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Influence of Higher Speed Loading on the Damage of a Rigid Polyurethane Foam

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Abstract

Polyurethane foam with density 200 kg/m^3 was tested in compression with speeds of loading from 2 to 1000 mm/min. The rise direction gives a hardening response of the simple foam which behaves more compliant when foam is aged. The impregnation with the epoxy resin is improving the performance of the foam at higher speeds of loading as the modulus in the elastic region increases with the speed of loading up to 200 mm/min, and then decreases.

Key words: *polyurethane foam, strain rate, loading speed, strain hardening, modulus, initial yield*

Dynamic testing of cellular materials

Under quasistatic compressive loading, foams in general are known to exhibit a three-stage response consisting of elastic behaviour, plasticity-like hardening or softening response, and finally, a densification response with rapid stress increase [1]. Micromechanical models for the elastic behaviour and estimation of the elastic modulus and Poisson's ratio are well documented [2]. However, for the above mentioned three-stage response, modelling efforts have been mostly centred around phenomenological approaches that are either purely strain dependent, or in uncoupled terms of strain rate and strain, or in coupled terms of strain rate and strain or even temperature.

Recently, considerable literature has emerged on the determination of dynamic response of cellular structures. Zhang et al. [3] conducted high strain rate tests on polymeric foams using a drop weight method. Uniaxial dynamic response of materials at strain rates above 100/s is typically obtained using a split Hopkinson pressure bar apparatus [4].

Polymeric foams are extensively used in energy absorption applications such as automotive crash safety systems, where compressive strain rates may reach 500–800/s. These materials may also be considered for higher rate applications such as trauma attenuation in advanced protective equipment against ballistic impacts and blast waves where the rates of deformation exceed 1000/s. A significant increase in rate sensitivity is noted for many materials at higher rates of deformation and leads to uncertainty in the applicability of typical foam constitutive models at high rates [5-8]. The method for testing foams in compression depends on the desired strain rate [6]. Conventional servo hydraulic machines are capable of rates between 10 and 100/s, although slightly higher rates can be achieved by specialized equipment. Rates in the range of 101 to 102/s are readily achieved in controlled drop tower tests where the material sample is compressed by a falling mass. For higher strain rates, up to 3000/s for soft materials, more advanced techniques are required [7, 8].

Progressive collapse deformation mechanisms in Rohacell-51WF foam during uniaxial compression has been studied [9]. Measures of a macroscopic engineering strain are identified. The elastic and plastic parts of a macroscopic engineering strain can be predicted by using the compression failure strain, lock-up strain, and time dependent elastic and plastic parts of lock-up strain, which are material parameters. Identification of strain measures in a uniaxial compression test is essential to get material parameters for an elastoplastic model.

Higher speed testing of the rigid polyurethane foam

A Lloyd Instruments LRX *Plus* Series materials testing machine is able to load in compression a specimen with a speed up to 1000 mm/min. We concentrated on the higher speed compression testing of the foam with density 200 kg/m^3 by studying two influences: 1) insulation 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. Essentially, our tests have a quasistatic character. However, the influences on the compressive response of the polyurethane foam can be important.

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, as mentioned before, and had *three air exposed edges* (A). Specimens are tested along rise and transverse directions, notated 3 and 1, and 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

For a compression testing of a simple specimen on direction 3 we have considered the above mentioned speeds of loading (Fig. 1). From 2 mm/min to 200 mm/min the linear elastic part is practically the same as slope and the plateau region shows some hardening. At 2, 6, and 18 mm/min the damage of the wall cells is more evident, stress-strain variation showing many irregularities. For 54, 125, and 200 mm/min strain hardening is following about the same path. Stress-strain curves go apart when speed of loading becomes 350 mm/min, 500 mm/min and 1000 mm/min. Curves lean forward in the linear elastic domain as speed increases, and the strain hardening diminishes, the plateau with constant yielding stress region appearing clearly.

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. 1). 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.

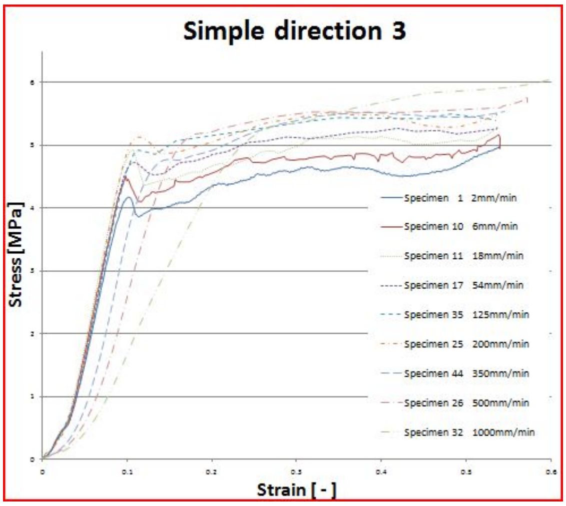

Fig. 1. Compression response of the simple foam on direction 3

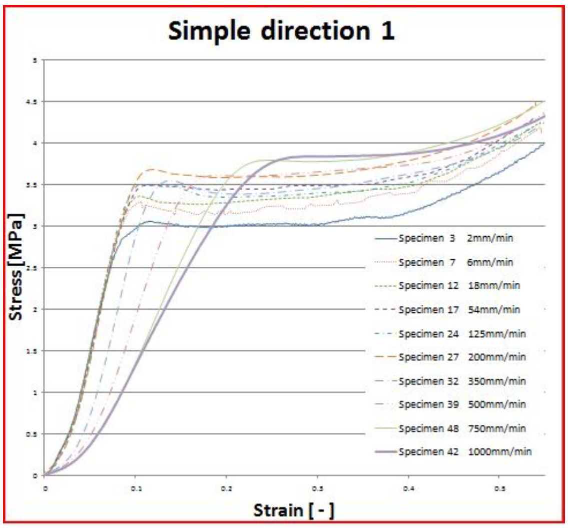

Fig. 2. Compression response of the simple foam on direction 1

When tests are done on the transverse direction 1, as in figure 2, 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. As an example, when tests are done on direction 1 the foam becomes stiffer (Fig. 3), 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. 2). Speed of loading is again influencing more the stress-strain curves if speed is above 350 mm/min.

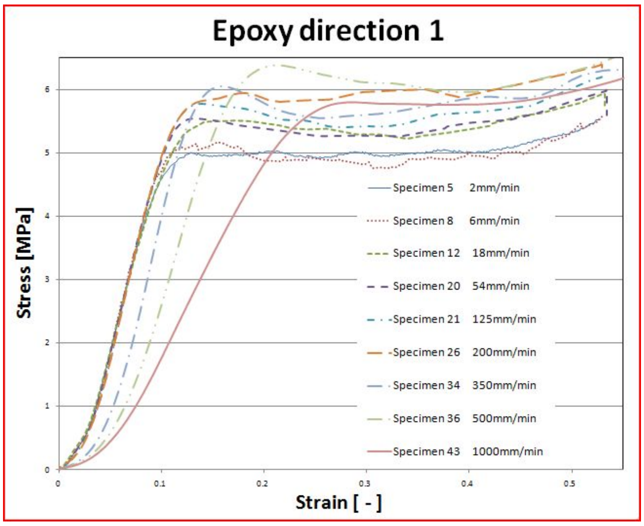

Fig. 3. Influence of impregnation with epoxy resin on direction 1

When impregnation is done with polyester, tests on specimens cut from the edge of the plate (three exposed edges) give curves shown in figure 4. Same strain hardening behaviour as for the simple specimens is noticed in the yielding region.

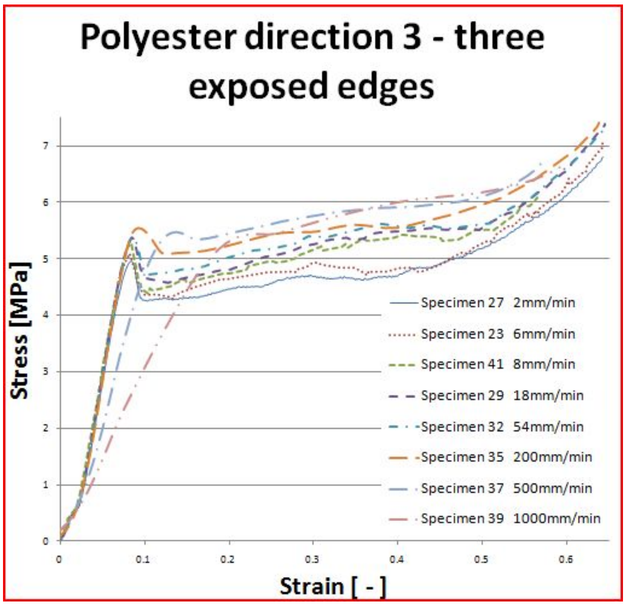

Fig. 4. Influence of impregnation with polyester resin on direction 3

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. 3), 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. 1). 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 5 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. 5. Comparison of simple to air exposed foam on direction 3

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 figure 5 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.

Variation of the modulus and of the initial yield stress with the speed of loading on the rise direction 3 is shown in figure 6. 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.

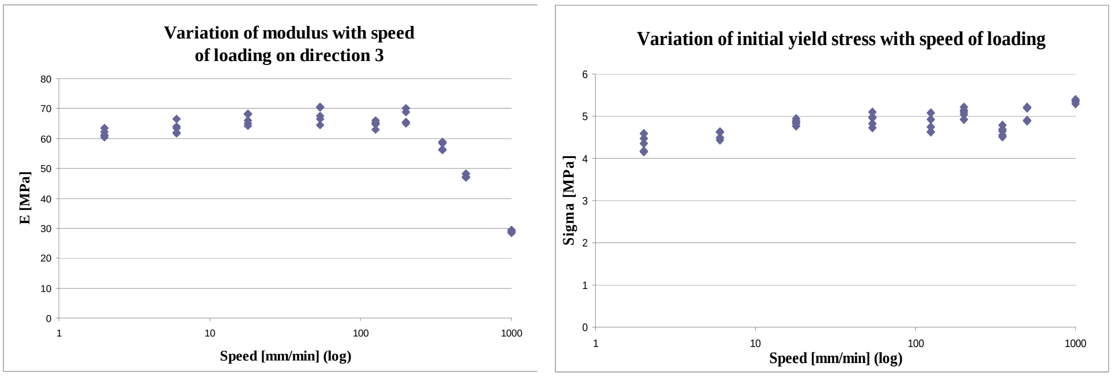

Fig. 6. Variation of the modulus and initial yield stress with the speed of loading on direction 3

When testing on direction 1 (Fig. 7) 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.

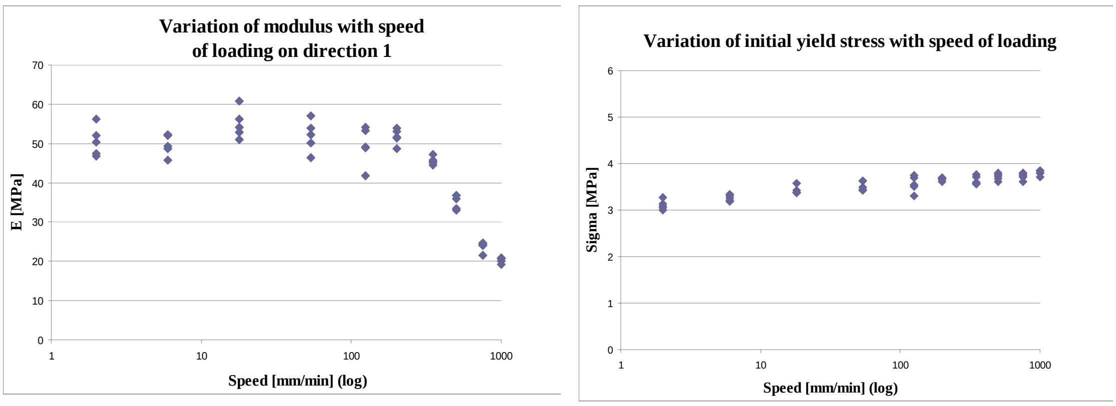

Fig. 7. Variation of the modulus and initial yield stress with the speed of loading on direction 1

On direction 3 we also present the influence of impregnating the faces of the specimens. In figure 8 is shown the influence of the epoxy resin and in figure 8 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. 9) 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.

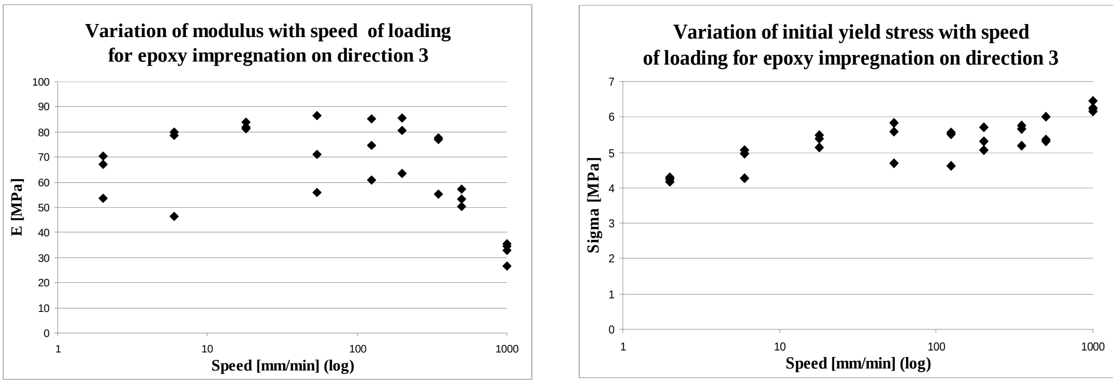

Fig. 8. Variation of the modulus and initial yield stress with the speed of loading on direction 3

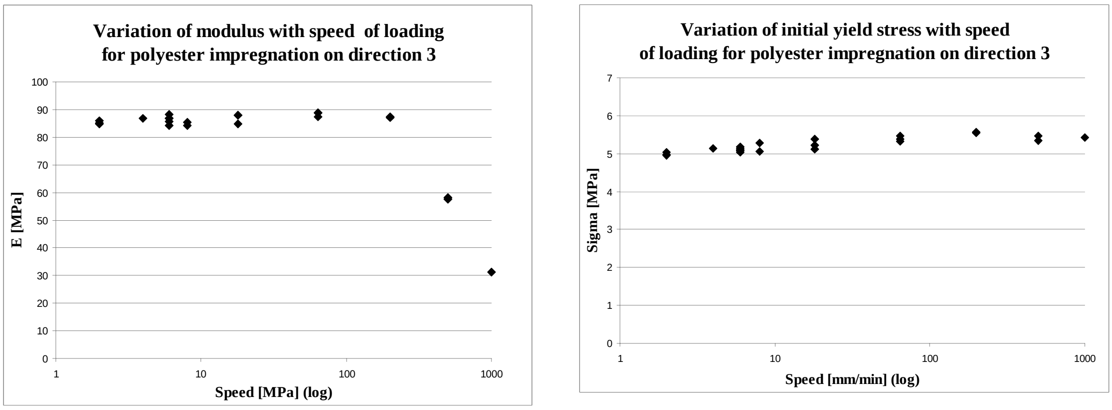

Fig. 9. Variation of the modulus and initial yield stress with the speed of loading on direction 3

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.

The modulus increases with the speed of loading up to 200 mm/min, and then decreases. On 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.

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References

1. Gibson, L.J., Ashby, M.F., *Cellular solids. 2nd ed*, Cambridge University Press, UK, pp. 312 - 322, 1997.
2. Mills N.J., *Polymer Foams Handbook*, Butterworth-Heinemann, 2007.
3. Zhang, J., Kikuchi, N., Li, V., Yee, A., Nusholtz, G., Constitutive modeling of polymeric foam material subjected to dynamic crash loading, *International Journal of Impact Engineering*, Vol. 21, pp. 369–386, 1998.
4. Kuhn, H., Medlin, D. (Eds), *ASM Handbook, Mechanical Testing and Evaluation*, Vol. 8, ASM International, 2000.
5. Mines, R. A. W., Impact energy absorption of polymer composite sandwich beams, *Key Engineering Materials*, Vol. 141–143, pp. 553 - 572, 1998.
6. Oulleta, S., Croninb, D., Worswick, M., Compressive response of polymeric foams under quasi-static, medium and high strain rate conditions, *Polymer Testing*, Vol. 25, pp. 731 - 743, 2006.
7. Viot, P., Beani, F., Lataillade, J.L., Polymeric foam behavior under dynamic compressive loading, *Journal of Materials Science,* Vol. 40, 5829-5837, 2005.
8. Bouix, R., Viot, P., Lataillade, J.L., Polypropylene foam behaviour under dynamic loadings: Strain rate, density and microstructure effects, *International Journal of Impact Engineering,* Vol. 36, pp. 329 - 342, 2009.
9. Li Q.M., Mines R.A.W., Strain measures for rigid crushable foam in uniaxial compression, Strain, Vol. 38, p. 132-140, 2002.

Influenta vitezei de incarcare marite asupra deteriorarii unei spume rigide din poliuretan

Rezumat

Spuma poliuretanica cu densitatea de 200 kg/m^3 a fost solicitata la compresiune cu viteze de incarcare de la 2 pana la 1000 mm/min. Pe directia de crestere spuma simpla se comporta cu ecruisare si devine mai putin rigida daca este imbatranita. Impregnarea cu rasina epoxidica imbunatateste raspunsul spumei la viteze mai mari de incarcare pentru care in regiunea elastica modulul creste pana la o viteza de 200 mm/min si apoi se micsoreaza.