INFLUENCE OF SPEED OF TESTING AND TEMPERATURE ON THE BEHAVIOUR OF POLYURETHANE FOAMS

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Abstract. Polyurethane foams with densities of 35, 93, and 200 kg/m^3 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 behaviour are commented. The variations of the modulus of elasticity, maximum stress at yielding, behaviour in the yielding region, and foam recovery are analyzed showing that they are density, speed of testing, direction of testing, and temperature dependent. For the foam with 200 kg/m^3 density the influence of the coating on parallel surfaces – perpendicular to the rise direction – with epoxy or polyester resins is also discussed.

Key words: polyurethane foams, mechanical testing, microstructure, testing speed, temperature.

1. INTRODUCTION

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. The combination of these properties opens a wide field of potential applications, i.e. as core materials in sandwich panels. Their basic design concept is to space strong, thin facings far enough apart to achieve a high ratio of stiffness to weight; the lightweight core should be required to have resistance to shear and to be strong enough to stabilize the facings to their desired configuration through a bonding medium such as an adhesive layer. 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 [1,2].

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Rev. Roum. Sci. Tech. – Méc. Appl., Tome 57, Nº 1, P. 27-61, Bucarest, 2012

Polyurethane (PU) foam is an engineering material for energy absorption and has been widely used in many applications such as packaging and cushioning. The foam protects sensitive objects from damage by undergoing large deformation at constant crush stresses as mentioned by Gibson and Ashby [1]. The mechanical behaviour of PU foams has drawn attention to engineers and researchers. The mechanical response 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.

There are two approaches to the modelling of the constitutive behaviour of foam materials. The first is continuum modelling. A number of theories have been presented, namely the critical state theory, which is used in standard finite element codes such as ABAQUS, and enhancements have been developed to take account of specific foam behaviour [3-8]. The second approach is micro-modelling, in which the actual cellular structure is modelled [9]. This approach has the advantage of differentiating between micro-mechanical failure modes, but it is computationally demanding for complete sandwich structures with progressive crush. 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. In the case of strain-softening cell foams, macroscopic strain softening can occur after the initiation of the crush of a cell, leading to strain localisation during crush. In other words, a band of cells crush and then a damage front propagates through the material, giving zones of damaged foam and undamaged foam. Thus, the standard continuum approach becomes inaccurate for certain classes of foams. Localisation in cellular materials has been extensively studied for honeycombs, and accounts have been given for in-plane biaxial crushing. Deformation localisation has been studied for shear loading, compression and punch problems [6-8].

Gong et al. [10] and Gong and Kyriakides [11] 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 Kelvin cell model was used to describe the initial elastic behaviour of the foams under uniaxial compression. The nonlinear aspects of the compressive response and crushing of open cell foams were also studied based on this anisotropic cell model.

Other complexities in the constitutive behaviour of foams also occur. The post-collapse behaviour is influenced by the air pressure enclosed in the closed cell foam which is compressed [1]. Properties for polymeric foams are viscoelastic and hence time dependent. Recovery after loading is also time dependent, and matters are further complicated if foam damage has occurred.

Compression, shear and bending tests were carried out by Vogel et al. [12] to characterise the mechanical properties of plane panels made of a seldom used aluminium alloy combination. Clear differences can be found in both the compressive stress-compressive strain curves and the bending stress-deflection curves as a function of the realised expansion stage. Only full foamed sandwiches possess material parameters with good reproducibility.

In [13] is mentioned that compression data is available in literature up to 250/s which is considered to be a significant deficit as many applications are involving higher rates. It was used a polymeric split Hopkinson pressure bar apparatus to achieve strain rates from 500 to 2500/s. It is emphasized that strain rate effects become more pronounced at rates above approximately 1000/s.

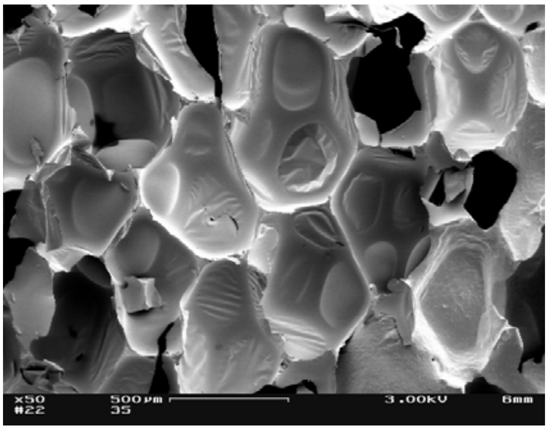
We started testing different grades of foams as: PVC foam, Coremat, extruded polystyrene, polyurethane foam with density 200 kg/m^3, polyurethane foam with density 40 kg/m^3, expanded polystyrene [14, 15]. Initially we tested the Coremat core in traction, and polyurethane foams with densities of 40 kg/m^3 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 to see what differences may appear.

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. Some tests are done in traction to establish their influence on the modulus of elasticity, yielding stress and elongation at failure. Most of the testing is dedicated to the compressive response of these foams to study their modulus of elasticity and yielding behaviour on one hand, and the recovery of the foams after unloading on the other hand. In these tests strain rates started from as low as 0.0014/s to a maximum value of 545/s. Specimens were tested in the *rise direction* of the foam and in one *in-plane direction*. Differentiating the foam properties according to the testing direction is an issue of practical interest and significance. Other important results were obtained by studying the influence of the temperatures which are encountered in engineering applications.

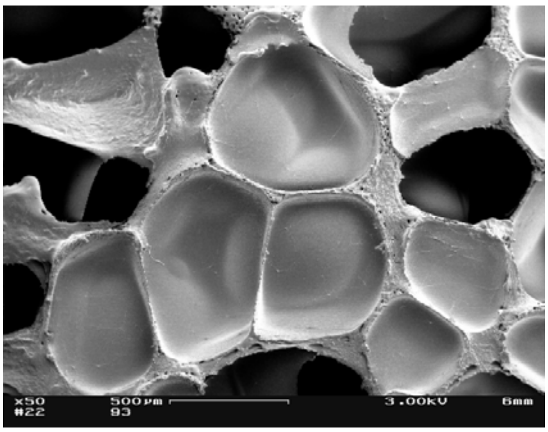
2. MICROSTRUCTURAL EVALUATION OF FOAM MORPHOLOGY

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. It is important to mention than in the following figures the rise direction of the foam is always in vertical position, as to be able to notice the orientation of the cells for each density.

Some of the already damaged cells were destroyed during vacuuming and in Fig. 1 several empty cells can be noticed. In Fig. 1.a) a SEM image of the foam with the density of 35 kg/m^3 is shown; 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 ones before, 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 1.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. 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)



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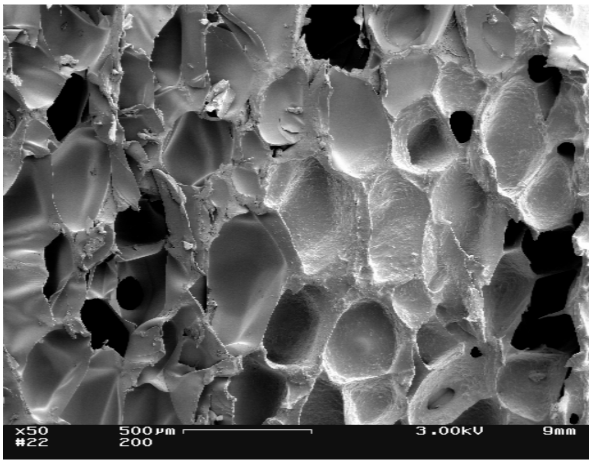

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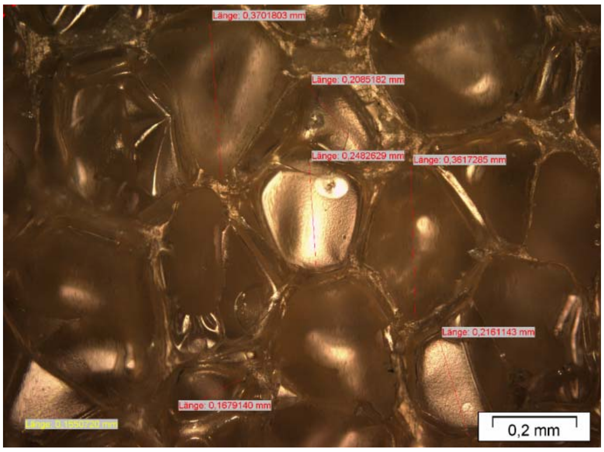

d)

Fig. 1 – SEM images of the cell morthology 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.

3. MECHANICAL TESTING OF THE FOAMS

All three grades of foams were tested in traction and in compression. Tractions tests were done on a Zwick-Roell testing machine, model Z250, having a 10 kN force cell at testing speeds of 2, 54, 200 and 500 mm/min. The machine is equipped with an environmental chamber which can work in between -80 °C and 120 °C. The selected temperatures for our tests were -60 °C, 23 °C and 80 °C, as to cover a range of temperatures possible in engineering applications, from aerospace at low temperatures to automotive when an extreme hot environment may appear. A Micro extensometer used during tests has independently moving levers and is suitable for materials with small rigidity as not introducing a bending loading; it can be used for low and high temperatures with special protected extensions made from ceramic material. Specimens of type 1B were cut according to standard ISO 527-1 [16].

Compressions tests 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 and then 1, 3, and 6 m/s. Standards [17, 18] were used as giving a general orientation on the testing procedures but the requirements on the specimens dimensions could not be fulfilled due to the size of the PU plates from which specimens were cut. The specimens for the three densities had the approximate dimensions, with the height being the last of the three dimensions: 25×25×24 mm for 35 kg/m^3, 15×15×11 mm for 93 kg/m^3, 12×12×11.9 mm for 200 kg/m^3. Therefore the strain rate started from as low as 0.00139/s to a maximum value of 545.45/s. 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 results of the mechanical properties were obtained. Only for the 200 kg/m^3 foam the outer surfaces of the plates from which specimens were cut (normal to the rise direction) were impregnated with epoxy or polyester resins and compression tests were done on direction 1 in order to see the influence of a thin layer impregnation. The thickness of the layer is in between 100-273 μm; however different sizes of voids, up to about 440 μm, showing that the impregnation was not perfect on the surface were observed.

Specimens are compressed up to a 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.

4. TRACTION TESTING OF POLYURETHANE FOAMS

Conventional stress-strain characteristic curves were established only for the loading speeds of 2, 54, 200, and 500 mm/min for the three studied densities of 35, 93, and 200 kg/m^3. The temperatures of testing were, as mentioned before, -60 °C, 23 °C and 80 °C. Tests are done on *direction 1* as specimens were cut from polyurethane plates. Each curve is an average of three tests. The corresponding diagrams are shown in Figs. 2, 3, and 4.

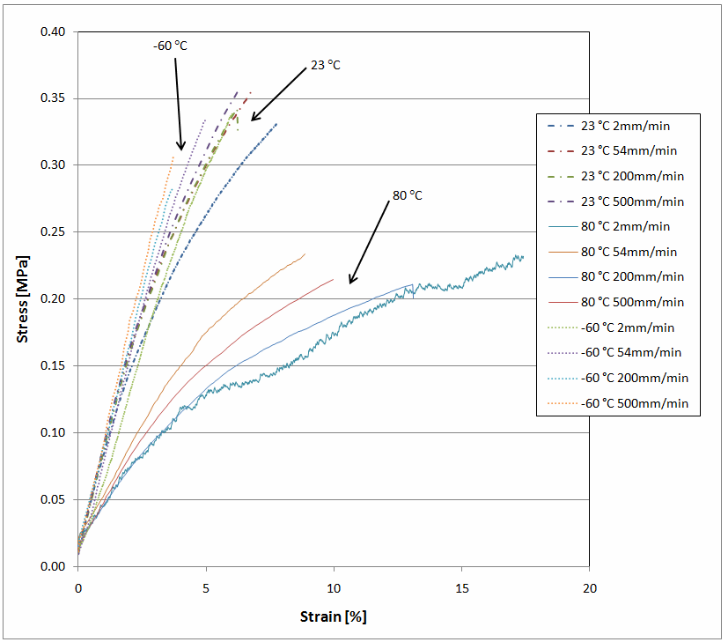

Fig. 2 – Tensile stress-strain characteristic curves for foam with density 35 kg/m^3.

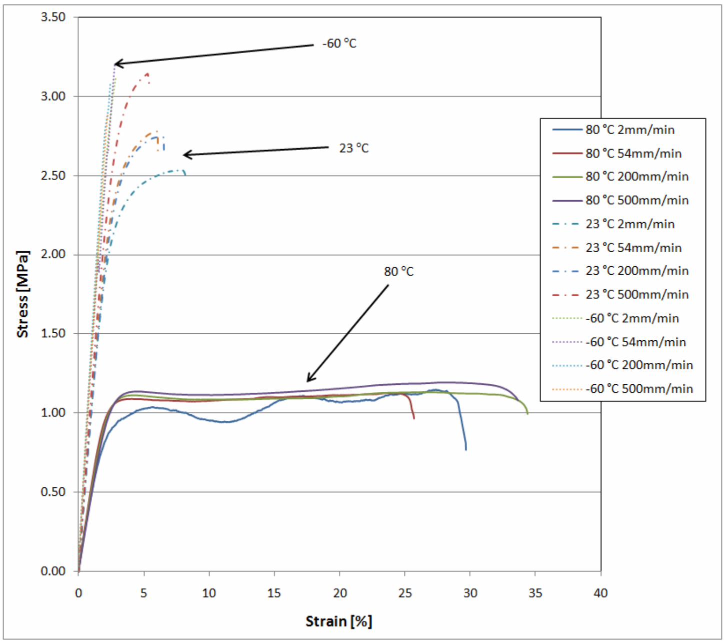

Fig. 3 – Tensile stress-strain characteristic curves for foam with density 93 kg/m^3.

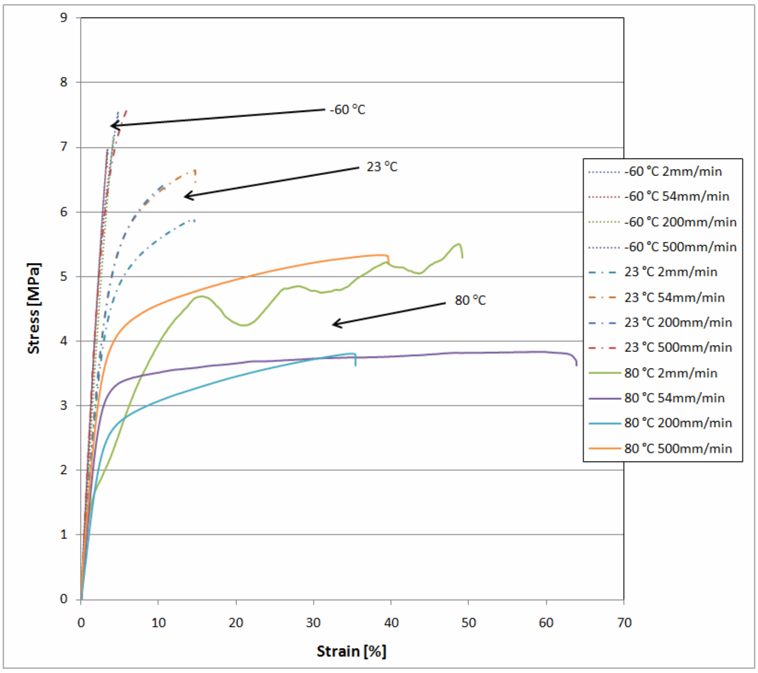

Fig. 4 – Tensile stress-strain characteristic curves for foam with density 200 kg/m^3.

As one can notice the low negative temperature makes the behaviour of the foams more fragile than at 23 °C, but not as much as expected. The curves for the higher two speeds of loading at 23 °C (dashed lines) are coming above the curves resulting at -60 °C (doted lines) for the lower speed of loading 2 mm/min for the foam with density 35 kg/m^3. For -60 °C the increase of speed of loading doesn't change much the characteristic curves, especially for the higher densities of 93 kg/m^3 and 200 kg/m^3. On the other hand the temperature of 80 °C increases significantly the ductile behaviour of foams, with greater emphasis on the 93 and 200 kg/m^3 densities.

The compared mechanical properties are: modulus of elasticity, maximum stress at yielding – notated as maximum stress, and elongation at failure. Obtained results are given in Tables 1, 2, and 3 for the three increasing densities. The increse of speed of loading doesn't increase significantly the values of the moduli of elasticity for each temperature level and density, regardless the temperature, but these values are significantly different at different temperatures. For each of the densities the moduli of elasticity decrease about 2 times or even more – mainly for the 200 kg/m^3 foam – when the temperature is increased from -60 °C to 80 °C (see corresponding columns in Tables 1, 2, 3). Maximum stress (at yielding) is about the same for the 35 kg/m^3 density foam regardless the temperature level, and – in average – is reduced to half for the densities 93 kg/m^3 and 200 kg/m^3 when temperature is increased from -60 °C to 80 °C. Elongation at failure increases about

3 times for the density 35 kg/m^3, about 9 times (even more for 500 mm/min) for density 93 kg/m^3, and more than 10 times for the highest density of 200 kg/m^3 when temperature increases. At the temperature of 23 °C elongation at failure is about the same for 35 and 93 kg/m^3 densities, decreasing with the increase of testing speed; for 200 kg/m^3 elongation is greater. For -60 °C the decrease is 2-3 times as compared to 23 °C for the 93 and 200 kg/m^3 densities, and less than once for the 35 kg/m^3 density. Finally, for 80 °C compared to 23 °C, elongation at failure doubles for the density 35 kg/m^3 (Table 1), and is 4-5 times greater for the other two densities of 93 and 200 kg/m^3 (Tables 2, 3).

Table 1

Traction mechanical properties for the foam of density 35 kg/m^3 at different temperatures.

Speed of testing [mm/min]	Modulus of elasticity [MPa]			Maximum stress [MPa]			Elongation at failure [%]		
	-60 °C	23 °C	80 °C	-60 °C	23 °C	80 °C	-60 °C	23 °C	80 °C
2	7.09	8.67	3.94	0.30	0.33	0.21	5.52	7.37	12.52
54	7.98	8.24	3.95	0.29	0.36	0.22	4.48	7.10	12.18
200	7.66	8.55	3.65	0.26	0.34	0.13	3.85	5.75	13.00
500	8.38	8.13	3.54	0.27	0.32	0.23	3.58	5.20	11.00

Table 2

Traction mechanical properties for the foam of density 93 kg/m^3 at different temperatures.

Speed of testing [mm/min]	Modulus of elasticity [MPa]			Maximum stress [MPa]			Elongation at failure [%]		
	-60 °C	23 °C	80 °C	-60 °C	23 °C	80 °C	-60 °C	23 °C	80 °C
2	169.01	105.84	59.58	2.83	2.48	1.16	2.88	8.07	29.00
54	137.61	117.46	67.74	2.72	2.82	1.19	2.63	6.50	26.67
200	149.65	107.61	73.84	2.66	2.86	1.40	2.41	6.03	23.67
500	143.22	112.73	53.78	2.49	3.08	1.17	2.23	5.03	29.00

Table 3

Traction mechanical properties for the foam of density 200 kg/m^3 at different temperatures.

Speed of testing [mm/min]	Modulus of elasticity [MPa]			Maximum stress [MPa]			Elongation at failure [%]		
	-60 °C	23 °C	80 °C	-60 °C	23 °C	80 °C	-60 °C	23 °C	80 °C
2	279.49	185.42	121.20	7.22	6.06	4.82	3.70	13.00	48.00
54	259.94	190.41	139.66	7.85	6.68	4.25	3.93	12.33	57.00
200	258.22	176.08	96.70	6.66	6.21	3.66	3.80	9.95	41.33
500	259.51	237.43	168.97	7.17	7.49	5.17	3.40	6.90	36.67

Clearly, the temperature influence on the discussed mechanical properties is significant for each foam densities. For each temperature of testing and density of the foam the increase of the speed of loading in the mentioned interval (2 to 500 mm/min) reduces somehow the elongation at failure, but keeps about the same modulus of elasticity and maximum stress.

5. COMPRESSION TESTING OF POLYURETHANE FOAMS

Tests in compression were done for the three foam densities and the three levels of temperature at the testing speeds: 2, 6, 18, 54, 125, 200, 350, 500, 1000, 2000, 3500, 6000, 10000, 20000, 30000, 40000 mm/min. Later on were added the speeds of 1 m/s (60000 mm/min), 3 m/s (180000 mm/min), and 6 m/s (360000 mm/min). For each testing case (density, temperature, speed) five specimens were tested and an average value will be presented in the following discussion; if a test gave suspicious results it was disregarded. The volume of obtained data is significant and only a part, considered as relevant, is presented hereby.

The direction of testing, notated as *direction 3* or *rise direction* and *direction 1* or *in-plane direction*, was considered as an additional parameter to influence the mechanical properties for each density and temperature. Only for the foam of density 200 kg/m^3 a possible influence of the coating of the foam – thin layer of an epoxy or polyester resin applied on surfaces normal to the rise direction – was also analysed. In this case testing is done only on direction 1, parallel to the coated surfaces.

Compression is produced up to when specimen height becomes 1.5-2 mm (strain becoming about 90 %), followed by unloading and foam recovery controlled with 0.6 mm/min which was found to be sufficient for all loading speeds at the three temperatures of testing regardless the speed of testing, temperature and density. Foam recovery values are established having as a reference the moment when unloading starts and in the following tables are notated as non-dimensional.

5.1. Foam with density of 35 kg/m^3

In Fig. 5 are presented the characteristic curves obtained at 23 °C on direction 1 for all speeds of testing up to 6 m/s. When yielding starts a hardening behaviour is noticed in all curves. For speeds starting from 10000 mm/min, although stress-strain values are filtered, the curves show "peaks and valleys" as local instabilities are to be clearly seen up to strains of 40%, while cells walls are damaged in an unstable manner. On direction 3 (Fig. 6) a plateau at yielding is obtained and local different types of damages which probably appear are to be noticed. Clearly phenomena are difficult to be quantified as besides various local failure mechanisms one should also consider the rapid loading influence. At 6 m/s the obtained curve keeps the general trend but stress is first decreasing on the yielding plateau and then is increasing with the onset of densification.

When comparing the mechanical properties obtained in compression as modulus of elasticity, maximum stress, foam recovery for all testing speeds in between the two directions it is to be clearly seen in Table 4 that the direction of testing influences the results. The modulus of elasticity is greater on direction 3 than on direction 1, and from a speed of 500 mm/min it is two times greater; only at the higher speeds of 1 m/s, 3 m/s and 6 m/s it is less than twice bigger. Maximum stress (when yielding starts) is increasing slowly with the speed of loading being greater on direction 3 than 1. The foam recovers better on the in plane direction (direction 1) than on rise direction (direction 3) and generally decreases with the increase of speed of loading, showing that higher speeds produce irreversible damage processes.

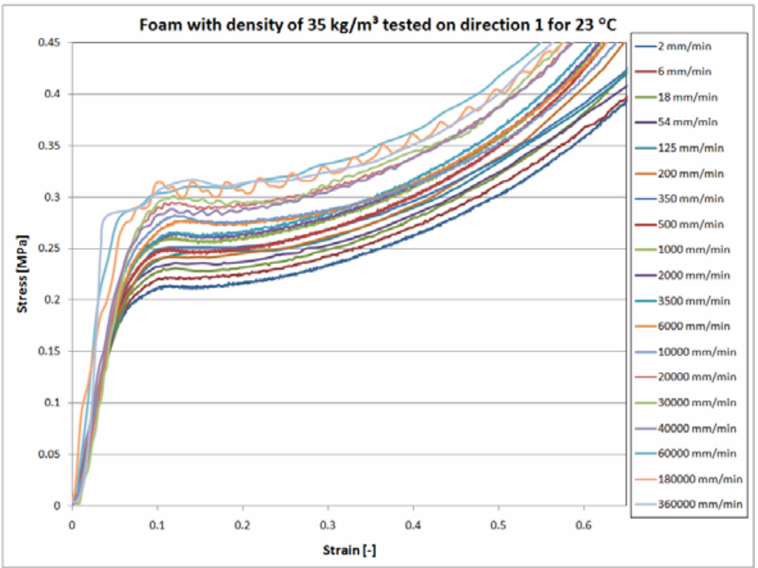

Fig. 5 – Stress-strain diagrams in compression on direction 1 at 23 °C (35 kg/m^3).

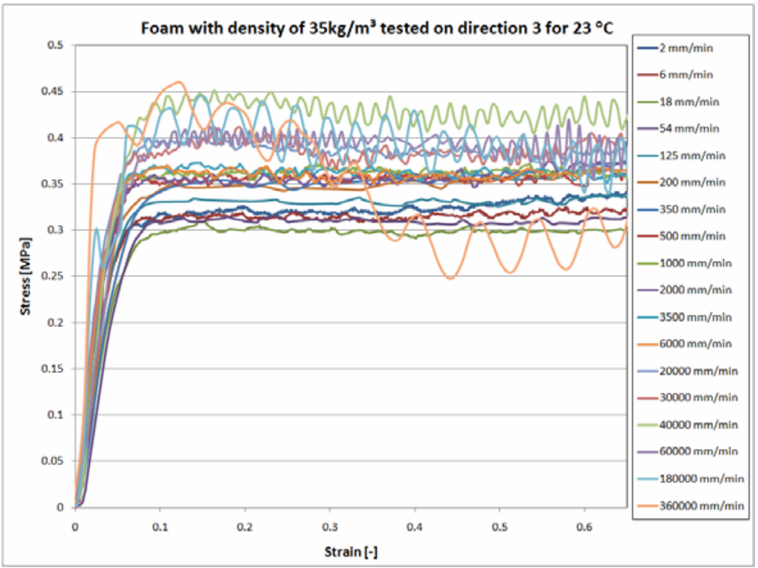

Fig. 6 – Stress-strain diagrams in compression on direction 3 at 23 °C (35 kg/m^3)

For selected speeds of loading the influence of the temperature on the properties for direction 1 is given in Table 5. The increase of temperature at each speed of testing reduces the modulus of elasticity and the maximum stress. For each temperature the modulus increases with the testing speed up to 1 m/s, followed by significant increases for 3 m/s and 6 m/s. Maximum stress decreases slightly with the increase of temperature for each testing speed, but increases at each temperature level with the increase of speed. Foam recovery varies in an opposite way: increases with the increase of temperature for each testing speed, but somehow decreases at each temperature level with the increase of speed. On direction 3 the trends of variation discussed above are same as on direction 1 for all three properties (Table 6). The modulus of elasticity is significantly greater on direction 3 than on direction 1. Maximum stress is greater and foam recovery is smaller for all testing speeds and all test temperatures (values compared for the same parameters) on direction 3 than on direction 1.

Table 4

Comparison of compression mechanical properties on directions 1 and 3 for the foam of density 35 kg/m^3 at 23 °C.

Speed of testing [mm/min]	Modulus of elasticity [MPa]		Maximum stress [MPa]		Foam recovery [-]	
	dir. 1	dir. 3	dir. 1	dir. 3	dir. 1	dir. 3
2	4.07	6.29	0.21	0.29	0.084	0.068
6	4.11	6.70	0.21	0.31	0.086	0.065
18	4.26	6.45	0.23	0.31	0.083	0.066
54	4.30	6.60	0.25	0.31	0.080	0.062
125	4.42	6.81	0.25	0.33	0.079	0.055
200	4.45	6.89	0.25	0.33	0.083	0.055
350	4.46	7.00	0.26	0.34	0.078	0.053
500	4.21	9.31	0.26	0.36	0.073	0.044
1000	4.76	8.71	0.27	0.36	0.068	0.044
2000	4.52	8.33	0.27	0.35	0.070	0.044
3500	4.43	9.09	0.27	0.36	0.070	0.044
6000	4.47	9.25	0.28	0.37	0.069	0.049
10000	4.76	9.43	0.28	0.38	0.074	0.043
20000	4.81	9.06	0.29	0.40	0.082	0.044
30000	4.50	10.40	0.30	0.41	0.075	0.049
40000	4.11	10.92	0.28	0.44	0.078	0.050
60000	5.38	9.78	0.28	0.41	0.078	0.051
180000	8.60	14.60	0.31	0.43	0.078	0.046
360000	15.41	21.00	0.32	0.45	0.072	0.041

Table 5

Compression mechanical properties on direction 1 for the foam of density 35 kg/m^3.

Speed of testing [mm/min]	Modulus of elasticity [MPa]			Maximum stress [MPa]			Foam recovery [-]		
	-60	23 [°C]	80	-60	23 [°C]	80	-60	23 [°C]	80
2	4.21	4.07	2.75	0.29	0.21	0.16	0.140	0.084	0.210
54	5.04	4.30	3.08	0.32	0.25	0.19	0.092	0.080	0.097
500	5.26	4.21	3.02	0.31	0.26	0.21	0.065	0.073	0.079
6000	5.88	4.47	3.08	0.34	0.28	0.21	0.057	0.069	0.078
20000	5.87	4.81	3.50	0.36	0.29	0.22	0.055	0.082	0.076
40000	7.11	4.11	3.61	0.38	0.28	0.24	0.055	0.078	0.074
60000	6.11	5.38	3.76	0.33	0.28	0.24	0.056	0.078	0.074
180000	10.89	8.60	7.18	0.37	0.31	0.29	0.046	0.078	0.066
360000	17.23	15.41	12.97	0.40	0.32	0.37	0.044	0.072	0.063

Table 6

Compression mechanical properties on direction 3 for the foam of density 35 kg/m^3.

Speed of testing [mm/min]	Modulus of elasticity [MPa]			Maximum stress [MPa]			Foam recovery [-]		
	-60	23 [°C]	80	-60	23 [°C]	80	-60	23 [°C]	80
2	8.35	6.29	4.67	0.40	0.29	0.24	0.056	0.068	0.061
54	8.70	6.60	6.45	0.37	0.31	0.28	0.048	0.062	0.054
500	9.03	9.31	7.06	0.41	0.36	0.32	0.041	0.044	0.049
6000	10.47	9.25	8.17	0.44	0.37	0.34	0.043	0.049	0.049
20000	10.48	9.06	9.21	0.45	0.40	0.35	0.048	0.044	0.053
40000	10.92	10.92	8.56	0.47	0.44	0.37	0.051	0.050	0.052
60000	10.57	9.74	7.68	0.48	0.41	0.34	0.034	0.051	0.053
180000	17.32	14.60	14.90	0.50	0.43	0.41	0.031	0.046	0.045
360000	22.28	21.00	17.71	0.66	0.46	0.49	0.033	0.041	0.049

It is also interesting to analyze the response of the foam with density of 35 kg/m^3 on direction 1 by observing the characteristic curves at -60 °C and 80 °C, as compared to the ones presented already in Fig. 5 for 23 °C. In Fig. 7 at -60 °C, for the selected speeds, yielding is produced on a plateau and the fragile wall damage is to be seen in the local ups and downs. For the lower speeds of testing at 2, 54, and 500 mm/min the characteristic curves move one by one to the right, as the onset of densification is produced later. For the higher selected speeds of 6000, 20000, and 40000 mm/min densification starts at about the same moment and the three curves superpose at a strain of approximately 80%. At 1, 3 and 6 m/s densification strts also at about 80% strain (Fig. 7). For the same foam and a temperature of testing of 80 °C, yielding is produced with hardening as the loading speed is increased (Fig. 8). Curves have a smooth variation; only from 40000 mm/min starts to appear an evident influence of the local instabilities, test being done with an initial strain rate of 56/s.

On direction 3 at -60 °C, on the plateau region, the cells of the foam are breaking in a fragile manner, but curves stay together up to 40000 mm/min (Fig. 9). From 60000 min/min up to 360000 mm/min (1m/s to 6 m/s) the behaviour of the 35 kg/m^3 density foam is quite difficult to be predicted for such compressive tests. Although the presented curves are averaged from the experimentally obtained ones, in Fig. 9 it is to be seen that for higher speeds the stress-strain diagrams go initially above and then (from 60%) bellow the curves which result at lower speeds. For the temperature of 80 °C (Fig. 10) the yielding plateau shifts up in a more evident way as before with the increase of speed of testing (see also Table 6 for maximum stress values), and from 1 m/s testing speed the curves show a random variation, especially above a strain of 50%. Again, it is difficult to quantify correctly tests done at speeds of m/s.

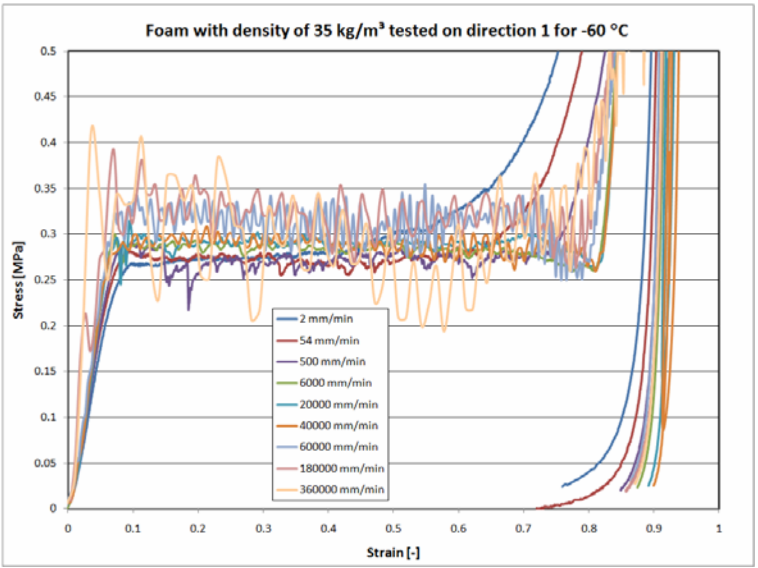

Fig. 7 – Selected stress-strain diagrams in compression on direction 1 at -60 °C (35 kg/m^3).

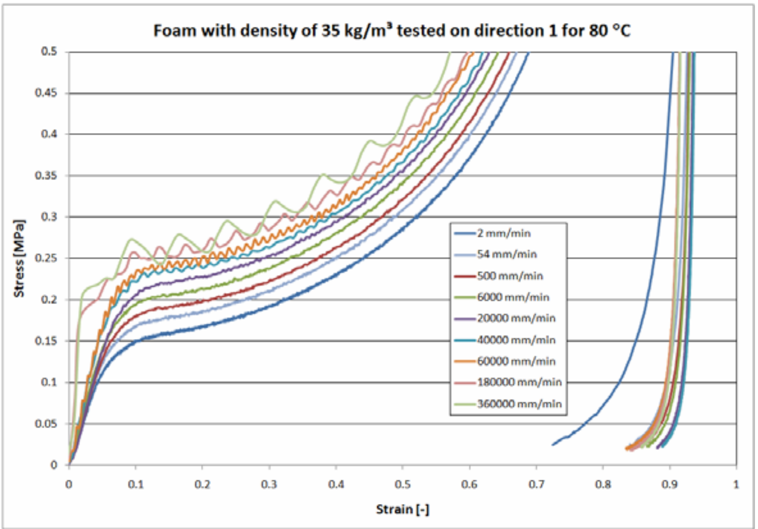

Fig. 8 – Selected stress-strain diagrams in compression on direction 1 at 80 °C (35 kg/m^3).

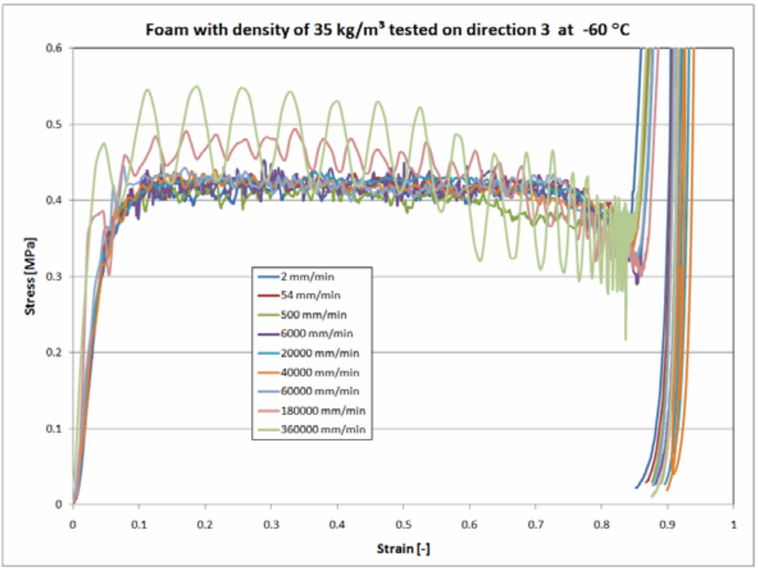

Fig. 9 – Selected stress-strain diagrams in compression on direction 3 at -60 °C (35 kg/m^3).

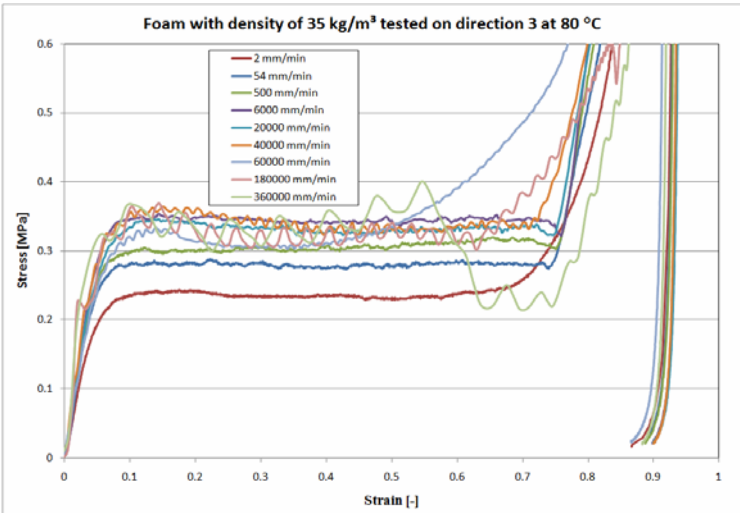

Fig. 10 – Selected stress-strain diagrams in compression on direction 3 at 80 °C (35 kg/m^3).

5.2. Foam with density of 93 kg/m^3

At 23 °C we have represented in Fig. 11 for direction 1 and in Fig. 12 for direction 3 all the stress-strain curves which we have obtained experimentally for 19 speeds of testing. Both figures are overcrowded with curves but show the general trends: hardening in the yielding region and more irregular variations when testing speed is towards the highest values. When yielding is produced the maximum stress drops more on direction 3 than on direction 1. It is interesting to notice that on direction 3 the 19 curves gather in three groups as first 6 – 2 to 200 mm/min, then 10 – 350 to 40000 mm/min, and finally 3 speeds – from 1 to 6 m/s.

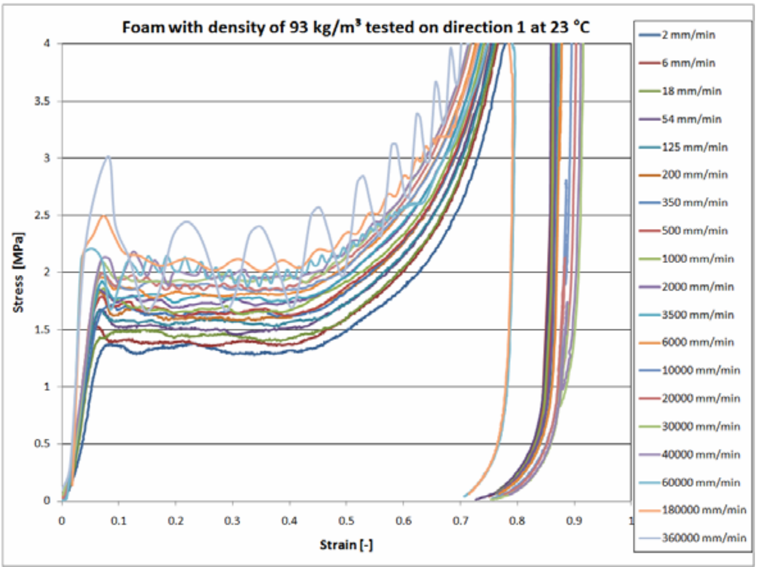

Fig. 11 – Stress-strain diagrams in compression on direction 1 at 23 °C (93 kg/m^3).

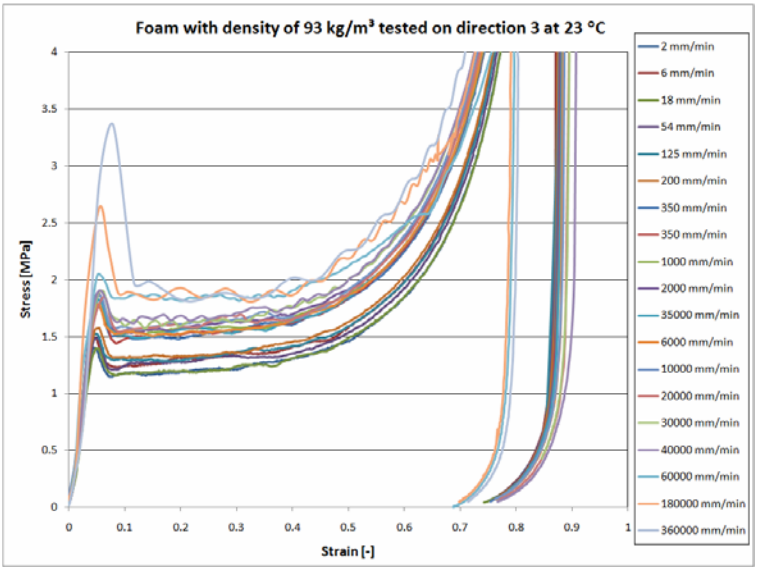

Fig. 12 – Stress-strain diagrams in compression on direction 3 at 23 °C (93 kg/m^3).

In Table 7 is made a comparison of the obtained modulus of elasticity, maximum stress and recovery of the foam in between directions 1 and 3. The modulus of elasticity is about the same on both directions (remember the SEM image from Fig. 1.b) being in average towards 10 times greater than for the foam of 35 kg/m^3. Maximum stress is close to one order of magnitude greater. Foam recovery is again decreasing with the increase of speed of loading from about 11-13 % to 7-9 % and is greater than for the foam of 35 kg/m^3, but about the same on both directions 1 and 3.

Table 7

Comparison of compression mechanical properties on directions 1 and 3 for the foam of density 93 kg/m^3 at 23 °C.

Speed of testing [mm/min]	Modulus of elasticity [MPa]		Maximum stress [MPa]		Foam recovery [-]	
	dir. 1	dir. 3	dir. 1	dir. 3	dir. 1	dir. 3
2	30.95	41.07	1.42	1.39	0.110	0.131
6	36.76	42.41	1.50	1.47	0.110	0.130
18	36.11	41.26	1.57	1.48	0.108	0.130
54	38.81	41.75	1.64	1.50	0.105	0.126
125	39.59	41.14	1.72	1.52	0.106	0.125
200	40.60	43.23	1.79	1.64	0.105	0.125
350	36.19	47.40	1.72	1.77	0.106	0.127
500	40.57	45.95	1.80	1.64	0.107	0.125
1000	42.49	46.40	1.88	1.74	0.108	0.131
2000	42.85	46.78	1.90	1.83	0.112	0.130
3500	44.24	49.11	1.95	1.84	0.115	0.131
6000	43.56	45.03	2.00	1.80	0.120	0.135
10000	43.98	47.75	2.01	1.89	0.128	0.137
20000	45.93	46.62	2.06	1.82	0.139	0.141
30000	43.64	50.13	2.09	2.02	0.145	0.139
40000	45.48	48.95	2.12	1.95	0.142	0.149
60000	60.42	53.54	2.32	2.04	0.079	0.087
180000	79.23	69.43	2.51	2.64	0.075	0.088
360000	90.14	83.92	3.02	3.36	0.072	0.086

Table 8 compares, for selected speeds of testing, the variation of the foam properties at the three temperatures on direction 1. Table 9 does the same thing, but on direction 3. At all temperatures the moduli are generally greater on direction 1 than on direction 3, mainly when speed of testing increases; exception is the temperature of 80 °C for which at speeds starting from 1 m/s the values are almost the same on both directions. Maximum stress decreases on both directions with the increase of temperature, but increases with the speed of loading, as happens in fact for the foam of density 35 kg/m^3. As values, they are about 5-8 times greater than for the lower density foam. Foam recovery increases with the increase of temperature but is about the same on each direction at the temperatures of -60 °C and 23 °C for speed of 1 to 6 m/s; values are 8-9% at -60 °C and 25-30 % at 80 °C.

Table 8

Compression mechanical properties on direction 1 for the foam of density 93 kg/m^3.

Speed of testing [mm/min]	Modulus of elasticity [MPa]			Maximum stress [MPa]			Foam recovery [-]		
	-60	23 [°C]	80	-60	23 [°C]	80	-60	23 [°C]	80
2	58.45	30.95	48.93	2.38	1.42	1.19	0.075	0.110	0.181
54	57.48	38.81	53.90	2.48	1.64	1.41	0.076	0.105	0.181
500	60.35	40.57	54.50	2.60	1.80	1.55	0.083	0.107	0.177
6000	63.52	43.56	62.60	2.70	2.00	1.77	0.079	0.120	0.192
20000	70.13	45.93	63.32	2.80	2.06	1.86	0.072	0.139	0.211
40000	89.34	45.48	60.79	2.82	2.12	1.93	0.064	0.142	0.220
60000	70.90	60.42	39.64	3.13	2.32	1.52	0.086	0.079	0.250
180000	93.67	79.23	55.26	3.83	2.51	2.56	0.082	0.075	0.256
360000	107.67	90.14	61.30	4.63	3.02	2.81	0.079	0.072	0.249

Table 9

Compression mechanical properties on direction 3 for the foam of density 93 kg/m^3.

Speed of testing [mm/min]	Modulus of elasticity [MPa]			Maximum stress [MPa]			Foam recovery [-]		
	-60	23 [°C]	80	-60	23 [°C]	80	-60	23 [°C]	80
2	41.72	41.07	32.09	2.11	1.39	1.00	0.116	0.131	0.206
54	47.39	41.75	36.12	2.31	1.50	1.20	0.108	0.126	0.210
500	50.52	45.95	38.28	2.41	1.64	1.33	0.105	0.125	0.207
6000	52.77	45.03	41.14	2.48	1.80	1.51	0.105	0.135	0.218
20000	55.68	46.62	42.93	2.51	1.82	1.63	0.110	0.141	0.245
40000	57.39	48.95	44.37	2.48	1.95	1.63	0.111	0.149	0.245
60000	66.35	53.54	38.97	3.01	2.04	1.45	0.093	0.087	0.295
180000	84.02	69.43	50.55	3.46	2.64	1.93	0.090	0.088	0.287
360000	92.98	83.92	68.04	4.15	3.36	2.91	0.081	0.086	0.266

As seen recovery is greater at 80 °C but, again, doesn't change with the increase of the last three speeds. For all temperatures recovery is in fact greater on the rise direction (direction 3) than on the transverse one (direction 1).

Figs. 13 and 14 present selected stress-strain curves on direction 1 for -60 °C and 80 °C, respectively. Only parts of the curves containing the yielding region for strains up to 60% are shown. The issues of onset of densification and densification region are not discussed here.

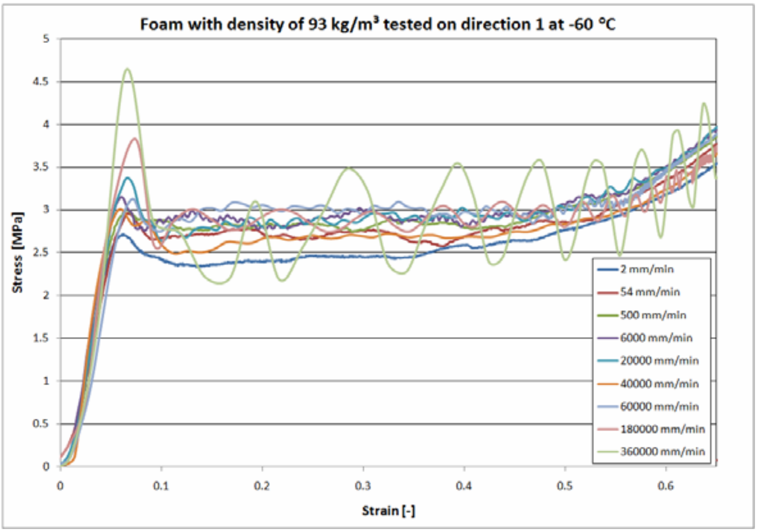

Fig. 13 – Selected stress-strain diagrams in compression on direction 1 at -60 °C (93 kg/m^3)

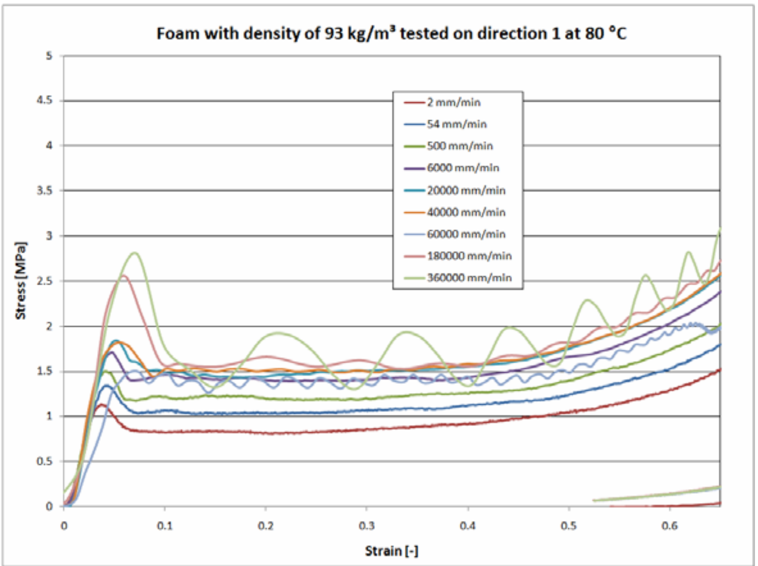

Fig. 14 – Selected stress-strain diagrams in compression on direction 1 at 80 °C (93 kg/m^3)

On direction 1 yielding is in between 2-3 MPa at -60°C (Fig. 13) and between 1-2 MPa for 80 °C (Fig. 14) for all speeds of testing. On direction 3 (Figs. 15 an 16) yielding is mostly produced around a value of 2.5 MPa for -60 °C, and again between 1-2 MPa for 80 °C. This confirms that for this foam in-plane and rise directions produce a not too much different response with the variation of speed of loading and temperature.

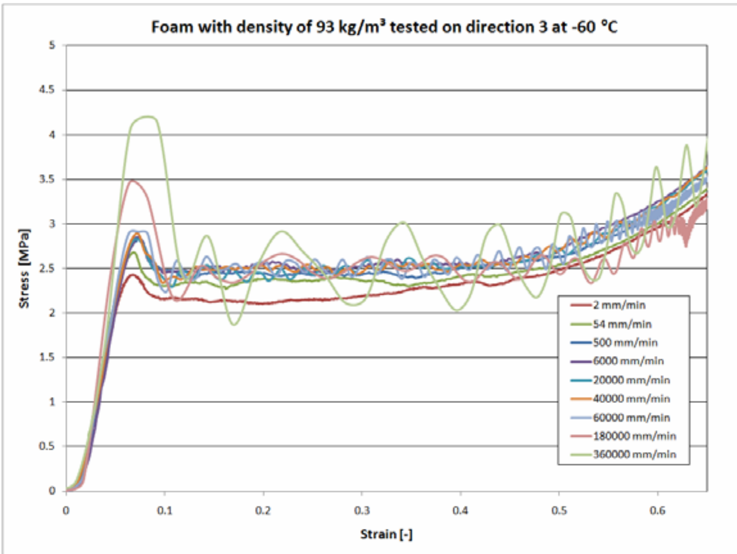

Fig. 15 – Selected stress-strain diagrams in compression on direction 3 at -60 °C (93 kg/m^3).

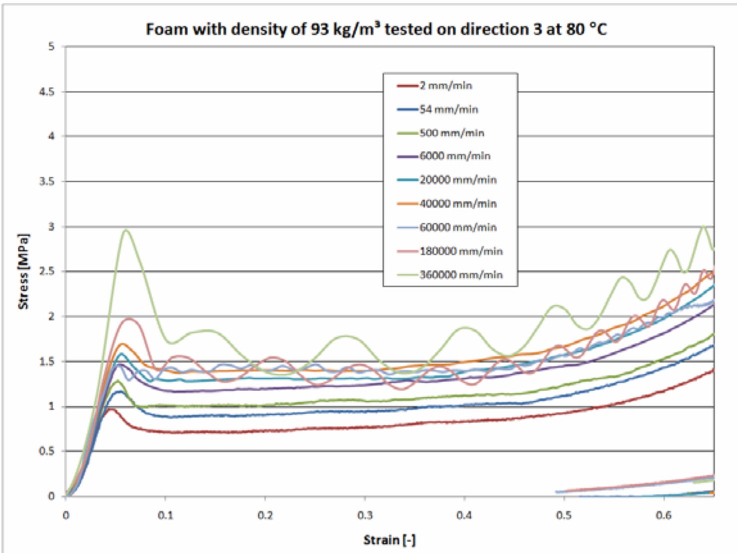

Fig. 16 – Selected stress-strain diagrams in compression on direction 3 at 80 °C (93 kg/m^3).

5.3. Foam with density of 200 kg/m^3

For the highest of the densities of the tested foams when tests are done at 23 °C on direction 1 we show in Fig. 17 all 19 obtained curves by changing the testing speed; they go up as speed is increased with a clear difference when speed becomes of the order of m/s. Yielding is produced with hardening.

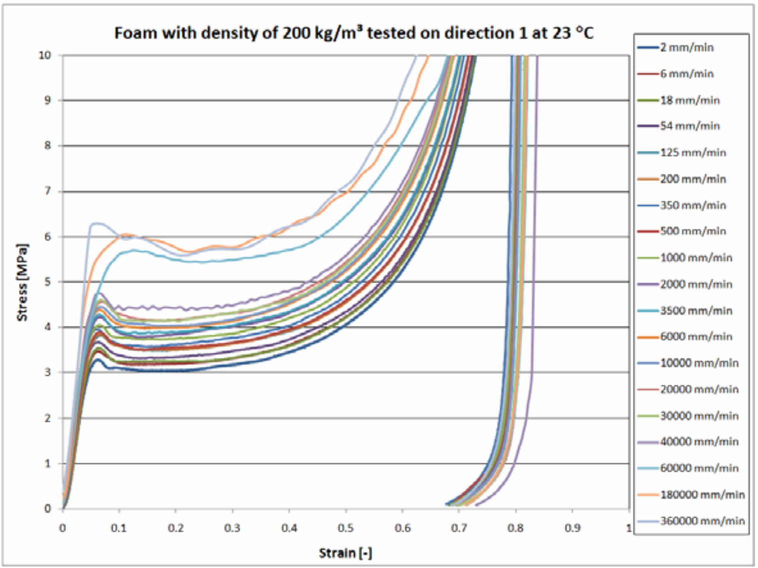

Fig. 17 – Stress-strain diagrams in compression on direction 1 at 23 °C (200 kg/m^3).

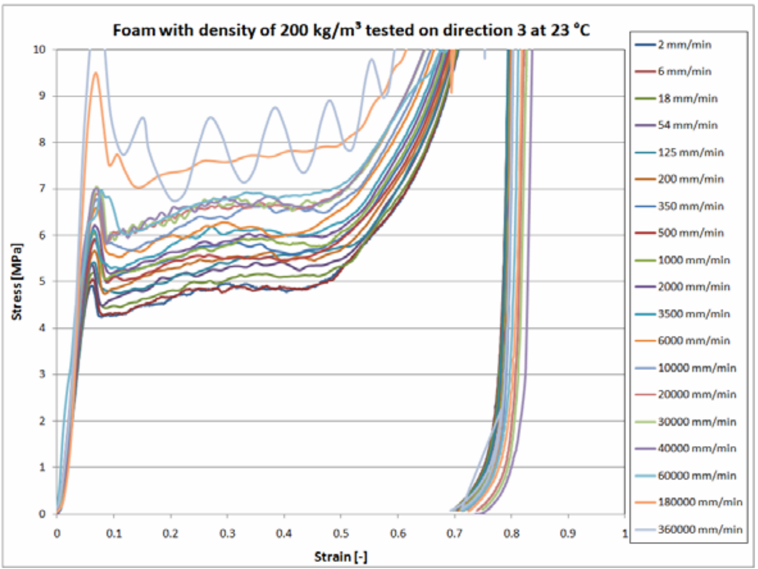

Fig. 18 – Stress-strain diagrams in compression on direction 3 at 23 °C (200 kg/m^3).

For the same types of curves obtained after testing on direction 3 (Fig. 18) yielding stress is increasing and the "trembling" of the curves indicate different mechanisms of failure on the rise direction. It is interesting to notice that the difference between the maximum and minimum yielding stress is greater on direction 3 than on direction 1. In Table 10 is registered only the maximum stress at yielding which is greater on direction 3 than on direction 1.

The modulus of elasticity is also greater on direction 3 than 1. It is almost constant on direction 1 for speeds between 125 mm/min and 20000 mm/min and then increases with almost 50% when speed reaches 6 m/s (Table 10). On direction 3 the modulus increases constantly from 125 mm/min and doubles in value when speed of testing becomes 6 m/s.

Table 10

Comparison of compression mechanical properties on directions 1 and 3 for the foam of density 200 kg/m^3 at 23 °C.

Speed of testing [mm/min]	Modulus of elasticity [MPa]		Maximum stress [MPa]		Foam recovery [-]	
	dir. 1	dir. 3	dir. 1	dir. 3	dir. 1	dir. 3
2	86.88	114.56	3.30	4.91	0.126	0.105
6	90.06	116.59	3.47	5.01	0.126	0.104
18	93.50	116.70	3.56	5.22	0.125	0.102
54	94.76	114.27	3.67	5.37	0.122	0.098
125	101.50	122.02	3.79	5.47	0.122	0.096
200	101.94	122.64	3.82	5.60	0.121	0.094
350	104.11	121.83	4.05	5.85	0.122	0.093
500	105.75	126.78	3.89	5.92	0.121	0.091
1000	105.41	127.97	4.04	6.02	0.122	0.092
2000	102.38	128.52	4.19	6.18	0.121	0.090
3500	107.24	130.54	4.30	6.36	0.121	0.090
6000	109.14	134.74	4.35	6.57	0.119	0.089
10000	104.34	132.92	4.48	6.82	0.121	0.089
20000	105.93	134.07	4.57	6.83	0.122	0.091
30000	113.33	144.20	4.71	6.99	0.121	0.090
40000	115.58	151.58	4.69	7.00	0.122	0.095
60000	116.52	161.63	5.65	7.27	0.110	0.100
180000	133.24	229.47	6.04	9.49	0.110	0.102
360000	154.34	248.01	6.27	11.28	0.110	0.099

Foam recovery decreases slightly with the increase of speed of loading on both directions, being a little bit greater on direction 1 as 13-11%, compared to 11-10% on direction 3.

For the three temperatures of testing the mechanical properties obtained on directions 1 and 3 are recorded in Table 11, respectively Table 12.

Table 11

Compression mechanical properties on direction 1 for the foam of density 200 kg/m^3.

Speed of testing [mm/min]	Modulus of elasticity [MPa]			Maximum stress [MPa]			Foam recovery [-]		
	-60 [°C]	23 [°C]	80 [°C]	-60 [°C]	23 [°C]	80 [°C]	-60 [°C]	23 [°C]	80 [°C]
2	139.15	86.88	79.87	7.21	3.30	2.50	0.144	0.126	0.179
54	153.76	94.76	85.46	8.19	3.67	2.91	0.121	0.122	0.176
500	163.95	105.75	93.41	8.67	3.89	3.26	0.111	0.121	0.179
6000	208.32	109.14	96.07	9.05	4.35	3.69	0.104	0.119	0.183
20000	196.57	105.93	99.12	9.41	4.57	3.99	0.099	0.122	0.184
40000	208.58	115.58	99.24	9.52	4.69	4.24	0.101	0.122	0.182
60000	242.58	116.52	100.26	9.53	5.65	3.75	0.112	0.110	0.193
180000	322.49	133.24	137.35	12.66	6.04	5.09	0.105	0.110	0.190
360000	379.21	154.34	171.49	14.79	6.27	7.00	0.111	0.110	0.183

Table 12

Compression mechanical properties on direction 3 for the foam of density 200 kg/m^3.

Speed of testing [mm/min]	Modulus of elasticity [MPa]			Maximum stress [MPa]			Foam recovery [-]		
	-60 [°C]	23 [°C]	80 [°C]	-60 [°C]	23 [°C]	80 [°C]	-60 [°C]	23 [°C]	80 [°C]
2	196.29	114.56	80.43	9.58	4.91	3.19	0.123	0.105	0.154
54	209.53	114.27	91.19	10.68	5.37	3.80	0.101	0.098	0.156
500	219.74	126.78	91.54	11.17	5.92	4.26	0.086	0.091	0.157
6000	224.95	134.74	99.93	11.80	6.57	4.86	0.075	0.089	0.159
20000	226.03	134.07	109.67	12.32	6.83	5.07	0.077	0.091	0.157
40000	225.81	149.94	119.80	13.49	7.00	5.28	0.081	0.095	0.160
60000	265.79	161.63	109.11	12.83	7.27	4.50	0.089	0.100	0.161
180000	414.33	229.47	153.45	15.94	9.49	6.75	0.084	0.102	0.160
360000	520.91	248.01	183.68	18.10	11.28	8.87	0.082	0.099	0.169

In Tables 11 and 12 above, on both directions 1 and 3, the modulus of elasticity decreases with the increase on temperature at each speed of testing, but increases with the increase of the speed at each temperature. Let's say at 6 m/s it is on direction 3 compared with direction 1 greater with: 37.4% at -60 °C, 60.7% at 23 °C, and with 7.1% at 89 °C. Generally, the smaller differences for the moduli are obtained at 80 °C. In fact at 23 °C and 80 °C the corresponding values at each speed of testing are not so much different on directions 1 and 3, especially on direction 1.

As mentioned (Figs. 17 and 18) maximum stress is greater on direction 3 than on direction 1, and decreases with the increase of temperature at each speed (Tables 11 and 12).

Foam recovery is increasing with the increase of temperature at each speed and is greater on direction 1 than on direction 3 (Tables 11 and 12). At temperatures of -60 °C and 23 °C the recovery is about the same on both directions, but is greater at 80 °C.

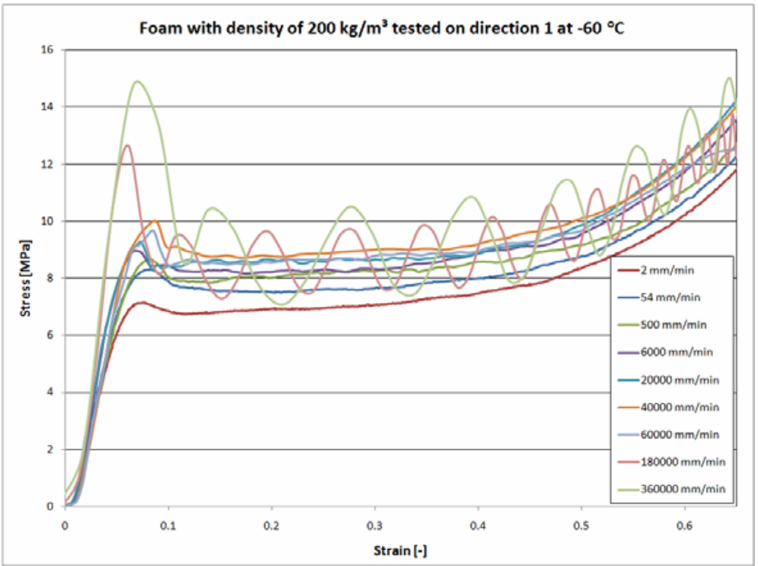

Fig. 19 – Selected stress-strain diagrams in compression on direction 1 at -60 °C (200 kg/m^3).

As seen in Figs. 19 and 20 (-60 °C and 80 °C) for tests done on direction 1 for some selected speeds, yielding shows some hardening for both temperatures and is produced in between 7-9 MPa at -60 °C, and 2-4 MPa at 80 °C. For same temperatures on direction 3 (Figs. 21 and 22) yielding is in between 9-12 MPa at -60 °C, and 3-5 MPa at 80 °C. So, on one hand the increase of temperature reduces the yielding plateau average value, and on the other hand on direction 3 these values are greater than on direction 1. On direction 3 at -60 °C the foam behaves in a "fragile" manner as the walls of the cells break suddenly, especially when speed of testing is increased – the curves show, as seen, many fluctuations.

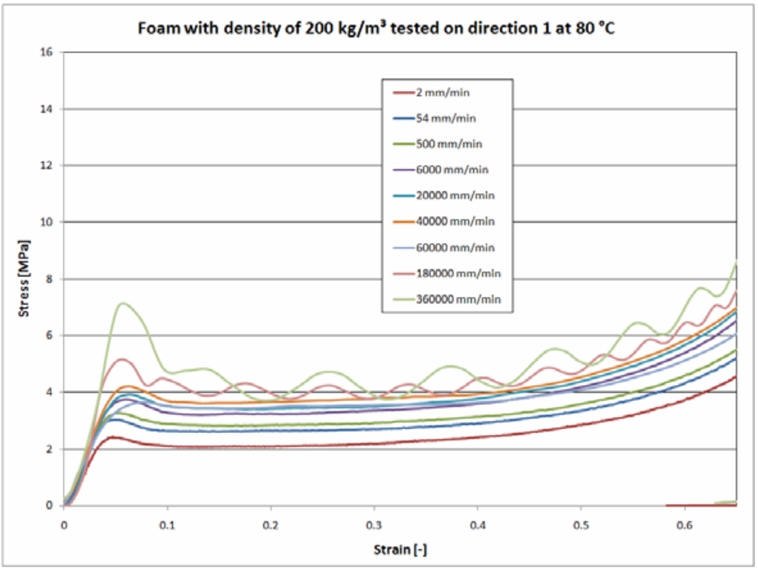

Fig. 20 – Selected stress-strain diagrams in compression on direction 1 at 80 °C (200 kg/m^3).

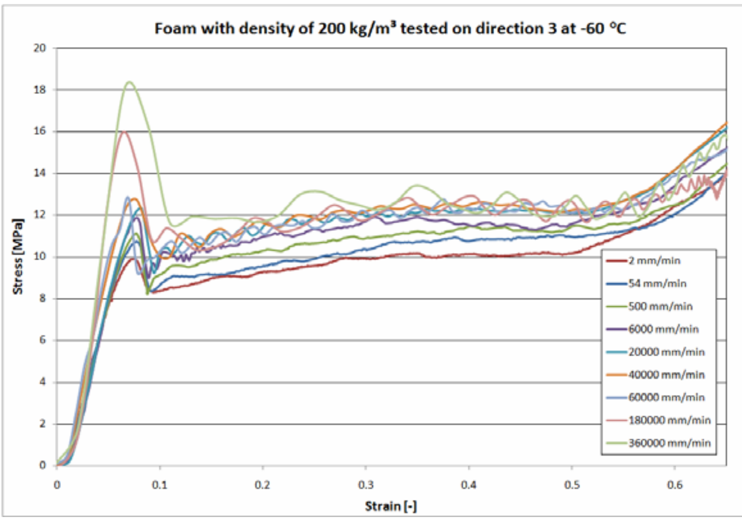

Fig. 21 – Selected stress-strain diagrams in compression on direction 3 at -60 °C (200 kg/m^3).

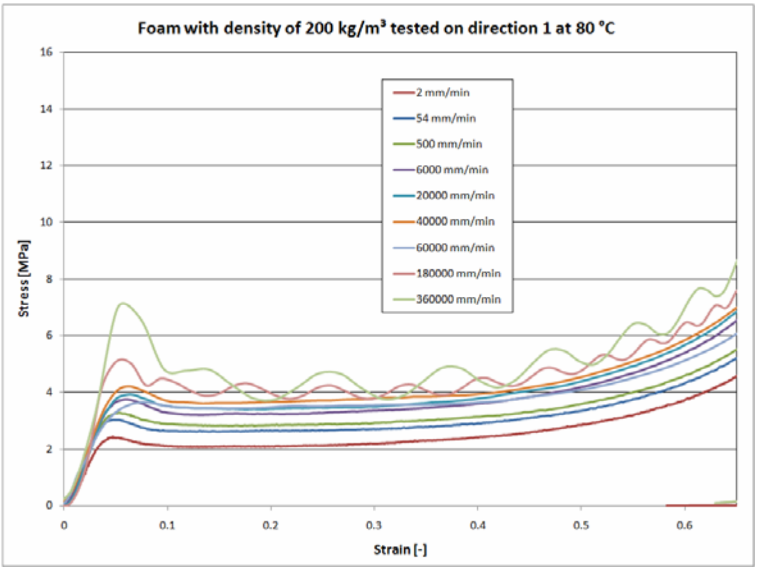

Fig. 22 – Selected stress-strain diagrams in compression on direction 3 at 80 °C (200 kg/m^3).

Another problem which was analyzed is concerning the possible improvement of the mechanical properties if the foam lateral surfaces (which are perpendicular to the rise direction, respectively thickness of the plate from which specimens are cut) are impregnated with epoxy or polyester resin. Therefore compression is done in fact on direction 1. The impregnation is done making a thin layer by brushing the surface in open air without any vacuum control. Figs. 23 and 24 show the stress-strain curves at 23 °C for all testing speeds. Both curves look quite similar, with a slight increase of the stress yielding when epoxy is used to impregnate the surfaces. Table 13 gives a general overview of the differences when the two resins are used to impregnate the 200 kg/m^3 foam. Modulus of elasticity and maximum stress (at yielding) are greater when epoxy impregnation is used.

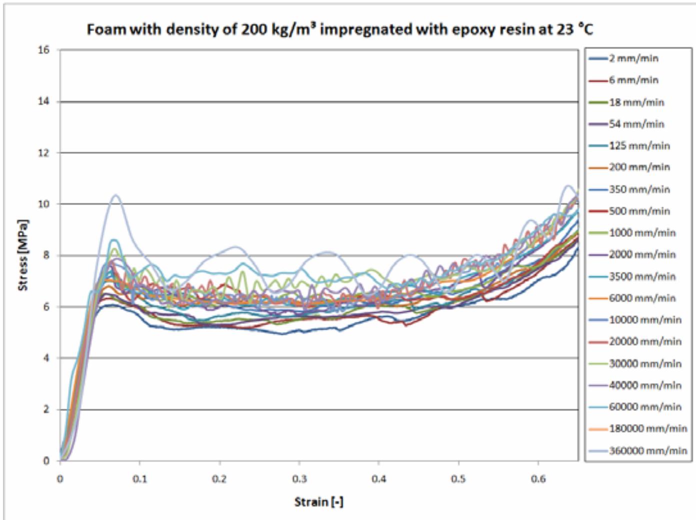

Fig. 23 – Stress-strain diagrams in compression for foam impregnated with epoxy resin at 23 °C.

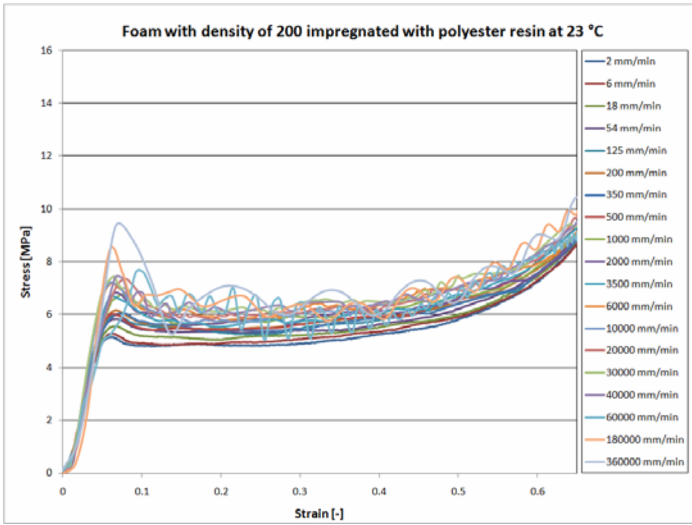

Fig. 24 – Stress-strain diagrams in compression for foam impregnated with polyester resin at 23 °C.

In more detail, from Table 14 – epoxy resin and Table 15 – polyester resin, it is clear that the modulus of elasticity is increased at all temperatures and all speeds of loading when epoxy is used. Again modulus is decreasing when the temperature of testing is increasing. Maximum stress at yielding is significantly increased when epoxy is used at a temperature of testing of -60 °C, but is not much different at 23 °C and 80 °C when using epoxy or polyester resins for impregnation. Foam recovery is almost the same for all temperatures and speeds of testing either of the resins is used.

Table 14

Influence of temperature and speed of loading on the 200 kg/m^3 foam impregnated with epoxy resin.

Speed of testing [mm/min]	Modulus of elasticity [MPa]			Maximum stress [MPa]			Foam recovery [-]		
	-60 [°C]	23 [°C]	80 [°C]	-60 [°C]	23 [°C]	80 [°C]	-60 [°C]	23 [°C]	80 [°C]
2	246.37	156.08	98.91	11.76	6.16	2.68	0.136	0.126	0.187
54	279.22	165.26	103.35	12.60	6.68	3.33	0.115	0.121	0.188
500	310.07	188.35	108.00	12.79	7.29	3.84	0.101	0.123	0.189
6000	338.50	199.68	120.67	14.25	7.70	5.07	0.098	0.122	0.189
20000	341.09	189.90	128.62	14.38	7.88	5.35	0.092	0.119	0.191
40000	376.33	198.19	132.20	14.55	8.40	5.42	0.090	0.136	0.185
60000	369.42	200.00	130.35	15.26	8.55	5.43	0.100	0.109	0.196
180000	483.11	252.82	214.52	21.33	8.99	6.65	0.108	0.109	0.191
360000	596.82	246.23	225.87	26.47	10.35	8.14	0.094	0.106	0.188

Table 15

Influence of temperature and speed of loading on the 200 kg/m^3 foam impregnated with polyester resin.

Speed of testing [mm/min]	Modulus of elasticity [MPa]			Maximum stress [MPa]			Foam recovery [-]		
	-60 [°C]	23 [°C]	80 [°C]	-60 [°C]	23 [°C]	80 [°C]	-60 [°C]	23 [°C]	80 [°C]
2	226.16	122.67	78.58	9.28	5.015	2.29	0.134	0.129	0.192
54	243.97	159.35	86.45	9.45	5.766	2.79	0.116	0.124	0.191
500	281.66	164.60	98.17	10.53	6.28	3.21	0.101	0.124	0.190
6000	289.59	190.20	115.10	11.25	7.18	3.88	0.095	0.123	0.191
20000	294.97	157.23	113.79	8.00	7.18	4.16	0.095	0.119	0.195
40000	325.17	173.31	118.37	10.28	7.29	4.45	0.095	0.149	0.194
60000	341.53	181.95	124.32	10.95	7.38	4.76	0.102	0.114	0.209
180000	417.42	197.50	156.85	10.78	8.26	6.04	0.104	0.112	0.198
360000	468.03	178.52	180.84	10.59	9.63	7.60	0.095	0.110	0.198

Figs. 25 and 26 look in more detail at what happens at -60 °C for the use of these resins at selected speeds of testing. For the impregnation with the epoxy resin (Fig. 25) when yielding starts it is a significant difference between the upper a lower yield limit; on the contrary, for polyester impregnation (Fig. 26) yielding is produced at a steady stress. Both curves show clearly a yielding plateau as compared to the 23 °C curves (Figs. 23 and 24) for which hardening occurs.

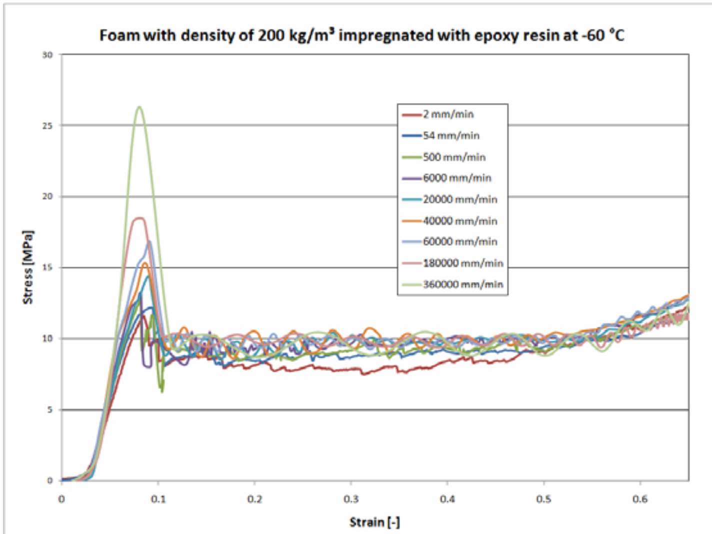

Fig. 25 – Selected stress-strain diagrams in compression for foam impregnated with epoxy resin at -60 °C.

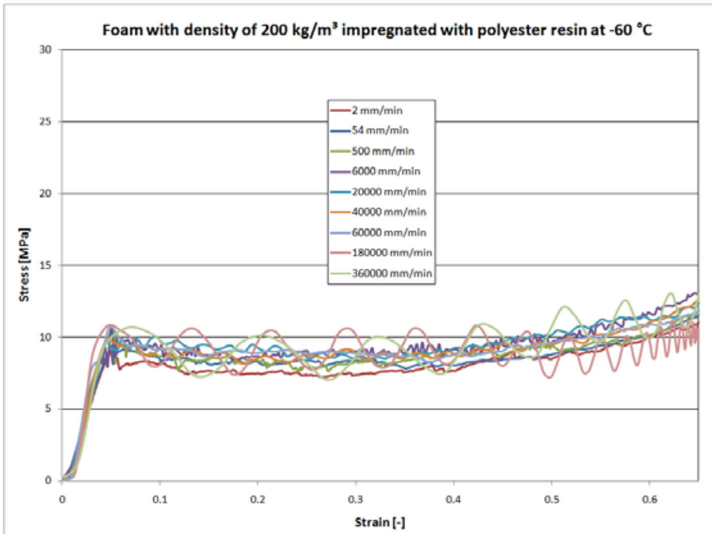

Fig. 26 – Selected stress-strain diagrams in compression for foam impregnated with polyester resin at -60 °C.

At 80 °C in Fig. 27 for epoxy and Fig. 28 for polyester, the selected stress-strain diagrams drawn at the same speeds of testing as before indicate a behaviour of the impregnated foam with hardening in the yielding region as for 23 °C.

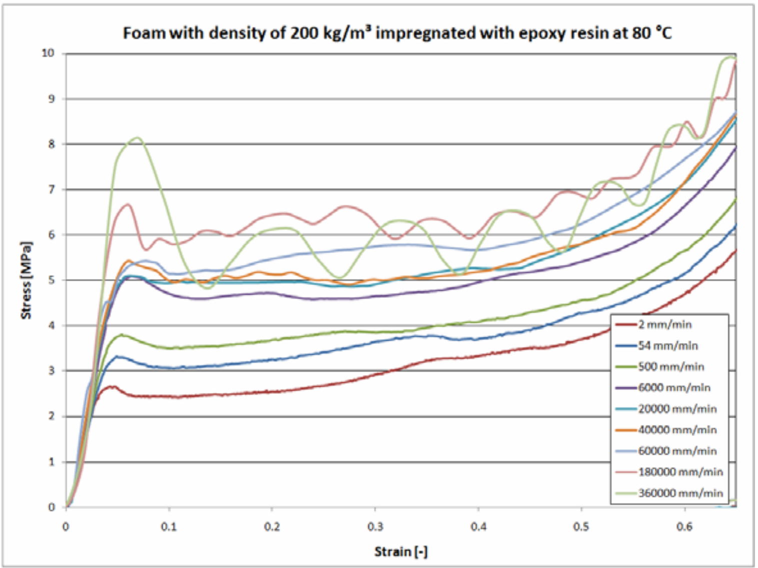

Fig. 27 – Selected stress-strain diagrams in compression for foam impregnated with epoxy resin at 80 °C.

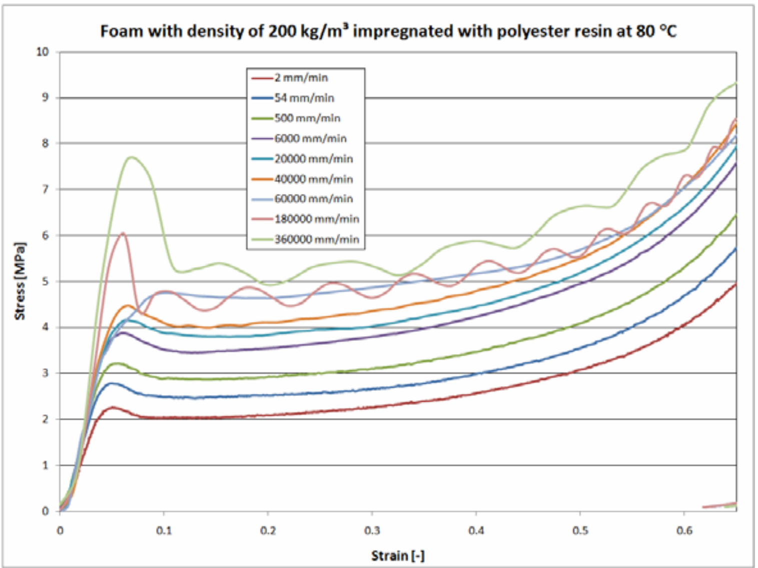

Fig. 28 – Selected stress-strain diagrams in compression for foam impregnated with polyester resin at 80 °C.

The differences which were noticed at -60 °C in between the use of the two resins at the onset of yielding now disappear. At this temperature the curves show the influence of the speed of testing and are clearly separating in the stress-strain plots. Yielding stress grows in average from 2-2.5 MPa at 2 mm/min to 5-6 MPa at speeds of 1-3 m/s. At 23 °C (Figs. 23 and 24) yielding stress is about 5-7 MPa being greater in average when epoxy is used for impregnation.

6. CONCLUSIONS

Traction and compression tests on polyurethane foams of three densities were done and results were presented.

In traction, for the 93 kg/m^3 and 200 kg/m^3 densities, the low temperature of -60 °C made very fragile foams behaviour compared to the ductile behaviour at 80°C. For the 35 kg/m^3 foam the differences for the extreme temperatures are reduced in the characteristic curves up to 500 mm/min (Figs. 2, 3, 4). For each of the densities the moduli of elasticity decrease about 2 times or even more (especially for the 200 kg/m^3 foam) when the temperature is increased from -60 °C to 80 °C. For each temperature of testing and density of the foam when the speed of loading is increased from 2 to 500 mm/min the elongation at failure is somehow reduced, but the modulus of elasticity and maximum stress remain mainly constant.

A considerable amount of tests made available data for the testing in compression of polyurethane foams of three densities at different temperatures and at speeds of testing starting from 2 mm/min up to 6 m/s. Attention is given to the direction on which testing is done, that is rise direction or direction 3 and in-plane direction or direction 1.

Foam with density 35 kg/m^3 is behaving in overall differently compared to the foams with densities 93 kg/m^3 and 200 kg/m^3. This foam is very sensitive to the increase of speed and temperature of testing when modulus of elasticity is compared. On direction 3 moduli are always greater than on direction 1. When speeds increase from 2 mm/min to 6 m/s moduli are increased in average about 3-4 times when temperature covers the domain from -60 °C to 80 °C. Maximum stress decreases slightly with the increase of temperature for each testing speed, but increases at each temperature level with the increase of speed of testing. Foam recovery varies in an opposite way: increases with the increase of temperature for each testing speed, but somehow decreases at each temperature level with the increase of speed. Maximum stress is greater and foam recovery is smaller for all testing speeds and all test temperatures (values compared for the same parameters) on direction 3 than on direction 1. At all temperatures and testing speeds foam recovery is 4-9% on direction 1 (excepting the speed of 2 mm/min) and 3-6% on direction 3 being much smaller than for the foams of 93 and 200 kg/m^3. This means that the energy absorption is greater for this grade of foam and damage is produced to a higher extend.

For the foam of 93 kg/m^3 the modulus of elasticity is about the same on both directions being in average close to 10 times greater than for the foam of 35 kg/m^3. At 23 °C for all temperatures the moduli are generally greater (but not too different) on direction 1 than on direction 3, mainly when speed of testing increases. Maximum stress is close to one order of magnitude greater than for the density of 35 kg/m^3. Foam recovery is decreasing with the increase of speed of loading from about 11-13% to 7-9% and is greater than for the foam of 35 kg/m^3, but about the same on both directions 1 and 3. Foam recovery increases with the increase of temperature being 8-9% at -60 °C and 25-30% at 80 °C.

The 200 kg/m^3 foam has at 23 °C moduli of elasticity greater on direction 3 than on direction 1 with about 20-30%, difference increasing with the increase of testing speed up to 60% at 6 m/s. On both directions the modulus of elasticity decreases with the increase on temperature at each speed of testing, but increases always with the increase of the speed. Foam recovery decreases slightly with the increase of speed of loading on both directions, being a little bit greater on direction 1 as 13-11%, compared to 11-10% on direction 3 at 23 °C. It is increasing with the increase of temperature at each speed and is greater on direction 1 than on direction 3. At temperatures of -60 °C and 23 °C the recovery is about the same on both directions as 8-12%, but is greater at 80 °C being 16-19%.

If the faces of the plates from which specimens are manufactured are impregnated with epoxy or polyester resins, the epoxy resin is preferable as it improves considerably the mechanical properties of the foam. At 23 °C, comparing Table 10 (impregnated foam) and Table 13 (direction 1 non-impregnated) the growth of the moduli of elasticity at different testing speeds is significant; let's say at 1 m/s using epoxy we increase the modulus with about 70% and at 10000 mm/min the increase is 85%. Maximum stress at yielding can be even twice bigger. However, foam recovery is the same as the layer of the resin is destroyed after foam is crushed. The modulus of elasticity is decreasing when the temperature of testing is increasing, as happens for the non-impregnated foam. Maximum stress at yielding is significantly increased when epoxy is used at a temperature of testing of -60 °C, but is not much different at 23 °C and 80 °C when using epoxy or polyester resins for impregnation. Foam recovery is almost the same for all temperatures and speeds of testing either of the resins is used, being about 10 % at -60 °C and 19% at 80 °C; almost same values were obtained for the simple foam on direction 1.

Acknowledgements. The research done by the PhD student eng. Dragoş Alexandru Apostol has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement POSDRU/6/1.5/S/16.

Both authors are grateful to Professor Gerald Pinter for the help and guidance given to the first author while using the equipment and testing facilities from the Polymer Competence Centre Leoben (PCCL) at the University of Leoben, Austria.

Received on: November 18, 2011

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