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The Anisotropy Effect of Closed-Cell Polyisocyanurate (PIR) Rigid Foam under Quasi-Static Compression Loads

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Abstract. Lightweight polymeric cellular materials are increasingly used in many industrial applications because of their high mechanical and energy absorption properties. This paper investigates the effect of foam anisotropy under quasi-static compression tests. A 35 kg/m³ closed-cell rigid Polyisocyanurate (PIR) structural foam was tested in the experimental programme with a loading speed of 10 mm/min. Experimental results show that the investigated foam presents a highlighted anisotropic behavior and the main mechanical properties such as Young's modulus, yield stress, plateau stress and onset strain of densification varies with changing the loading direction. In addition, during compression, the energy absorption performance of PIR foam is strongly affected by the anisotropy.

1. Introduction

In comparison with fully dense solid materials, cellular materials such as polymeric [1-3] and metallic [4-8] foams exhibit low density with good shear and fracture strength, excellent stiffness-to-weight ratio, high porosity and exceptional ability to absorb impact energy at almost constant pressure. Therefore, due to their comprehensive physical and mechanical properties, cellular materials have expanded their application in different fields from packaging to aerospace industries [4]. In the last three decades, an extensive number of analytical [9-11], numerical [12-15] and experimental [16, 17] investigations were used in order to determine tensile [18, 19], compression [20], shear [21, 22], bending [23-25] and fracture [26, 27] properties of PU foams, under static and impact [28-30] loading conditions. In these studies the influence of density, anisotropy, loading speed, temperature, solidification rate, microstructure, size effect, constituent material and different fracture criteria were investigated.

On the other hand, in addition to the PU foams, Polyisocyanurate (PIR) rigid foams are a relatively new class of foam materials with low densities and high mechanical, physical, thermal and acoustic properties. PIR foams offer potential significant energy absorption performances in lightweight and stiff structures starting from the automotive, aerospace and especially building industry, up to many other specialized engineering applications. Only few research studies are related to manufacturing [3, 31, 32] and mechanical characterization [11, 15] of PIR foams. Studies on understanding the shear flow in PIR foam core-glass/epoxy face sheet sandwich composites by varying geometry (core thicknesses) and skin to core weight ratios were performed by Reddy [33]. Mode I fracture toughness in the foam rise direction has been experimentally characterized by Andersons et al. [34] for polyisocyanurate foams produced using polyols derived from rapeseed oil and filled with a montmorillonite nanoclay.



Most of these studies are focused on the determination of physical, thermal and acoustic properties and less on mechanical behavior. As a complement to recent studies, this paper investigate the effect of anisotropy of a rigid PIR foam on the main mechanical properties, under quasi-static compression tests.

2. Materials and experimental tests setup

2.1. Materials

A large closed-cell rigid polyisocyanurate (PIR) foam plate of 320 mm × 320 mm × 54 mm, having density of 35 kg/m³ was produced (see Fig. 1a). In order to investigate the anisotropy effect, the resulted foam samples were tested under three different loading directions as follows: an “out-of-plane” loading direction-named as *direction (1)*, and two “in-plane” loading directions-named *direction (2)* and *direction (3)*, according to Fig. 1b. Five cubic samples (50 mm × 50 mm × 50 mm) were provided for each loading condition.

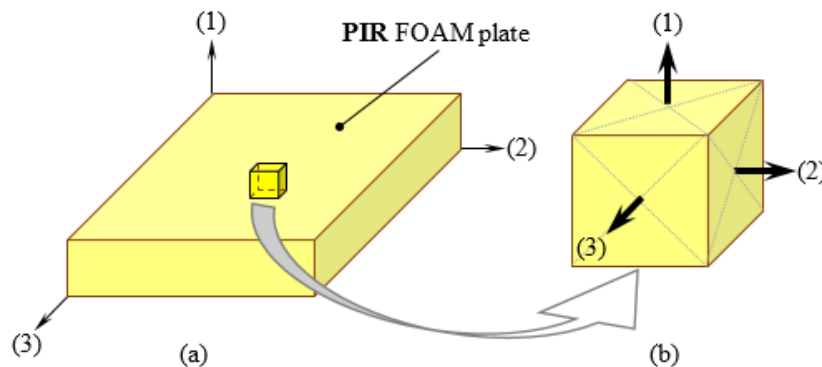


Figure 1. Produced PIR foam plate (a) and different loading directions (b)

2.2. Experimental program

The experimental tests were carried out on a universal Zwick Proline Z005 quasi-static testing machine having the maximum load cell of 5 kN. The tests were performed at room temperature (25°C), with a loading speed of 10 mm/min, according to ASTM D 1621-00 standard [35]. The loading was applied slowly, continuously and without shocks.

3. Results and discussion

Figure 2 presents the typical compressive stress (σ)-strain (ϵ) curves for three specified loading directions (one out-of-plane and two in-plane), up to approximately 90% engineering strain.

Regardless of the loading direction, all investigated PIR specimens show the classic stress-strain behavior of polymeric foams, which consist of three different regions [36-39]: (i) a linear-elastic region (from which the compressive modulus- E is determined) where the stress rises sharply up to a specified yield point; followed by (ii) a plateau region (where the plateau stress- σ_p is determined), over a large deformation; and ends with (iii) an abrupt increase in stress named onset strain of densification (OSD).

From Fig. 2 it is observed that only in the direction (1) a peak yield stress is obtained, located immediately after the linear-elastic region. On the other two directions (2) and (3) there is a smooth transition from the elastic region to the plateau region. Also, an extended and approximately constant plateau with some small stress drops (when plastic collapse of foam occur) is highlighted in direction (1), while a slight strengthening/hardening for the other two loading directions is obtained. The OSD of PIR foam represents the start of the cell-wall interactions, which enhance the compressive resistance of the solid material of which the foam is made. It was observed that the OSD depends on several factors: foam material, loading speed, testing temperature [40] etc. According to the Fig. 2 and data summarized in Table 1 it seems that OSD also depends on the foam anisotropy, this property decreasing from a value of 66.43% (for direction (1)) to a value of 58.81% (for direction (3)).

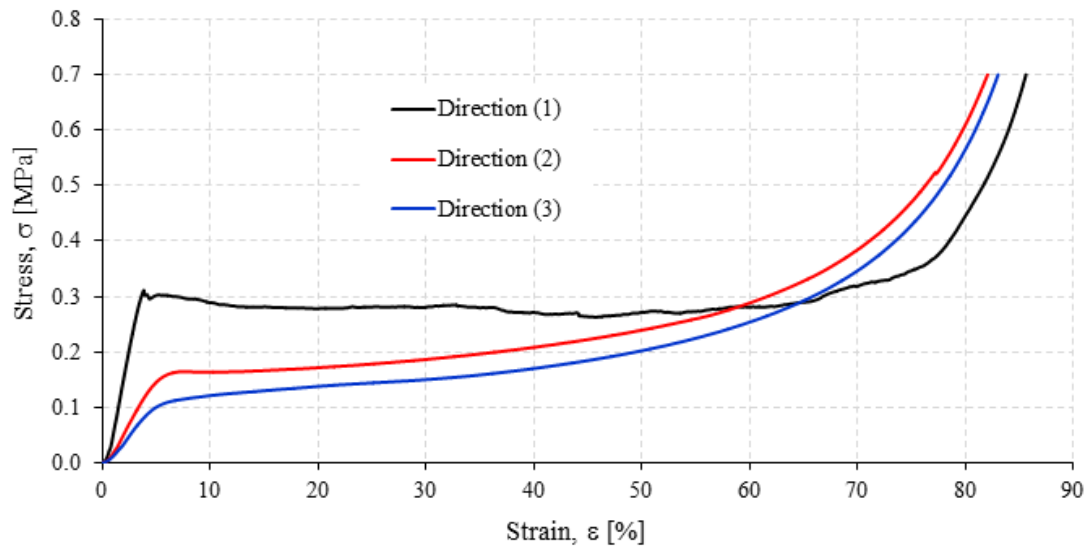


Figure 2. Stress-strain curves of investigated PIR foam

The anisotropic behavior of the PIR foam is also highlighted by the average values of the compression characteristics presented in Table 1. The values of the mechanical characteristics E , σ_y , σ_p are superior in direction (1) compared to the directions (2) and (3) about 3 times for the modulus of elasticity, respectively 2 times the values of the yield and plateau stresses.

Table 1. The mechanical properties of investigated PIR foams under different loading directions.

Loading direction	Geometrical parameters			Mechanical properties			
	b_1 [mm]	b_1 [mm]	h [mm]	E [MPa]	σ_y [MPa]	σ_p [MPa]	ϵ_D [%]
(1)				10.42	0.32	0.28	66.43
(2)	50	50	50	3.71	0.16	0.18	60.06
(3)				2.88	0.12	0.15	58.81

According to Fig. 3, different collapse mechanisms were observed during quasi-static compression tests. Under loading direction (1) the tested specimen present only one straight deformation band, approximately located at the same level on each side (near the middle of the specimen height) and perpendicular to the loading direction (see Fig. 3a), while the specimen loaded on direction (3) shows two deformation bands on each side, arbitrarily located on the specimen height. Otherwise, the direction (2) is deformed similarly to (1), but two of the sample faces presents curvilinear deformation surfaces.

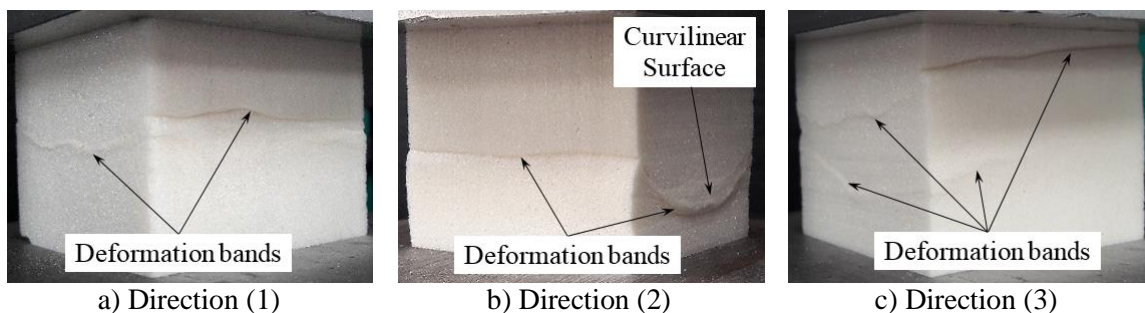


Figure 3. Deformed specimens under different loading directions

The energy absorption (W) was calculated using Eq. (1) [41-46], and a variation of W with strain for different loading directions is shown in Fig. 4a.

$$W = \int_0^{\varepsilon} \sigma d\varepsilon \quad (1)$$

As it can be seen from Figure 4b, the energy absorption at onset strain of densification (W_D) decreases by up to 50% for direction (3) compared to direction (1).

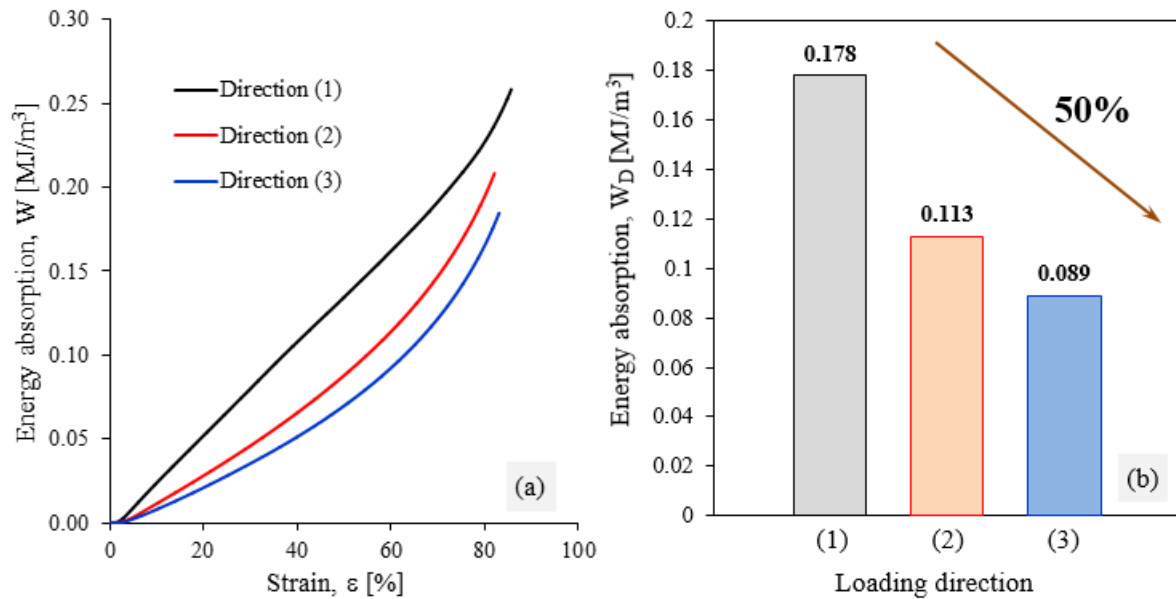


Figure 4. Energy absorption-strain curves (a) and W_D values (b) for different loading directions

The biggest difference (of 67%) in terms of energy absorption is obtained in the area of small strains, where the plateau region begins (around 10% strain); this difference decreasing significantly up to 27% at large strains (80% strain). The W difference, between different loading directions, can be observed most easily by analyzing the data from Table 2 and Fig. 5.

Table 2. The energy absorption values of investigated PIR foams for different loading directions.

Loading direction	Energy absorption at different strains, W [MJ/m ³]							
	10%	20%	30%	40%	50%	60%	70%	80%
(1)	0.024	0.052	0.080	0.108	0.135	0.162	0.192	0.227
(2)	0.012	0.028	0.046	0.066	0.088	0.114	0.147	0.195
(3)	0.008	0.021	0.036	0.051	0.070	0.093	0.122	0.166

It is very important to correctly position the closed-cell PIR foam in practical applications because it presents a strong anisotropic behavior [47]. Therefore, by simply placing the foam in the correct position in the designed resistance element, the mechanical properties will increase by over 50%.

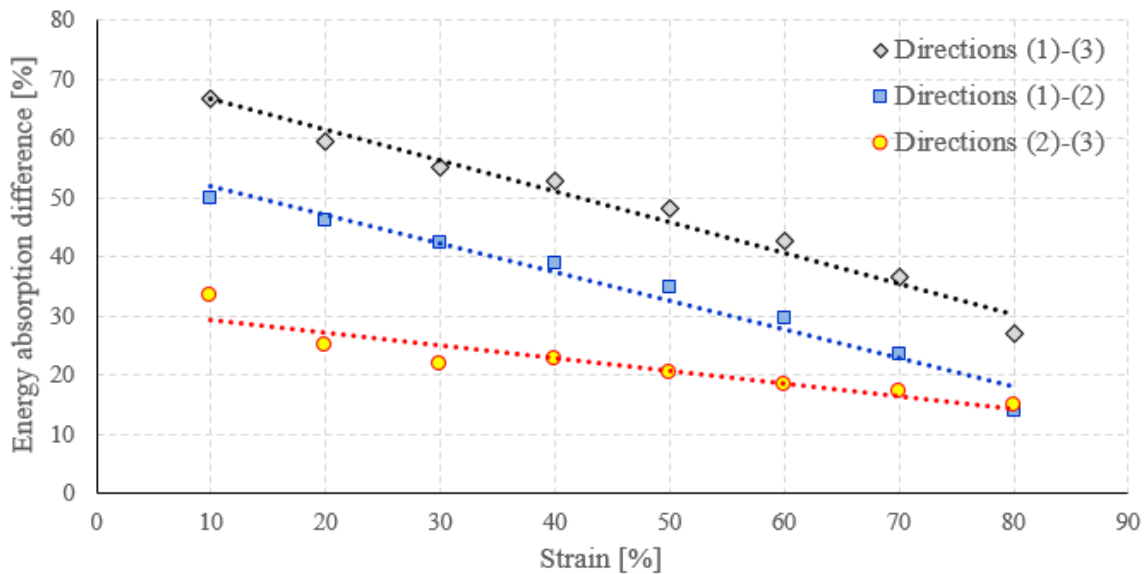


Figure 5. W difference-strain variations for different loading directions

4. Conclusions

In order to determine the effect of anisotropy, the quasi-static compression properties of a closed-cell Polyisocyanurate (PIR) rigid foam (35 kg/m³ density) was investigated under different loading directions (directions (1), (2) and (3)).

It was obtained that the PIR foam shows higher mechanical properties in out-of-plane loading direction (direction (1)) than in-plane (directions (2) and (3)), about 3 times for E , respectively 2 times the values of σ_y and σ_p (see Table 1).

Furthermore, the energy absorption capacity of PIR foam is strongly affected by the anisotropy. The biggest energy absorption difference (67% for low strains and 27% for high strains) was obtained between directions (1) and (3), and the smallest difference (34% for low strains and 15% for high strains) between directions (2) and (3)-see Table 2 and Fig. 5.

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