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EFFECT OF DENSITY, ANISOTROPY AND TEMPERATURE ON DYNAMIC COMPRESSION BEHAVIOUR OF PUR FOAMS

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Abstract. Polyurethane (PUR) foam is ideally suited as packing materials or dampers for many safety applications because of its chemical and design versatility and excellent energy absorbing properties. For this purpose, this paper investigates the effect of density, material orientation (anisotropy) and temperature on the main mechanical properties of cellular materials such as rigid polyurethane (PUR) foams. The experimental tests were carried out on specimens in the form of cubes using four different densities (40, 80, 120 and 140 kg/m^3). The specimens were subjected to uniaxial dynamic compression with loading speed of 1.67 m/s, using different temperature (20, 60, 100°C). Significant differences in the behavior of the foam were observed depending on the density and testing conditions. Over the range of examined densities, the yield and plateau stresses as well as the Young modulus of the foam exhibited polynomial power-law dependencies with respect to density and have found that one of the most significant effects of mechanical properties in compression of rigid polyurethane foams is the density. In the process of absorbing impact energy, cell walls deform plastically and get damaged. After compression tests the foam shows a plastic collapse of cells, which increases the stress delivered to an almost constant strain (known as densification). In the moment of densification, due to the filling of the gaps in the foam, this one acts almost like a solid material.

Keywords: PUR foams, dynamic compression, density, anisotropy, temperature.

1. INTRODUCTION

Rigid polyurethane foams are widely used in engineering applications because they have certain properties that cannot be elicited from many homogeneous solids [1, 2]. Foams can be compressed to a relatively high strain under an approximately constant load [3–6]. This makes them very useful for impact absorption because they can dissipate significant kinetic energy while limiting the magnitude of the force transferred to more fragile components that they shield [7–9]. Hence, they are used in the packaging of electronic products and in car bumpers. The strength, stiffness

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and weight of foams depend on their density, which can be varied [10–13]. Hence, the properties of foams can be controlled, making them attractive in structural application requiring particular strength or stiffness to weight ratios [14–19].

Foam materials show a brittle fracture in tension [20–23], but crush in compression. Research on characterization of cellular materials under compressive loading conditions has been widely reported as in Refs [24–29]. The various properties and attributes investigated include energy absorption, density, cell structure, yield criteria, strain rate, energy efficiency. Avalle *et al.* [24] presented an optimization procedure in order to identify the micromechanical parameters from uniaxial compression test of different types of foams. The effect of the density and filler size was also investigated in [25]. Ramsteiner *et al.* [30] analyzed the parameters influencing the mechanical properties of foam. The following parameters were identified and studied: the structure of the foam, the matrix material of the foam, the density of the foam, cell orientation and testing temperature. Linul *et al.* [31] presented a comparison, of stress–strain response in compression, between experimental results and micromechanical modelling for PUR foams. The crush behaviour of Rohacell structural foam was investigated by Li *et al.* [32]. Tu *et al.* [33] presented the plastic deformations of PUR foam under static compressive loading and proposed a theoretical approach to describe the deformation localization.

The mechanical behaviour of rigid polyurethane foams under compressive loading is probably the primary property that distinguishes it from non-cellular solids. The use of foams in kinetic energy absorption and structural applications, whereby they are subjected to static and dynamic loading, motivates the need to study their mechanical properties [34].

2. EXPERIMENTAL PROCEDURE

For the characterization of mechanical behaviour on dynamic compression loading, rigid polyurethane foams used in the experimental program had the following densities: 40, 80, 120 and 140 kg/m^3. Fig. 1 presents a comparison of used specimens between the initial shape, undistorted (before loading) and the final shape, deformed (after loading).

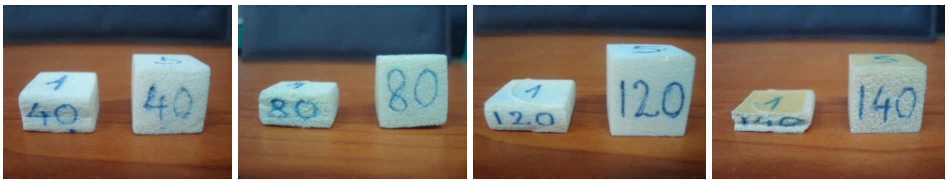

Fig. 1 – Specimens used in the experimental program.

The specimens were subjected to uniaxial dynamic compression with loading speed of 1.67 m/s, using different temperatures (20, 60, 100°C). For each test type five specimens were used. Experimental tests were made on the Strength of Materials Laboratory from Lublin University of Technology, Poland. Tests were carried on an Instron-Dynatup impact testing machine.

Mechanical behaviour of rigid PUR foams under compression tests was determined according to the ASTM D1621-00, Standard Test Method for Compressive Properties of Rigid Cellular Plastics [35].

3. RESULTS AND DISCUSSIONS

The present work presents a detailed study of the influence of density, material orientation (anisotropy) and temperature on the main mechanical properties of rigid PUR foams, subjected to dynamic compression loads. These parameters such as Young's modulus, yield stress, plateau stress and densification have a very important role in the real applications of these materials and due to this reason in the following it will be presented the foam behaviour under different loading and temperature conditions. From data provided by the test machine, were drawn the conventional characteristic curves for the tested specimens [1, 24]. Figure 2 shows a comparison of typical stress-strain curves for different densities of polyurethane foam (40, 80, 120 and 140 kg/m^3), subjected to dynamic compression. Presented curves were obtained from a perpendicular load to the forming plane (out-of-plane direction) at a temperature of 20°C.

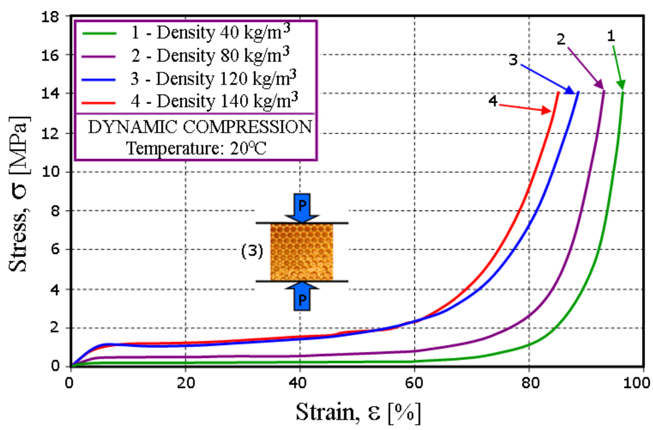

Fig. 2 – Typical stress-strain curves. Effect of density.

On the recorded stress-strain diagrams the following regions can be identified: the first part of the curve shows linear-elastic behaviour up to yield (up to a strain of 5% approximately), a small softening in stress after yield, a plateau after yield (between 10–50%), and in the end there is an increase in stress without a significant increases in strain, commonly known as densification (above 50% strain). Variations of mentioned mechanical properties with density for out of plane direction – direction (3) – are presented in Figs. 3–5.

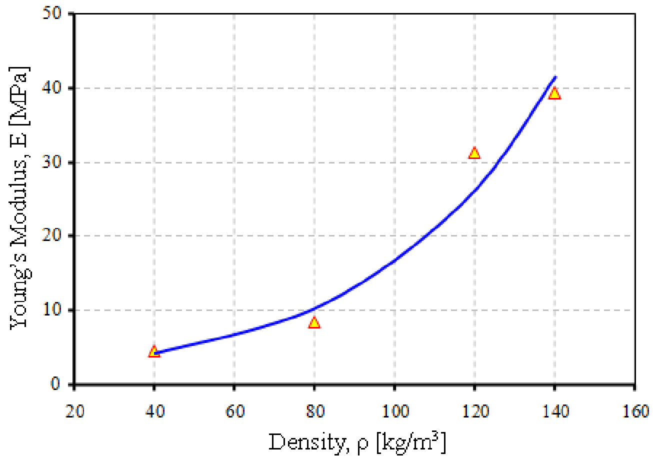

Fig. 3 – Young's modulus variation with density. Effect of density.

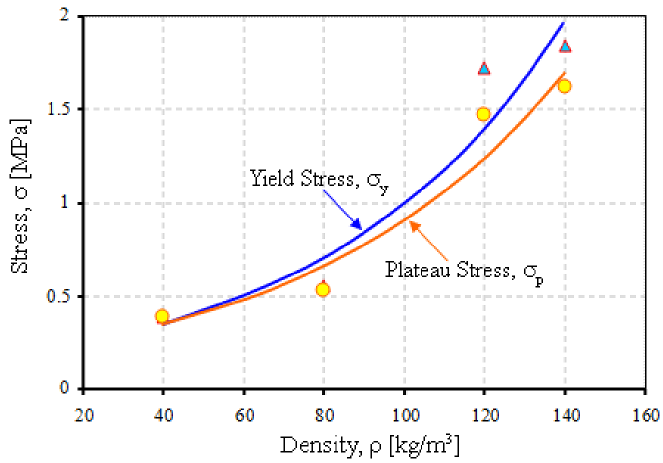

Fig. 4 – Yield and plateau stress variations with density. Effect of density.

All of these figures (Figs. 2–5) show a significant increase of mechanical characteristics with increasing of density, which means that the density has a major role in determining the mechanical properties in compression. The Young's modulus difference between the highest and lowest density foam is about 10 times, when yield stress and plateau stress increases about 4 times. On the other hand, as can be seen from Fig. 5 it was found that only densification decreases with increasing of foams density. In this case, densification decreases from a value of about 67% to a value of about 57%.

Foam anisotropy is a very important parameter of foam and should be considered for both in practical applications and in the modelling of the mechanical properties. Thus, choosing properly this parameter, we can obtain the desired characteristics for practical applications.

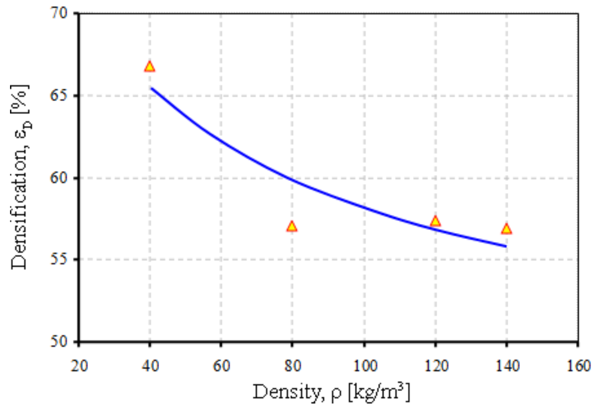

Fig. 5 – Densification variation with density.
Effect of density.

Figure 6 presents the influence of forming plane and loading direction on dynamic compression while in Fig. 7 is shown the sampling of the specimens from a rectangular plate, respectively the loading direction according to the formation plane of the foam. In this case was studied a foam with density of 140 kg/m^3 at room temperature.

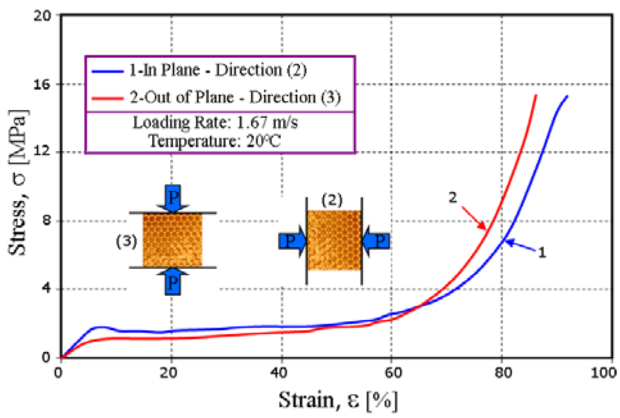

Fig. 6 – Typical stress-strain curves. Effect of forming plane.

For the in-plane loading direction a constant plateau was obtained, while for out-of-plane loading direction the plateau has a linear hardening for the same foam density (Fig. 6).

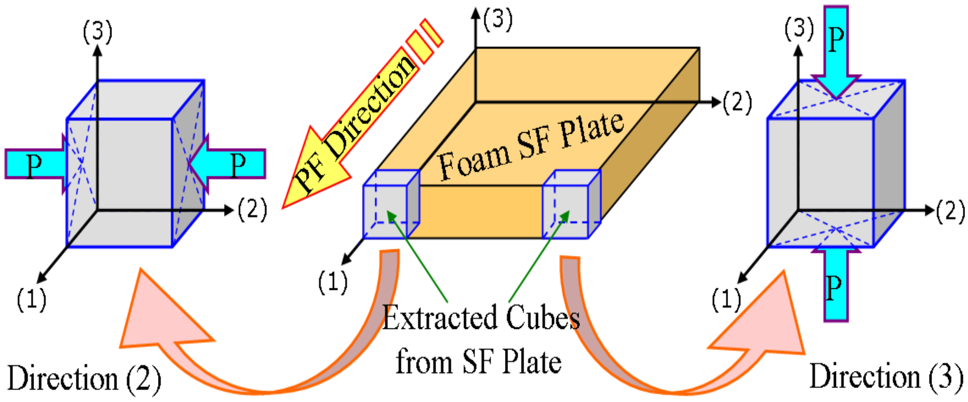

Fig. 7 – The sampling of the cube specimens
from a rectangular plate.

Variations of studied mechanical properties with density (four different densities) for out-of-plane direction – direction (3) and in-plane direction – direction (2) are presented in Figs. 8–11.

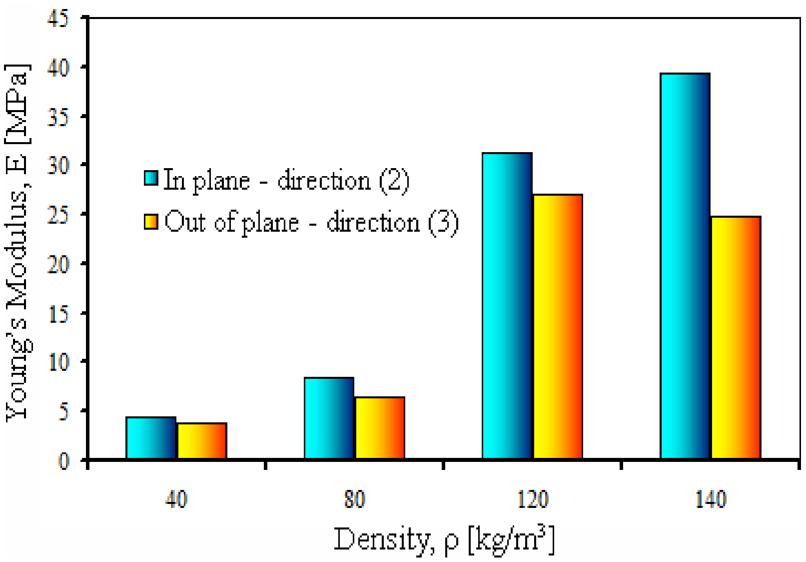

Fig. 8 – Young's modulus versus density.
Effect of forming plane.

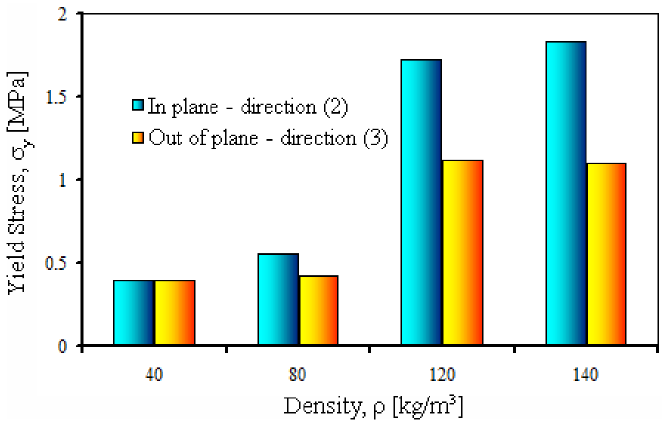

Fig. 9 – Yield stress versus density. Effect of forming plane.

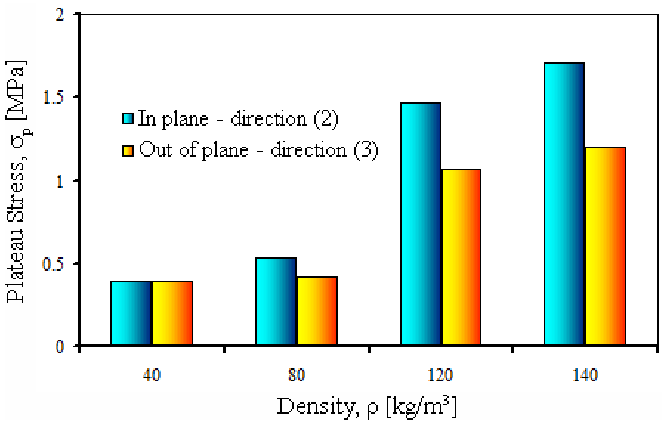

Fig. 10 – Plateau stress versus density. Effect of forming plane.

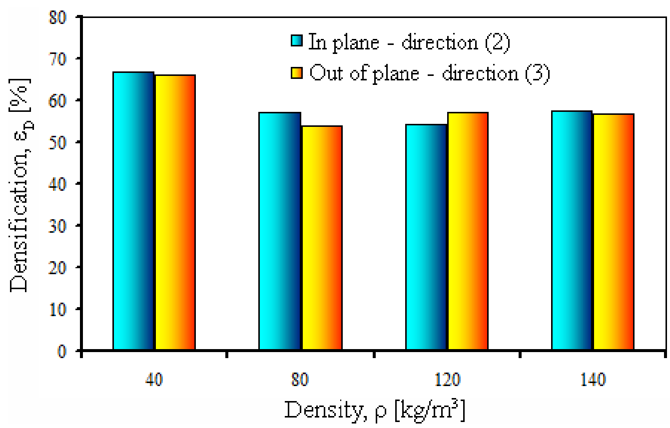

Fig. 11 – Densification versus density. Effect of forming plane.

Loading direction has a significant contribution to the compressive mechanical properties; this aspect highlights the anisotropic behaviour of foam. Anisotropy aspect is particularly strong for high-density foam (140 kg/m^3), while in the case of low-density foams (40 kg/m^3) is almost unobservable. In this case (for 140 kg/m^3), the material is highly anisotropic with a much higher in-plane than out-of-plane, as follows: the Young's modulus increases from 24.82 MPa to 39.43 MPa, the yield stress increases from 1.10 MPa to 1.83 MPa and plateau stress increases from 1.20 MPa to 1.71 MPa, while the densification remains the same (approximately 57%).

Considering both sudden temperature and different areas of use of these materials is important to carrying out a study of the effect of temperature on the mechanical behaviour. This study was performed for four different rigid PUR foams at three different temperatures: 20, 60 and 100°C and two loading directions (in-plane and out-of-plane). For this purpose and for easier understanding of the behaviour, Fig. 12 shows the effect of temperature on the stress-strain curves only for 140 kg/m^3 foam density (load has been applied in-plane).

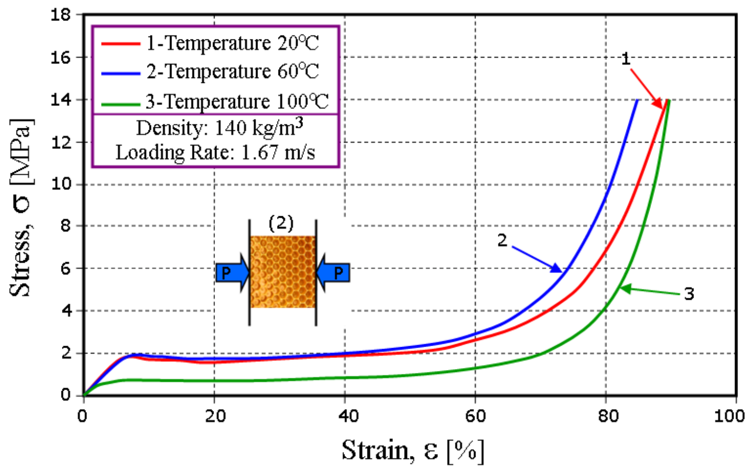

Fig. 12 – Typical stress-strain curves. Effect of temperature.

According to the results shown in Fig.12 it can be seen that at room temperature (20°C) and a temperature of 60°C the foam behaviour is approximately the same, while at higher temperatures (100°C), foam changes significant its properties. It should be noted that for polyurethane foams temperature of 100°C can be considered high because they have a melting temperature around 150°C.

4. CONCLUSIONS

The experimental study was carried out on four different density of rigid PUR foams (40, 80, 120 respectively 140 kg/m^3), and presents a comparison of the stress-strain response in dynamic compression. After the experimental investigations the following conclusions can be drawn:

- It can easily observed that with increasing of density we obtain a significant increase of mechanical properties, which means that the density has an important role in determining the dynamic compressive mechanical behaviour (Figs. 2–4).
- The loading direction has a major influence on the mechanical properties in dynamic conditions, clear evidence of anisotropic behaviour of foam. For the same foam density in-plane loading direction a constant plateau was obtained, while for out-of-plane load the plateau presents a linear hardening (Figs. 8–11).
- According to the results presented in Fig. 12, it can be observed that at lowest temperatures (20 and 60°C), the behaviour of foam is approximately the same, while at high temperature (100°C), foam shown a major change in their mechanical properties.
- In the process of absorbing impact energy, cell walls deform plastically and get damaged. After compression tests the foam shows a plastic collapse of cells, which increases the stress delivered to an almost constant strain (known as densification). In the moment of densification, due to the filling of the gaps in the foam, this one acts almost like a solid material.

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