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Powder Modifier Effect on the Mechanical Behavior of Polyurethane Foams

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Abstract

The paper investigated the influence of a powder modifier in the form of finely dispersed perlite on the mechanical behavior of rigid polyurethane foams under static monotonic and multi-cycle loading, which causes the material's plastic deformation. The studies were conducted for polyurethane foam samples with different weight contents of perlite powder, ranging from 0 to 10 mass parts. Infrared spectroscopy established heterogeneous inclusion of the perlite additive as a mineral filler into the polymer matrix without changing the main structural bonds of modified polyurethane foam (MPU). The change in the values of Young's modulus, yield strength and relative plastic deformation depending on the quantitative content of the powder modifier was investigated. It was established that the addition of a powder modifier, perlite, contributes to an increase in the stiffness of MPU foam. The change in Young's modulus under multi-cycle loading within each series of experimental samples was evaluated. The results confirm the effectiveness of perlite powder for modifying polyurethane foam not only for solar radiation protection, but also to increase the stability of the mechanical characteristics of rigid polyurethane foams.

Keywords: polyurethane foam; modification; mechanical characteristics; Young's modulus; plastic deformations; multicycle loading.

1. Introduction

Polyurethane (PU) foams belong to a class of polymer foams with a wide range of applications and potential for innovation (Kim et al., 2023). Their popularity is explained by the accessible manufacturability and flexibility of chemical composition, which determines a rather diverse nomenclature of PU foam from soft and elastic foams to hard and rigid foam materials and allows them to be adapted to specific requirements (Ates et al., 2022). PU foams are effective for the manufacture of products in various industries and household needs (Akindoyo et al., 2016), as well as in innovations, for example, for shielding electromagnetic radiation (Wang et al., 2018), as shape memory elements and for biomedical purposes (Dong et al., 2024).

Various foaming techniques are used to produce PU foams from different raw materials (Cyzio et al., 2017). The main components are polyol and polyisocyanate, to which catalysts, foaming agents and other additives are also added, allowing the foaming process to be optimized and setting the foam's properties. The ratio of the main components determines the properties of

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PU foam. In soft, elastic foam, the polyol content prevails over the polyisocyanate content, proving greater flexibility of the foam structure (Šebenik et al., 2007). To obtain rigid PU foam, the polyisocyanate content must exceed polyol content, resulting in a more rigid and stable structure (Wang Z. et al., 2023). Rigid PU foams, due to their porous (cellular) structure, low density and low thermal conductivity, are good insulating materials and are widely used in practical solutions for heat and sound insulation in such industries as construction (Schiavoni et al., 2016), chemical industry equipment, aerospace industry (Gwon et al., 2016), water supply, hydropower and other engineering industries.

However, PU foams have certain disadvantages during operation, such as fragility under variable loads and ageing under environmental conditions. Fig. 1 presents laboratory samples exposed to solar radiation for 6 months. Sections of the material structure (Fig. 1 c) show the nonlinear influence of this effect.

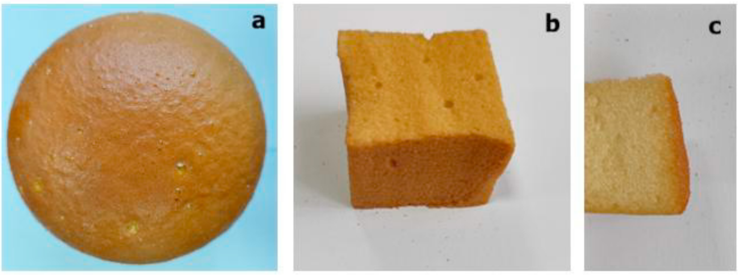


Fig. 1. View of PU foam (a) and sample (b) under the influence of solar radiation, and range of this influence (c).

Therefore, for optimising their properties and expanding their functionality, they are modified by adding various types of additives, such as mineral, organic, and polymeric, to the PU foam (Mikulich et al., 2024; Chmiel et al., 2018; Chai et al., 2019; Obiechefu et al., 2024).

The direction of modifying PU foams is developing now and remaining relevant. In this study, expanded perlite of mineral origin was used as a powder modifier. The paper investigated the influence of modification on the mechanical behavior of rigid polyurethane foam under loads that cause plastic deformation.

Nomenclature

MPU	Modified Polyurethane Foam
PU	Polyurethane Foam
E	Young's modulus
σ_y	Yield strength
δ_{pl}	Relative plastic deformation

2. Methods of experimental research

The main components for obtaining rigid polyurethane foam were polyol and polyisocyanate in a fixed ratio of 20:40 mass parts. The composition of the polyol included: a mixture of polyester, stabilisers, catalysts, flame retardant, and water as a foaming agent. Mineral filler, such as powdered perlite obtained by mechanical grinding of expanded granular material, was used as a modifying additive. Perlite, as a light porous material, was used as a modified addition because it has the ability to reflect light and a low thermal conductivity coefficient, which is lower compared to PU foam. This approach is advisable for optimising the properties of modified polyurethane foam (MPU) as a heater and sound insulator.

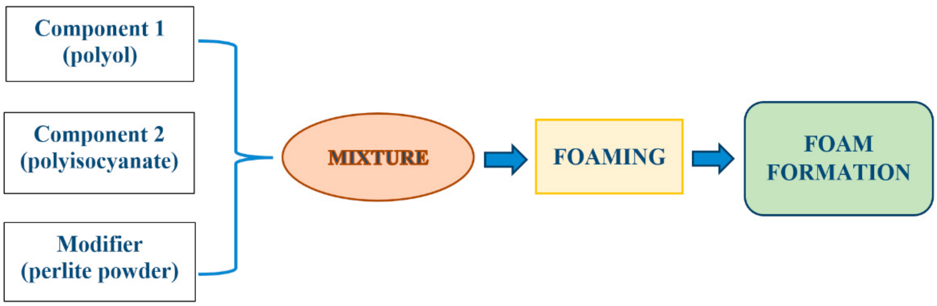


Fig. 2. Stage of obtaining MPU foam samples by pouring the reaction mixture into molds.

Polyurethane foams were obtained as a result of a chemical foaming reaction that occurred when mixing the two main components of polyol and polyisocyanate with the addition of a powder modifier, perlite (Fig. 2). The reaction mixture (Fig. 3, left) was poured into plastic molds, where further foaming and molding of MPU foam compositions took place (Fig. 3, right). In this way, 4 groups of MPU foam compositions with powder perlite content from 0 to 10 mass parts were obtained. Experimental samples of cubic shape with a size of 30×30×30 mm^3 were cut from the obtained foam compositions.

Fig. 3. Reaction mixture (left) and samples of MPU foam compositions (right).

The influence of the powder modifier on the structure of MPU foam was investigated using IR Fourier transform infrared spectrometer IRAffinity-1S. The research was carried out by the single-beam method in reflected light in the frequency range of 4000-400 cm^{-1}.

The influence of the modifier on the change in the mechanical behavior of MPU foam was studied on the basis of mechanical compression tests. Two series of tests were performed for all groups of samples. The first series concerned the study of the influence of the content of the powder perlite additive on the behavior of rigid MPU foam in axial compression under the action of a uniformly applied compressive load. The rate of change in the load intensity was 2 mm/min. A series of further tests was carried out under multi-cycle loading of samples within the limits of plastic deformation. Based on compression diagrams, the influence of the modifier on the change in the values of the mechanical characteristics of materials was studied.

3. Results and discussion

IR spectroscopic study of polyurethane foam samples (Appendix A) showed the presence of characteristic absorption bands corresponding to the main structural fragments of the polymer matrix. In all samples, intense peaks were recorded in the region of 1720–1730 cm^{-1}, which correspond to vibrations of carbonyl groups (C=O) in urethane-type bonds, as well as bands at 1530–1550 cm^{-1}, which are related to N–H and C–N deformation vibrations.

In samples with the addition of powdered perlite, an increase in absorption in the region of 500–700 cm^{-1} is observed, which is due to the presence of Si–O and Al–O vibrations characteristic of the inorganic filler. An increase in the intensity of the bands in the range of 1200–1300 cm^{-1}, which corresponds to the valence vibrations of the C–O–C and C–N bonds, is also recorded, which may indicate the formation of additional interfacial bonds between the components of the polymer matrix and perlite particles. At the same time, the position and shape of the carbonyl bands remain stable, which confirms the preservation of the main polyurethane structure when the mineral component is introduced. The results obtained indicate that the powder perlite additive is included in the MPU foam structure heterogeneously as filler.

To assess the influence of the quantitative content of the powder modifier on the change in mechanical characteristics under different loading conditions, the change in deformations under the action of single and multi-cycle loading was investigated. Analysis of deformation diagrams (Appendix B) under the action of compressive loading with the presence of plastic deformations allowed us to assess the change in mechanical characteristics of the modified material. The corresponding results for each component composition of the samples regarding the determination of Young's modulus, yield strength and the value of relative plastic deformation are given in Table 1.

Table 1. Mechanical characteristics of MPU foam samples

Partial mass correlation (A : B : C)*	Young’s modulus E, MPa	Yield strength σ_y, MPa	Relative plastic deformation δ_{pl}, %
20:40:0	11.81	1.07	31.22
20:40:3.7	12.30	0.93	30.46
20:40:5	13.20	0.91	31.18
20:40:10	12.60	1.05	37.51

*A – polyol, B – polyisocyanate, C – perlite powder

Based on the results obtained, the change in the mechanical characteristics of rigid MPU foam from the weight content of perlite powder was established. It was found that with an increase in the proportion of powder modifier, Young's modulus increases to a maximum value at a ratio of 20:40:5 (E = 13.20 MPa), which is an increase of 11.8% compared to the initial composition of rigid PU foam (20:40:0). However, with a further increase in the modifier to 10 mass parts, the stiffness decreases slightly (E = 12.60 MPa), but remains higher than that of the initial material. Thus, the addition of a mineral filler, perlite, increases the stiffness of polyurethane foam, and the optimal content of this modifier for maximum stiffness is achieved at 5 mass parts.

The amount of perlite powder up to 5 mass parts reduces the yield point, i.e. MPU foam becomes less resistant to the onset of plastic deformation. With a further increase in the modifier concentration to 10 mass parts, this indicator returns almost to the level of the rigid PU foam. The relative plastic deformation practically does not change up to 5 mass parts of the powder modifier and increases slightly only at a content of 10 mass parts, which may be a consequence of changes in the pore structure.

According to the experimental data of the multi-cycle load compression of MPU foam samples, the change in Young's modulus was determined at each load cycle. These results are presented in Table 2.

Table 2. Change in Young's modulus under multi-cycle loading

Partial mass correlation (A : B : C)*	Young's modulus E, MPa								
	Load cycle								
	1	2	3	4	5	6	7	8	9
20:40:0	11.81	10.76	8.82	8.02	7.75	7.43	7.10	6.74	6.48
20:40:3.7	12.30	11.11	9.39	8.04	9.07	10.96	9.04	9.39	9.46
20:40:5	13.20	13.04	12.63	12.29	12.58	13.82	13.31	12.63	13.12
20:40 :10	12.60	12.46	12.09	10.37	10.86	9.68	10.08	9.52	9.54

*A – polyol, B – polyisocyanate, C – perlite powder

The Young's modulus increases for modified polyurethanes by 4-12% depending on the mass part of perlite. The most optimal samples were in the third group with a 5 mass part of perlite. With a further increase in the modifier fraction to 10, a decrease in Young's modulus E occurs, which may be associated with the aggregation of perlite particles.

Changing the Young's modulus over 9 cycles is not a monotonic process for all samples. Thus, for the PU foam sample (20:40:0, without a modifier), a decrease in the Young's modulus at all stages of loading is observed within 45%. For MPU foams, the decrease in Young's modulus is somewhat slighter with multi-cycle loading, within 7-25%.

The numerical results in Table 2 confirm that for multi-cycle loading, the effect of the modifier allows for improving not only the chemical properties of the foam, but also the mechanical elastic characteristics. Analysis of the data in Table 1 does not show a significant decrease in the yield strength. Therefore, it can be concluded that the addition of the perlite powder modifier increases the ability of the foam to fatigue resistance.

Analysis of the microstructure of the modified material shows the presence of cavities inside. Their number increases with the increasing amount of the modifier (Fig. 4, b, c).

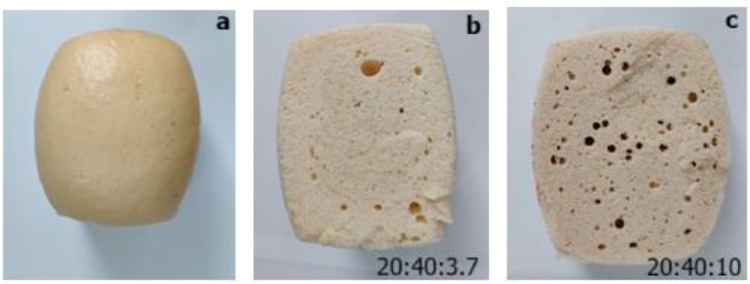


Fig. 4. View of MPU foam (a) under the influence of solar radiation and their internal structures (b, c).

Fig. 4 a shows the appearance of the sample after 6 months of exposure to solar radiation. Comparing Fig. 3 and Fig. 4, it can be seen that perlite does not cause chemical changes in the materials from the influence of solar radiation. However, comparing Fig. 4 b and c shows that changes occur in the internal structure of the material.

4. Conclusions

Based on the obtained results of the experimental study of the influence of the powder modifier perlite on the mechanical behavior of rigid polyurethane foams, the following was established:

1. IR spectroscopic analysis showed that powder perlite enters the structure of MPU foam homogeneously as an inorganic filler, without changing the main structural bonds of the polyurethane matrix.

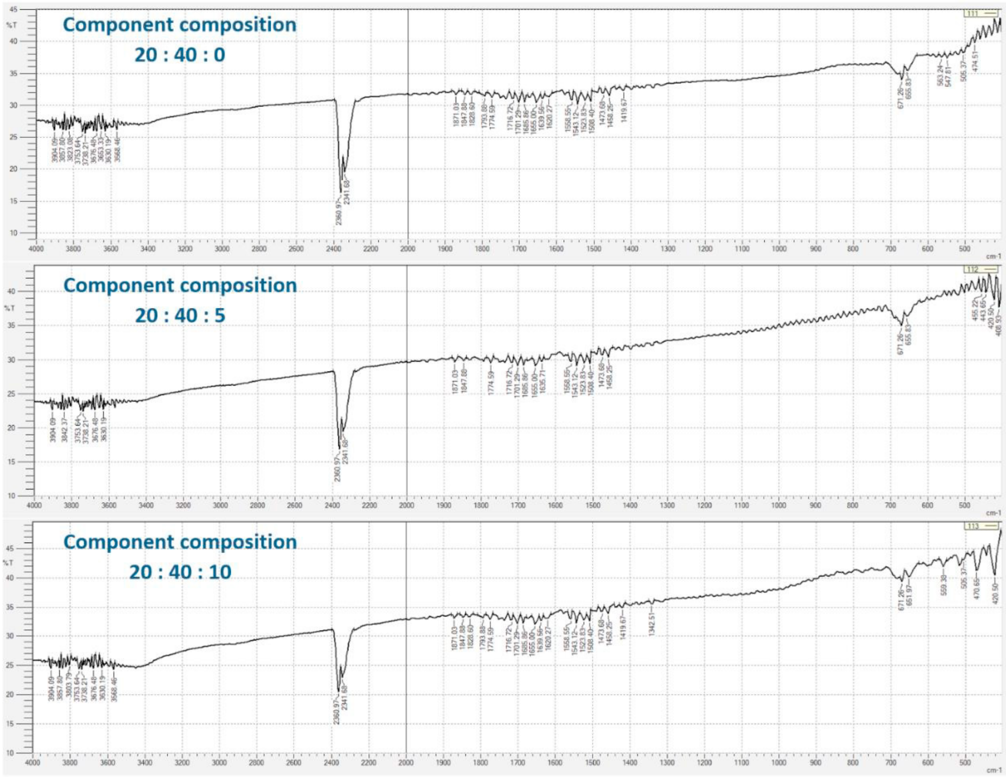
2. Mechanical compression tests did not show a significant change in the elastic characteristics (Young's modulus) in the modified material. At the same time, the yield strength of the modified foam decreases insignificantly. The relative plastic deformation increases.

3. Under multi-cycle loading, perlite-modified samples improve the fatigue resistance of rigid PU foam.

4. However, small cavities appear in the structure of the material. Their number increases with the amount of modifier in the material.

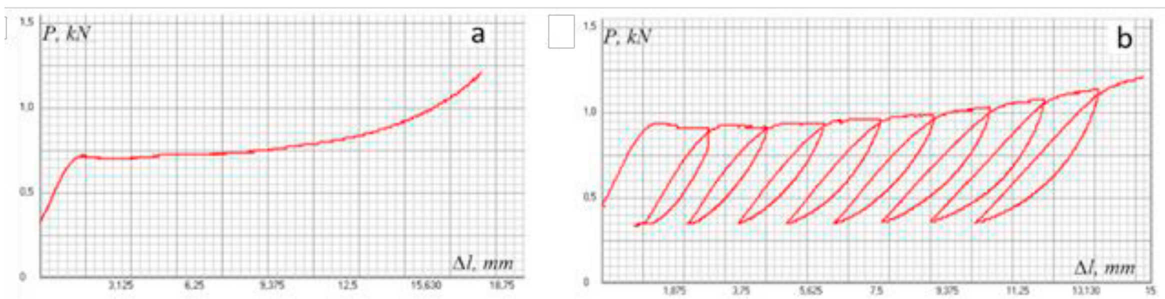
Therefore, the use of powder perlite to protect polyurethane foam from ultraviolet radiation is advisable. Further research will be aimed at studying the influence and interaction of these defects.

Appendix A. IR-spectra of polyurethane foam samples

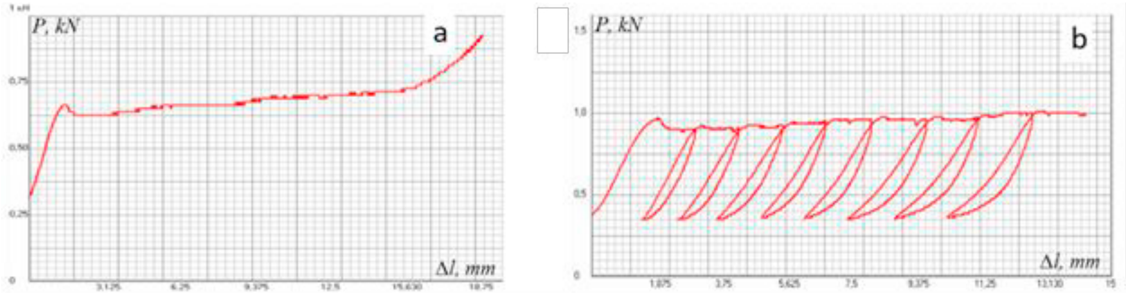


Appendix B. Compressive stress diagrams for single and multi-cycle loading for different groups of specimens

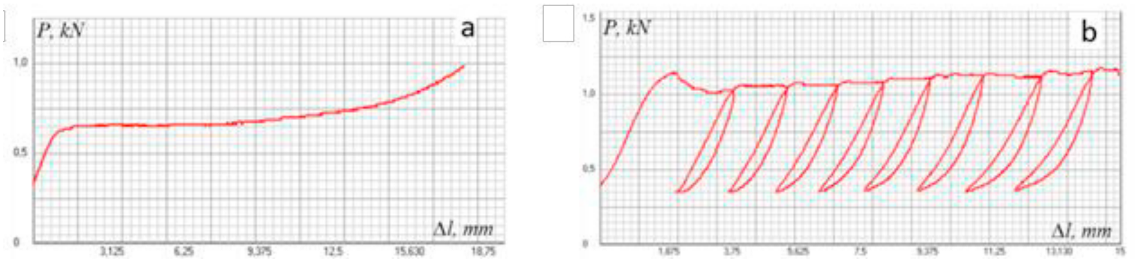
B.1. PU foam without modifier (20:40:0)



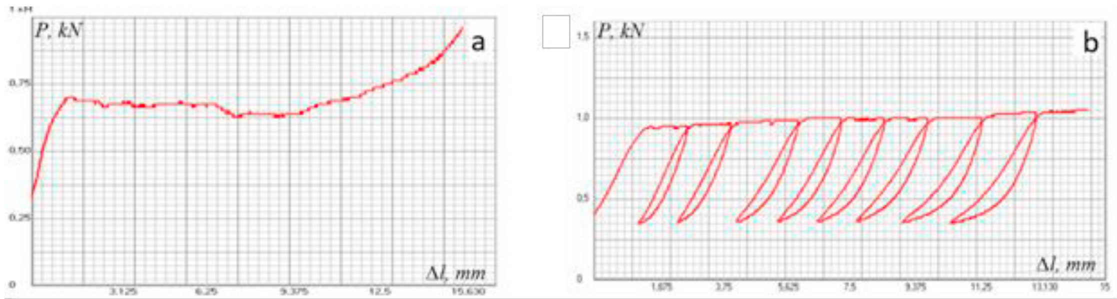
B.2. MPU foam with 3.7 mass part modifier (20:40:3.7)



B.3. MPU foam with 5 mass part modifier (20:40:5)



B.4. MPU foam with 10 mass part modifier (20:40:10)



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