Study of factors influencing the mechanical properties of polyurethane foams under dynamic compression

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Abstract. Effect of density, loading rate, material orientation and temperature on dynamic compression behavior of rigid polyurethane foams are investigated in this paper. These parameters have a very important role, taking into account that foams are used as packing materials or dampers which require high energy impact absorption. The experimental study was carried out on closed-cell rigid polyurethane (PUR) foam specimens of different densities (100, 160 respectively 300 kg/m³), having a cubic shape. The specimens were subjected to uniaxial dynamic compression with loading rate in range of 1.37 – 3.25 m/s, using four different temperatures (20, 60, 90, 110°C) and two loading planes (direction (3) – rise direction and direction (2) - in plane). Experimental results show that Young’s modulus, yield stress and plateau stress values increases with increasing density. One of the most significant effects of mechanical properties in dynamic compression of rigid PUR foams is the density, but also the loading speed, material orientation and temperature influences the behavior in compression.

1. Introduction

Cellular materials are being increasingly used in many applications because of their crashworthiness characteristics. Research on their behaviour under quasistatic and high strain rates is of value for engineering applications such as those related to impact absorption (sandwich panel, packaging of electronic products) [1]. Foams can be compressed to a relatively high strain under an approximately constant load.

Characterization of cellular materials under compressive loading conditions covering elastic properties, failure modes, constitutive modeling and other related issues associated with foams have been investigated by several researchers [1-6]. The behavior of a family of polymeric structural foams with various initial bulk densities (porosity levels) was experimentally investigated under quasistatic and high strain rate loading conditions by Subash et al. [1]. In this context, Gibson and Ashby [2] performed an extensive study of the research results on cellular solids with applications from packaging cushions to lightweight structures. The impact response of rigid PUR foams has been studied by Linul et al. [3] using different densities (40, 80, 120 and 200 kg/m³).

The dynamic compressive stress – strain behavior of a rigid polyurethane foam with four values of density (78, 154, 299, and 445 kg/m³) has been determined by Chen et al. [4] in the strain-rate range of 1000-5000 s⁻¹. Uniaxial strain impact experiments have been performed by Chahabildas [5] to obtain shock compression and release response of a 0.22 g/cm³ polyurethane foam in a configuration where...
the foam impacts a thin target witness plate. Compressive mechanical behavior of three common polymeric foams (expanded polystyrene, high-density polyethylene, and polyurethane) under quasi-static, medium and high strain rate conditions (ranging from 0.0087 to 2500/s), have been studied by Oullet et al. [6].

This study was motivated by a need to understand foam properties for energy-absorbing applications in different loading directions (direction (2) – in plane and direction (3) – rise direction) at high loading rates (up to 3.25 m/s), respectively high temperature (up to 110°C). The rise direction of foams is given by the used manufacturing process.

2. Mechanical testing in compression of rigid PUR Foams

Experimental tests were performed in the Strength of Materials Laboratory at Lublin University of Technology, Poland. Compressions tests were carried on with a 40 KN Instron – Dynatup impact testing machine shown in figure 1.

![Figure 1. 40 KN Dynamic Instron – Dynatup testing machine](image)

The specimens were subjected to uniaxial dynamic compression with maximum loading rate up to 3.25 m/s. An environmental chamber was used for tests at high temperature (up to 110°C). For tests performed at higher temperatures than room temperature, the samples were placed in the environmental chamber for 30 min before the test, to ensure thermal equilibrium [7].

The tests were performed following the ASTM D1621-00 standard [8] using cubic specimens (15 mm x 15 mm x 15 mm) sown in figure 2a. Also in the same figure are shown fully densified state for the same 3.09 m/s loading rate (for each density). Different densities of PUR foams (100, 160 and 300 kg/m³) were used in this investigation for the characterization of mechanical behavior on dynamic compression. The relative densities were 0.085, 0.137 and 0.256, respectively. Samples were cut from a semi-finished plate using a pendulum saw, and then cut to the desired length using a Proxxon DS 230/E cut machine to avoid deformation of the specimen during cutting. Special care was taken when cutting samples to ensure that the specimen’s end surfaces were parallel [6].

For each testing case (density, temperature, speed and forming plane), five samples were tested.
Figure 2. a) Photographs of the as-received PUR foams specimens; (b) Micrographs of the interior pore structure of the specimens

Figure 2b shows the corresponding pore structures in the interior sections of the specimens at the 1000x magnification. An examination of the microstructure (figure 2b) indicates that the foam has a typical closed-cell structure [4, 9]. It is seen that the low-density (100 and 160 kg/m³), foams exhibit a wide variation in pore size and shape (wall thickness in range 3-18 μm), whereas the high-density (300 kg/m³), foam exhibit smaller uniform sized pores separated by large amount of solid polymer (wall thickness in range 8-48 μm). The measured porosity for each family of foams is also indicated in figure 2a [1].

3. Results and discussions
Conventional force–displacement data was obtained from the impact tests and converted to stress–strain data using the sample dimensions. A comparison of typical stress-strain curves for three different densities of rigid PUR foams (100, 160 and 300 kg/m³), subjected to dynamic compression are shown in figure 3. This data was obtained with 3.09 m/s loading rate from direction (3) – rise direction at room-temperature (20°C).

Figure 3. Stress-strain curves. Influence of density

Figure 4. Stress-strain curves. Influence of forming plane
In figure 3 it can be seen easily an increase of mechanical properties with density, which means the density has a major influence in dynamic compression of cellular materials.

Figure 4 presents the influence of loading direction on forming plane, at room temperature and 3.09 m/s loading rate. For the tested compression specimens, the rise direction of the foam was noted as direction (3) and in-plane directions as direction (2).

From stress-strain curves, the basic properties of foams in compression were determined such as Young’s Modulus, Yield Stress, Plateau Stress and Densification. Mean values of these properties for both loading directions: direction (2) and direction (3), depending on density at 3.09 m/s loading rate are presented in table 1.

| Density [kg/m^3] | Loading direction | Young’s Modulus [MPa] | Yield Stress [MPa] | Plateau Stress [MPa] | Densification [%] |
|------------------|-------------------|-----------------------|--------------------|----------------------|------------------|
| 100 (Foam A)     | (2)               | 26.06                 | 1.52               | 1.18                 | 54.15            |
|                  | (3)               | 32.69                 | 1.59               | 1.17                 | 53.98            |
| 160 (Foam B)     | (2)               | 39.13                 | 2.29               | 1.91                 | 49.58            |
|                  | (3)               | 58.85                 | 2.58               | 1.91                 | 56.20            |
| 300 (Foam C)     | (2)               | 139.26                | 7.21               | 5.55                 | 61.83            |
|                  | (3)               | 152.05                | 7.80               | 6.02                 | 59.57            |

The results obtained with a load in the rise direction of the foam presents a small increase compared with those obtained in – plane loading direction.

For the same density, loading direction (rise direction) and temperature (20 °C) yield stress, plateau stress and densification remain approximately constant while a decrease in Young’s Modulus with the increase in loading rate was observed (except for the first two small loading rates where results are not conclusive). Mean values of mechanical properties on dynamic compression for rise direction of foam depending on density and loading rate are listed in table 2.

| Density [kg/m^3] | Loading rate [m/s] | Young’s Modulus [MPa] | Yield Stress [MPa] | Plateau Stress [MPa] | Densification [%] |
|------------------|-------------------|-----------------------|--------------------|----------------------|------------------|
| 100 (Foam A)     | 1.37              | 39.91                 | 1.58               | 1.16                 | 53.95            |
|                  | 1.94              | 30.08                 | 1.51               | 1.15                 | 54.88            |
|                  | 2.39              | 37.55                 | 1.58               | 1.15                 | 54.31            |
|                  | 2.77              | 35.95                 | 1.42               | 1.15                 | 54.44            |
|                  | 3.09              | 32.69                 | 1.59               | 1.17                 | 53.98            |
|                  | 3.25              | 30.16                 | 1.59               | 1.17                 | 57.65            |
| 160 (Foam B)     | 1.37              | 61.84                 | 2.51               | 1.97                 | 55.90            |
|                  | 1.94              | 66.57                 | 2.61               | 1.92                 | 57.97            |
|                  | 2.39              | 65.22                 | 2.57               | 1.74                 | 55.10            |
|                  | 2.77              | 63.13                 | 2.55               | 1.93                 | 55.49            |
|                  | 3.09              | 58.85                 | 2.58               | 1.91                 | 56.20            |
|                  | 3.25              | 56.17                 | 2.48               | 1.90                 | 54.96            |
| 300 (Foam C)     | 1.37              | 166.54                | 7.52               | 6.29                 | 58.32            |
|                  | 1.94              | 190.38                | 8.13               | 7.14                 | 57.98            |
|                  | 2.39              | 163.85                | 7.55               | 6.46                 | 59.18            |
|                  | 2.77              | 157.33                | 7.50               | 6.55                 | 57.14            |
|                  | 3.09              | 152.05                | 7.80               | 6.02                 | 59.57            |
|                  | 3.25              | 136.61                | 7.04               | 5.58                 | 60.59            |
The effects of temperature (20, 60, 90 and 110°C) on stress-strain curves for 300 kg/m³ foam density at 2.77 m/s loading rate are shown in figure 5. Load was applied in the rise direction of foam.

![Stress-strain curves](image)

**Figure 5.** Stress-strain curves. Influence of temperature.

In table 3 are shown mean values of mechanical properties on dynamic compression depending on temperature for a load applied according to the rise direction of foam.

| Density [kg/m³] | Temperature [°C] | Young’s Modulus [MPa] | Yield Stress [MPa] | Plateau Stress [MPa] | Densification [%] |
|----------------|------------------|------------------------|--------------------|----------------------|-------------------|
| 100 (Foam A)   | 20               | 35.95                  | 1.42               | 1.15                 | 54.44             |
|                | 60               | 18.48                  | 0.85               | 0.73                 | 53.88             |
|                | 90               | 8.50                   | 0.68               | 0.60                 | 53.00             |
|                | 110              | 5.36                   | 0.54               | 0.44                 | 52.16             |
| 160 (Foam B)   | 20               | 63.13                  | 2.55               | 1.93                 | 55.49             |
|                | 60               | 49.11                  | 2.23               | 1.69                 | 54.20             |
|                | 90               | 32.55                  | 1.69               | 1.28                 | 52.89             |
|                | 110              | 24.82                  | 1.28               | 1.06                 | 52.00             |
| 300 (Foam C)   | 20               | 157.33                 | 7.50               | 6.55                 | 57.14             |
|                | 60               | 108.86                 | 5.48               | 4.40                 | 54.86             |
|                | 90               | 56.35                  | 3.11               | 2.67                 | 53.99             |
|                | 110              | 38.97                  | 1.62               | 1.52                 | 52.01             |

According to the results presented in figure 5 and table 3 we observed that the mechanical properties significantly decrease with the increase of temperature. After compression tests the foam shows a total destruction 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 [3].

**4. Conclusions**

This paper presents an investigation of few parameters like effect of density, loading rate, material orientation and temperature on dynamic compression behaviour of rigid polyurethane foams. Compression tests were made for three different densities of closed-cell PUR foams (100, 160 and 300 kg/m³). After dynamic compression tests the following conclusions can be drawn:
From typical stress-strain curves the basic properties of foam were determined such as Young’s Modulus, Yield Stress, Plateau Stress and Densification. These parameters have a very important role, taking into account that foams are used as packing materials or dampers which require high energy impact absorption.

Also, from the analysis of results presented in figure 3 and table 1 it can be seen that with increasing of density we obtain a significant increase of the mechanical properties of foam. For example Young’s Modulus is approximately 5 times higher for ‘Foam C’ than for ‘Foam A’ for the same loading rate, material orientation and temperature conditions.

It was also found that for the same density, loading direction (rise direction) and temperature (20 °C) the Young’s Modulus decrease with increasing of loading rate while Yield Stress, Plateau Stress and Densification remain approximately constant, (see table 2).

The results obtained with a load in the rise direction of the foam show a small increase compared with those obtained in-plane loading direction, (see figure 4 and table 1).

According to the results presented in figure 5 and table 3 we observed that the mechanical properties significantly decrease with increases of temperature. For example Young’s Modulus for ‘Foam C’ is approximately 7 times lower at 110°C than 20°C for the same material orientation and loading rate conditions.

As the final conclusion we can say that one of the most significant parameter on mechanical properties in dynamic compression of rigid PUR foams is the foam density, but also we must consider the temperature, loading rate and material orientation.

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