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Response of a Rigid Polyurethane Foam in Compression Testing

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Abstract

Polyurethane foam with density 200 kg/m^3 was tested in compression after impregnating the outer surface with epoxy resin, polyester resin, and exposing it at room temperature to air and light. Secondly, the influence of speed of loading from 2 mm/min up to 54 mm/min on the crush response of the rigid foam is analyzed. The presence of the resins improves the compression properties, especially the epoxy one. The influence of long time exposure to air and light is evident by damaging the polyurethane foam. The simple polyurethane foam behaves better in compression on the rise direction than on the transversal one.

Key words: *rigid polyurethane foam, compression, face impregnation, testing speed, microstructure*

Overview of foam behaviour characterization

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 subject 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. The effects of core shear properties on deflection, buckling, and stress state for the sandwich composite are crucial. 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].

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 attracted attention from engineers and researchers. The mechanical response of rigid PU foams under compression in the rise and transverse direction gives different deformation responses in different directions which are attributed to the anisotropy in the internal cellular structure. A theoretical analysis employing the concept of deformation bands was proposed to describe the deformation localization.

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, which can be used with standard finite element codes and is computationally efficient for modelling the progressive crush of foam. However, the approach assumes smooth stress gradients in the material, which implies 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 and this leads 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 foam. 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] recently 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 elastic modulus of the foam is non-linear due to air pressure in the foam [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 expansion stage realised. Only full foamed sandwiches possess material parameters with good reproducibility.

Investigations of foam behaviour at national level

Under the PN1 national plan a joint research programme started in 2006 [13], having University POLITEHNICA of Bucharest and POLITEHNICA University of Technology Timisoara as partners. Other tests were done later at the Lublin University of Technology – Poland. When testing different composite materials a special attention was given to the testing of 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. At that time we tested the Coremat core in traction, and polyurethane cores 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 to see what differences may appear [14-17].

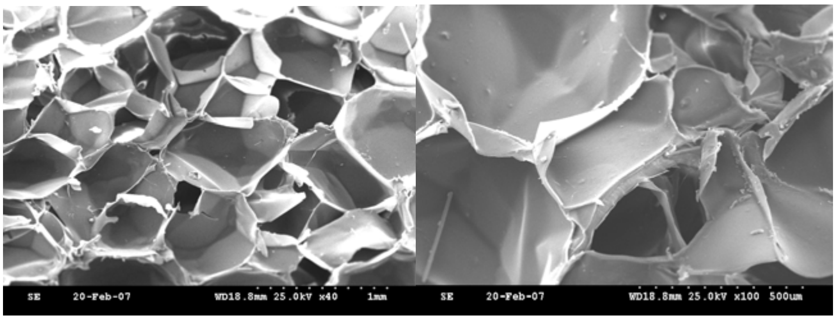
The effect of impregnation of the closed cell polyurethane foam with density 200 kg/m^3 on mechanical properties of foams was presented by Marsavina et al. [18-20]. Three approaches were considered for the characterization of PU foams: experimental investigations, micromechanical models and finite element analysis. Fracture mechanics testing in mode I for different densities of polyurethane foams was discussed in [21, 22].

Microstructural evaluation of foam morphology

The SEM investigations of different types of foams were done by using an equipment HITACHI S2600 which has also a dispersive energy analysis system [13]. The SEM examinations established the morphology, the dimensions and arrangement of the micro structural entities as to correlate them with the micro structural characteristic properties. Untested and tested specimens were analysed as to be able to observe the changes in the microstructure at the very intimate level. As the foams are non-conductive from electrical point of view all specimens were covered with thin layer of a silver of thickness as 5-6 A. By also taking into account the high level of light chemical elements (C,H,O, etc.), the only foam on which was done a local qualitative microanalysis with X rays was the Coremat core.

Only as examples, we show the analyses obtained on the PVC foam, the Coremat core, and the polyurethane foam.

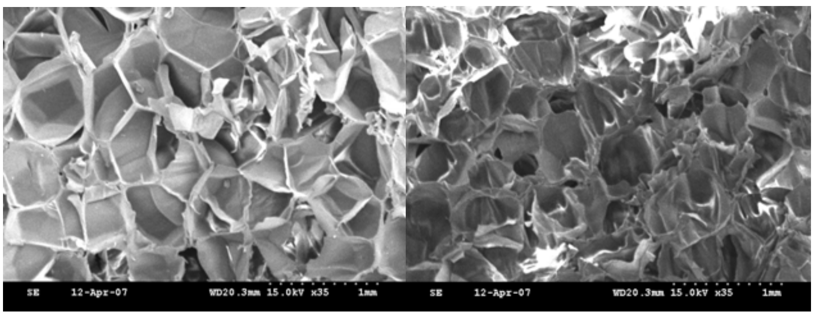
The untested PVC foam specimens have voids of about 200-500 μm and a wall thickness of 3-4 μm; these are smooth with no striations. Figure 1 shows the microstructure of the foam.



a) b)

Fig. 1. PVC foam; voids have dimensions in between 200-500 μm.
Wall thickness of 3-4 μm (a) x40; b) x100)

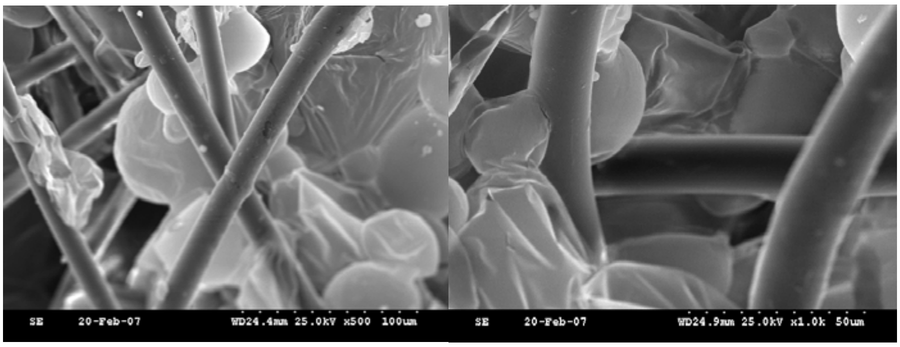
After being tested in compression the specimen behaved mostly elastically as the voids kept their polyhedral shape after the removal of the loading, but reduced their size. However the walls of the cells showed some buckling in a consistent way for all tested specimens (Fig. 2).



a) b)

Fig. 2. PVC foam: a) untested; b) tested in compression.
Buckling of walls due to loading (x35)

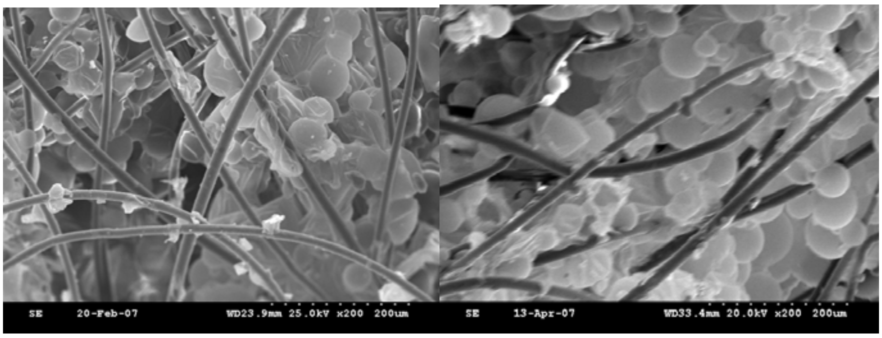
For the Coremat core (very much used for sandwich composites) the fibres of diameter 10 -12 μm have a random orientation with the spaces in between fibres partially occupied by rounded particles, some of them even spherical (Fig. 3). Qualitative X rays analysis showed chemical elements as Si, Cl, Ti with traces of Cu.



a) b)

Fig. 3. Microstructure of Coremat. Fibrous structure with voids filled with rounded particles, some of them spherical: a) x500; b) x1000

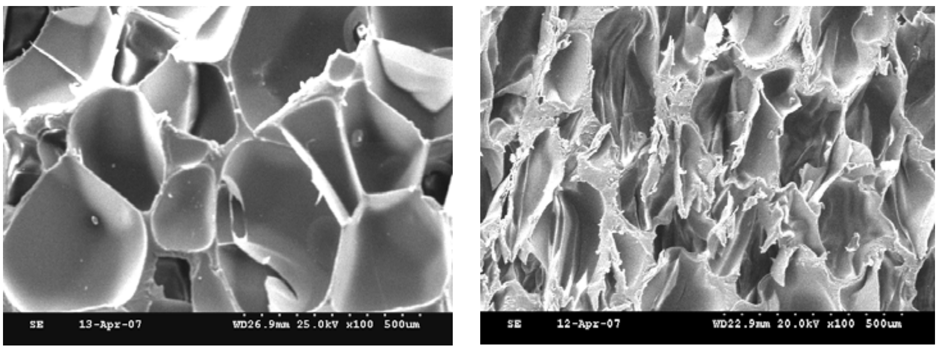
The loading in traction gives the extension of the fibres and their orientation along the direction of loading, the separation of the conglomerations of spherical particles and the failure of the fibres together with the formation of bigger microcracks. In figure 4, pictures of a) untested and b) tested specimens are not taken in the same location, therefore the inclination of fibres is different. Such a specimen could be tested only in traction as the delivered material is of thickness of about 3 mm.



a) b)

Fig. 4. Microstructure of Coremat: a) untested; b) tested in traction, for same magnification (x200)

For the polyurethane foam of density 200 kg/m^3 the closed cells have a polyhedral morphology with dimensions in between 100-300 μm, and wall thickness of about 5 μm. Tests in traction and compression (Fig. 5 a), b)) reveal deformation of cells, especially in compression.



a) b)

Fig. 5. Deformed cells of polyurethane foam: a) traction x 100; b) compression x 100

In compression the cells deform strongly, and wall cell thickness doesn’t remain constant (Fig. 6, right x 500).

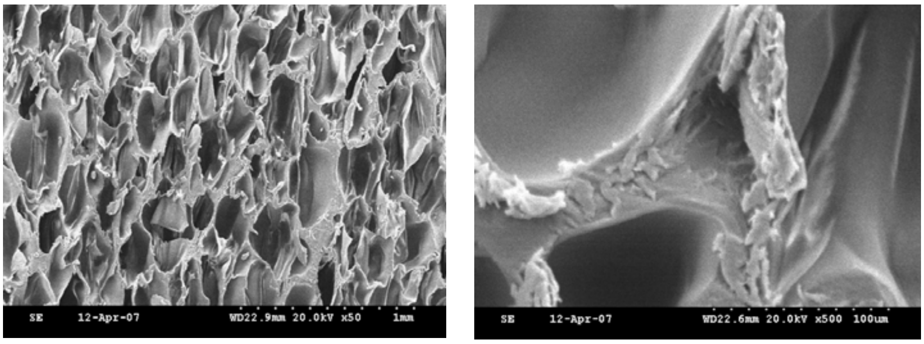


Fig. 6. Deformed cells of polyurethane foam in compression (left x 50, right x 500)

Compression testing of polyurethane foams

A Lloyd Instruments LRX *Plus* Series materials testing machine comes together with the NEXYGEN*Plus* software. Closed cell polyurethane foams with density densities of 40 kg/m^3 and 200 kg/m^3 were tested in traction, compression, and three-point bending. For the bending of the foam with density 200 kg/m^3 we have also impregnated it with polyester and epoxy resins to see what differences may appear in the improve of the mechanical performances. In three-point bending we have obtained some interesting patterns of crack propagation in the foams as: branching, gradual turning and zigzag stable propagation [13-18].

More recently, we concentrated on the compression testing of the foam with density 200 kg/m^3 by studying two influences: 1) impregnation of the outer surface with epoxy resin, polyester resin, and exposure at room temperature to air and light for about three years on the free edges of the polyurethane plate from which specimens are cut; 2) influence of speed of loading on the crush response of the rigid foam, from 2 mm/min up to 54 mm/min. Engineering stress-strain curves are drawn for all tests.

Thickness of the plate is 12 mm – rise direction, notated 3 – and the in plane dimensions about 300 x 400 mm – transverse directions, notated 1. Cubic specimens are cut. Some of the plates tested after they were made are considered *simple* (S). Other plates were initially impregnated on all surfaces with *epoxy* (E) or *polyester* (P) resins. Therefore some of the specimens cut along the perimeter of the plate had *three exposed edges*. Other plates were exposed a long time, that is aged, and had *three air exposed edges* (A). Specimens are tested along directions 3 and 1. The corresponding tests are named:

1. Epoxy direction 1
2. Epoxy direction 1 – three exposed edges
3. Polyester direction 1
4. Polyester direction 3 – three exposed edges
5. Simple direction 1
6. Simple direction 3
7. Simple direction 3 – three air exposed edges
8. Comparison on direction 3: simple – three air exposed edges
9. Comparison on direction 3: epoxy – polyester – three air exposed edges
10. Comparison on direction 1: epoxy – polyester – simple

Tests are done by taking into account specifications given in [23], although cubic specimens are smaller in dimensions. As mentioned, the outer surfaces are covered for some of the tests with epoxy or polyester resins. In figure 7 is shown, just as an example, a specimen impregnated with epoxy. Thickness of the layer is in between 100-273 μm, and on the surface different sizes of voids can be observed, up to about 440 μm.

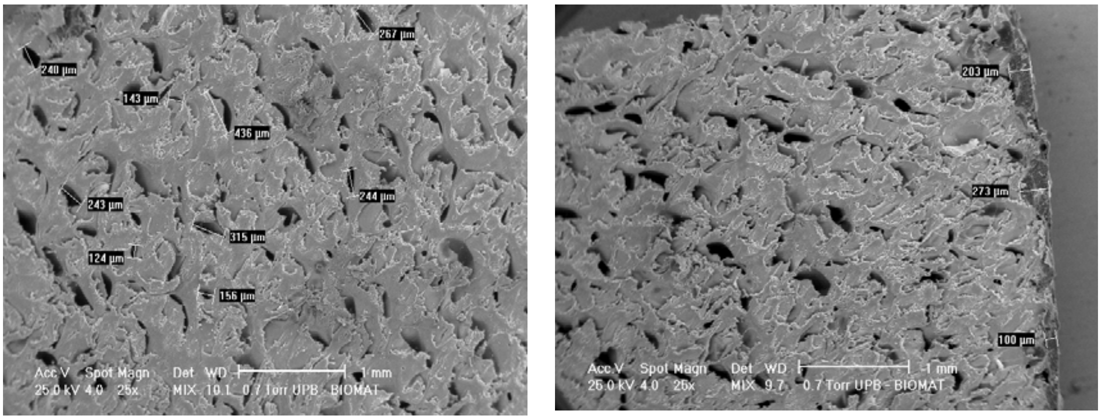
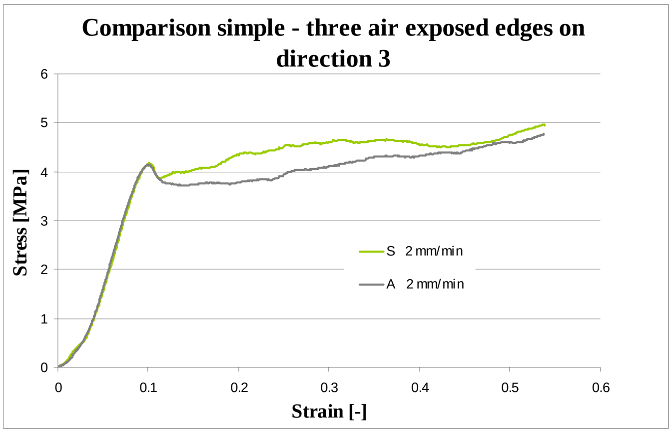
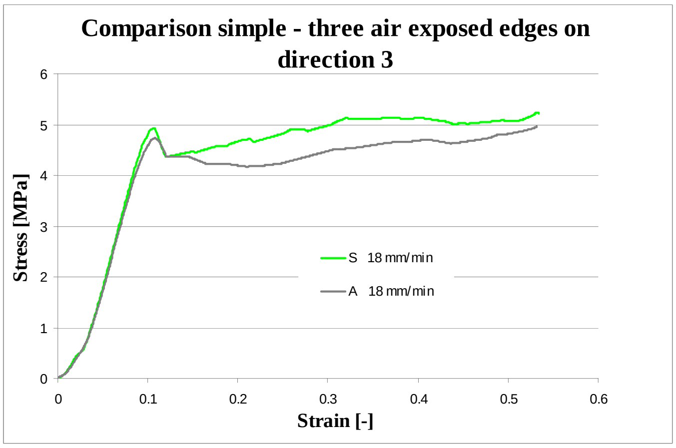


Fig. 7. Layer of epoxy on the outer surface of the polyurethane foam

Our main interest is to compare the behaviour of the rigid foam with epoxy and polyester impregnated layers in the direction of the rise – direction 3, and in transversal direction – direction 1. On the other hand the influence of the exposure to air and light is studied. Hereby are presented comparisons only for three different speeds of loading: 2, 18, and 54 mm/min.

In figure 8 is presented the influence of long time exposure to air and light (A), compared to "fresh" foam (S) in direction 3 – as being the rise direction of the foam. Clear differences appear in the plateau region; at these small speeds of loading the initial yield stress is about the same.





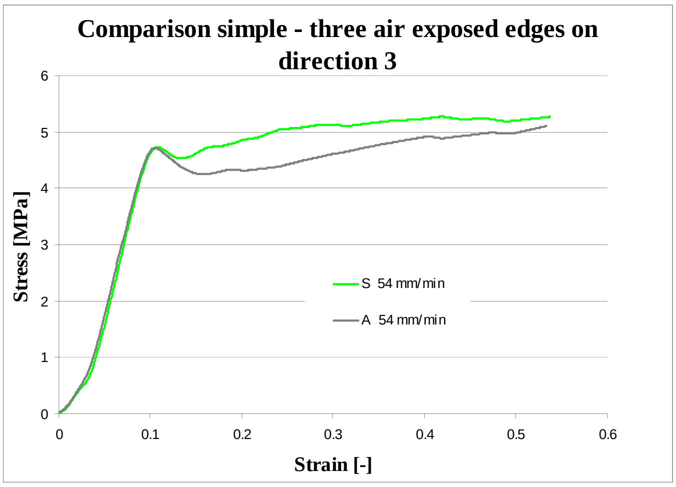
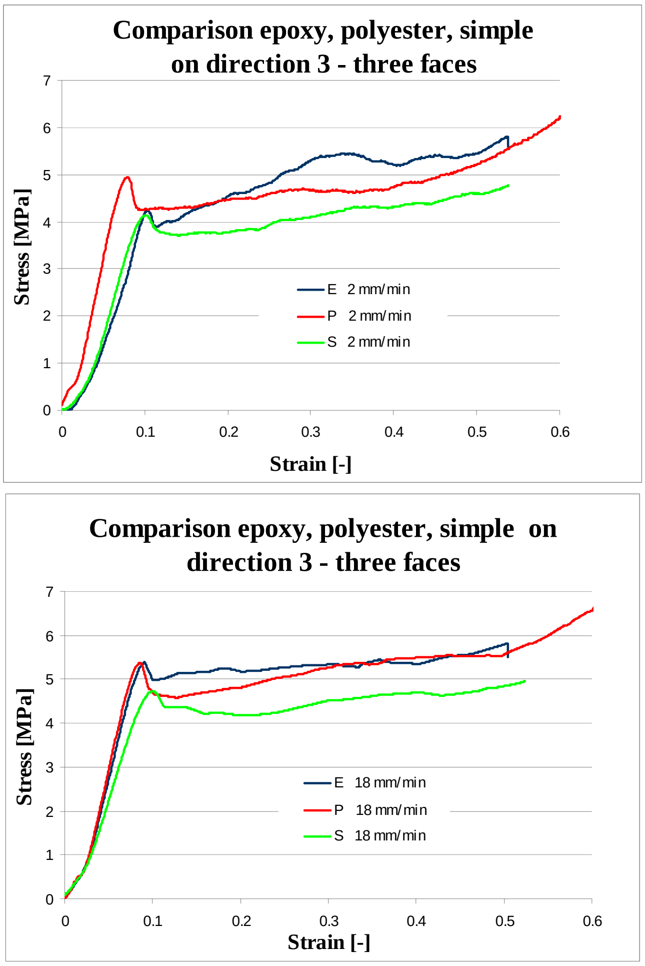


Fig. 8. Degradation of foam in rise direction with the exposure to air

If compression in produced in the rise direction 3 for epoxy (E), polyester (P) and simple specimens (S) in specimens cut from the edge of the polyurethane foam plates, there are three faces which have been exposed to impregnation; in fact one face of the specimens will be parallel to the through thickness direction of loading 3 (Fig. 9).



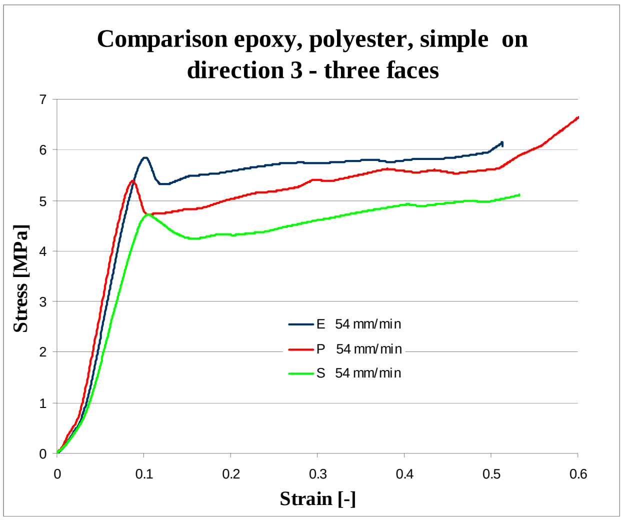
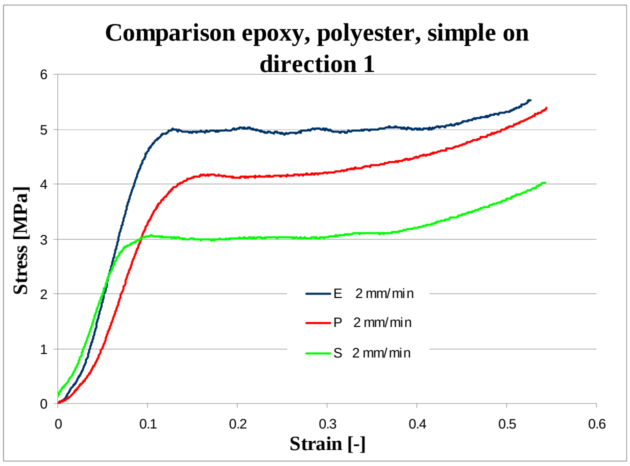
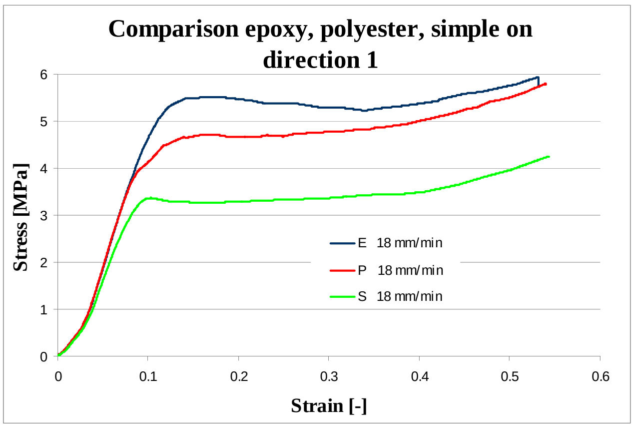


Fig. 9. Behaviour of epoxy, polyester, and simple specimens on rise direction 3

Clearly the presence of the resin improves the compression properties, especially the epoxy one. Increase of speed of loading separates more the stress-strain curves in the plateau region, plastic yielding in compression. The initial yield stress increases from simple, to polyester, and to epoxy impregnated foams, especially for higher speed of loading presented here as 54 mm/min.

Impregnation of two surfaces parallel to the loading direction are beneficial, improving significantly the compressive response, especially for the epoxy resin. Increase of speed of loading increases a little bit the initial yield stress, especially when resins are used (Fig. 10).





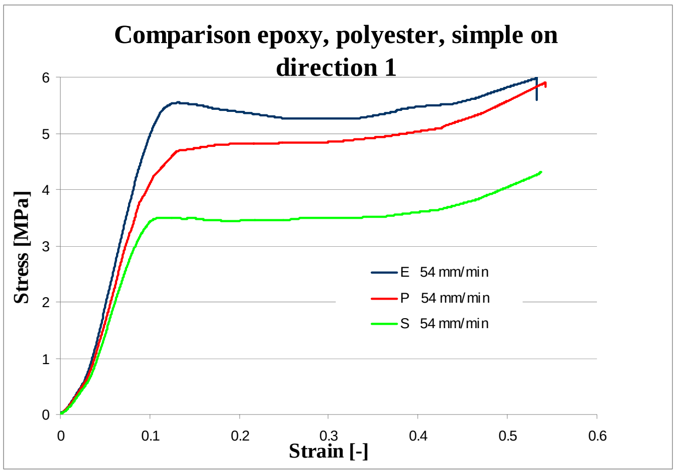
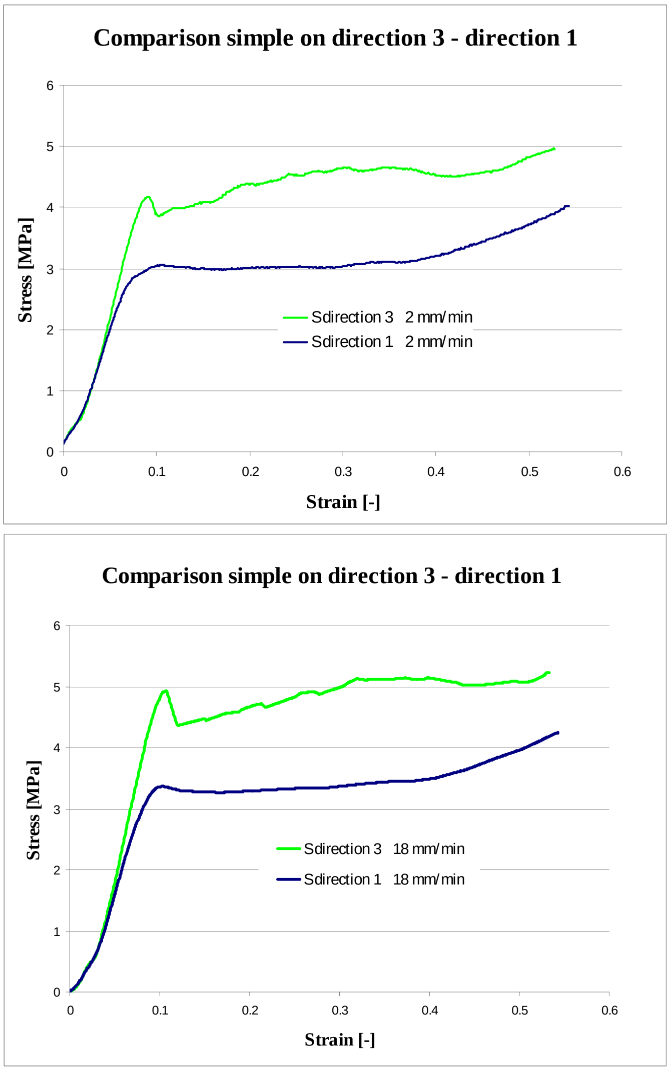


Fig. 10. Behaviour of epoxy, polyester, and simple specimens on transverse direction 1

In transverse direction 1 polyurethane simple foam behaves worse than on rise direction 3, for the same speed of loading (Fig. 11). For all three speeds presented here the comparison keeps its trend. When increasing speed of loading curves shift up for the same direction of loading.



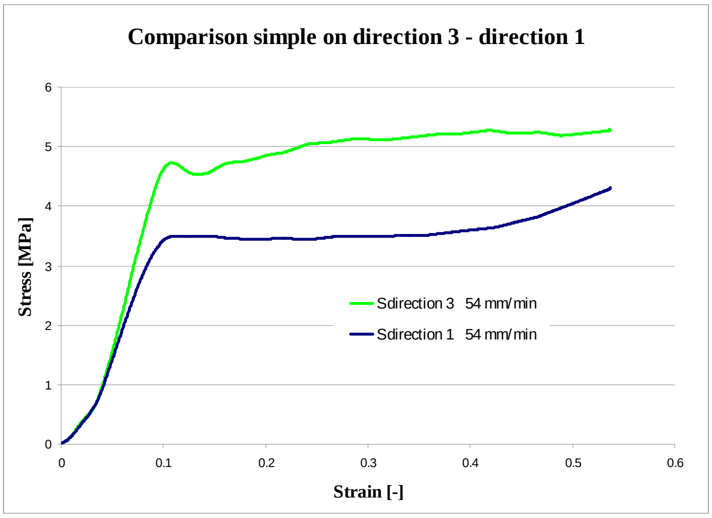


Fig. 11. Behaviour of simple specimens on rise direction 3 and on transverse direction 1

It is to be noticed that in the plateau region on direction 3 the stress-strain curve presents several irregularities, which are to be "smoothed" when the speed of loading increases to 54 mm/min. In the collapse plateau on direction 3 the brittle crushing of the closed cells is evident. In fact, on this direction of compression the plateau shows some elastic buckling and strain hardening as stresses slightly increase.

Conclusions

Compression testing of a polyurethane foam with density 200 kg/m^3 is done by studying two influences: 1) impregnation of the outer surface with epoxy resin, polyester resin, and exposure at room temperature to air and light for about three years on the free edges; 2) influence of speed of loading on the crush response of the rigid foam, from 2 mm/min up to 54 mm/min. The microstructure of closed cells after compression is shown before and after testing.

Cubic specimens are cut out from plates and are notated as: *simple* (S), impregnated on all surfaces with *epoxy* (E) or *polyester* (P) resins – therefore some of the specimens cut along the perimeter of the plate had *three exposed edges*. Other specimens were exposed a long time, and had *three air exposed edges* (A). Specimens are tested along directions 3 and 1.

Clearly the presence of the resin improves the compression properties, especially the epoxy one. The initial yield stress increases from simple, to polyester, and to epoxy impregnated foams, especially for higher speed of loading, as 54 mm/min in this paper.

The influence of long time exposure to air and light (A), compared to simple "fresh" foam (S) in the rise direction of the foam is evident by damaging the polyurethane foam. Clear differences appear in the plateau region; at these small speeds of loading the initial yield stress is about the same. The simple polyurethane foam – not exposed to air and not impregnated with resins – behaves better in compression on the rise direction than on the transversal direction.

Acknowledgements

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Comportarea unei spume rigide din poliuretan la solicitarea de compresiune

Rezumat

Spuma poliuretanica cu densitatea de 200 kg/m^3 a fost solicitata la compresiune dupa impregnarea suprafetei exterioare cu rasina epoxidica, rasina poliesterica si prin expunerea materialului in aer si lumina la temperature camerei pentru o durata lunga de timp. In al doilea rand a fost studiata influenta vitezei de incarcare de la 2 mm/min pana la 54 mm/min asupra comportarii la compresiune a spumei rigide. Prezenta rasinilor imbunatateste proprietatile la compresiune, inspecial cea epoxidica. Influenta expunerii spumei la aer si lumina pe timp indelungat produce in mod evident deteriorarea spumei. Spuma poliuretanica simpla se comporta mai bine la compresiune pe directia de crestere a acesteia decat pe directie transversala.