ISSN 1392-1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 10, No. 1. 2004

Experimental Analysis of Mechanical Behaviour and Damage Development Mechanisms of PVC Foams in Static Tests

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Received 23 October 2003; accepted 16 December 2003

Cellular foams are being used increasingly as core materials in conjunction with high strength skins, to produce strong, stiff, and light weight sandwich structures for aerospace, marine and transport industry. Due to their higher impact resistance and energy absorbing capability, cellular foams are being extensively used in automobile applications.

This paper presents the results of experimental investigation of foam density effect on mechanical behaviour and damage development that induce the rupture of PVC foams in static tests. The experimental investigation was conducted using compression, flexural, indentation and shear tests for the foams of four densities. The damage mechanisms and properties of different foam densities were evaluated in monotonic loading tests and were compared.

The obtained results show the better performances of the foam with higher density. The strength of foam material increases with the increase of its density. The complete damage of the test specimens is caused by deterioration of the PVC cells. The mode of damage depends on the density of material and the type of loading.
Keywords: foam, compression, indentation, shear, flexural.

1. INTRODUCTION

In the context of sandwich composite materials, the material consists of high modulus reinforcing fibres embedded in low modulus polymeric matrix bonded to low density core material laminate. Laminate and core materials are non-homogeneous and anisotropic, therefore properties will vary throughout the entire structure. Mechanical properties of sandwich composite depend on the properties of constituent laminate and core materials. Composite face sheets fail as a result of an interaction among matrix cracks, fibre fracture, delamination, etc. Mechanical properties of laminates strongly depend upon the quantity, orientation of the fibre and type of the matrix. In the core it depends upon the thickness, density and cell structure of the core. Therefore, it is necessary to understand the behaviour of constituents of sandwich in details [1 – 5].

Foam cores in sandwich components can be used as a cost-reducing production aid and for structural applications. Foamed plastics also referred to as cellular or expanded plastics have a higher flexural modulus. They achieve a higher load-bearing capacity per unit in weight, as well as higher energy storage and energy dissipation capacities. Examples of commonly produced foamed plastics are polyurethane, PVC, polystyrene, polypropylene, epoxy, phenol-formaldehyde, cellulose acetate, silicone, etc. It is virtually possible to produce every thermoplastic and thermoset polymer in a cellular form.

Foamed plastics can be classified according to the nature of the cells into closed-cell and open-cell types. Each individual cell in a closed-cell type of foam, more or less spherical in shape, is completely enclosed by a wall of plastic, while in an open-cell type of foam the individual cells are interconnected as in a sponge. Free expansion during cell formation usually produces open-cell foams. Closed-cell foams are produced in processes, where some pressure is maintained during the cell formation stage. Close cell foams can absorb more energy than open cell foams because of entrapped gas within the cell, which acts as medium of energy absorption. During compression loading, the entrapped gas inside the cell can compress as either isothermally or adibatically depending on compression rate. Foamed plastics are produced in a wide range of densities.

The shape, size and distribution of cells can be regular or highly inhomogeneous, depending on the particular material and adopted foaming process. Accordingly, polymer foams may be homogeneous, with a uniform cellular morphology throughout, or they may be structurally anisotropic.

Foaming of plastics can be achieved in several ways. One possibility is to create gases inside the mass of the polymer. Once the polymer has been expanded, the cellular structure must be stabilised rapidly. The expansion is carried out above the melting point, and the foam is then immediately cooled below the melting point (such a process is referred to as physical stabilisation) if the polymer is thermoplastic. Otherwise, chemical stabilisation can be performed. Gas can be whipped into solution of the plastic as low temperature boiling liquid or incorporated in the plastic mix and then volatilised by heat. Carbon dioxide gas can be produced within the plastic mass by chemical reaction, or other gases (e.g., nitrogen, air) can be dissolved in the plastic melt under the pressure and then allowed to expand by reducing the pressure as the melt is extruded.

The typical process of uniaxial behaviour of cellular materials is described in [6 – 7]. Typical stress strain

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diagrams for cellular materials in tension and compression are given. In compression, after the initial elastic response and «yield» plateau, the material suddenly stiffens due to densification of the material after pure collapse. In uniaxial tension, the cell walls align themselves in the direction of tension, which causes recovery of stiffness after a certain amount of non-linear deformation. The tensile and compressive stress–strain diagrams are typically asymmetric.

In the following sections experimental studies of foam core behaviour under different loading conditions are presented.

2. EXPERIMENTAL PROCEDURE

2.1. Materials

Foam specimens of 60, 80, 100 and 200 kg/m^3 densities with 15 mm of thickness were used for compression, indentation, shear, and three point bending in static tests.

The series of the specimens were cut from foam the panels for each type of the test. The dimensions and shape of the test specimens depend on the type of the tests and reasonable compromise between their load and strength.

2.2 The Experimental Set-up

The experimental tests were carried out on a standard hydraulic machine INSTRON 8516 used for static and fatigue tests. The force was measured by a load cell. The displacement was measured by a linear displacement transducer (LVDT).The tests were carried out with a load cell of ±100 kN. The maximum displacement of the actuator is ±75 mm in a frequency range up to 100 Hz. The machine is interfaced with a designed for controlling and data acquisition computer.

Compression tests were carried out according to the standard ASTM C 365.

Static indentation tests were carried out according to the standard ASTM C 364.

Shear tests were carried out according to the standard ASTM C 273.

Three-point bending tests were carried out according to the standard ASTM D 790. The lower supports were positioned on a rail allowing the variation of the span length between supports.

3. RESULTS AND DISCUSSION

3.1. Static test

Requirement for static testing of structural elements with various modes of damage and different modes of loading should be defined in the beginning of testing procedure to provide necessary information for fatigue testing. Results from the static tests were used to design the fatigue experiments. Initial number of static tests were performed to obtain the values for F_u (ultimate load), d_u (ultimate displacement), and stiffness for each foam specimen. Static tests were performed in compression, indentation, shear, and flexural mode for the foams of different densities, where specimens were loaded at a constant rate of 2 mm/min. The average value of stiffness F_u and d_u for each series of the specimens was determined.

3.2. Compression test

The mechanical response of foams under compression must be well characterised in order to analyse the extent of damage in sandwich structures. Quasi-static compression tests were carried out on foams to study the mechanical behaviour under compression for different densities. Four foams of different densities were considered for the static tests. The series of specimens, having nominal dimensions of 50×50×15 (mm) were cut from foam plates with 60, 80, 100 and 200 kg/m^3 densities. The size of the specimens was chosen to obtain a reasonable compromise between the maximum amount of relative compression of entire group of specimens. Each test was repeated five times under the same nominal condition to determine the significance of response variability. Test data showed that the repeatability of the tests was excellent for quasi-static loading. These specimens were compressed at constant rate of 2 mm/min between two steel plates.

3.2.1 Results of compression test

Polymeric foams often exhibit very high strain rate dependence compared to that of solid metallic materials. This dependence is due to the solid material properties and due to the presence of a fluid, generally air, inside the foam. The air is compressed or forced outside, depending on the foam cellular structure when the foams deform. The compressive response is also related to its relative density, which is the ratio of foam density and the density of the solid from which it is made. Typical load displacement curves for rigid closed cell PVC foam for all densities, obtained by compressing a specimen quasi-statically along one direction are shown in Fig.1.

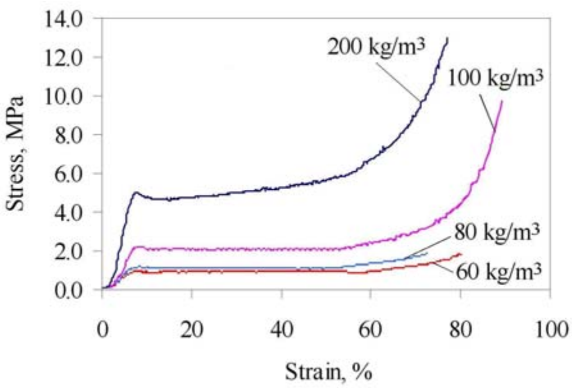


Fig. 1. Stress versus normalised displacement for four core densities in monotonic compression tests.

As the relative density increases the cell size decreases. It means that more of the solid is contributed to the foam mechanical properties rather than the gas within the cells. For this reason as the density of PVC foams increases, the increase of compressive strength was observed, as can be seen in Fig.1 for higher density foams (e.g. 200 kg/m^3).

These curves exhibit three definite regions: linear elastic, long plateau and densification. The behaviour is linear elastic with a slope equal to Young's modulus of the foam at small displacements, usually less a 5 %. The foam cells begin to collapse by plastic collapse, plastic yielding or brittle crushing, depending on the mechanical properties of the cell walls as the load increases. The collapse progresses at roughly constant load, giving the stress plateau, until the opposing walls in the cell meet and touch each other, when densification causes the stress to increase steeply.

For the characterisation of foams and the evaluation of their potential applications, the determination of their compression behaviour, or, more specifically, their compression strength and the length and slope of the plateau are important. It is observed from Fig. 1 that the value of stress for starting the plateau region is increased from 1 MPa for lower density (60 kg/m^3) up to 5 MPa to higher density (200 kg/m^3), when the density of foams increases.

Higher stress is needed for the start of plateau region for high density foams. Values of mechanical constants obtained from the results are presented in Table 1.

Table 1. Characteristic of foams

Properties	Density (kg/m^3)			
	60	80	100	200
Young's modulus E (MPa)	25.0	39.0	50.0	89.0
Poisson ratio	0.42	0.42	0.42	0.42
Characteristic at the start of plateau: - stress σ1 (MPa) - strain ε1 (%)	 0.85 4.82	 1.30 4.89	 2.10 8.9	 3.20 9.5
Characteristic at the end of plateau: - stress σ1 (MPa) - strain ε1 (%)	 0.90 45.0	 1.20 49.0	 2.16 57.0	 4.26 58.0

All these parameters in this table are found to increase with the increase of density of foams.

The work done per unit volume in deforming the foam to a given strain or displacement is simply the area under the stress-strain curve. Very little energy is absorbed in the linear elastic region; it is long plateau of the stress-strain curve that allows the energy absorption at nearly little increase in the load. It is apparent that with the increase in core density, the energy absorbing rate increased. Cell size decreases with the increase of the core density, which offer higher resistance in the deformation of the foam; thus, more energy is needed in compression. Increasing the density of the foams, increases the slope of the linear elastic part, raises the plateau and reduces the strain at which densification starts. Also as the density of PVC foam increased, the rapid densification occurs at smaller strains, which lead to the shortening of stress plateau that can be observed for the foam of 200 kg/m^3 density.

3.3. Static indentation test

Sandwich beams can fail in several different ways. Indentation is one of the failure modes strongly affecting the behaviour of sandwich composites. Indentation of the core generally occurs due to the concentrated loadings that can appear in the corners or in the joints. Indentation can also be caused by accidental drops of loads on the cores. Therefore it is also necessary to take into account the effect of core indentation in the overall behaviour of sandwich composites. A systematic discussion of failure modes for sandwich beams with foam cores and some tests exhibiting failure by core indentation can be found [7 – 14]. Since the main interest in this study is the mechanical behaviour in foams, we will consider, among the possible failure modes that which is governed by deformation of the foam core, that is, the failure by core indentation.

Procedure of experiments for indentation tests was the same as used in the compression tests. In these tests, indentation was performed with a roller of 35 mm diameter. The rate of the indentation was 2 mm/min. The length, width, and thickness of the specimens were 100, 40 and 15 mm respectively.

3.3.1. Results from static indentation test

During the test, the load increases approximately linearly until the displacement of 1 mm. After this foams continuously behave in a non-linear manner. Typical load displacement curve for the static indentation tests is shown in Fig. 2. Three distinct regions can be identified from the load displacement curves. Each core density displayed the initial elastic region up to initial damage, followed by stress plateau, then a region of densification. Each of three phases correlates to the specific failure mechanisms that the foam undergoes during indentation. The linear region is controlled by the stretching of cell faces with the application of load for closed cell PVC foams. The cell wall touches the other one and further strains the solid itself, giving the final region of rapidly increasing load until the cells have completely collapsed. However, before the failure the core deforms largely in proximity of the point of application of the load and foam deformation affects significantly the overall mechanical response up to failure.

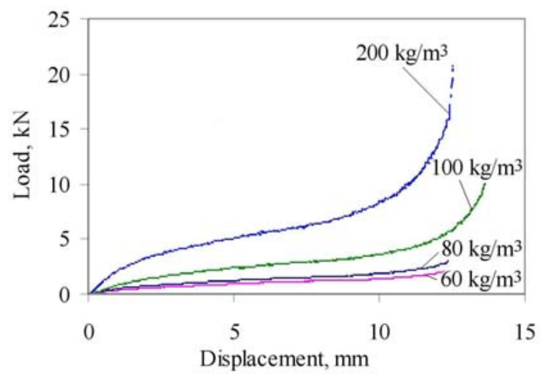


Fig. 2. Evolution of load versus displacement for foams of four densities in static indentation

The indentation response of the foams is related to its relative density. For this reason as the density of the PVC foams increases, the increase in failure load is observed. Also, as density of PVC foam increased, the sudden densification occurs at lower strain, which leads to the shortening of plateau, and can be apparently seen in Fig. 2 in the case of foam 200 kg /m^3 of density.

3.4. Shear test

Shear tests were performed for foam specimens of 60, 80 and 200 kg/m^3 densities in order to study the shear behaviour of foams.

For each type of the core, the series of specimens, having nominal dimensions of 250×50×15 (mm) were cut from foam plates. The size of the specimens was chosen to obtain a reasonable compromise between the maximum amount of relative compression of entire group of the specimens. These tests were carried out using Instron Machine with load cell of 100 kN.

3.4.1. Results from static shear test

The load increase linearly with increasing of the strain at the beginning of the test. Fig. 3 shows stress-strain curves for the foams of three different densities. It is observed that at the strain of 3.5 %, the first slip occurs during loading of the foam 60 kg/m^3 of density. This slip is caused by the cracks in the corners of the core material due to the stress concentration, where the corners of the core material are glued to the loading plates. The mean shear stress is about 0.7 MPa at the first slip. The reliable value of shear modulus is assumed to be average slope in the stress interval of 0.1 and 0.5 MPa. After these slips, the curves reach the maximum stress of about 0.78 MPa and numerous cracks occur causing total fracture of the specimen at the strain of 15 %. Similar trend was observed for other foam of 80 kg/m^3.

The static characteristic increases with the increase of the density as seen in the Table 2.

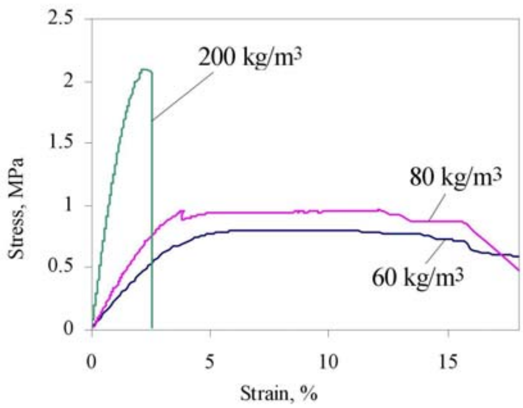


Fig. 3. Stress-strain curves of 60, 80 and 200 kg/m^{3}densities foams in static shear tests

Table 2. Shear characteristics of PVC foams for different densities

Proprieties	Density (kg/m^3)		
	60	80	200
Shear modulus G (MPa)	22.0	30.0	Not determined
Elastic limit: – stress τ (MPa) – strain γ	 0.7 0.058	 0.95 0.038	
Characteristic at failure: – stress τ (MPa) – strain γ	 0.8 0.11	 1.1 0.17	

3.5. Flexural static test

Flexural tests were performed for the PVC foam specimens of four densities. Foam specimens of 200×40×15 (mm) dimensions were cut from the foam panels for quasi-static tests using saw fitted with a diamond coated steal blade. The specimens were tested in three point bending at a span length of 160 mm. Tests were conducted on the Instron machine in displacement control at a cross head speed of 5 mm/min.

3.5.1. Results from static flexural test

Number of static tests were performed in order to obtain strength and stiffness data, which would be used for fatigue tests. Fig. 4 shows the load displacement curves in static tests for PVC foams of four densities. All the curves reveal the non-linear elastic behaviour up to the fracture. The failure process and load displacement responses were indicative of ductile material behaviour. The properties of the core material in particular are also found to control the static strength of the foams. The higher core density, the better static strength. Lower density core material tends to fail in shear, while higher density core material tends to crush under the central roller in three point bending. All the foams show that there is no increase in the load after yield point, while the displacement increases until failure.

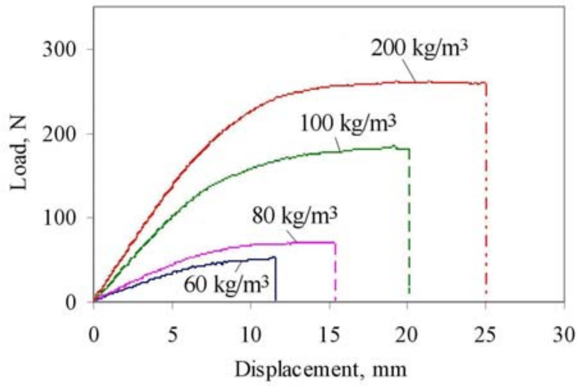


Fig. 4. Load displacement curves for cores of four densities in three point bending static tests

The static strength increases with the increase of density and failure is characterised by ductile manner. The initial portion of the load displacement curve is linear elastic with some decreasing slope. After the peak point, the load displacement response follows the plateau where cellular structure collapses by the buckling cell walls and edges. The walls of loaded cells start to come in to the contact with each other at higher strains (displacements) and further strain compresses the solid leading to failure. The failure should initiate on the compression side. However, the failure was characterised by almost vertical crack that initiated on the tension side of the beam. The failure process and the load deformation response are indicative of ductile to brittle failure.

Values of failure loads, failure displacements and stiffness are presented in Table 3. All the parameters are found to increase with the increase of density.

Table 3. Static characteristics of PVC foams for different densities

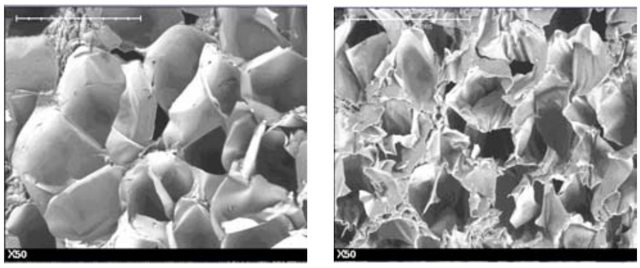
Values	Density (kg/m^3)			
	60	80	100	200
Failure load (N)	51.50	70.00	181.00	258.00
Failure displacement (mm)	12.00	15.00	20.00	25.00
Stiffnes (N/mm)	7.40	9.00	21.00	28.00

3.6. Static failure analysis

Foams are generally composed of a large number of interconnected cells, forming a cellular network. The cell is the basic unit of the foam; its morphology and the chemical composition of the struts both define the final properties of the foam. The study of the cell is, therefore, a key approach to develop and design new foams according to the given specifications and requirements. The deformation of the foams is dependent on the mechanical properties of the material, of which the cells are made, and on the dimensions and arrangement of the struts and plates, of which cells are composed. In the closed celled PVC foams under the compressive loading the struts and plates are oriented in loading directions under pure compression, while the oblique struts and plates, that is the struts and plates in any other direction, will have bending stresses induced in them. Since most of the members in the foams are oblique struts and plates, the bending is believed to be the most important deformation mechanisms in the foams. Because of the usually large slenderness ratio of struts for the low-density foams, the strut in the loading direction will rather fail by elastic buckling than by compressive load. The buckling of the struts will be resisted by the cell walls. Actually, any bending or buckling of the strut will produce tension and compression in the attached cell walls. It has also been reported that strut always will move to the state where one wall is in the tension and other in the compression. When the strut is in tension all the attached cells are stretched in tensile direction. In addition, the walls are stretched in the tensile direction subjected to the tensile strains due to the bending of oblique struts. For this reason the strains in the walls are larger than those in the struts and the cell walls are likely to be ruptured first. Cell arrangements of the foams under compressive loading change continuously and these changes were observed in the load displacement curves continuously.

Small sections of the foams from the selected failed specimens were cut transversely to the beam axes 5 mm away from the failed centre region. Similarly, specimens were cut from the foams of the four densities (60, 80, 100 and 200 kg/m^3). Also, virgin specimens were cut from the foam planks. Fig. 5 – 8 show representative SEM micrographs taken at suitable magnification for the virgin and the failed specimens of four densities.

From the SEM pictures of damaged specimens it can be clearly seen that for the low-density foams, some cells are deformed by buckling, while in other cells the walls touch each other. In low density foams, after deformation cells shape become irregular due to the buckling, bending, and stretching of the cell walls. Faces of the closed cells can be seen opened due to the compression of the adjacent cells. Compressed air inside the cells ruptures the faces of the cell and opens it. The core cells of the PVC foam are unique among rigid plastic foams since it can be compressed up to 50 percent of its thickness without rupture or crumbling of the cell walls. It can be seen in the damaged specimens of all the densities.



a b

Fig. 5. SEM photos of 60 kg/m^3 density foam of undamaged (a) and damaged (b) specimens in indentation tests

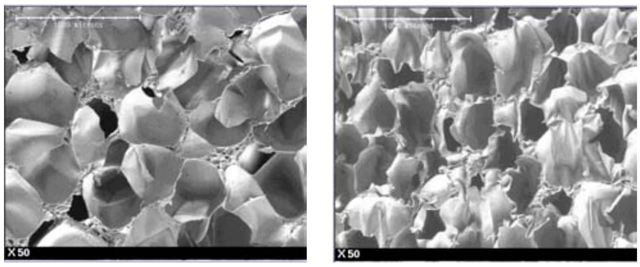


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Fig. 6. SEM photos of 80 kg/m^3 density foam of undamaged (a) and damaged (b) specimens in indentation tests

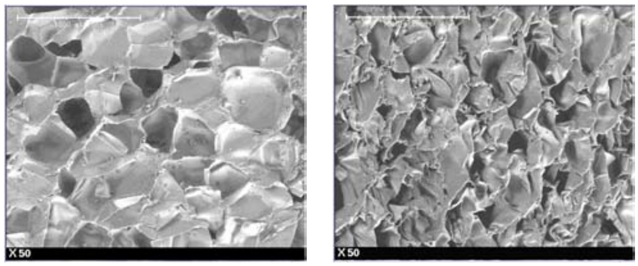

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Fig. 7. SEM photos of 100 kg/m^3 density foam of undamaged (a) and damaged (b) specimens in indentation tests

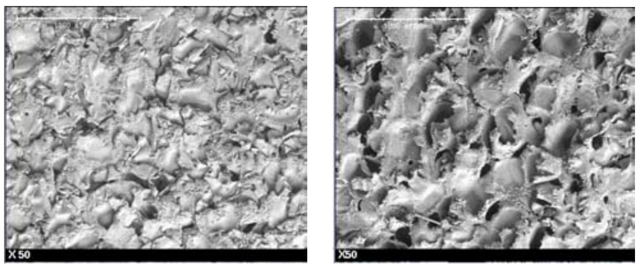

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Fig. 8. SEM photos of 200 kg/m^3 density foam of undamaged (a) and damaged (b) specimens in indentation tests

The observation of the fracture topographies of the various test specimens shows that the total damage depends on the mode of the rupture of unit cells of constituting material. In the case of the compression test or indentation the total damage of the test specimens is obtained by the progressive collapse of the unit cells. The initiation of this collapse is observed in the zones of the contact of the test specimen with the rigid faces of supports or indentors.

In the case of the shear test the total rupture of the test specimen is caused by the progressive rupture in shear of the unit cells. The zone of damage is situated in the middle part of the test specimen according to the shear line.

In the case of the flexural test the total rupture of the test specimen has the brittle nature. This rupture is caused by the instantaniously rupture of the unit cells in tense face. In the compressed face under central support the same unit cells collapse zone is observed.

4. CONCLUSIONS

The static strength of the foam (core material) directly depends on their density. The static tests highlighted the performances of the higher density foam.

The foams show some elasticity until the failure of the cells.

Lower density core material tends to fail in shear, while higher density core material tends to crack in the stress concentration zone.

The observation of the fracture surfaces of the failed specimens in flexural tests permitted to reveal that the brittle rupture of the foams is obtained by rupture-of the tensile face caused by rupture of the cells and itercellular rupture in tension.

However, the damage in the compression and indentation tests is less brittle than that the flexion caused by consequence collapse of the cells wals.

The damage of the foams in the shear test is observed by the internal longitudinal cracking of the specimen induced by the rupture of the cells and the itercellular rupture in the shear.

It is to be noted that the fracture and rupture of specimen or cruching of the cells of the foam is the result of damage processes induced randomly in the test specimens. These processes are the main cause of characteristic dispersion even at the same loading conditions with the same type of specimens. These dispersions are due to the heterogeneous nature of the foam related to their fabrication (volume fraction, density, dimension of the specimens, etc.).

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