INFLUENCE OF THE SPEED OF LOADING ON THE RESPONSE OF A RIGID POLYURETHANE FOAM IN COMPRESSION TESTING

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Spuma poliuretanică cu densitatea de 200 kg/m³ a fost solicitată la compresiune după impregnarea suprafeței exterioare cu rășină epoxidică, rășina poliesterică și prin expunerea materialului în aer și lumină la temperatura camerei pentru o durată lungă de timp. A fost studiată influența vitezei de încărcare de la 2 mm/min până la 1000 mm/min asupra comportării la compresiune a spumei rigide.

Prezența răsinilor îmbunătățește proprietățile la compresiune, înspecial cea epoxidică. Influența expunerii spumei la aer și lumină pe timp îndelungat produce în mod evident deteriorarea spumei. Spuma poliuretanică simplă se comportă mai bine la compresiune pe direcția de creștere a acesteia decât pe direcție transversală.

Polyurethane foam with density 200 kg/m³ 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 1000 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.

Keywords: rigid polyurethane foam, compression, surface impregnation, testing speed, microstructure

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 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

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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 each direction 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 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 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] have performed recently 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.

When testing different composite materials a special attention was given to the testing of different grades of foams as [13]: 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].

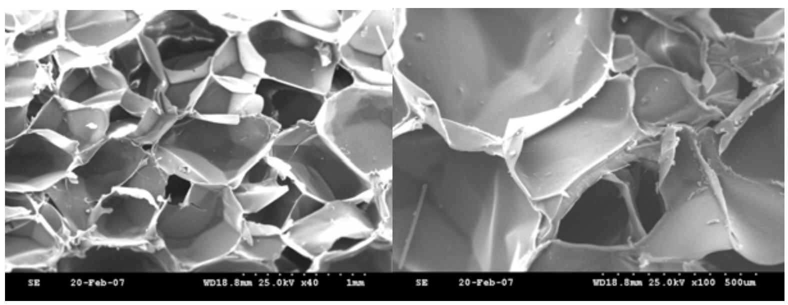
The effect of impregnation of the closed cell polyurethane foam with density 200 kg/m^3 on mechanical properties of foams was presented by Marsavina et al. [18-20]. Three approaches were considered for the characterization of PU foams: experimental investigations, micromechanical models and finite element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

2. 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.

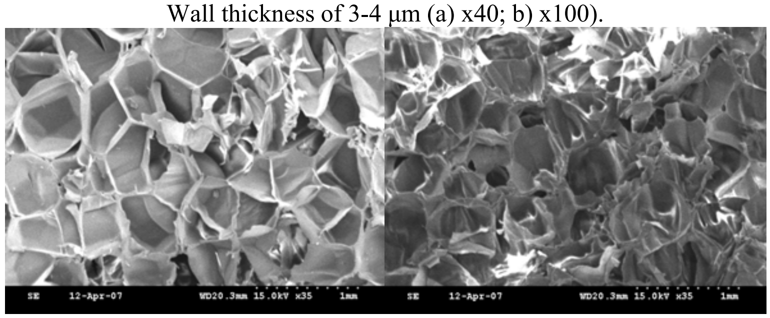
Only as examples, we show the analyses obtained on the PVC foam, and the polyurethane foam. The untested PVC foam specimens have voids of about 200-500 μm and a wall thickness of 3-4 μm; these are smooth with no striations. Figure 1 shows the microstructure of the foam.

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)

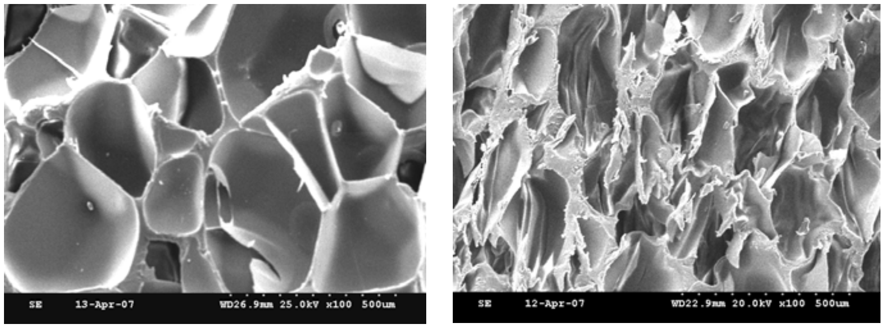
Fig. 1. PVC foam; voids have dimensions in between 200-500 μm.
Wall thickness of 3-4 μm (a) x40; b) x100).



a) b)

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

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. 3 a), b)) reveal deformation of cells, especially in compression.



a) b)

Fig. 3. 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. 4, right x 500).

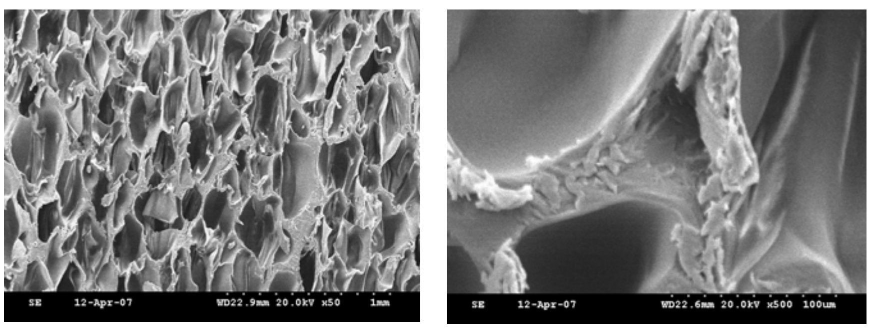


Fig. 4. Deformed cells of polyurethane foam in compression (left x 50, right x 500).

3. 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 1000 mm/min. Engineering stress-strain curves are drawn for all tests. Speeds of loading are: 2, 6, 18, 54, 125, 200, 350, 500, 1000 mm/min. Only for some tests we also used a speed of 750 mm/min.

The rigid polyurethane foam was used for making cubic specimens of 12 mm edge length. This means that the maximum attained strain rate can be 1.39/s. Therefore, our tests have a quasistatic character. However, the influences on the compressive response of the polyurethane foam can be important.

Thickness of the plate is 12 mm – as 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 5 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.

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. For the beginning are presented comparisons only for three different speeds of loading: 2, 18, and 54 mm/min.

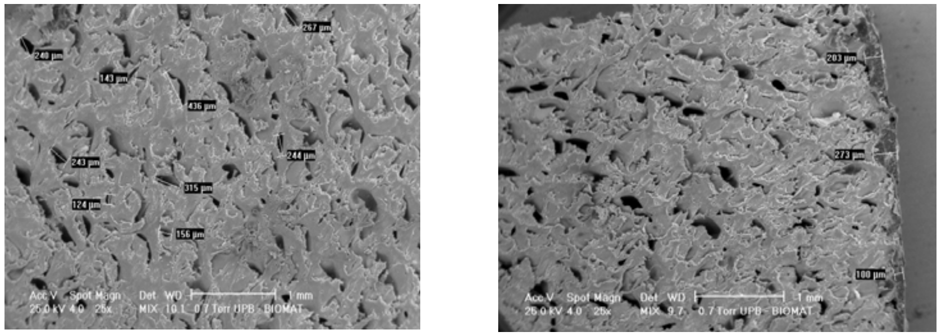
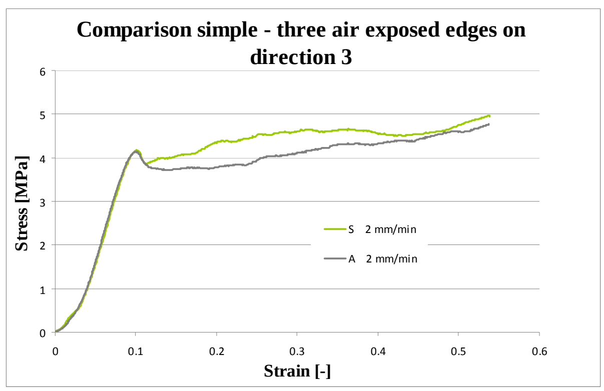
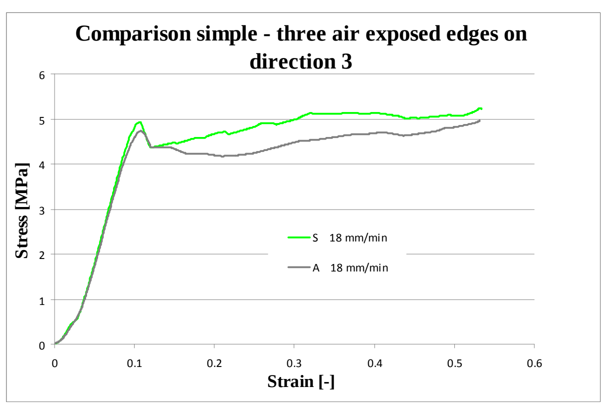


Fig. 5. Layer of epoxy on the outer surface of the polyurethane foam

In Fig. 6 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.





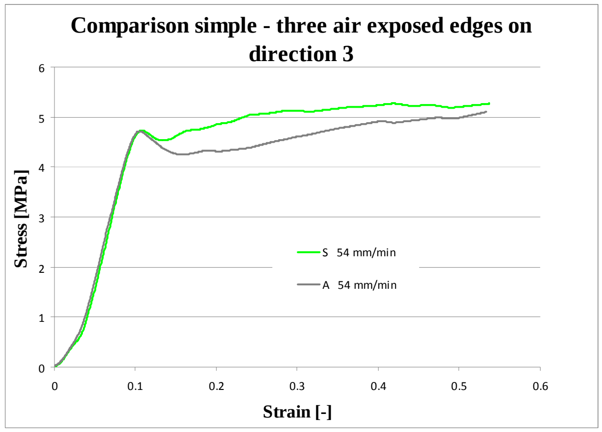
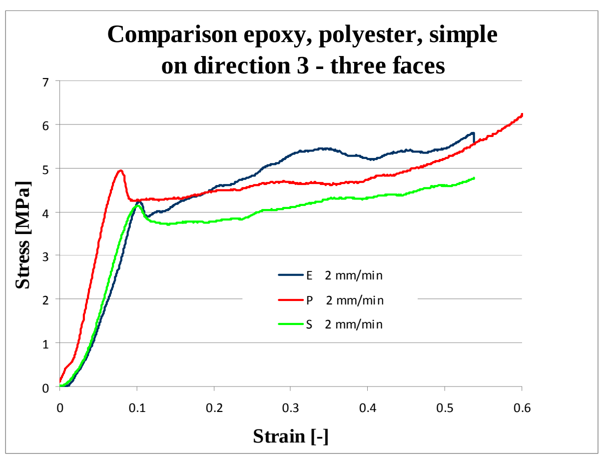
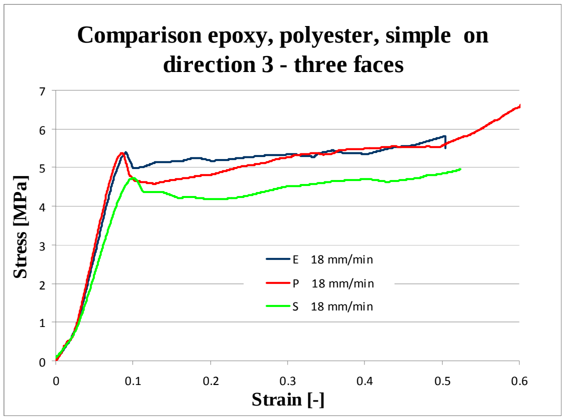


Fig. 6. Degradation of foam in rise direction with the exposure to air.

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 two faces of the specimens will be parallel to the through thickness direction of loading 3 (Fig. 7).





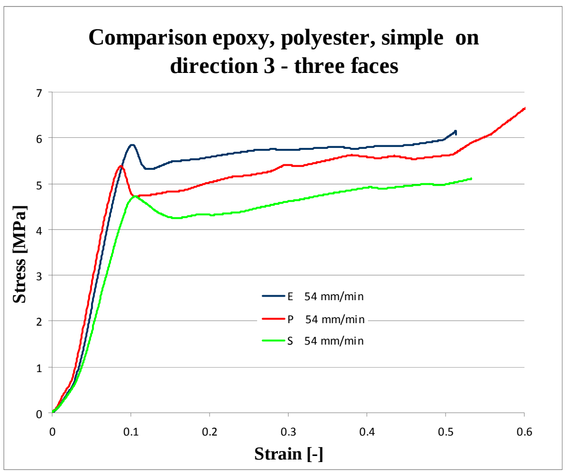


Fig. 7. Behaviour of epoxy, polyester, and simple specimens on rise direction 3.

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.

The mechanisms of the cell behaviour are described in the following. As soon as the compression force/strain reaches a critical value, called the compression failure stress/strain, the cell walls collapse. Cell wall collapse could be caused by cell wall buckling, cell wall breaking and the formation of plastic hinge in the cell wall, or their combination [1]. Cell lock up occurs when all of the air in the cells has been displaced and hence the cells behave in a similar manner to the solid parent material. Then, further deformation in this cell needs an increased compression force, which will trigger another neighbouring cell to collapse, and the same process will be repeated. The macroscopic response of the foam cannot copy the single cell response, because the deformation softening oscillation of each single cell is eliminated when the average statistical method is applied to a group of cells. Instead, the macroscopic average result of this mechanism keeps the macroscopic compression stress (plateau region) as a constant during this process, which continues until all cell layers in the specimen reach the lock-up strain. Clearly the lock-up mechanism is different when speed of loading is increased (Fig. 8). This is distinguished from a strain hardening foam that deforms uniformly under compression. After all the cells lock up, the foam cells start to interact with each other, and the compression stress will increase with further increase of compression strain. The deformation across the specimen gauge length becomes uniform. The plateau region of crushable foam in compression is the primary concern for crashworthiness applications. The analyses and experimental evidences have shown that the compression deformation of a progressively crushable foam is not uniformly distributed in the plateau region in a uniaxial compression test.

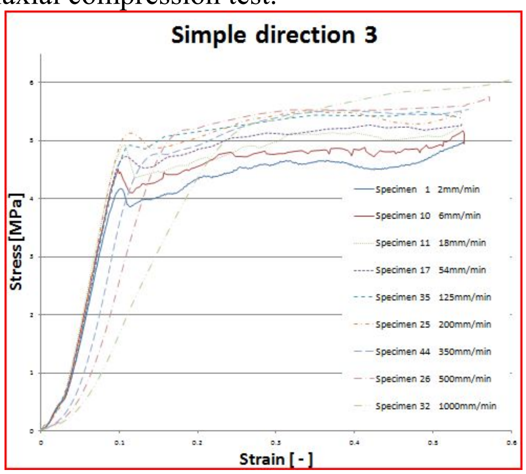


Fig. 8. Compression response of the simple foam on direction 3.

When tests are done on the transverse direction 1, as in figure 9, one more speed of loading is added as 750 mm/min. Again, up to 200 mm/min the linear part is about the same, and strain hardening occurs. When increasing the speed above 350 mm/min the modulus in the elastic region decreases. On direction 1 the plateau region appear more clearly at a constant stress, as compared to the direction of rise 3, where the polyurethane foam hardens in deformation under compression when speed of loading is increased.

When impregnating the foam with epoxy and polyester resins behaviour of the polyurethane foam changes.

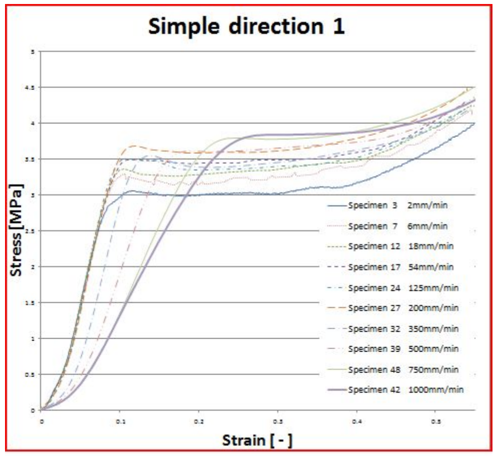


Fig. 9. Compression response of the simple foam on direction 1.

As an example, when tests are done on direction 1 the foam becomes stiffer (Fig. 10), and in the plateau region the yielding strength gives a stress in between 5-6 MPa as compared to the values of 3-3.5 MPa obtain on this direction for the simple foam (Fig. 9). Speed of loading is again influencing more the stress-strain curves if speed is above 350 mm/min.

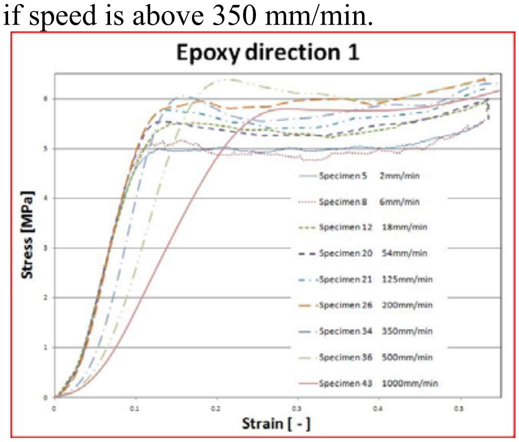


Fig. 10. Influence of impregnation with epoxy resin on direction 1.

The average compression yielding stress in the plateau region increases from 3.5 MPa for the simple foam to 5 MPa for the foam impregnated with polyester. On direction 1 epoxy impregnation increases this stress to about 5.5 MPa (Fig. 10), although on direction 1 the polyurethane foam is more compliant than on direction 3. This shows that the impregnation with the epoxy resin is improving the performance of this foam at higher speeds of loading.

The rise direction 3 gives a hardening response of the simple foam (S) in compression for the tested speeds of loading (Fig. 8). Another issue is to study the influence of long time – ageing about three years – air and light exposure of the foam edges (A) on the performance of the polyurethane foam. In figure 11 the comparison is done for: 2, 54, 200, and 1000 mm/min. Strain hardening shape of the stress-strain curve is kept as speed increases. Exposure to air (A) compared to simple foam (S) is evident by damaging the polyurethane foam – strain hardening diminishes when foam is exposed. Clear differences appear in the plateau region; when speeds of loading increase the initial yield stress is also increasing for both type of specimens, different behaviour appearing at strain hardening. At 1000 mm/min the shape of the stress-strain curves is again different in nature, as it also resulted from the previously presented tests.

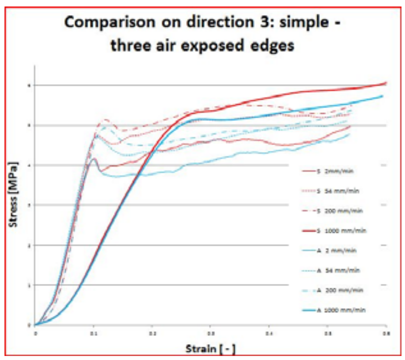


Fig. 11. Comparison of simple to air exposed foam on direction 3.

4. Influence of speed of loading in the elastic region

The behaviour in the linear elastic region depends on whether cells are open or closed. For closed cells, as those of the polyurethane foam, the cell edges bend and extend or contract increasing the contribution of the axial cell-wall stiffness to the elastic moduli. Longitudinal (Young's) modulus of the foam is notated E^*, and of the solid material from which the foam is made is E_s. Of interest is the ratio E^*/E_s which depends on the relative density ρ^*/ρ_s, in which notations * and *s* are same [1]. Value of E_s is rarely known because it depends on the degree of polymer chain alignment, on chemical changes brought by the foaming agent, and on the gradual ageing and oxidation of the polymer (see figures 6 and 11 to this respect). The fraction of the solid which is contained in the cell faces is also an important parameter. So, when the foam is crushed, there is a combination of mechanisms which influence its behaviour: cell wall bending, edge contraction and membrane stretching, and influence of enclosed gas pressure in the closed cell which should be added when it is important. As stated in [1] there are several constants of proportionality which are to be used in the general equation to establish the ratio E^*/E_s.

Up to now, from the engineering stress-strain curves, we have established only a modulus in the linear elastic region – we may call it apparent or equivalent – without getting into the details discussed above. Therefore this value will be called *modulus*. We also established from the plotted diagrams the initial yield stress at which the plateau region begins – either with strain hardening or constant stress. We are making comments on the influence of the speed of loading and on the impregnation with epoxy and polyester resins. Only some plots are enclosed hereby in order to reduce the number of diagrams.

For a simple foam variation of the modulus and of the initial yield stress with the speed of loading on the rise direction 3 is shown in figure 12. Speed is represented on logarithmic scale. At least three tests are done for each speed. Modulus slightly increases from about 60 to 70 MPa, and then decreases to 30 MPa when speed reaches 1000 mm/min. Initial yield stress is from about 4.5 MPa to above 5 MPa in the range of testing speeds.

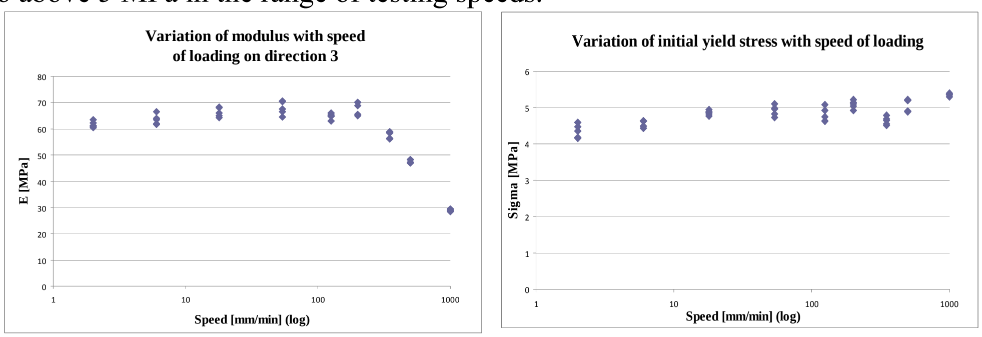


Fig. 12. Variation for simple foam of the modulus and initial yield stress on direction 3.

When testing on direction 1 the same simple foam (Fig. 13) modulus increases from about 50 to 55 MPa, and then decreases to 20 MPa. Clearly direction 1 is more compliant than direction 3. Initial yield stress is in between 3-4 MPa, slightly increasing with the speed of loading.

On direction 3 we also present the influence of impregnating the faces of the specimens. In figure 14 is shown the influence of the epoxy resin and in figure 15 of the polyester resin. For the epoxy tests we have quite a substantial scatter of data in the variation of the modulus. Values start from 50 MPa, reach almost 90 MPa, and then decrease to 30 MPa at 1000 mm/min. Initial yield stress increases from 4 MPa to above 6 MPa. For polyester impregnation (Fig. 15) modulus is almost constant with increasing the speed of loading up to 200 mm/min as 85-90 MPa, and then starts to decrease from 350 mm/min up to 30 MPa at 1000 mm/min, same modulus value as before. So impregnation really doesn't make differences at higher speeds of loading. Initial yield stress is again almost constant in between 5 MPa and 5.5 MPa. Maximum speed of loading increases less the yield point than for the epoxy resin, which is greater than 6 MPa.

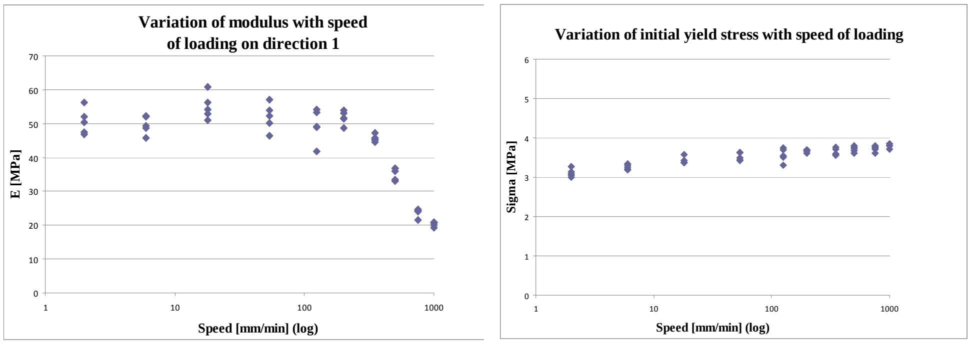


Fig. 13. Variation for simple foam of the modulus and initial yield stress on direction 1.

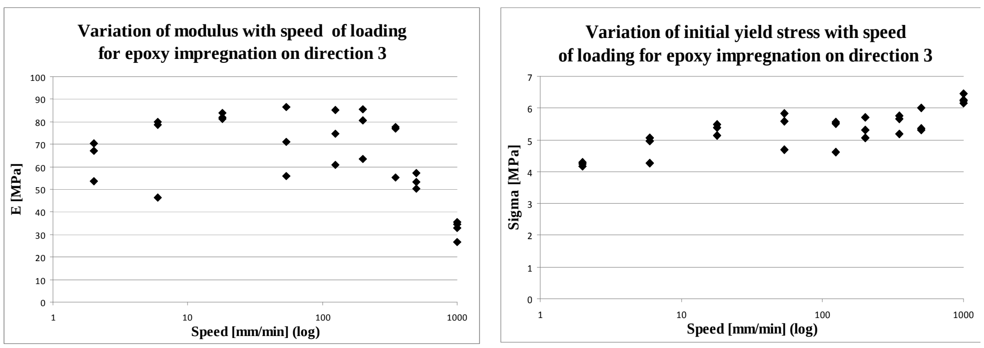


Fig. 14. Variation for epoxy impregnation of the modulus and initial yield stress on direction 3.

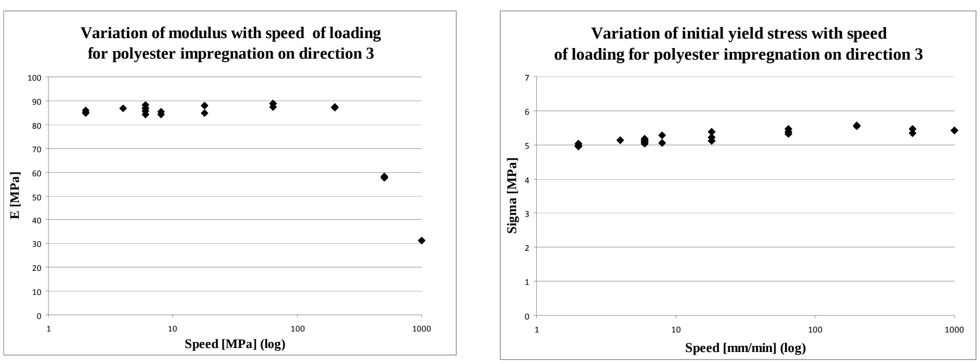


Fig. 15. Variation for polyester impregnation of the modulus and initial yield stress on direction 3.

5. Conclusions

Compression testing of a polyurethane closed cell 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 ageing – 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 1000 mm/min.

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 direction of rise 3 and transverse direction 1. The rise direction 3 gives a hardening response of the simple foam (S) in compression for the tested speeds of loading. Exposure to air (A) compared to simple foam (S) is evident by damaging the polyurethane foam – strain hardening diminishes when foam is exposed.

The average compression yielding stress in the plateau region increases from 3.5 MPa for the simple foam to 5 MPa for the foam impregnated with polyester. On direction 1, epoxy impregnation increases this stress to about 5.5 MPa. This shows that the impregnation with the epoxy resin is improving the performance of this foam at higher speeds of loading. On direction 1 the modulus increases with the speed of loading up to 200 mm/min, and then decreases. On the rise direction 3 modulus slightly increases and then decreases when speed reaches 1000 mm/min. When testing on direction 1 modulus keeps the same trend, but on this direction foam is more compliant than on direction 3. The initial yield stress increases on direction 3 for epoxy impregnation up to about 6 MPa and up to about 5.5 MPa for polyester impregnation.

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