Investigation of Mechanical Behaviour of Expanded Polystyrene Under Compressive and Bending Loadings

CRISTIAN VILAU, MIRCEA CRISTIAN DUDESCU*

Technical University of Cluj-Napoca, Department of Mechanical Engineering, 103-105 Muncii Blvd., Cluj-Napoca, Romania

Abstract: Expanded polystyrene (EPS) is used in a variety of applications due to its characteristics, light weight, good thermal insulation and durability. Expanded polystyrene, when used to insulate buildings, undergoes various mechanical stresses, such as: compression stresses, bending stresses, dynamic stresses or shock stresses. This paper presents the results of three-point compression and bending tests for four types of polystyrene (EPS-50, EPS-80, EPS-100 and EPS-120) at different speeds. Based on the data resulting from the compression tests, the theoretical mathematical model was determined, which can be used both for determining the theoretical mechanical characteristics and for modelling the EPS properties in numerical simulations.

Keywords: expanded polystyrene, compression tests, strain rate, phenomenological material model

1. Introduction

Polystyrene (PS) is a polymeric material (synthetic hydrocarbon) thermal processing (thermoplastic), obtained from styrene monomer. Representing one of the most widespread cellular plastics [1, 2] due to its physical properties. Expanded polystyrene can be used in a wide range of applications, such as: housings protection products, shock attenuation panels or sandwich structures [3].

After the production process the polystyrene products are divided into two categories: extruded polystyrene (XPS) and expanded polystyrene (EPS). Expanded polystyrene (EPS) is a closed cell foam which is produced by "expanding" of the polymer (raw beads are expanded using steam, the expanded version of polystyrene is about forty times the volume of the original polystyrene granule) and extruded polystyrene (XPS) is a rigid foam formed by the "extrusion" of polymers (polystyrene is in a solid state at room temperature but flows if heated above about 100 °C, this temperature behaviour is exploited for extrusion).

EPS is the most used form of polystyrene and can be seen in glasses for water, insulation, packaging, etc. EPS consists of 96-98% air and 2-4% polystyrene [4-6]. The granules are heated with steam in such a way as they quickly expand (foaming) and form a low-density block. EPS foam material is easy - usually weighing 15-30 kg per cubic meter. Expanded polystyrene does not lose its fundamental properties over time and can be completely recycled and reused.

Extruded polystyrene (XPS) has the same chemical composition as expanded polystyrene (EPS), but is manufactured using a different technology, thus extruded polystyrene has smaller air bubbles and is more uniform. The colours most used for this type of polystyrene (XPS) are blue and green (but may also have other colours). The XPS polystyrene layer is ideal for making demonstration parts [7-9].

One of the main applications of the EPS are structural insulated panel (SIP), a high-performance lightweight engineered building structural component that is used in a wide range of industrial, residential and commercial construction. It can be used in the building envelopes as exterior wall, framing, partition, wall, roof and floor. SIP has advantages of being economical, easy to install, environmentally sustainable, lightweight, high strength to weight ratio, thermal insulated, moisture resistant, acoustic insulated and flame retardant. Expanded polystyrene is widely used as the insulation core in the structural insulated panels. Therefore, it is essential to understand the material mechanical properties, both in static and especially in the dynamic range, the proper material proprieties description ensures a reliable prediction of the performances of the structural insulated panels subjected to the different loads from low velocity impact to blast loading.

*email: mircea.dudescu@rezi.utcluj.ro

Measuring the mechanical response of polymeric foams at quasi-static deformation rates ~0.01 1/s is reachable by standard test machines high sensibility and resolution to measure the material response in the elastic region, while high load capacity is required when the material reaches densification. Intermediate deformation rates, on the order of 100 1/s are achieved through high inertia devices and impact loading of test materials, such as a drop tower or pendulum impact test apparatus.

The paper investigates the mechanical behaviour in compression and bending of polystyrene with different densities. This group of materials exhibits a certain degree of strain rate sensitivity, fact analysed in the paper and introduced in the created material model. The mathematical description of the polystyrene behaviour under mechanical loads consists of two parts, one for elastic region and one for the inelastic one. The behaviour above the limit of proportionality was described with a power law considering the strain rate effect and densification phenomena. In the first part of the paper are presented the materials and the methods of investigations. The second part shows the obtained results in compression and bending and presents the developed mathematical model. The paper ends with the conclusions.

2. Materials and methods

Expanded polystyrene (EPS) specimens, were tested for compressive and bending test in accordance with existing standards, using universal testing machine Instron type 3366 (10 kN). The tests were performed in accordance to ISO 844:2007 [10] for compression tests and ISO 1209-2:2007 [11] for the bending tests. Results from 6 to 8 specimens were averaged. Samples were conditioned at room temperature for a period of 24 h prior to testing

Four types of expanded polystyrene (EPS) with the densities of 11 kg/mc (EPS-50), 15kg/mc (EPS-80), 20 kg/mc (EPS-100) and 25 kg/mc (EPS-120) were investigated. For the compression and bending tests, the following test speeds were used: 15mm/min, 75 mm/min, 225mm/min and 375mm/min. These speeds correspond to the initial strain rates of 0.01, 0.05, 0.15, and respectively 0.25 1/s.

For the compression tests specimens of dimensions 50/50/25 mm were used (Figure 1a). Respecting the above standard recommendations, the specimens were full thickness of the product from they were cut and have the minimum required thickness of 25mm. The specimens placed between the compressions platens and their centre line were aligned at the centre line of the compression platens and the load was distributed uniformly over the entire loading surface of the specimen. The compression platen displacement and the corresponding load data were recorded until the specimen has been compressed 10% of its original thickness at the initial constant strain rates mentioned above. For the evaluation of the mechanical behaviour above the elastic limit the specimens have been compressed up to 85% of its initial thickness.

For the three-point bending tests specimens were cut at the dimensions 15/30/200mm (Figure1b), with the supports span of 180mm. The test setup consists of typical span arrangement, the EPS test specimen was considered as a beam on two supports of the span and loaded by means of a load fitting midway between the supports. Load with the corresponding deformation of the test specimen was recorded till its failure.
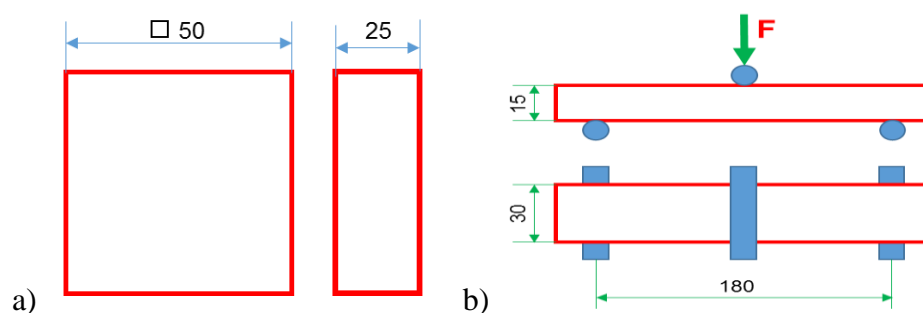

Figure 1. Specimen dimensions: a) for compression test, b) for bending test

3. Results and discussions
3.1. Compression Tests

After performing the tests, stress-strain curves for compression of the polystyrene were obtained for the test speeds listed above. The notation of the specimens was according to their commercial name, the number after EPS term representing the compressive strength al 10 % strain, measured in kPa. Maximum strain was limited according to the standard ISO 844:2007 to a conventional value of 10%. Later tests will analyse the material behaviour above this limit where onset of densification occurs.

The influence of the strain rate upon strain-stress behaviour of EPS with different densities is shown in Figure 2. Each curve results from average points of minimum five measurements and analysing the measured curves that were practically overlapped a mean value of stress for each strain was considered as relevant.
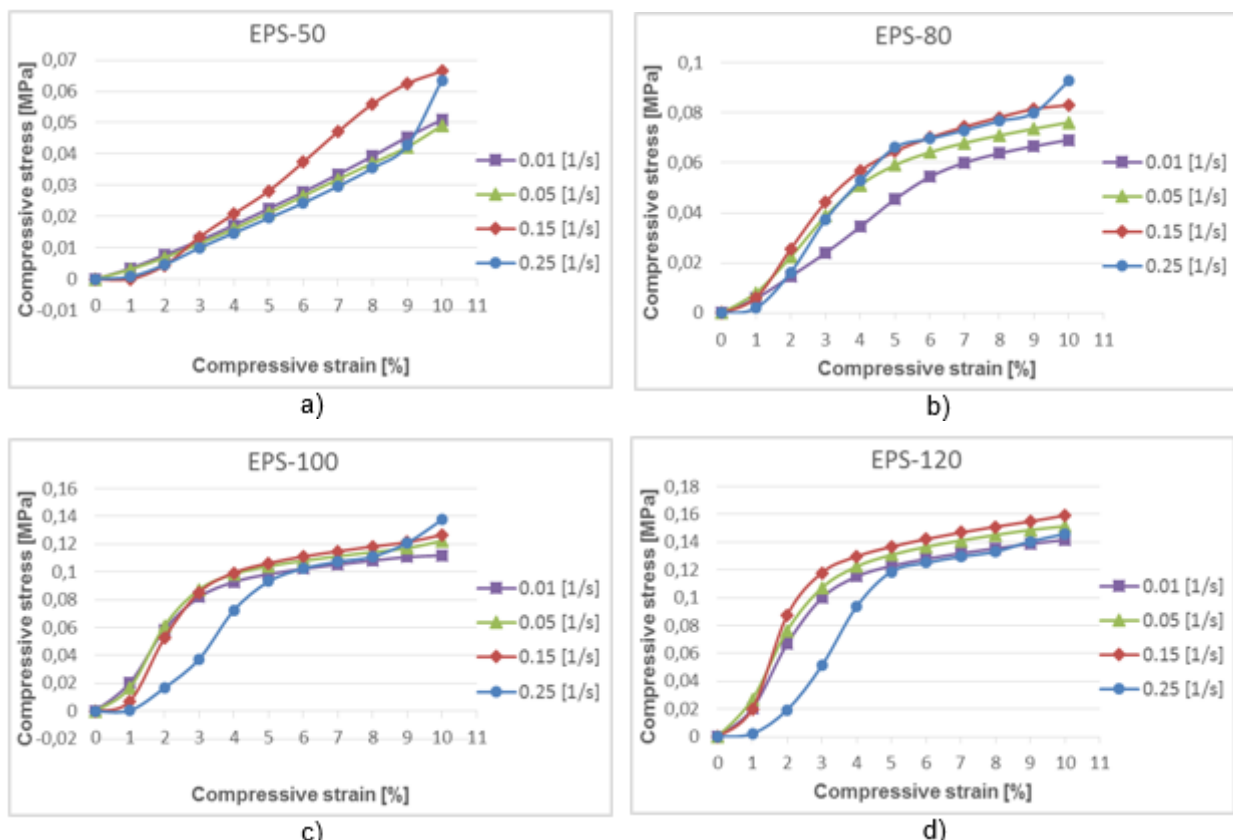

Figure 2. Compression strain-stress curves of EPS for different strain rates:
a) EPS-50, b) EPS-80, c) EPS-100 and d) EPS-120

When EPS is subjected to compressive loading, the existing air within the cells is compressed and viscous force is generated, forces that increase with the loading rate, which results in the increase of strain rate sensitivity [13]. Moreover, the behaviour of EPS is stiffer as the air trapped within the cells cannot be released at high strain rates, the material undergoing a cushioning effect. An increase in strain rate produced a slight increase in the elastic modulus of EPS. For EPS-100 and EPS-120 at increased strain rates at the beginning of test, we observed an increase in strain with a slight increase in stress and a shifting of the curves. The effect can be explained by a reduced force transfer through the EPS at the beginning of test.

Table 1 shows the compressive strengths corresponding to 10% maximum strain for the tested polystyrene types at different test speeds.

Table 1. Compressive strength.

σ [kPa]				v	$\dot{\varepsilon}_0$ [1/s]
EPS-50	EPS-80	EPS-100	EPS-120	[mm/min]	
53.38	70.55	111,9	138,14	15	0.01
55.96	81.10	122,39	148,24	75	0.05
60.15	84.88	128,14	156,32	225	0.15
69.79	92.72	133,62	145,8	375	0.25

It can be observed that all types of EPS have a significant dependence of compressive strength with the strain rate. The higher the material density the stronger influence of the strain rate upon compressive stress can be noticed.

In Figure 2a we can see a slow increase of the compressive strength of the polystyrene EPS-50 for initial strain rates 0.01, 0.05 and 0.25 1/s and a noticeable increase for initial strain rate of 0.15 1/s. It can be seen in Figure 2b, for EPS-80, at stain rates of 0.01 1/s the characteristic curve has a slow growth, up to 6%, and for the stain rates of 0.05, 0.15 and 0.25 the characteristic curve has a marked increase until at 5%. For EPS-100 and EPS-120, as can be seen in Figures 2c and 2d there is a sharp increase in the characteristic compression curve up to 4% strain followed by a relatively smooth increase (almost a plateau, the stress remains almost constant over the range) up to 10% strain. The stress change in this area, of so-called stress plateau, for EPS-100 is smaller than for EPS-120.

After performing the compression tests according to the standards (for which the maximum strain is limited to 10%), they were carried out a set of tests to determine the compressive strength curves (for which the strains were limited to 85%) of polystyrene EPS-50 (Figure 3), EPS-80 (figure 4), EPS-100 (Figure 5) and EPS-120 (Figure 6). The main idea is to examine the material behaviour under larger deformations where the densification effect will occur.

As shown in Figure 3,4,5 and 6 typical compressive stress–strain curve for EPS consists of three regions, i.e. linear elastic (marked I in the figures), plateau stress (II) and densification region (III). It can be clearly observed the border between the linear elastic region and the plateau stress considered the region where the stress remains almost constant over the range. A significant increase in stress was observed at strains higher than 40%, a value of 50% was chosen as crushing stress (onset of densification), value considered also as representative stress in other studies [2, 13].

From the test results it is observed that the compressive stress increases sharply with strain when the densification strain is reached. The effect is due to cell densification or compactions. Analysing the strain stress-curves in the plateau region and the densification region large amount of energy is dissipated [14], [15]. EPS has a very low apparent Poisson's ratio that determine low lateral elongation until full densification. Polymeric foam exhibits a certain degree of strain rate sensitivity through increased elastic modulus, plateau stress and decreased densification strain [12, 13]. The influence of the strain rate upon material properties can be considered in the material model. The stress at a given strain can be expressed as a function of strain rate [16, 17], given in the next paragraph.

The following are the experimental and theoretical curves obtained in the polystyrene compression test for the test speeds v=15 mm/min and v=75 mm/min. The theoretical curves were drawn base on the analytical expression of the strain-stress relationship that combines the material model in the three stages described previously and fit the experimental results.
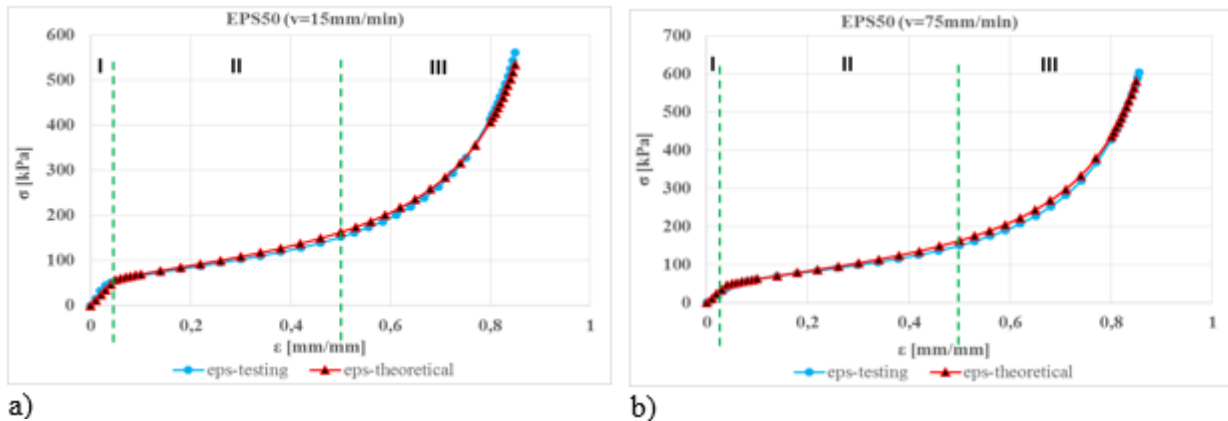
Figure 3. Expanded polystyrene EPS-50 loaded at different speeds of testing (transverse speed): a) v=15 mm/min, b) v=75 mm/min
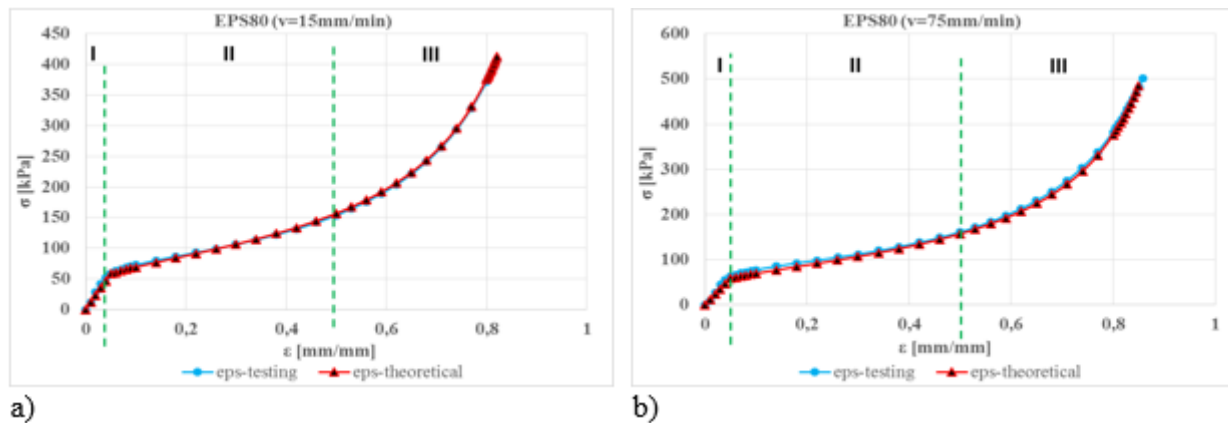

Figure 4. Expanded polystyrene EPS-80 loaded at different speeds of testing (transverse speed): a) v=15 mm/min, b) v=75 mm/min
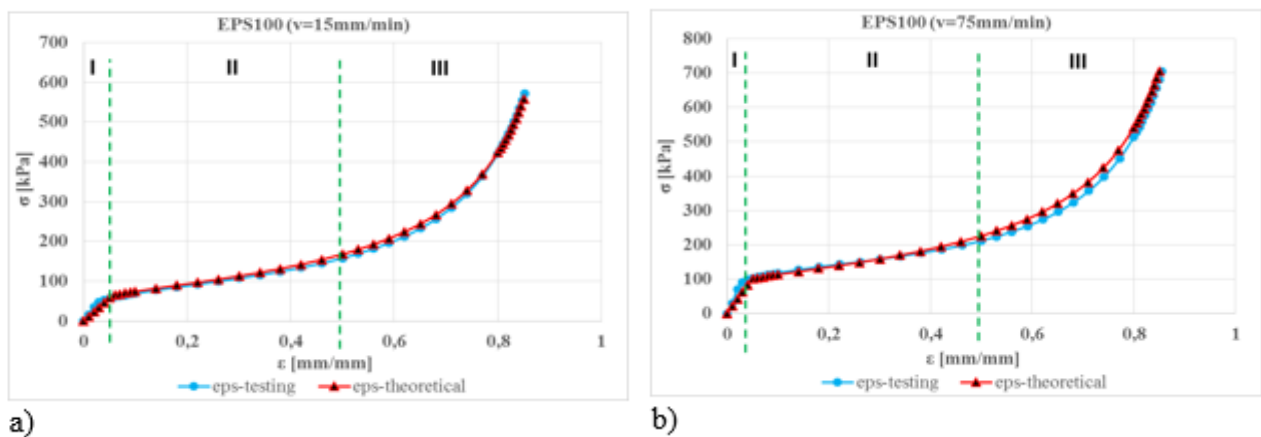

Figure 5. Expanded polystyrene EPS-100 loaded at different speeds of testing (transverse speed): a) v=15 mm/min, b) v=75 mm/min
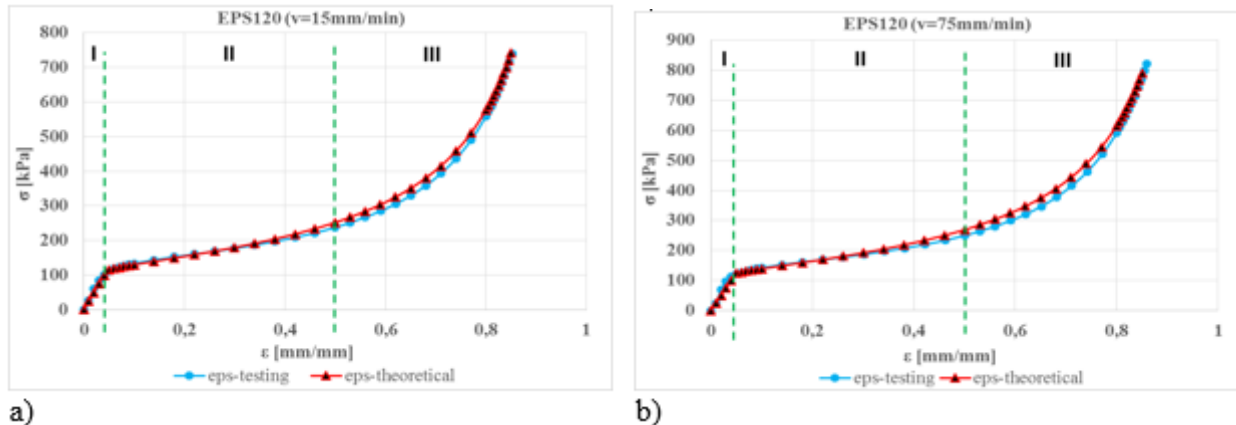
Figure 6. Polystyrene Expanded EPS-120 loaded at different speeds of testing (transverse speed):
a) v=15 mm/min, b) v=75 mm/min

In the graphs above, two intervals of compression curves can be observed for both the experimental (blue curve) and the theoretically determined curve (red curve). The first interval represents a zone of proportionality in which the compressive strength increases proportionally to the deformation. This proportionality region is up to 5% of the deformation, (as can be seen in Figures 3, 4, 5 and 6). The second interval represents a plateau area (from 5 to 50% of the strain) followed by a sharp increase in compressive strength due to densification phenomenon.

The rate dependency of expanded polystyrene is attributed to the viscoelastic properties of the base material, cell collapse or rupture, locking mechanisms that may occur between adjacent deforming cells and movement of air within the structure. The change in densification strain is attributed to deformed cell orientations and their inability to re-orient at high deformation rates to minimize the volume of the compressed material.

An analytical expression of stress–strain curve for EPS is necessary and desirable for the structural analysis and design in structural applications of EPS. As can be seen from Figures 3-6, the stress–strain curve of EPS under uniaxial compression has different geometric features, which can be given mathematically as follows:

a) initial stage of loading characterized by a linear relation between the stress and strain, the proportionality coefficient being equivalent with the modulus of elasticity (tangent modulus):

$$\sigma_e = m * \varepsilon \tag{1}$$

b) the plateau area and the densification zone can be described by a power law including the effect of strain rate [2]:

$$\sigma_p = k * \varepsilon^a * \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^b \tag{2}$$

$$\dot{\varepsilon}_0 = \frac{v}{h_0} \tag{3}$$

$$\dot{\varepsilon} = \frac{v}{h_i} \tag{4}$$

$$h_i = h_0 - \Delta h \tag{5}$$

$$\Delta h = h_0 * x\% \tag{6}$$

(1) - equation for the proportionality domain (elastic area).

(2) - equation for the plastic domain.

(3) – initial strain rate, in relation to the test speed (*v=mm/min*) and the initial height of the specimen (*h_0=25mm*).

(4) – instantaneous strain rate, in relation to the test speed (*v=mm/min*) and the height "h_i" (*h_i=mm*).

(5) – "h_i" represent difference between the initial height and displacement.

(6) – "x" represents the percentage of displacement.

For the EPS with different densities and loaded at different strain rates, the model parameters m, k, a and b are shown in Table 2.

Table 2. Model parameters

Density [kg/m³]	Testing velocity [mm/min]							
	15	75	15	75	15	75	15	75
	Coefficients							
	m		k		a		b	
11	1.16	1.16	0.1	0.1	0.2	0.25	0.9	0.95
15	1.16	1.16	0.1	0.1	0.2	0.2	0.85	0.85
20	1.16	2.1	0.1	0.13	0.17	0.1	0.92	0.9
25	2.5	2.5	0.15	0.16	0.1	0.1	0.85	0.85

The comparison results between theoretical and experimental stress–strain curves of the test group specimens are illustrated in Figures 3-6. It can be found that the theoretical curves exhibit good agreement with the test results in general. It means that the above proposed analytical formulas to describes the EPS behaviour using the parameters presented in Table 2 fit well the experimental results and can be used in a numerical simulation.

3.2. Bending Testing

Bending testing were performed on specimens made according to ISO 1209-2:2007 standard. After the tests, the characteristic bending curves in terms of flexure stress versus flexure strain were obtained for the studied polystyrene types. These bending testing was performed until the specimen was broken or the rupture appeared (about 4-5 % bending strain).

Figure 7 is presented the measured flexural strain-stress curves for the test speeds: v=15 mm/min (Figure 7a), v=75 mm/min (Figure 7b); v=225 mm/min (Figure 7c) and v=375 mm/min (Figure 7d), in the legend is written also the corresponding strain rate $\dot{\varepsilon}_0$
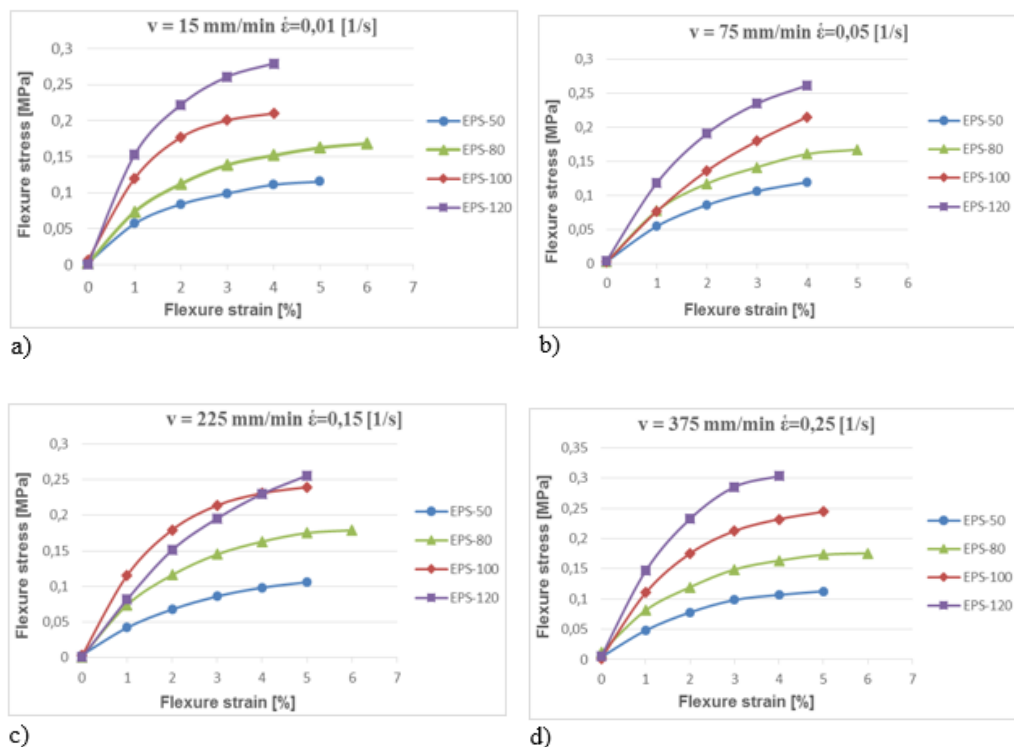

Figure 7. Strain-stress curves obtained by three-point bending test at different speeds of testing

In Figure 7 (a, b and d) can be noticed the higher strength of EPS-120 polystyrene for testing speeds of 15, 75 and 375 mm/min and a maximum bending stress at ~4 % strain. Beyond this value the specimen starts to crack and densification in the contact regions of the supports and point application of load occurs. In figure 7c it can be seen that at a testing speed of 225 mm/min polystyrene EPS-50, EPS-100 and EPS-120 have a maximum bending stress at a level of 5 % strain. It can be seen that the EPS-80 polystyrene has a higher elongation that the other types of polystyrene, for all test speeds.

Table 3 presents the maximum flexural stress for investigated polystyrene types at different test speeds.

Table 3. Flexural stress

σ [kPa]				v	$\dot{\varepsilon}_0$
EPS-50	**EPS-80**	**EPS-100**	**EPS-120**	**[mm/min]**	**[1/s]**
115,17	168,02	209,93	279,29	15	0.01
119,69	167,50	215,65	262,05	75	0.05
105,93	178,81	239,25	255,55	225	0.15
112,85	175,56	244,34	303,32	375	0.25

From the test results, it is observed that the flexural strength of EPS increases with the increase in density. Higher density test specimen failed at lower deformation due to increase in the stiffness with an increase in density.

4. Conclusions

In this study were carried out compression tests and three points bending tests to determine the mechanical characteristics of expanded polystyrene with different densities. The influence of the strain rate upon the mechanical behaviour of the expanded polystyrene was investigated for compression tests and quantified for different densities of the material. Based on experimental compression tests for expanded polystyrene it was determined a phenomenological material model describing the strain-stress behaviour of expanded polystyrene considering different strain rates. Best mechanical strength in compression and bending has EPS-120.

From the test results, it is observed that the higher density of EPS develops higher compressive strength. Regarding the flexural behaviour of EPS, the increase in density will lead to an increase of the flexural strength. Higher density test specimen failed at lower deformation due to increase in the stiffness with an increase in density. A significant increase in stress was observed at strains higher than 40%, a value of 50% was chosen as crushing stress (onset of densification), value considered as representative.

The compressive stress–strain curve for EPS shows three stages one linear elastic, an approximative plateau followed by a rapid increase of stress due to cell compaction and densification. The behaviour of EPS depends significantly by the density. Up to 10% compressive strain, value provided by some standards, the relationship between stress and strain is almost linear for low density polystyrene (EPS-50). The increase in density will change the behaviour, the plateau where the stress remains almost constant over the range is reached for lower strain values ~5% for EPS-80, ~4% for EPS-100 and ~3% for EPS-120. The testing speed will influence the compressive stress mostly for low density polystyrene (~23% increase in stress between 15 mm/min and 375 mm/min for EPS-50 and EPS-80 comparatively with ~9% for EPS-100 and ~5% for EPS-120 for the same speeds of testing). For flexure stress the difference between the EPS-50 tested at transverse speed of 15 mm/min and 375 mm/min is about 2%. For the higher density polystyrene EPS-120 we get a higher difference ~8%.

The proposed stress–strain model agreed well with the test results in the range of analysed testing speeds and could be used for the analysis and design of the structural application of EPS. The derived material model can be implemented in a numerical simulation of EPS elements that undergo quasi-static

loads. Future tests are necessary to validate the formula in the case of higher strain rates like those who characterize shock or impact phenomena.

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