n	5n	2n	4n	3n	1f	2f	3f	4f	5f
$F_{5\,mm}$ [N]	12.5	21.2	32	42.7	43.5	136.8	46.3	27.4	13.2	9.7
E_c [kPa]	34	76	83	103	155	870	170	114	51	35
E_e [kPa]	57	78	84	100	167	345	145	90	47	40
ρ [kg/m^3]	126	142	156	170	197	166*	166*	166*	166*	166*

* Density range: 160–170 kg/m^3

Figs. 1 and 2 illustrate the comparison of the first and last hysteresis loops for the investigated samples, the range of the displacement control is 2 to 10 mm.

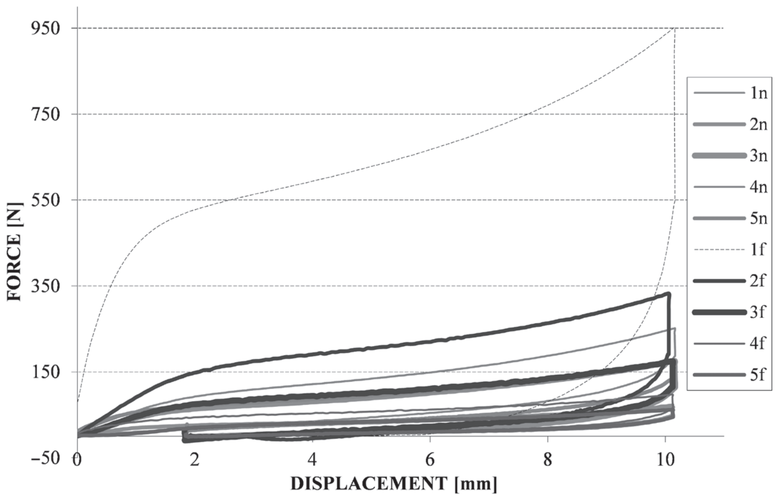

Fig. 1. Comparison of the hysteresis loops at the beginning of the testing of each foam sample – displacement control in the range of 2 to 10 mm

Dynamic loads applied at a rate of 200 mm/min in the form of kinematic excitations caused the hysteresis loop to change from linear (of fixed rigidity) to progressive (with increasing rigidity). Nevertheless, this rigidity tended to decrease in each subsequent cycle leading to the reduced capability of mechanical energy dissipation. The majority of the dissipated energy is released in the second part of the cycle when the larger pressure is applied. It is apparent that the best energy dissipation performance was registered for sample 1f which featured the highest rigidity and the lowest polyol content (see Figs. 1, 2).

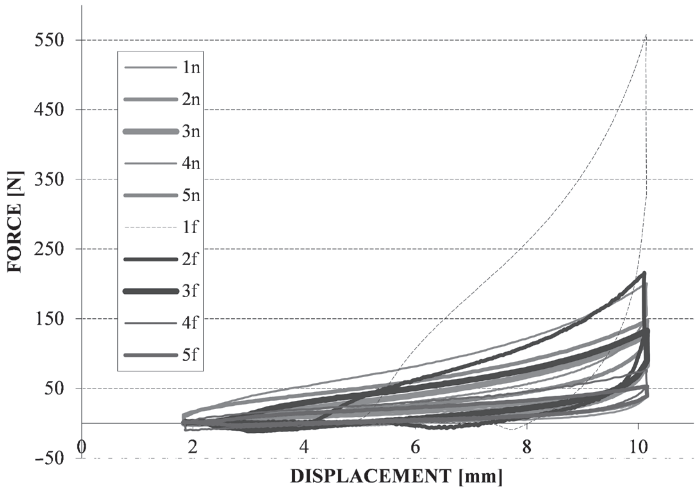

Fig. 2. Comparison of the hysteresis loops at the end of the testing of each foam sample (after 50 cycles) – displacement control in the range of 2 to 10 mm

The microstructures of the investigated materials (at 1000× magnification) were obtained using.

The microstructures of samples 2n and 1f, which were obtained using the JEOL JSN5510LV scanning microscope are shown in Figs. 3 and 4. They reveal the open pores and microstructure features most characteristic of polyurethane materials. Pores in foams indexed with ‘f’ contain spherical elements, those in samples denoted by ‘n’ are elongated with an

a) b)

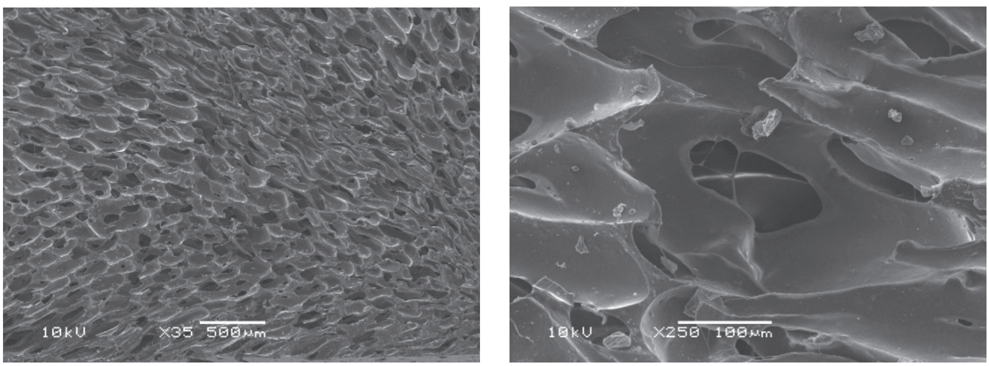

Fig. 3. SEM image of microstructure of polyurethane foam sample 2n (A – mag 35×, B – mag 250×)

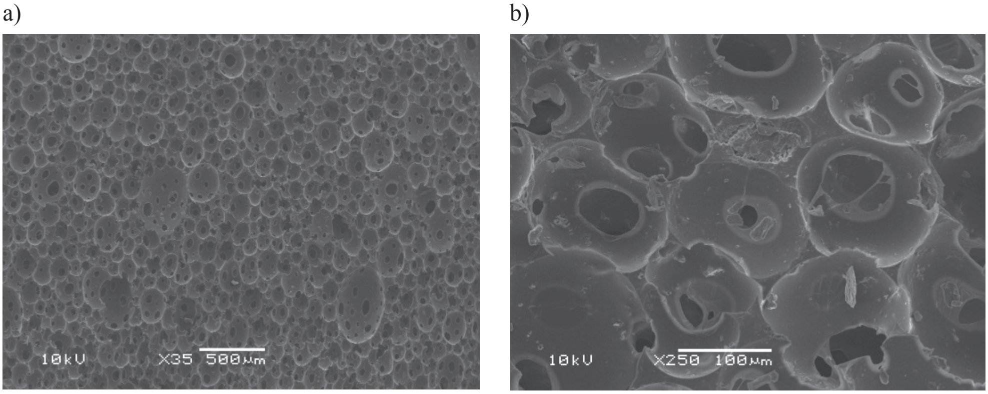

Fig. 4. SEM image of microstructure of polyurethane foam sample 1f (A – mag 35×, B – mag 250×)

irregular structure. In the case of sample 1f, the regular arrangement of pores and their fully-closed condition results in enhanced rigidity and anisotropy of the elasticity modulus.

4. Impedance tube and measurement method of absorption coefficient

4.1. Methodology

The normal incidence sound absorption coefficient of a material (α_n) is the fraction of normally incident sound energy absorbed by that material. The absorption coefficient will, in general, depend on both the structure of the material and its method of mounting. The normal absorption coefficients were measured in an impedance tube. The measuring technique employed here was that stipulated in document PN-EN ISO 10534-1 [10].

A schematic diagram of the impedance tube and measurement equipment used in testing is shown in Fig. 5. The translation from a set of angle-dependent free field absorption coefficients to random incidence values is normally carried out using Morse's formula [11]. Measurements were taken with the type 4002 standing wave apparatus by Bruel & Kjaer [12].

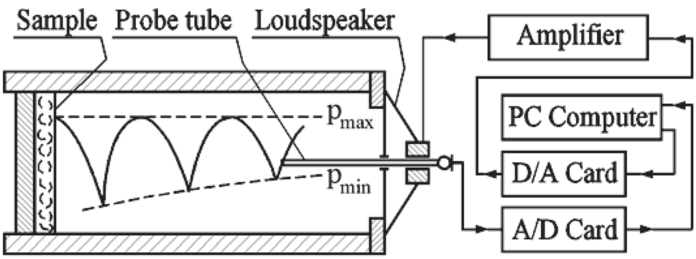

Fig. 5. The impedance tube and the measurement equipment

4.2. Measurement results

Fig. 6 plots the sound absorption coefficient determined in accordance with the procedure specified in the normative standard [13] for materials of different densities. It appears that the best sound absorption performance (in terms of the adopted criterion) is offered by materials whose densities range from 160 to 170 kg/m^3 whilst the materials with the density nearing the upper limit of the investigated range give the worst results.

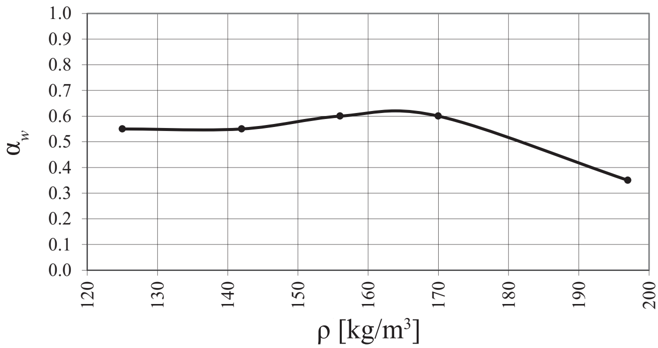

Fig. 6. Relationship between sound absorption factor and sample density

The influence of density on sound absorption behaviour in particular frequency ranges is illustrated in Fig. 7. In low frequency ranges (125 Hz, 250 Hz), the best sound absorption performance is observed for materials whose densities range from 160 to 170 kg/m^3. For frequencies of 500 Hz, 1 kHz and 2 kHz, and for densities up to 170 kg/m^3, the value of the sound absorption coefficient is scarcely affected by the density of the material. For higher densities, the value of the sound absorption coefficient tends to decrease. In the high frequency range (4 kHz), increased density is accompanied by a reduction of the sound absorption coefficient α across the entire investigated range.

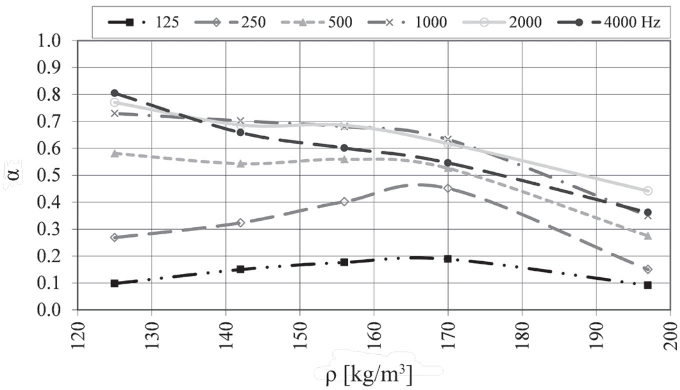

Fig. 7. Coefficient α verses density at the excitation frequencies

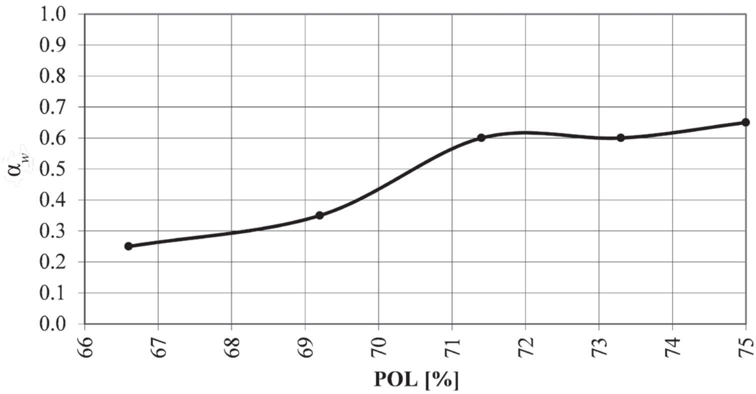

Fig. 8. Influence of the polyol content on sound absorption performance

Fig. 8 plots the values of the sound absorption coefficient determined in accordance with the procedure set forth in the normative standard [13] for materials with variable polyol contents. The percentage fraction expressing the polyol content in the sample mass is indicated on the x-axis. It appears that materials containing at least 71% of polyol exhibit the best sound absorption features.

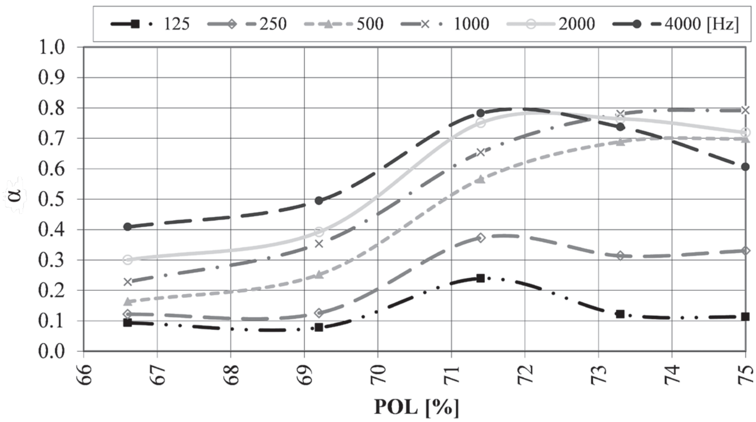

Fig. 9. Influence of polyol content on the coefficient α in specified frequency ranges

The influence of the polyol content on the sound absorption behaviour in specified frequency intervals is illustrated in Fig. 9. In the low (125 Hz, 250 Hz) and high (4 kHz) frequency ranges, the materials with the polyol content in the range of 71 to 72% shows the best sound absorption performance. In the frequency range 500 Hz and 1 kHz, the value of coefficient α increases with the increasing polyol content. At 2 kHz, the sound absorption coefficient α of materials with a polyol content in excess of 71% changed only to a minor degree.

5. Conclusions

The research investigation was undertaken to determine the mechanical and acoustical behaviour of polyurethane foams whose properties were predetermined at the stage of design. The behaviour of the investigated material can be modified by varying the weight proportions of the component mix and by varying the value of the POL/IZO ratio. The results of experimental tests lead us to the following conclusions:

– relationships are revealed between the ratio of polyols and isocyanate in the component mix and the mechanical and acoustical behaviour of the material, it is therefore reasonable to expect that the sound absorption and mechanical behaviour of polyurethane foams can be already modified at the stage of design;
– for samples characterised by the fixed ratio POL/IZO, the value of the sound absorption coefficient α varies with frequency and with sample density;
– tests results reveal the influence of the POL/IZO ratio on the acoustical parameters of samples; furthermore, the increased polyol content gives rise to improved sound absorption behaviour, particularly in the medium and high frequency ranges;
– measurements of the mechanical parameters revealed the dependence between density and the Young modulus – increased density gives rise to an increase of the Young modulus;
– the value of the Young modulus is found to decrease when the proportion of polyols in the component mix increases; however, an increased proportion of polyols does not lead to a significant enhancement of their rigidity or energy dissipation performance;
– the relationship is established between the sample density and the sound absorption coefficient α, the highest values of the coefficient are registered for densities in the range of 160 to 170 kg/m^3.

The results of this research investigation reveal a relationship between the values of selected mechanical and acoustical parameters. In particular, the improved mechanical energy dissipation behaviour goes alongside the reduced acoustic energy absorption performance, which may be attributable to the cell structure of investigated foams.

Further research should be undertaken to establish the relative importance of other factors – the mixing time and method, and their influence on the mechanical and acoustical behaviour of foam materials.

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