MODELING THE INFLUENCE OF SPEED OF TESTING AND TEMPERATURE ON THE BEHAVIOR OF POLYURETHANE FOAMS

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Abstract

Polyurethane foams with densities of 35, 93, and 200 kg/m3 were tested in tension and compression at three levels of temperatures as: -60 °C, 23 °C, and 80 °C. The influence of speed of testing from 2 mm/min up to 6 m/s (0.0014 to 545/s) 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 behavior are commented. The variations of the modulus of elasticity, maximum stress at yielding, behavior in the yielding region are analyzed showing that they are density, speed of testing, direction of testing, and temperature dependent. An analytical model, based on the one established by Nagy, is proposed to generate the characteristic curves for different speeds of testing and densities, starting from a reference curve established experimentally at 2 mm/min.

1 Introduction

Foam materials have a cellular structure and hence behave in a complex manner, especially under conditions of progressive crush. This crush behavior 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 behavior, 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 behavior 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, [1], [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. Strain rate and temperature effects on the crush behavior of foams were studied in [3]. Following, Mines [4] studies strain rate effects on Divinycell PVC foam, Rohacell PMI foam and Alporas aluminum 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. 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 behavior of such materials. Their experimental results are then compared in the linear domain to the theoretical approaches of Gibson and Ashby [1] and Christensen and Lo [6]. The modeling is then extended to the description of the mechanical behavior in the non-linear domain. 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.

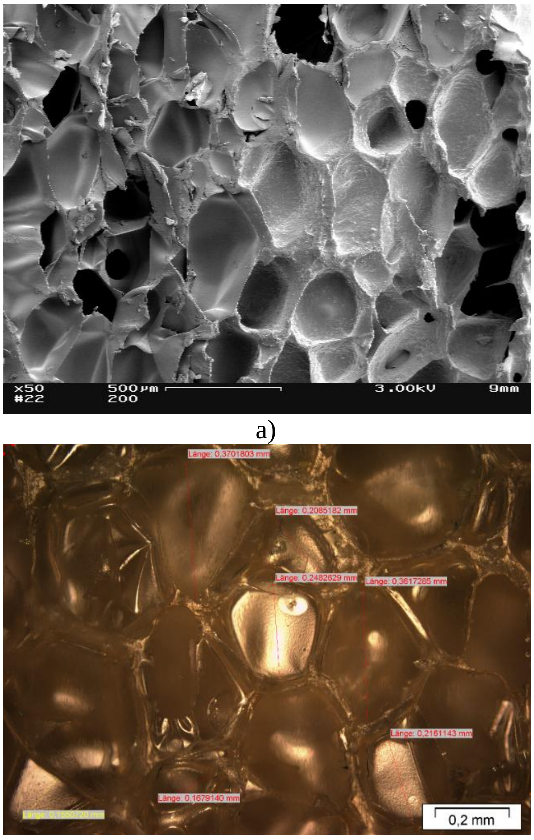
We initially started testing different grades of foams as: PVC foam, Coremat, extruded polystyrene, polyurethane foam with density 200 kg/m^3, polyurethane foam with density 40 kg/m^3, expanded polystyrene, [9], [10]. Initially we tested the Coremat core in traction, and polyurethane foams with densities 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 behavior 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 behavior on one hand, and the possibility to generate through a model the characteristic curves. 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)*. Differentiating the foam properties according to the testing direction is an issue of practical interest and significance.

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. After a discussion of the presently used foam models, a phenomenological model based on the mechanical behavior of PU foams is proposed. Starting from a reference cvasi-static stress-strain curve established for each of the three densities at different temperatures of testing, model generated stress-strain curves are obtained and compared with the experimental ones. Thus the two parameters of the model are established.

2 Mechanical testing in compression of the PU foams

2.1 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. For 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 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 (Figure 1) main sizes of the cells are in the interval 472 μm to 110 μm and wall thickness in between 20.7 and 35 μm. 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.



a)

b)

Figure 1. Cell morphology for the PU foam of 200 kg/m^3 density: a) SEM image; b) optical microscopy image.

2.2 Description of the experimental testing

Compressions tests [11] were done on a hydraulic MTS testing machine specially conceived for testing polymers. 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. 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. 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. 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. Only as an example, in Figure 2 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.

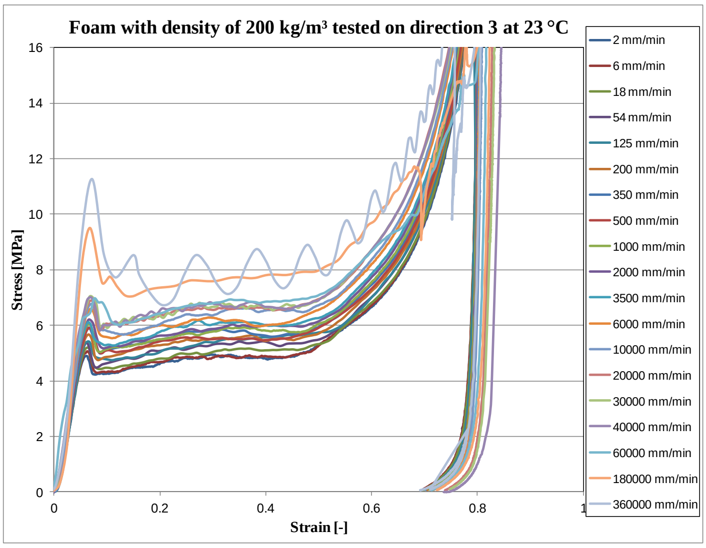


Figure 2. Compression engineering stress-strain curves obtained experimentally at 23 °C (200 kg/m^3).

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. A slight hardening is noticed till the onset of densification. 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 lower temperatures. In Figure 3 are presented only for 9 selected speeds the stress-strain curves at -60 °C obtained on direction 3. The plateau is in between 9-12 MPa. 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. The differences in between upper and lower yielding limits are greater on direction 3 than on direction 1 for this density and temperature.

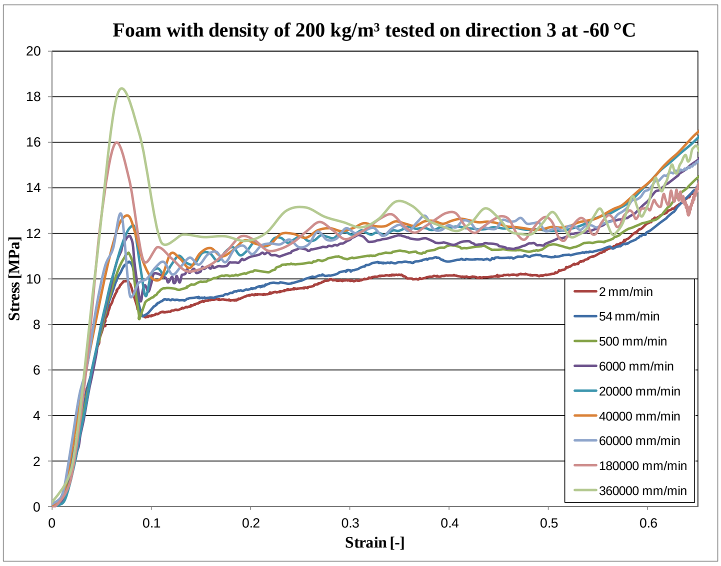


Figure 3. Selected stress-strain curves on direction 3 at -60 °C (200 kg/m^3).

2.3 Variation of plateau stress

The behavior of the foams in the plateau region is significantly changed function of foam density and temperature over the whole interval of testing speeds. For the foam of density 35 kg/m^3 the plateau region exhibits hardening on direction 1 and is constant on direction 3 at a temperature of 23 °C. Same hardening behavior is to be noticed also on direction 1at 80 °C. At -60 °C, on both directions, the plateau stress remains constant till densification occurs. In the case of the foam with 93 kg/m^3 density the plateau region remains mostly constant till the onset of densification for both directions of testing, regardless the temperature and speed of testing. For the last tested foam of 200 kg/m^3 at -60 °C the plateau region shows some hardening, but is constant at 23 °C and 80 °C for all speeds of testing.

The variation of the plateau stress (initial stress of the plateau region) for all three densities can be represented for each level of the testing temperature at different speeds of testing. In Figure 4 variations are represented on direction 3, but similar results were also obtained on direction 1. For 23 °C data being shown in the figure, the plateau stress is almost constant for

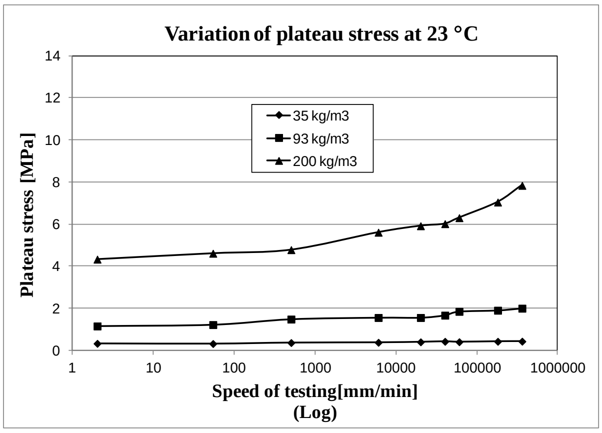


Figure 4. Variation of plateau stress with speed of testing at 23 °C for all densities.

the densities of 35 kg/m^3 and 93 kg/m^3 (with a slight increase) and doubled its value from 4 MPa to 8 MPa for the 200 kg/m^3 density, when speed of testing is increased from 2 mm/min up to 360000 mm/min. At -60 °C plateau stress is again constant for the densities of 35 and 93 kg/m^3 and increases with 50% for the foam of 200 kg/m^3. Finally, at 80 °C tendencies are about the same, with a slight increase of the plateau stress at the density of 93 kg/m^3, and a stronger increase for the density of 200 kg/m^3 from 3 MPa to 6 MPa, as for the temperature of 23 °C. Therefore the speed of testing (strain rate) influences significantly the foam with the highest density of 200 kg/m^3 by doubling the plateau stress at 23 °C and 80 °C, and increasing it with only 50% at -60 °C.

3. Reconstruction of stress-strain curves

3.1 Some presently used analytical models

Several factors such as the mechanical properties of the constitutive material, foaming process, porosity (directly affecting apparent density) and microstructure can lead to the design of a foam material in order to get the mechanical characteristics needed for the particular application. As a consequence the proper mechanical characterization of such a material and the identification of the mathematical model parameters have at its bases a high number of experimental tests. One can rely on a phenomenological model, as the well-known Rusch model ([12], [13], [14]) which does not take into account the density effect, or consider the Gibson and Ashby density dependency (of micro-mechanical type) or other laws, but with limited applicability. While a number of phenomenological models are intended to fit the experimental results but do not account for the density dependency of the foam mechanical characteristics, Avalle et al. [15] have proposed a model as to improve the fitting capabilities of previous models. Clearly, the type and quality of the mathematical model can reduce significantly the number of tests needed to have a complete understanding of the particular design relying on the strain rate, interval of temperature variation, and last but not least the apparent density of the foam as to consider an optimal density to improve foam efficiency.

3.2 Numerical interpolation of experimental stress-strain curves

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:

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

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. [16] 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:

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

4 Proposed model for generating stress-strain curves

A modified model of Nagy [17] is proposed with the relation:

$$\sigma = \sigma_0(\varepsilon_0)\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{a+b\varepsilon_0} , \tag{4}$$

where $\sigma_0(\varepsilon_0)$ and $\dot{\varepsilon}_0$ are established experimentally at the lowest testing speed of 2 mm/min for each foam density and temperature of testing. Here parameters a and b include the influence of density, of direction of testing, and of temperature by having available a reference stress-strain curve at an initial strain rate and that particular temperature.

Difficulties appear as the speed of testing is increased. In Figure 5 are compared the stress-strain curves obtained for the density 200 kg/m^3 on direction 3, at 23 °C and a speed of 360000 mm/min (6 m/s). There are presented together three curves: the one obtained experimentally, the one which resulted from functions interpolation by using relations (1) and (2), and the one generated with relation (4) starting from the speed of 2 mm/min. The model generated curve gives some differencies when the yielding of the foam occurs (at the end of the linear region and beginning of the plateau region), but this is not important on the global response of the compressed foam. At the end of the shown experimental data curve, the drop of the stress close to 80% strain is given by the sudden reduction of the speed of testing of the machine as we limit the compression strain to about 90% and some readjustment of the hydraulic system is needed before reaching this limit. In the densification region the model generated curve slightly overestimates experimental data and correspondingly the functions interpolation curve. The validation of the proposed model is done by calculating with relation (3) the specific strain energy from the experimental stress-strain curves (through the interpolation functions on the plateau and densification region) and from the generated curves by using the model and relation (4). Calculations are done up to a strain of 70% which is for all cases above the onset of densification strain. The model to experimental compared values of the specific strain energies are below 10% for all the testing speeds and temperatures. The highest strain energy is absorbed at -60 °C and the lowest one at 80 °C.

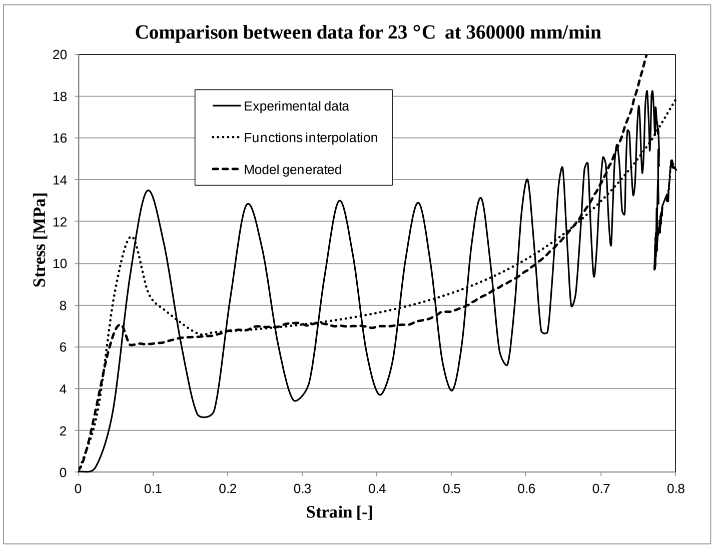


Figure 5. Comparison of obtained characteristic curves for 23 °C at 360000 mm/min (200 kg/m^3).

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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* in Proceedings of *3rd Asia Pacific Conference on Shock and Impact Loads on Structures*, (1999).

[4] Mines R.A.W. Strain rate effects in crushable structural foams. *Applied Mechanics of Materials*, **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. *Composites Science and Technology*, **66**, pp. 2700–2708 (2006).

[6] Christensen, R.M., Lo K.H. Solutions for effective shear properties in three phase sphere and cylinder models. *Journal of the Mechanics and Physics of Solids*, **27**, pp. 315-330 (1979).

[7] Gong L., Kyriakides S., Jang W.Y. Compressive response of open-cell foams. Part I: Morphology and elastic properties. *International Journal of Solids and Structures*, **42**, pp. 1355-1379 (2005).

[8] Gong L., Kyriakides S. Compressive response of open-cell foams. Part II: Initiation and evolution of crushing. *International Journal of Solids and Structures*, **42**, pp. 1381-1399 (2005).

[9] Apostol D.A., Miron M.C., Constantinescu D.M. *Experimental evaluation of the mechanical properties of foams used in sandwich composites* in Proceedings of *24th DANUBIA-ADRIA Symposium on Developments in Experimental Mechanics*, Cluj-Napoca, Romania, (2007).

[10] Marsavina L., Sadowski T., Constantinescu D.M., Negru R. Polyurethane foams behaviour. Experiments versus modelling. *Key Engineering Materials*, **399**, pp. 123-130 (2009).

[11] Apostol D.A. *Investigations concerning the behaviour and damage of composites made with rigid and semirigid foams*, PhD thesis, University POLITEHNICA of Bucharest (in Romanian), (2011).

[12] Rush K. Load-compression behavior of flexible foams. *Journal of Applied Polymer Sciences*, **13**, pp. 2297-2311 (1969).

[13] Rush K. Energy-absorbing characteristics of foamed polymers. *Journal of Applied Polymer Sciences*, **14**, pp. 1133-1147 (1970).

[14] Rush K. Load-compression behavior of brittle foams. *Journal of Applied Polymer Sciences*, **14**, pp. 1263-1273 (1970).

[15] Avalle M., Belingardi G., Ibba A. Mechanical models of cellular solids: Parameters identification from experimental tests. *International Journal of Impact Engineering*, **34**, pp. 3–27 (2007).

[16] Li Q.M., Magkiriadis I., Harrigan J.J. Compressive strain at the onset of densification of cellular solids. *Journal of Cellular Plastics*, **42**, pp. 371-392 (2006).

[17] Nagy A., Ko W.L., Lindholm U.S. Mechanical behaviour of foamed materials under dynamic compression. *Journal of Cellular Plastics*, **10**, pp. 127-134 (1964).