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Fracture Toughness Investigation of PUR Foams Using Asymmetric Semi-Circular Bend (ASCB) Specimens

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Abstract

This paper presents the experimental fracture toughness results of three different rigid PUR foams densities (100, 145 and 300 kg/m^3) using asymmetric semi-circular bend (ASCB) specimens. In this respect a numerical determination of stress intensity factor (SIF) solutions for ASCB specimen were performed using Abaqus software. Using a polynomial interpolation the pure mode II exact position of support S_2 was determined. The von Mises stress contours plot in front of the crack tip show that in pure mode I and pure mode II loading, the stress contour is symmetric relative to the crack plane, while in mixed-mode conditions the contour plot is asymmetric with respect to the crack plane. It was also determined experimentally and numerically the crack propagation angle and the crack path. Based on the experimental data, a polynomial correlation is proposed which could be useful for estimation of mode I and mode II fracture toughness if relative density values of foams are available. Finally, was found that the mode II fracture toughness values are lower than the mode I fracture toughness results for low density foams (100 and 145 kg/m^3) and almost equal for 300 kg/m^3 density. Also, it was observed that both mode I and mode II fracture toughness increases with increasing of density.

Key words: *closed-cell PUR foams, fracture toughness, ASCB specimens, SIF solutions, crack path.*

Introduction

Cellular materials such as rigid PUR foams are made up of an interconnected network of solid struts or plates which form the edges and faces of cells [1]. Taking into account the main characteristics of PUR foams: light weight, high porosity, high crushability and good energy absorption capacity, foams are widely used as cores in sandwich composites, for packing and cushioning. It is well known that the foam crushes in compression, while in tension it fails by propagation of a single crack. Most of the rigid PUR foams have a linear elastic behavior in tension up to fracture, and a brittle fracture [2].

Determination of mode I rigid PUR foam fracture toughness has received considerable attention in recent years. This has led to a better understanding of mode I fracture processes occurring during fracture initiation and propagation. However, there is a dearth of investigation into mixed-mode I and II fracture of polyurethane foams, [3, 4].

Only several theoretical and experimental methods have been suggested by researchers for exploring mixed mode brittle fracture of rigid foams [5-7]. Some refinements on fracture toughness of rigid PUR foams were investigated by Marsavina et al. [5] on ASCB specimens. Two/three types of specimens were used for determining fracture toughness in mode I, mode II and mixed-mode, and also size effect, loading speed and loading directions were investigated. Also, they proposed some correlations for density, cell orientation and mixed mode loading. Also, Marsavina et al. [6] assesses the applicability of theoretical mixed mode fracture criteria for rigid polyurethane foams. The experimental results, obtained on asymmetric semi-circular bend specimen loaded in mixed mode, proof that the equivalent stress intensity factor criterion of Richard is most suitable, for this type of rigid plastic foams. A correlation between static and dynamic fracture toughness of polyurethane rigid foams were proposed in Ref. [2]. The authors have found that for all foam densities the dynamic fracture toughness values are higher than the static ones and the increase of fracture toughness with density was also highlighted. Hallsttröm and Grenestedt [7] investigated mixed mode fracture of cracks and wedge shaped notches in expanded PVC foams. They used different types of specimens for investigation and the non singular T-stress was considered in formulation of fracture criteria. Authors found that for predominantly mode II the use of T-stress improved the facture predictions.

This paper presents the experimental fracture toughness results of three different types of rigid PUR foams using asymmetric semi-circular bend (ASCB) specimens. For this purpose a numerical determination of stress intensity factor solutions for ASCB specimen were performed using Abaqus software. Finally, the experimental and FEA crack path, respectively a comparison between experimental and FEA crack path were presented. In this respect the experimental crack path were measured with Sigma ScanPro, while FEA crack path were obtained with Franc 2D software.

Numerical Determinations of SIF Solutions for ASCB Specimen

For the ASCB specimen the stress intensity factors K_I and K_{II} for the ASCB specimen are functions of the crack length a, the radius R and the locations of loading supports (S_1 and S_2) [3]. The stress intensity factors K_I and K_{II} can be written as:

$$K_I = \frac{F}{2Rt}\sqrt{\pi a}\, Y_I\left(a/R,\, xS_1/R,\, xS_2/R\right) \tag{1}$$

$$K_{II} = \frac{F}{2Rt}\sqrt{\pi a}\, Y_{II}\left(a/R,\, xS_1/R,\, xS_2/R\right) \tag{2}$$

where t is the specimen thickness, Y_I and Y_{II} are the geometry factors corresponding to mode I and mode II, respectively. For the case of $a/R = 0.5$ and $xS_1/R = 0.75$ the geometry factors Y_I and Y_{II} were calculated through a linear elastic finite element analysis using ABAQUS. Figure 1 shows a typical mesh pattern generated for simulating the ASCB specimen.

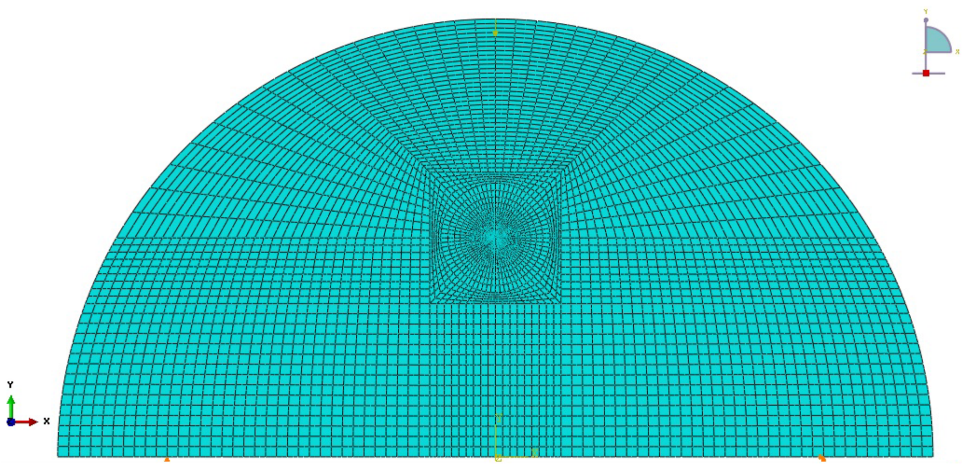


Fig. 1. Finite element mesh used for simulating ASCB specimen

A total number of 4566 quadratic elements (CPS8) were used for this model. The loading conditions were considered: R = 40 mm, t = 10 mm, P = 100 N and crack length of 20 mm. S_1 was set at a fixed value of 30 mm and S_2 varied from zero to 30 mm to obtain a wide range of mixed modes. The elastic material properties of PUR foam as E = 40 MPa and μ = 0.284 were also considered in the finite element model. A J-integral based method built in ABAQUS was used for obtaining the stress intensity factors directly from software.

In Figure 2 the variations of the geometry factors Y_I and Y_{II} with the normalized distance xS_2/R are presented, by varying the distance xS_2 from 0 mm to 30 mm, the loading conditions vary from pure mode I to dominant mode II conditions. Using a polynomial interpolation the pure mode II exact position of support S_2 was determined at distance xS_2 = 2.66 mm from the symmetry line of the semi-circle.

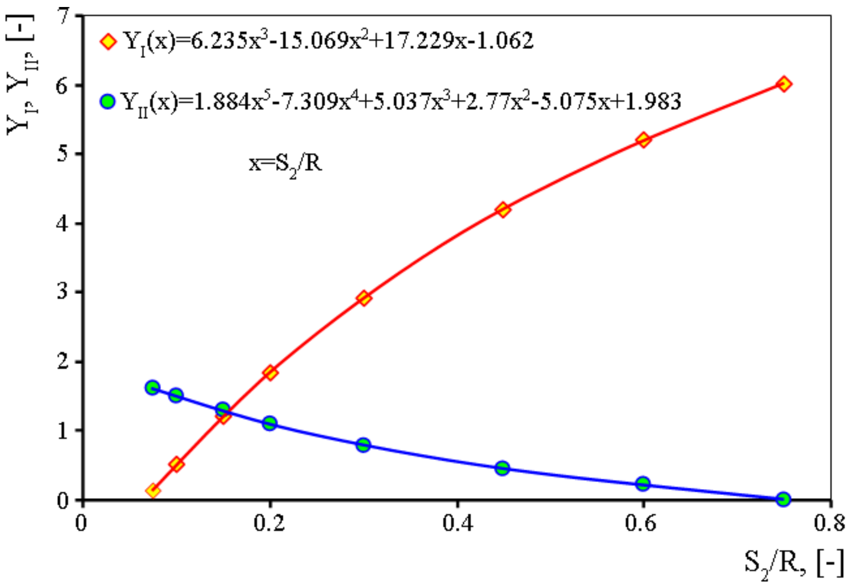


Fig. 2. Variations of Y_I and Y_{II} geometry factors with xS2/R for ASCB specimen

Figure 3 shows the von Mises stress contour plot for three different mode mixtures: pure mode I (K_{II} = 0), pure mode II (K_I = 0) and mixed mode loading with $K_I = K_{II}$.

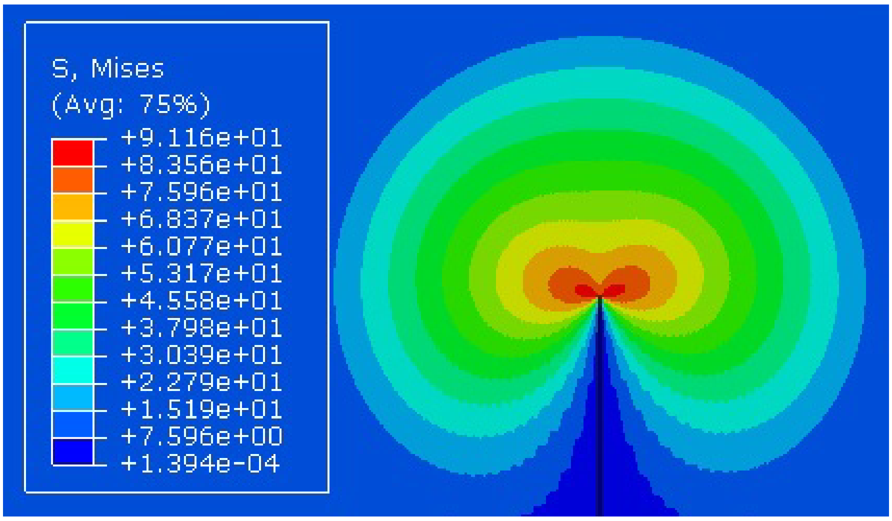
It can be easily seen that in pure mode I and pure mode II loading on ASCB specimens, the stress contour is symmetric relative to the crack plane, while in mixed mode conditions, the contour plot is asymmetric with respect to the crack plane [3].

Experimental Tests

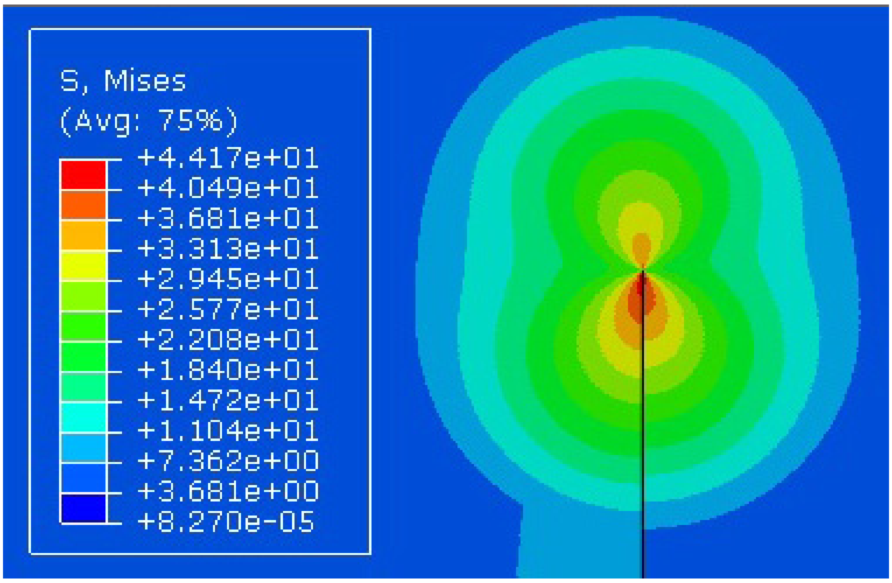
The experimental investigations were performed on a Zwick/Roell 5 kN testing machine with a loading rate of 2 mm/min at room temperature, see Figure 4. Figure 5 presents an image with the test set-up for ASCB specimen (before and after test) in the bending grips, with support rollers diameter 20 mm.

Closed-cell rigid polyurethane (PUR) foams with three different densities 100, 145 and 300 kg/m^3 made by NECUMER were used in experimental program. For each position of support S_2 four specimens were tested according to ASTM D5045-99 [8].

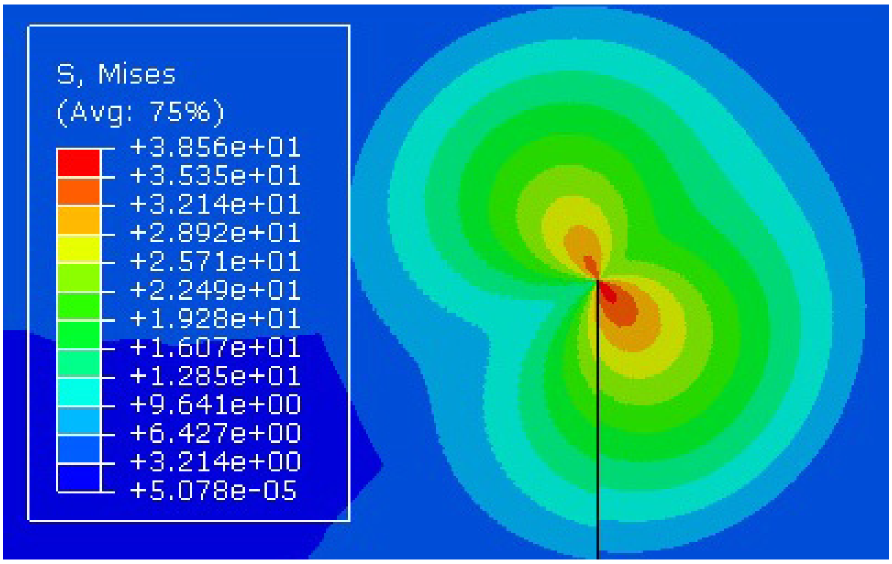
The microstructures of the investigated foams at 500X magnification were obtained using QUANTA^{TM} FEG 250 SEM and are shown in Figure 6. Based on the obtained microstructure analysis the cell length and the cell wall thickness were determined using Sigma ScanPro software.



a. Mode I (K_{II}=0)



b. Mode II (K_I=0)



c. Mixed mode ($K_I = K_{II}$)

Fig. 3. The von Mises stress contours plot in front of the crack tip

Fig. 4. A 5 kN Zwick/Roell testing machine

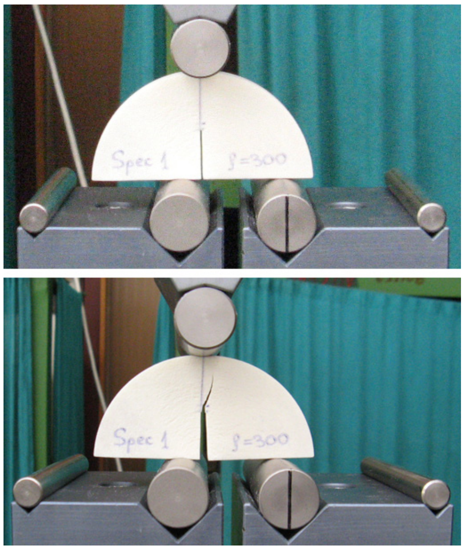
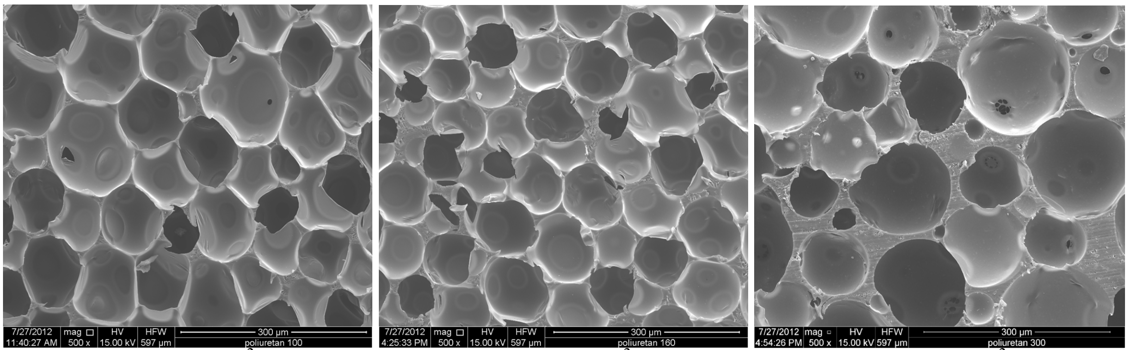


Fig. 5. ASCB specimen on bending grips



a. 100 kg/m^3 b. 145 kg/m^3 c. 300 kg/m^3

Fig. 6. SEM microstructures of investigated PUR foams

Mode I, mode II and mixed-mode fracture toughness tests were performed on asymmetric semi-circular bend (ASCB) specimens. Figure 7 shows the geometry and loading conditions of used specimens. In this test configuration, a semi-circular specimen of radius R that contains an edge crack of length *a* emanating normal to the flat edge of the specimen is loaded asymmetrically by a three-point bend fixture.

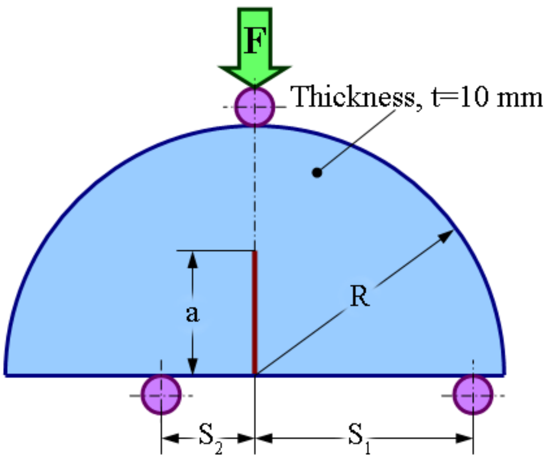


Fig. 7. Geometry of the ASCB specimen

The loading with a three-point bend fixture was chosen to give a wide range of mixed modes from pure mode I (S_1=S_2) to pure mode II ($S_1 \neq S_2$), only by changing the position of one support, [3, 9]. The considered geometry of the specimen has: R=40 mm, a=20 mm, t=10 mm, S_1=30 mm and S_2=30, 24, 18, 12, 8, 6, 4, 2.62 mm.

Figure 8 presents the load-displacement curves for the foam with 300 kg/m^3 density and different S_2 positions.

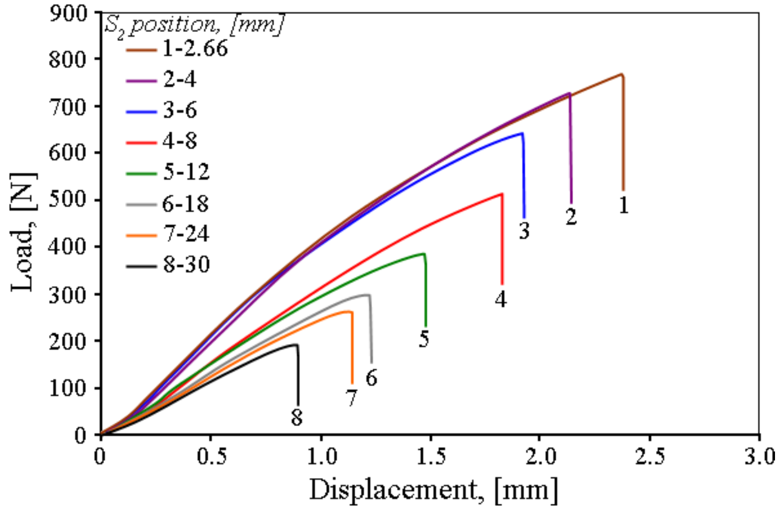


Fig. 8. Load-displacement curves on ASCB specimens

For all specimens a linear-elastic region was obtained followed by an abrupt drop of load to zero after reaching the maximum load. All tested specimen's present brittle fracture without plastic deformation remains after the test.

Crack Path Investigation and Fracture Toughness Results

The obtained crack paths for six different support position S_2 (mode I (a), predominantly mode I (b, c), predominantly mode II (d, e) and mode II (f)) are shown in Figure 9. Excepting mode I case, when the crack propagates like a straight line, all other cases show curvilinear crack paths.

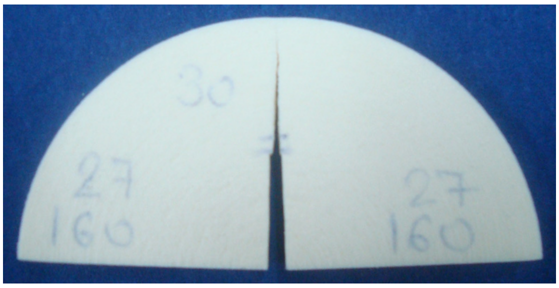
Figure 10 presents the experimental and FEA crack path, respectively a comparison between experimental and FEA crack path for support position S_2=8 mm. A good correlation was obtained. In this case the investigated foam shows 160 kg/m^3 density. In this respect the experimental crack path were measured with Sigma ScanPro, while FEA crack path were obtained with Franc 2D software.

The mean values of the experimental crack initiation angle θ_C measured on the specimens as a function of support ratio S_2/S_1 are presented in Figure 11.

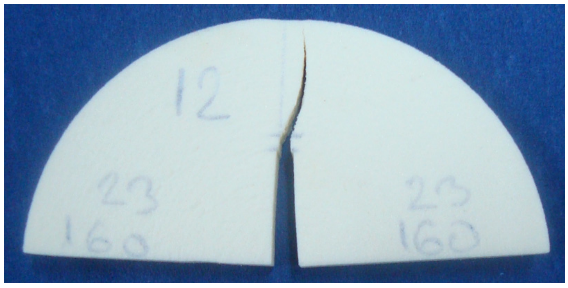
The crack initiation angle θ_C decreases from a value of 68.13 degrees for pure mode II to a value of 0 degrees for pure mode I. This angle variation is given by the following polynomial equation:

$$\theta_C = 196.77\left(\frac{S_2}{S_1}\right)^4 - 515.19\left(\frac{S_s}{S_1}\right)^3 + 502.89\left(\frac{S_2}{S_1}\right)^2 - 268.78\left(\frac{S_2}{S_1}\right) + 84.56 \qquad (3)$$

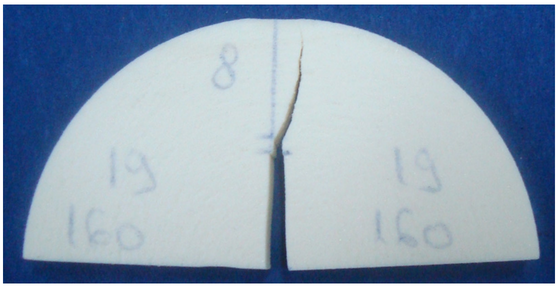
Figure 12 presents the variation of fracture toughness values for mode I and mode II with relative density.



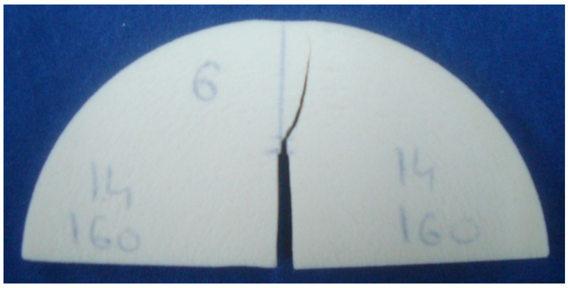
a. S_2=30 mm (pure mode I)



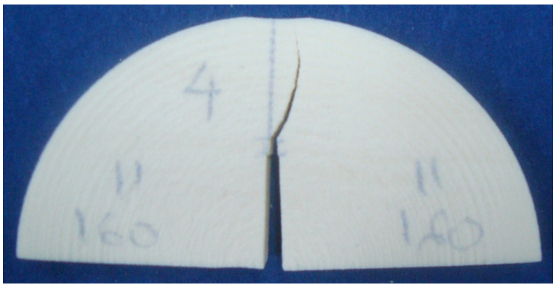
b. S_2=12 mm (mixed mode)



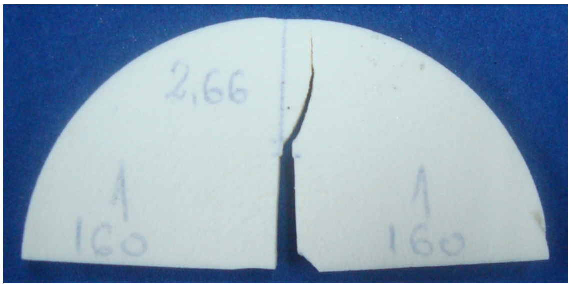
c. S_2=8 mm (mixed mode)



d. S_2=6 mm (mixed mode)



e. S_2=4 mm (mixed mode)



f. S_2=2.66 mm (pure Mode II)

Fig. 9. Crack paths for different positions of S_2 support

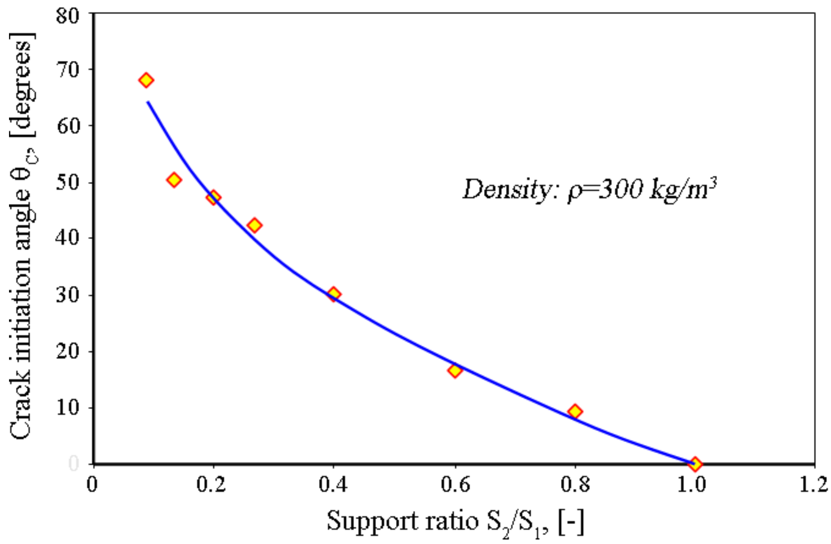


Fig. 11. Crack initiation angle θ_C versus support ratio S_2/S_1

Based on the experimental data, a polynomial correlation is proposed which could be useful for estimation of fracture toughness if relative density values are available (in the considered relative density range 0.085 to 0.256):

$$K_{IC} = 3.950 \cdot \left(\frac{\rho^*}{\rho_s}\right)^2 + 0.317 \cdot \left(\frac{\rho^*}{\rho_s}\right) + 0.031 \quad (4)$$

$$K_{IIC} = 38.464 \cdot \left(\frac{\rho^*}{\rho_s}\right)^2 - 0.992 \cdot \left(\frac{\rho^*}{\rho_s}\right) + 0.072 \quad (5)$$

with a coefficient of determination $R^2 = 1$.

The correlation equations (3) and (4) are very important in practical applications because the 3PB tests made on ASCB specimens are carried difficult than SENB ones. In this respect, through these equations can be estimated the K_{IC} and K_{IIC} values according to the relative density which is obtained relatively easily.

From Figure 12 it can be easily seen that on ASCB specimens the mode II fracture toughness is lower than the mode I fracture toughness for low density foams (100 and 145 kg/m^3) and almost equal for 300 kg/m^3 density. Also, it could be observed that both mode I and mode II fracture toughness increases with increasing of density.

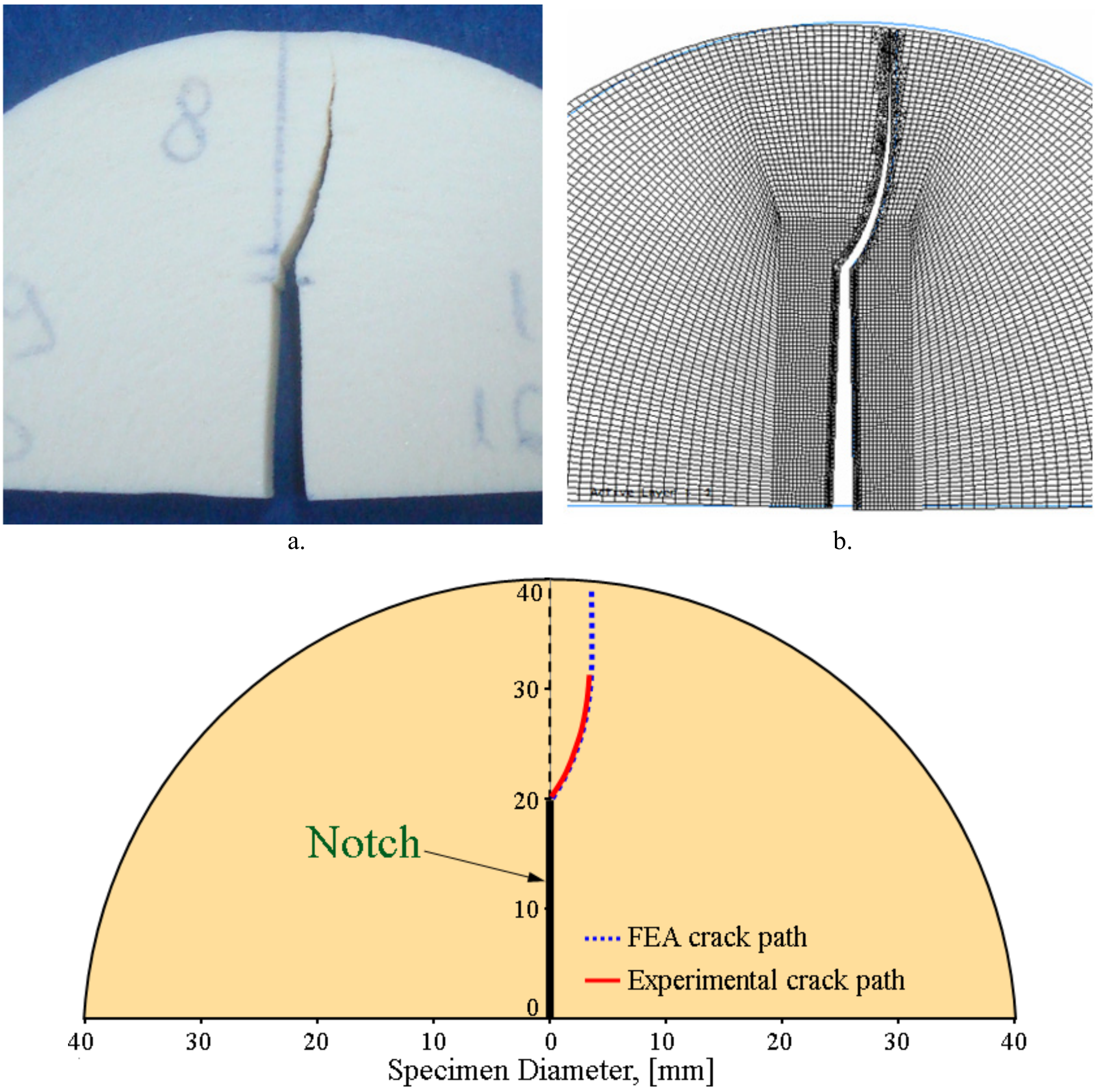


Fig. 10. Crack paths for support positions S_2=8 mm: Experimental (a), FEA (b), Experimental-FEA comparison (c)

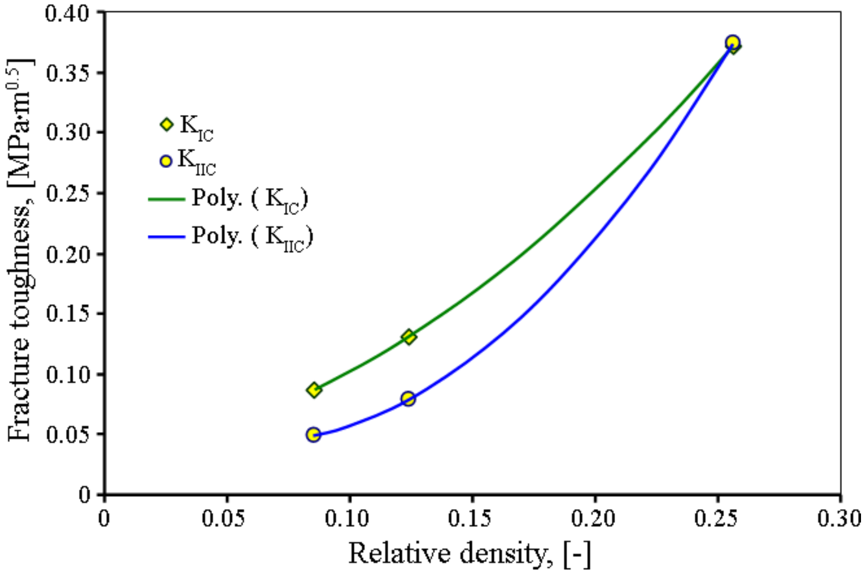


Fig. 12. Mode I and mode II fracture toughness variation with relative density

Conclusions

This paper presents the experimental fracture toughness results of three different types of rigid PUR foams using asymmetric semi-circular bend (ASCB) specimens. A numerical determination of SIF solutions for ASCB specimen was performed.

The following conclusions can be drowning:

- Using a polynomial interpolation the pure mode II exact position of support S_2 was determined at distance S_2 = 2.66 mm from the symmetry line of the semi-circle.
- The von Mises stress contours plot in front of the crack tip show that in pure mode I and pure mode II loading, the stress contour is symmetric relative to the crack plane, while in mixed mode conditions, the contour plot is asymmetric with respect to the crack plane
- It was also determined experimentally and numerically the crack propagation angle and the crack path. A good correlation was obtained between experimental and FEA crack path.
- Based on the experimental data, a polynomial correlation is proposed which could be useful for estimation of mode I and mode II fracture toughness if relative density values of foams are available (in the considered relative density range 0.085 to 0.256), with a coefficient of determination R^2 = 1, see eqs. (4) and (5).
- Finally, was found that the mode II fracture toughness values are lower than the mode I fracture toughness results for low density foams (100 and 145 kg/m^3) and almost equal for 300 kg/m^3 density. Also, it was observed that both mode I and mode II fracture toughness increases with increasing of density.

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Investigarea tenacității la rupere a spumelor poliuretanice folosind epruvete semicirculare încărcate asimetric la încovoiere

Rezumat

Această lucrare prezintă rezultatele experimentale ale tenacității la rupere pentru trei densități diferite (100, 145 şi 300 kg/m³) ale spumelor poliuretanice (PUR) rigide utilizand epruvete semicirculare încărcate asimetric la încovoiere. În acest sens, s-a realizat o determinare numerică a soluțiilor factorului de intensitate al tensiuni (SIF) pentru epruvete ASCB utilizând programul Abaqus. Folosind o interpolare polinomială s-a determinat poziția exactă a suportului S_2 *pentru modul II pur de încarcare. Tensiunilor echivalente von Mises înaintea vârfului fisurii arată faptul că pentru modul I şi modul II pur de încarcare, distributia tensiunilor este relativ simetrică planului fisurii, în timp ce pentru încărcările în modul mixt distributia tensiunilor este asimetrică față de planul fisurii. De asemenea, s-a determinat experimental şi numeric unghiul şi directia de propagare a fisurii. În cazul în care valorile densității relative ale spumelor sunt disponibile, pe baza datelor experimentale, s-a propus o corelație polinomială care ar putea fi utilă pentru estimarea valorilor tenacității la rupere pentru modul I şi modul II. În final, s-a constatat că valorile tenacității la rupere pentru modul II sunt mai mici decât valorile tenacității la rupere pentru modul I pentru spumele cu densitatea scazută (100 şi 145 kg/m³) şi aproape egale pentru densitatea de 300 kg/m³. De asemenea, s-a observat că atât tenacitatea la rupere pentru modul I cât şi pentru modul II cresc odată cu creşterea densității.*