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Influence of Temperature and Speed of Testing on the Compression Behaviour of Polyurethane Foams

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Abstract

Polyurethane foams with densities of 35, 93, and 200 kg/m^3 were tested in compression at three levels of temperatures as: -60 ℃, 23 ℃, and 80 ℃. The influence of speed of testing from 2 mm/min up to 6 m/s (0.0014 to 545 s^{-1}) on the response of the foams is analyzed. Testing is done separately on the rise direction and on the in-plane direction of the foams and differences in their behaviour are commented. With interpolation functions which approximate the plateau and densification region the specific strain energy is calculated together with the energy efficiency and onset strain of densification.

Key words: *polyurethane foams, mechanical behaviour, speed of testing, temperature, strain energy, energy efficiency*

Behaviour Characterization of Polyurethane Foams

Foam materials have a cellular structure and hence behave in a complex manner, especially under conditions of progressive crush. This crush behaviour is dependent on the geometry of the microstructure and on the characteristics of the parent material. Foam materials are often used as cores in sandwich construction, and in this application the material can be subjected to multi-axial stresses prior to and during crush. Well-known advantages of cellular metals are their excellent ability for energy adsorption, good damping behaviour, sound absorption, excellent heat insulation and a high specific stiffness combined with a low weight. The combination of these properties opens a wide field of potential applications, i.e. as core materials in sandwich panels. A good knowledge of the behaviour of different grades of foams is important for being able to design high performance sandwich composites adapted to the special needs of a particular application (Gibson and Ashby [1], Mills [2]).

Polyurethane (PU) foam is an engineering material for energy absorption and has been widely used in many applications such as packaging and cushioning. The mechanical testing of rigid PU foams under compression in the rise and transverse direction gives different deformation responses in each direction which are attributed to the anisotropy in the internal cellular structure.

Complex modelling approaches based on finite element method try to describe as finely as possible the foam microstructure. The continuum approach has been well proven, and can be used with standard finite element codes, being computationally efficient for modelling the progressive crush of foam. However, the approach assumes smooth stress gradients in the material, which implies that the foam consists of strain-hardening cells.

Strain rate and temperature effects on the crush behaviour of foams were studied by Li et al. [3]. Following, Mines [4] studies strain rate effects on Divinycell PVC foam, Rohacell PMI foam and Alporas aluminium foam. His impact tests used standard static test rigs, with the higher rate of loading being achieved using a high rate servo hydraulic machine which can achieve crosshead speeds of up to 10 m/s. As he mentions in the conclusions: "The conduct of impact materials tests requires careful design and data analysis, in order to filter out inertial and structural effects and hence to measure true material properties". Such a statement has to be considered.

Saint-Michel et al. [5] have evaluated the mechanical properties of studied foams in a quite wide relative density range (from 0.3 to 0.85) and present the microstructural characterization and the mechanical behaviour of such materials. The modelling is then extended to the description of the mechanical behaviour in the non-linear domain. Viot et al. [6] carried out tests on polypropylene foams under high strain rate compression tests on a flywheel for higher strain rates and the material behaviour has been determined as a function of two parameters, density and strain rate. The sample compression was filmed with a high speed camera monitored by the flywheel software as to obtain displacement and strain fields during tests. To complete our brief overview we have to mention that Gong et al. [7] and Gong and Kyriakides [8] have performed more thorough research on understanding the responses of open cell foams to uniaxial compression in the rise and transverse directions. They also characterized the cell and ligament morphology of PU foams with various cell sizes and experimentally studied the mechanical properties of these foams. The nonlinear aspects of the compressive response and crushing of open cell foams were also studied based on this anisotropic cell model.

We initially started testing different grades of foams as: PVC foam, Coremat, extruded polystyrene, polyurethane foam with density 200 kg/m^3, polyurethane foam with density 40 kg/m^3, expanded polystyrene Marsavina et al. [9], and Apostol and Constantinescu [10]. Initially we tested the Coremat core in traction, and polyurethane foams with densities of 40 kg/m^3 and 200 kg/m^3 in traction, compression, and three-point bending. For the bending of the 200 kg/m^3 foam we have also impregnated it with polyester and epoxy resins on the upper and lower faces of the specimens and studied the influence of such a layer on the behaviour of the foam.

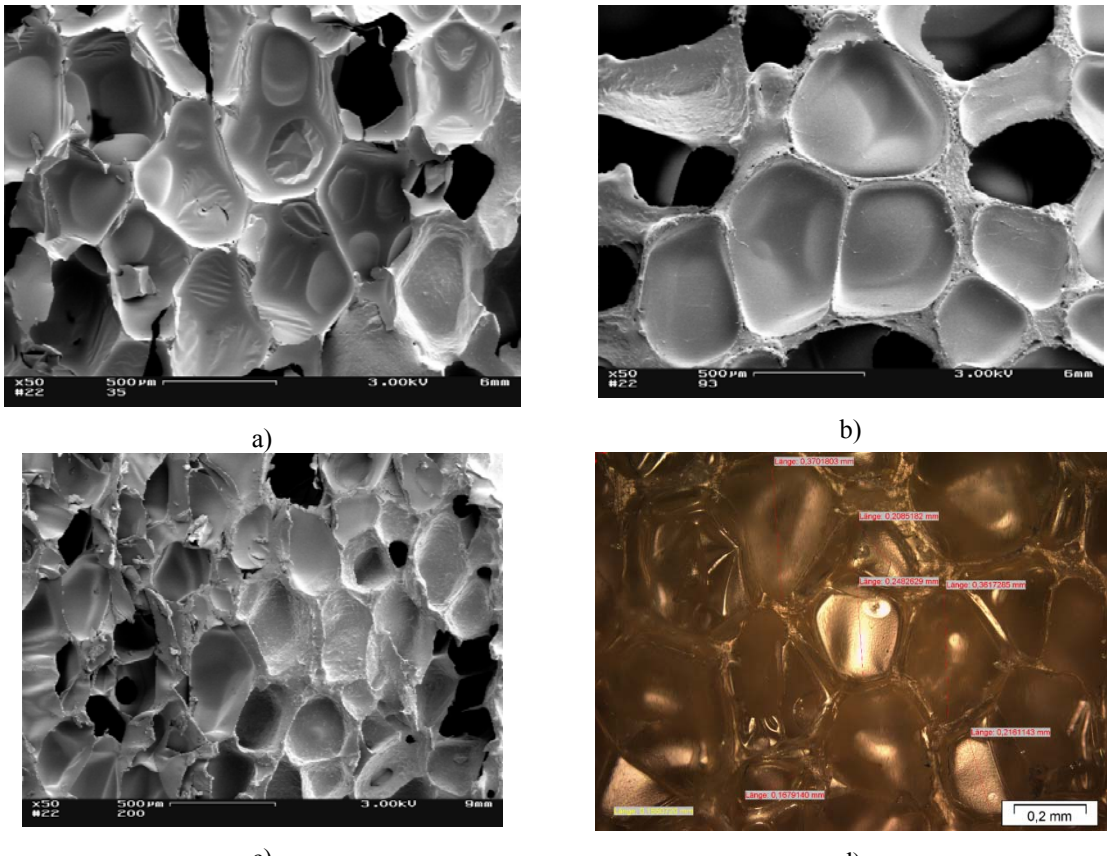
Present research concentrates on the mechanical testing of three densities of polyurethane foams of 35 kg/m^3, 93 kg/m^3 and 200 kg/m^3. It is studied the influence of the speed of loading from 2 mm/min up to 6 m/s and of the temperature at three levels which are considered as: -60 °C, 23 °C and 80 °C. The mechanical testing presented here is dedicated to the compressive response of these foams as to study their densification behaviour on one hand, and the recovery of the foams after unloading on the other hand. In these tests initial strain rates started from a value of 0.0014 s^{-1} to a maximum value of 545 s^{-1}. Specimens were tested in the *rise direction* (notated as *direction 3*) of the foam and in one *in-plane direction (direction 1)*. Other important results were obtained by studying the influence of the temperatures which are encountered in engineering applications.

The engineering stress-strain curves can be interpolated by polynomial functions on the linear and yielding regions till the beginning of the plateau region, and with exponential functions on the plateau and densification regions. The energy absorption efficiency concept is used to determine the onset strain of densification.

Mechanical Testing in Compression of the PU Foams

Microstructural evaluation of foam morphology

The PU foams cells morphology and dimensions for the three densities were studied before testing through optical microscopy (OM) and scanning electron microscopy (SEM). An Olympus optical microscope, model BX 51, having a maximum magnification factor of 200, made possible the measurement of the cells dimensions (length, width, and cell wall thickness). For the SEM analyses the specimens were covered with a very thin layer of gold (as foam is non-conductive from electrical point of view) and kept in vacuum for 14 hours. Some of the already damaged cells were destroyed during vacuuming and several empty cells were noticed. In Figure 1,a) a SEM image of the foam with the density of 35 kg/m^3 the closed cells have many "wrinkles", damaged areas, microcracks. The cells are having the maximum length of 683 μm and the minimum length of 130 μm, respectively wall thickness is in between 22.4 and 30 μm. When the density is 93 kg/m^3 (fig. 1,b)) cells sizes are becoming almost equal on the main directions being in between 541 μm and 180 μm, having a wall thickness quite similar to the previous foam, from 19 μm to 35.4 μm. Cells surface has a neat aspect. Finally, for the 200 kg/m^3 density foam (figs. 1, c) and d)) main sizes of the cells are in the interval 472 μm to 110 μm and wall thickness in between 20.7 and 35 μm.



a) b) c) d)

Fig. 1. SEM images of the cell morphology for the PU foams with densities: a) 35 kg/m^3; b) 93 kg/m^3; c) 200 kg/m^3; d) OM image for 200 kg/m^3

To summarize, the wall thickness is in average of 26-27 μm for all the three densities and maximum cells length decreases from 683 μm for 35 kg/m^3, to 541 μm for 93 kg/m^3, and to 472

μm for 200 kg/m^3. A more evident elongation of the cells on the rise direction is noticed for the cells with densities of 35 kg/m^3 and 200 kg/m^3.

Description of the experimental testing

Compressions tests were done on a hydraulic MTS testing machine specially conceived for testing polymers by Apostol [11]. Maximum testing speed is 6 m/s and our testing speeds started from 2 mm/min going up to 40000 mm/min (2, 6, 18, 54, 125, 200, 350, 500, 1000, 2000, 3500, 6000, 10000, 20000, 30000, 40000 mm/min) and then 1, 3, and 6 m/s. Foams of densities 35 and 93 kg/m^3 foams were produced by a Romanian company and the 200 kg/m^3 foam is Divinycell H 200, produced by DIAB. As the specimens were cut from PU plates of given thickness the approximate specimens dimensions, with the height being the last of the three dimensions, were: 25x25x24 mm for 35 kg/m^3, 15x15x11 mm for 93 kg/m^3, 12x12x11.9 mm for 200 kg/m^3 (fig. 2). Therefore the initial strain rate started from a value as low as 0.00139 s^{-1} to a maximum value of 545.45 s^{-1}. For the tested compression specimens the *rise direction* of the foam was notated as *direction 3* and *one of the in-plane directions* as *direction 1*; some preliminary tests showed that on both the in-plane directions practically the same values of the mechanical properties were obtained. The solid density (both for rigid and flexible PU foams) is reported by Gibson and Ashby as being 1200 kg/m^3. Therefore, for the three foams the relative density is approximately: 0.03, 0.08, and 0.17.

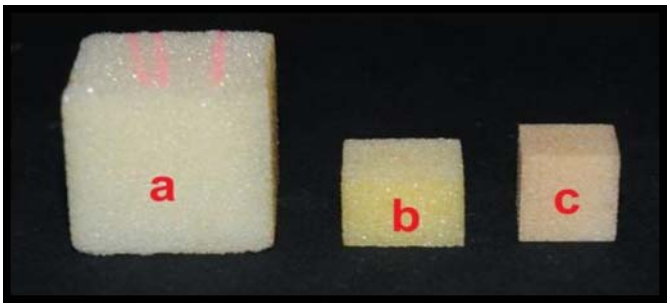


Fig. 2. Specimens of density: a) 35 kg/m^3 b) 93 kg/m^3 c) 200 kg/m^3

For the testing we used a specially designed MTS Composite testing machine, capable of reaching 8 m/s with the help of a three stage valve, valve that is being used for speeds higher than 0.7 m/s. This machine is also equipped with a piezoelectric quartz-crystal load cell washer. In our tests we haven't exceeded 6 m/s for safety reasons, due to the small height of our specimens. The machine is controlled by creating a command line program that carries on the task required for testing. The acquisition has been done by using a fast measurement buffer of 1024 values at a rate of 35 kHz for the beginning of the test and by using the highest possible acquisition rate provided by the machine in a normal manner at 5 kHz till the end of the test. In order to be sure of the generated results, a comparison has been done by using a SIGMA oscilloscope manufactured by Nicolet Technologies capable of measurements up to 500 kHz. By using the piezoelectric load cell washer together with the oscilloscope the obtained data have been compared to the data obtained by using only the machine, and latter on we took the decision to use only the results provided by the testing machine as they proved to be correct. On the other hand this method is simpler, and by using the crosshead movement to measure displacement and calculate strain, the conventional characteristic curve is generated.

For each testing case (density, temperature, speed) five specimens were tested and the representative one was selected; if a test gave suspicious results it was disregarded. The volume of obtained data is significant and only few of them are presented hereby.

Specimens are compressed up to when specimen height becomes 1.5-2 mm (maximum strain reaching a little bit more than 90 %) and data were recorded with specific frequency of data acquisition depending on the loading speed as to obtain a convenient volume of data, not in excess; for the recovery of the foams the same speed of unloading was chosen as 0.6 mm/min, always sampling data at the same frequency of 0.5 Hz which was found to be sufficient for all loading speeds at the three temperatures of testing regardless the speed of testing and density. Foam recovery strain values are established having as a reference the moment when unloading starts and in the following figures is named *recovered strain*.

Only as an example, in Figure 3 are shown the experimentally obtained engineering stress-strain curves obtained on direction 3 for all the 19 speeds of testing for the 200 kg/m^3 density foam, at 23 °C. As initial strain rate is increased the curves are shifting upwards having a bigger difference between the upper and lower yielding (crush) stress. The *plateau stress* is defined hereby the stress where the plateau region starts; this stress corresponds to a strain of 10%; in some cases, for higher speeds of loading – due to inertial oscillations, a difference of ±2% was considered. A slight hardening is noticed till the onset of densification for this case. At higher testing speeds the measurement of foam deformation during dynamic crush is not a simple task as inertial effects are present. Care has to be exercised in filtering out unwanted oscillations. Even so, for higher testing speeds, especially at 3 and 6 m/s foam deformations are showing important variations, becoming greater for the lower temperature.

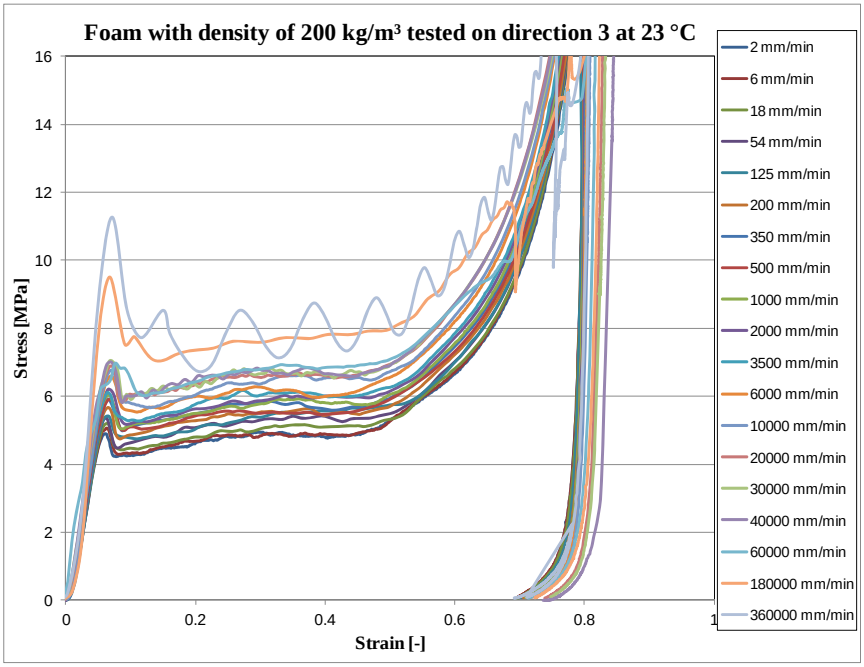


Fig. 3. Compression engineering stress-strain curves obtained experimentally at 23 °C (200 kg/m^3)

In Figures 4 and 5 are presented only for 9 selected speeds the stress-strain curves at -60 °C obtained on direction 1 and on direction 3. On direction 1 (fig. 4) yielding shows some hardening and is produced in between 7-9 MPa, and on direction 3 the plateau is in between 9-12 MPa. On direction 3 at -60 °C (fig. 5) the foam behaves in a more "fragile" manner as the walls of the cells break suddenly, especially when speed of testing is increased – the curves show, as seen, many fluctuations. Also the differences in between upper and lower yielding limits are greater on direction 3 than on direction 1 for this density and temperature of testing.

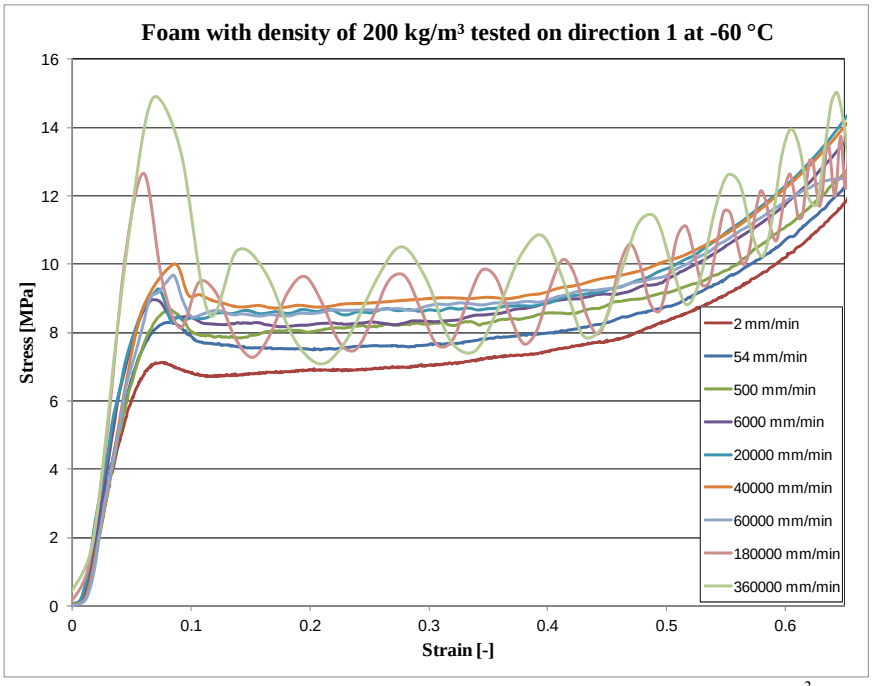


Fig. 4. Selected stress-strain curves on direction 1 at -60 °C (200 kg/m^3)

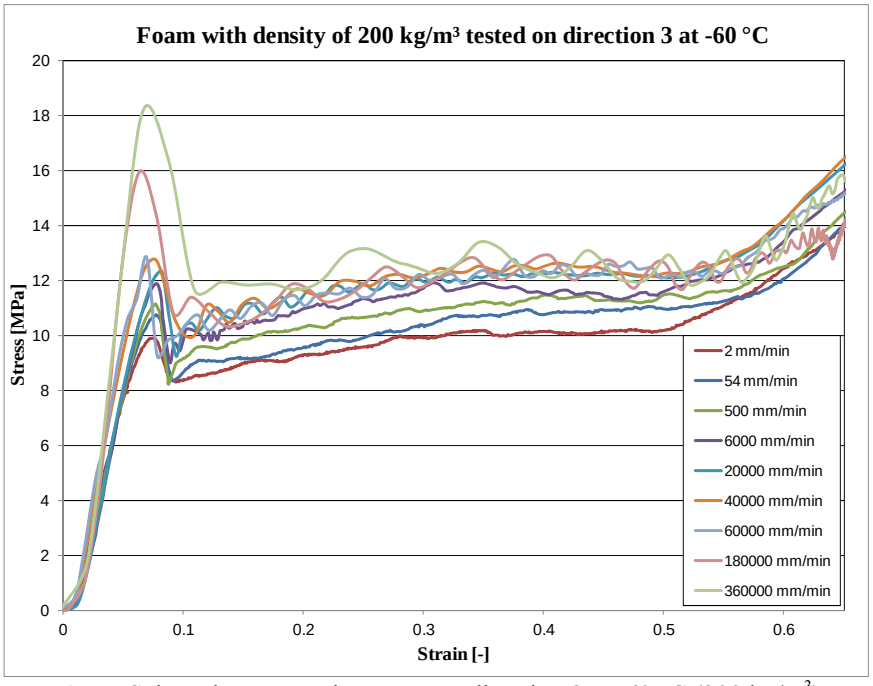


Fig. 5. Selected stress-strain curves on direction 3 at -60 °C (200 kg/m^3)

Reconstruction of stress-strain curves by numerical interpolation

The numerical interpolation of our experimental data uses a fifth degree polynomial function in the elastic region and at the beginning of the plateau region where appears sometimes a significant difference between the upper and the lower yield limit as follows

$$\sigma(\varepsilon) = C_0\,\varepsilon + C_1\,\varepsilon^2 + C_2\,\varepsilon^3 + C_3\,\varepsilon^4 + C_4\,\varepsilon^5 + C_5\,\varepsilon^6 \tag{1}$$

where C_0, C_1, C_2, C_3, C_4 and C_5 are constants to be established for each particular test.

In the plateau and densification regions the function which approximates the characteristic curve is of the form:

$$\sigma(\varepsilon) = \sigma_p + A_1 e^{\frac{\varepsilon}{t_1}} + A_2 e^{\frac{\varepsilon}{t_2}} , \tag{2}$$

where σ_p is the stress at the beginning of the plateau region, and A_1, A_2, t_1 and t_2 are parameters to be established for each test. These ones include the effects of density and strain rate.

Li et al. [12] have shown that the method based on the energy absorption efficiency curve gives unique and consistent results and makes possible the establishing of a representative strain at the onset of densification. The specific strain energy can be calculated by using relation (2) as

$$W = \int_{\varepsilon_p}^{\varepsilon} \left(\sigma_p + A_1 e^{-\frac{\varepsilon}{t_1}} + A_2 e^{-\frac{\varepsilon}{t_2}} \right) d\varepsilon \tag{3}$$

The energy absorption efficiency is defined by

$$E(\varepsilon) = \frac{1}{\sigma(\varepsilon)} \cdot W \tag{4}$$

Just to suggest the calculus which has been done for all three densities of foams at the three testing temperatures over the domain of crosshead speeds, in Tables 1 and 2 are given the constants and parameters established from the experimental data and by using relations (1) and (2) for the foam of density 200 kg/m^3 on directions 1, at the temperature of 23 °C.

Table 1. Coefficients of the polynomial function for the foam of density 200 kg/m^3 tested on direction 1 (23 °C)

Speed [mm/min]	2	54	500	6000	20000	40000	60000	180000	360000
C_0	-0.014	-0.0399	0.0473	0.04699	0.0886	0.09886	0.17747	-0.847	-0.035
C_1	5.0933	6.11452	43.548	43.7971	33.1756	34.1228	87.2520	211.64	159.17
C_2	3459.4	5131.50	2315.4	3449.8	4452.2	4212.1	551.7	-2457	-678
C_3	-51206	-110677	-41693	-78054	-108541	-91383	-19870	13258	-8819
C_4	-3072	736407	103463	537455	925355	624527	145246	-32394	77879
C_5E+05	21.2	-9.78	7.58	-10.5	-27.7	-12.2	-3.49	0.261	-1.65

Table 2. Parameters of the exponential function for the foam of density 200 kg/m^3 tested on direction 1 (23 °C)

Speed [mm/min]	2	54	500	6000	20000	40000	60000	180000	360000
σ_p	3.113	3.536	3.59948	4.0231	4.31821	4.4744	5.67512	5.10927	5.5807
A_1	1.24E-02	1.40E-03	1.26E-02	1.32E-04	0.00397	0.0022	0.00759	6.52E-16	0.0307
t_1	-0.12	-0.093	-0.1162	-0.0721	-0.1038	-0.0956	-0.1203	-0.0233	-0.1536
A_2	3.27E-10	1.40E-03	6.66E-10	2.28E-02	3.97E-03	2.20E-03	7.59E-03	1.34E-01	3.07E-02
t_2	-0.03	-0.093	-0.0355	-0.1322	-0.1038	-0.0956	-0.1203	-0.1806	-0.1536

Such an approach is particularly useful when experimental stress-strain curves are available and a correct calculation of the absorbed specific strain energy, together with the energy absorption efficiency and onset strain of densification are needed.

Acknowledgements

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References

1. Gibson L.G., Ashby M. F. – *Cellular Solids, 2nd ed.,* Cambridge University Press, Cambridge, 1997.
2. Mills N.J. – *Polymer Foams Handbook*, Butterworth-Heinemann, 2007.
3. Li, Q.M., Mines, R.A.W., Birch, R.S. – Combined strain rate and temperature effects on compression strength of Rohacell 51WF structural foam, *3rd Asia Pacific Conference on Shock and Impact Loads on Structures* (eds. T.S. Lok and C.H. Lim), pp. 221-226, 1999.
4. Mines, R.A.W. – Strain rate effects in crushable structural foams, *Appl. Mech. Mat.*, **7-8**, pp. 231-236, 2007.
5. Saint-Michel, F., Chazeau, L., Cavaille, J.-Y., Chabert, E. – Mechanical properties of high density polyurethane foams: I. Effect of the density, *Compos. Sci. Tech.*, **66**, pp. 2700–2708, 2006.
6. Viot, P., Beani, F., Lataillade, J.-L. – Polymeric foam behavior under dynamic compressive loading, *J. Mat. Sci.*, **40**, pp. 5829–5837, 2005.
7. Gong, L., Kyriakides, S., Jang, W.Y. – Compressive response of open-cell foams. Part I: Morphology and elastic properties, *Int. J. Solids Struct.*, **42**, pp. 1355-1379, 2005.
8. Gong, L., Kyriakides, S. – Compressive response of open-cell foams. Part II: Initiation and evolution of crushing, *Int. J. Solids Struct.*, **42**, pp. 1381-1399, 2005.
9. Marşavina, L., Sadowski, T., Constantinescu, D.M., Negru, R. – Polyurethane foams behaviour. Experiments versus modeling, *Key Engineering Materials,* **399**, pp. 123- 130, 2009.
10. Apostol, D.A., Constantinescu, D.M. – Influence of speed of testing and temperature on the behaviour of polyurethane foams, *Rev. Roum. Sci. Techn. Méc. Appl.*, **57**, 2012.
11. Apostol, D.A. – *Investigations concerning the behaviour and damage of composites made with rigid and semirigid foams*, Ph.D. thesis, University POLITEHNICA of Bucharest (in Romanian), 2011.
12. Li, Q.M., Magkiriadis, I., Harrigan, J.J. – Compressive strain at the onset of densification of cellular solids, *J. Cell. Plast.*, **42**, pp. 371-392, 2006.

Influența temperaturii şi a vitezei de încercare asupra comportării la compresiune a spumelor poliuretanice

Rezumat

Spume poliuretanice cu densități de 35, 93 şi 200 kg/m^3 au fost solicitate la compresiune la trei temperature diferite: -60 °C, 23 °C şi 80 °C. Influența vitezei de încercare asupra comportării spumelor a fost analizată de la 2 mm/min până la 6 m/s (0.0014 până la 545 s^{-1}). Incercările au fost realizate separat pe direcția de creştere a spumei şi pe o direcție din planul acesteia, fiind comentate diferențele obținute în comportarea acesteia. Cu ajutorul unor funcții de interpolare sunt aproximate regiunile de platou şi de densificare a spumei fiind calculată energia specifică de deformație împreună cu eficiența energetică a spumei, cât şi momentul de inițiere a densificării.