

Manufacturing and Compressive Mechanical Behavior of Reinforced Polyurethane Flexible (PUF) Foams

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Abstract. This paper presents a manufacturing method and mechanical behavior of unreinforced (U-PUF) and reinforced (R-PUF) polyurethane flexible foams. In order to obtain a new type of reinforced polyurethane composite foams, an amount of 0.5% (of the foam liquid mass) aluminum microfibers were used. The mechanical characterization of both U-PUF and R-PUF foams was carried out at room temperature through quasi-static compression tests. The compression tests were performed on cubic specimens with a loading speed of 10 mm/min. The obtained and investigated foam showed a density of 150 kg/m³. It was found that the new obtained R-PUF foams crushes progressively during compression and shows higher mechanical properties (in terms of compressive modulus, yield stress, plateau stress and densification strain) compared to U-PUF foam. Particular attention was given to the foam crush performances. Experimental results indicated that aluminum microfibers significantly improve the foam energy absorption capabilities in compression.

1. Introduction

Polyurethanes (PU) are polymers resulting from the polyaddition reaction between isocyanates and polyalcohols. They are used as foams, elastomers, plastic polyurethanes and mixtures [1]. Polyurethane foams can be rigid (PUR) or flexible (PUF) with open, closed and partly open-partly closed cellular structure [2-4]. Owing to the unique combination of excellent physical, thermal, acoustic and mechanical properties [5-8], PUR foams are used in various applications, but especially as core material for sandwich panels [9], while flexible ones are widely used in applications of different industries such as automobiles, furniture, transport, textiles and fibers [10-12].

Many analytical [13-15], numerical [16, 17] and experimental [18-20] results are reported on PUR foams, while literature shows far fewer results for PUF foams. In recent years, emphasis has been placed on the manufacturing of flexible PU foams with superior mechanical properties. For this purpose, different materials have been used as reinforcement to obtain PUF composite foams [10-12, 21, 22]. Usman et al. [21] investigates the effect of CaCO₃ filler in PUF foam matrix for achieving high mechanical properties at a low production cost. The effect of post-consumer PET (polyethylene terephthalate) as reinforcement filler in flexible PU foams was studied by Mello and coworkers [22]. They evaluated the physical, mechanical and morphological characteristics of the PUF foams. Also,



indentation hardness, tensile strength and elongation at break of the flexible PU foam composites were examined by Latinwo et al. [23] as a function of the filler content (calcite and dolomite) in the PU matrix.

Compared to reinforced materials used by other researchers, in the present paper we used aluminum fibers resulting from the aluminum processing process. These reinforcements are very cheap, obtained without further processing and the foam manufacturing acting as recycling process. Aluminum fibers with lengths between 5-10 mm were collected and introduced into the foam matrix material by a well-established procedure. Their use has led to a considerable increase in mechanical properties, while maintaining low foam density (due to low fiber density). Also, the energy absorption crush performances presents values to be considered for future possible applications that contain flexible foams

2. Materials and methods

In order to obtain reinforced polyurethane flexible (R-PUF) foams, aluminum microfibers were added into both component A (isocyanate) and component B (polyol) separately, and, in order to get a good dispersion, each component has been stirred with the aluminum fibers for about 3 minutes. After individual stirring, component A was mixed with component B and stirred together for 30 seconds; afterwards, the R-PUF foam has been allowed to dry at room temperature for 24 hours. Before being added to the polyurethane components, the aluminum fibers were dried at 80°C for about 1 hour. The same procedure was followed for obtaining unreinforced polyurethane flexible (U-PUF) foams.

After the drying and hardening process, large foam blocks were obtained. The density (150 kg/m³) of the foam material under consideration was measured using mass and specimens dimensions. The U-PUF and R-PUF foams microstructures are presented in Fig. 1.

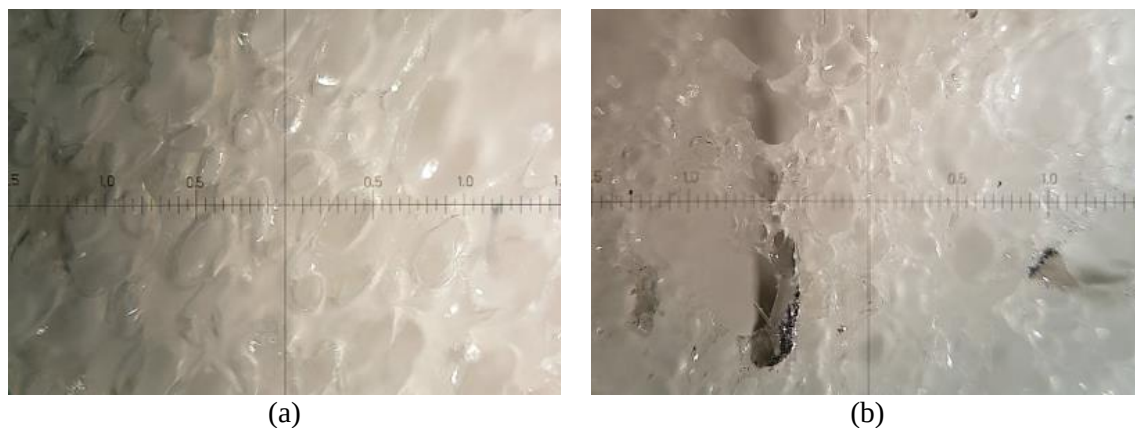


Figure 1. Microstructure of unreinforced (a) and reinforced (b) PUF foam specimens

To establish the material properties, uniaxial quasi-static compression tests on the foam cubic specimens were carried out. A 5 kN Zwick Roell testing machine has been used for this purpose. The experimental tests were performed with a loading speed of 10 mm/min. The foam material properties were established in the controlled room temperature and humidity conditions, according to [24].

3. Results and discussion

Typical load (F)-displacement (Δ) curves derived from the compression tests were converted to representative compressive stress (σ)-strain (ϵ) curves using geometrical parameters of the foam specimens. The σ - ϵ compression behavior is presented in Fig. 2a for both U-PUF and R-PUF foams. In Fig. 2b are shown the compressive damage stages of specimen in strain range from 0 to 80%. Both U-PUF and R-PUF composite foams presents a progressive elasto-plastic collapse behavior during compression test.

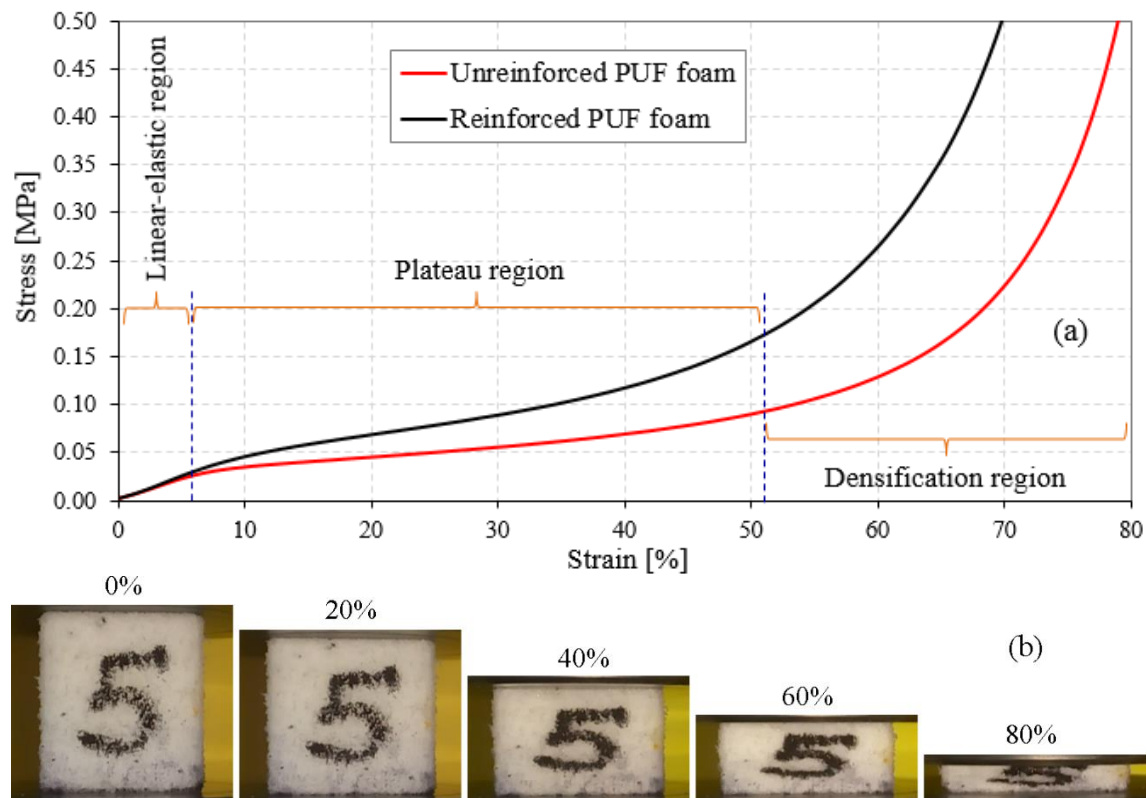


Figure 2. Stress-strain curves (a) and deformation sequences (b) of investigated PUF foam

The U-PUF and R-PUF foams show stress-strain profiles similar to other foams [25-28], which consists of a linear elastic region followed by a strain hardening (plateau) region. By comparing the reinforced samples results to the unreinforced ones, an increase in compressive modulus of elasticity by 12.6% is observed, as observed from Table 1.

Table 1. The main mechanical properties of unreinforced and reinforced PUF foams.

PUF foam type	Mechanical properties						
	E [MPa]	σ_y [MPa]	ϵ_y [%]	σ_p [MPa]	ϵ_D [%]	σ_D [MPa]	W_D [MJ/m ³]
Unreinforced	0.4510	0.0220	4.7900	0.0563	54.0900	0.1029	0.0293
Reinforced	0.5160	0.0295	5.8100	0.0960	51.0900	0.1735	0.0422

During strain hardening the strength of the foam material is increased and in the plateau area there is a large absorption energy. In this case, the major difference from other works [29-31] is that in this case the transition from the elastic region to the plateau region is smooth [32-34] without the presence of a peak stress drop. Upon further loading the specimens in compression, the stress starts rising in foam samples up to around 50% strain value after which there is a sudden increase in stress at a small increase in the strain. This last region is named densification region and starts from onset strain of densification (OSD) up to final failure. At the moment of OSD the R-PUF foam shows an energy absorption value about 0.0422 MJ/m³ with 31% more than U-PUF foam.

All the reinforced foams show an improvement in compressive strength compared to the unreinforced PUF foams, as shown in Fig. 3. Long aluminum microfibers induce a change in foam matrix strength and stiffness making them more stiff and strong as they are reinforced.

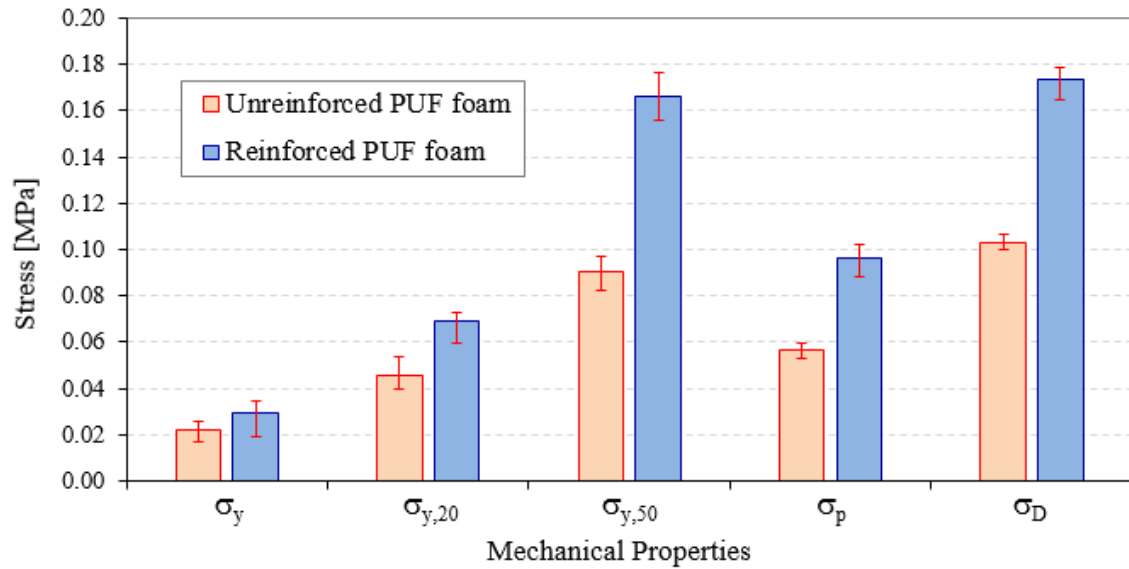


Figure 3. Comparison of main mechanical properties in compression

The energy-absorbing capability of these unreinforced and reinforced polyurethane flexible foams specimens was evaluated according to Refs. [35-42] and presented in Fig. 4 as a function of strain.

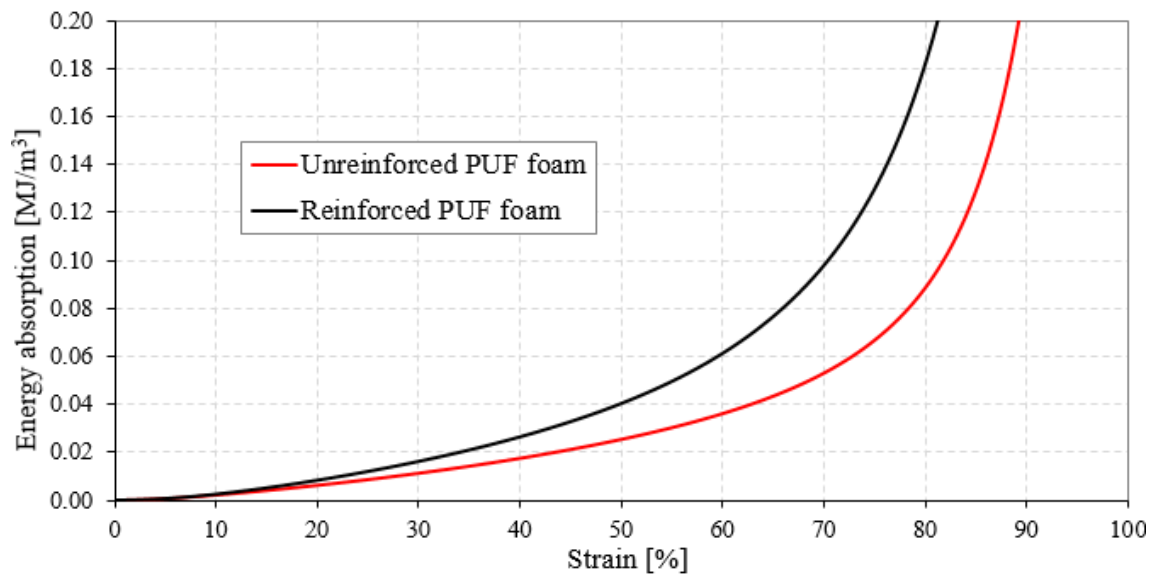


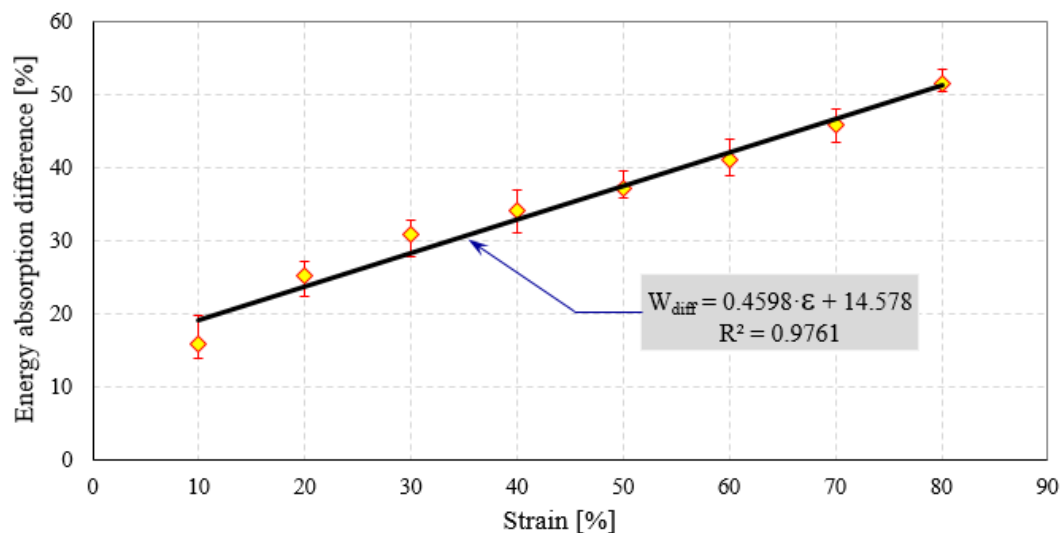
Figure 4. Energy absorption variation with strain of PUF foams

The absorbed energy by the R-PUF foam specimen is larger compared to the U-PUF foam to the fact that the long aluminum microfibers take over an important part of the quasi-static load. From Fig. 4 it is to be noted that in both cases (U-PUF and R-PUF foams), the energy absorption curves shows the same behavior with approximately the same W values up to a strain of 15%. The biggest difference (in the terms of W) being to a deformation of 80%. This energy absorption difference (W_{diff}) is presented in Fig. 5 as a function of ϵ .

Table 2 presents the energy absorption values corresponding to different strains.

Table 2. The energy absorption values of investigated PUF foams.

PUF foam type	Energy absorption at different strains, W [MJ/m ³]							
	10%	20%	30%	40%	50%	60%	70%	80%
Unreinforced	0.0021	0.0062	0.0112	0.0174	0.0253	0.0361	0.0529	0.0884
Reinforced	0.0025	0.0083	0.0162	0.0264	0.0403	0.0613	0.098	0.1824

**Figure 5.** Energy absorption-strain variation of investigated foams

In Fig. 5 the energy absorption difference rises linearly from a value of 16% for low strains to a maximum value of 51.54 %, associated to high strains.

It is therefore necessary to explore new foam materials that during crash events would provide enough energy absorption capabilities together with high mechanical properties and stable collapse mechanisms [43, 44]. Reinforced polyurethane composite foams may provide a good solution to this problem, especially if they are used as core material in advanced composite structures (sandwich structures, foam-filled tubes etc.). From the current investigation can be argued that instead of regular/standard polyurethane foams the reinforced polyurethane foams should be studied in more detail.

4. Conclusions

This paper discloses both a method for manufacturing and mechanical characterization of closed-cell polyurethane foams reinforced with aluminum microfibers. Compressive properties of unreinforced and reinforced composite flexible foams are investigated and compared in the present work.

In the present study it has been found that the new produced R-PUF foam (150 kg/m³ density) exhibit high mechanical properties per mass compared to U-PUF foam, which could be very promising composite foam material for the engineering applications.

A comparison of energy absorbing capabilities of U-PUF and R-PUF foams was presented. It was found that reinforced polyurethane composite foams have better crashworthiness performances (almost double) than standard foams used currently.

Moreover, using this foam manufacturing process a beneficial waste management has been achieved.

5. References

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