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PHYSICAL AND MECHANICAL CHARACTERIZATION OF POLYURETHANE FOAM CORE OF SANDWICH PANELS OF VARIOUS DENSITIES

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Abstract: *Sandwich foaming is a manufacturing process in which a liquid monomer mixture is injected on the bottom face sheet of the sandwich panel where it polymerizes to form cross-linked polyurethane (PUR) foam providing an adhesive joint between the bottom and upper metal sheets. The single-step process avoids manual operations in the assemblage of the panel and the use of adhesive. However, the PUR foam in the core of the panel and at foam-to-face sheet interface may present fluctuations in the mechanical properties. The aim of this study is the mechanical and thermophysical characterization of PUR foam of various densities produced by sandwich foaming. Additionally, a qualitative assessment of the foam-to-face sheet interface is carried out based on the results of the flatwise tensile and shear tests.*

Keywords: Polyurethane foam; Steel sandwich panel; Flooring system; Digital image correlation; Thermogravimetric analysis.

1. Introduction

Polyurethane (PUR) foam is one of the most common core materials used in sandwich panels for civil engineering applications. Sandwich panels are made of two thin and stiff face sheets separated by a low-density core material that result in a structure with high stiffness-to-weight ratio. In the literature [1,2] the most common production method of sandwich panels involves two phases: i) prefabricated foam blocks must be cut and then ii) adhered to both face sheets by manual operation. These foams are manufactured in bulk and their properties are relatively well controlled [3]. On the other hand, the dust resulting from the machining of the foam blocks may weaken the bond quality between core and face sheets [4]. Steel face sheet sandwich panels are currently produced continuously. The liquid monomers of the PUR foam are injected on the bottom face sheet where they polymerize and cross-links providing an adhesive bond in a single-step process called sandwich foaming [5]. Promising results have emerged in the use of novel foam-filled metal structures [6,7]. However, [8] indicates that this sandwich foaming process may result in high variability in the foam and the foam-to-face sheet interface characteristics. The main objectives of this study are to provide experimental data on the mechanical properties of PUR foam of various densities to be used as structural core in a novel steel sandwich panel for flooring system [9] and to assess the influence of the single-step production technology on the molecular structure of the foam by means of thermogravimetric analysis (TGA).

2. Experimental program

The mechanical properties of the PUR foam are required to efficiently design and correctly predict the failure modes of sandwich floor panels. In the context of application of flooring system, the shear, tensile, and compressive properties are particularly relevant. The shear properties are required to assess the integrity of the foam during its service life as it is mostly subjected to this kind of stresses. The latter two properties are necessary to predict common failure modes of sandwich panels involving local buckling phenomena such as wrinkling [10]. The experimental campaign also included a study of the thermal stability and composition of the PUR foam by means of TGA.

The mechanical tests of the experimental program include flatwise tensile and compressive tests, as well as shear tests. Regarding the flatwise tensile and compressive tests, they are carried out on three sets of specimens with nominal density of 40, 50, and 60 kg/m^3 according to [11] and [12], respectively. The specimens are extracted from large-scale steel face sheet sandwich panel. The specimens are tested in tension and compression up to failure at a rate of 0.5 and 2.4 mm/min, respectively. The load is recorded by a load cell with a capacity of 25 kN (±0.005 kN) and the vertical displacement by 4 linear variable differential transformers (LVDTs), one for each side of the specimen. Furthermore, the displacement of one of the faces is monitored using the digital image correlation (DIC) technique. Concerning the shear tests, they are carried out on one series of specimens with nominal dimensions 360×115×30 mm^3 and nominal density of 40 kg/m^3. The test setup follows the recommendation of [13] and [14]. The load and relative displacement are recorded with a load cell of 200 kN (±0.12 kN) and 2 LVDTs, one for each side. The different test setups are illustrated in Figure 1 and can be consulted in detail in [15].

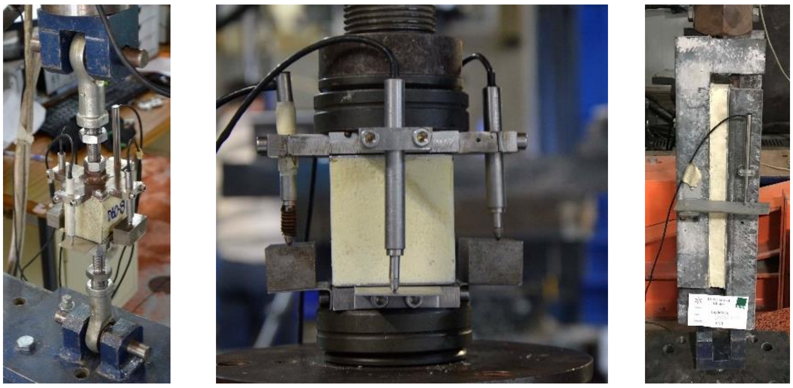
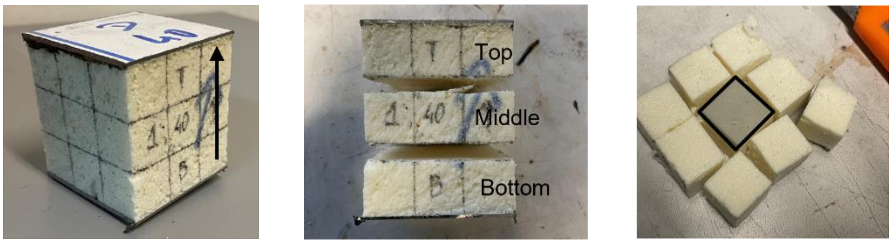

(a) (b) (c)

Figure 1. Mechanical test setups: (a) flatwise tensile test; (b) flatwise compressive test; (c) shear test

Thermogravimetric experiments were carried out according to [16] on specimens extracted from the cubic samples of the flatwise tensile and compressive specimens from three different levels across the thickness, namely top, middle, and bottom layer as shown in Figure 2. The tests are carried out in a TA Instruments SDT Q600 apparatus in a nitrogen atmosphere. The specimens' weight was approximately 2 mg, heated from 30°C to 700°C at a heating rate of 10°C/min, with a gas flow rate of 100 mL/min.



(a) (b) (c)

Figure 2. TGA specimen preparation: (a) foam rising direction; (b) top, middle, and bottom layers of the PUR foam specimen; (c) sample extraction location from one of the layers

3. Results and discussion

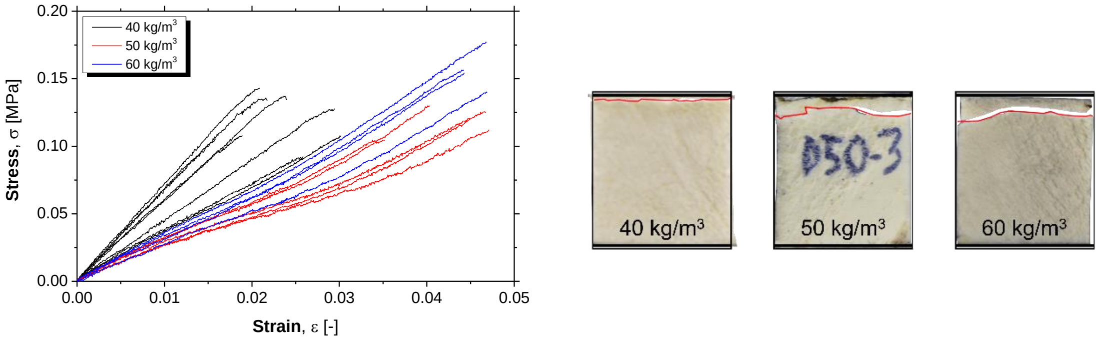
A summary of the mechanical properties of the PUR foam and their respective coefficients of variation is given in Table1. From the flatwise tensile and compressive tests carried out, the tensile strength (σ_t) and modulus (E_t), and the compressive yield strength (σ_c) and modulus (E_c) were obtained, respectively. The shear yield strength (τ) and modulus (G) were determined through the shear tests.

Table 1: Mechanical properties of the tested PUR foam

Density [kg/m^3]	σ_t [MPa]	E_t [MPa]	σ_c [MPa]	E_c [MPa]	τ [MPa]	G [MPa]
40	0.12 (±0.02)	5.7 (±1.4)	0.15 (±0.01)	5.9 (±0.6)	0.16 (±0.01)	2.9 (±0.3)
50	0.12 (±0.01)	2.8 (±0.3)	0.09 (±0.01)	3.2 (±0.3)	*	*
60	0.16 (±0.02)	3.5 (±0.3)	0.08 (±0.01)	2.8 (±0.5)	*	*

Note: (*) Shear tests are carried out only on the 40 kg/m^3 PUR foam due to the decrease in the mechanical properties with the increase of density

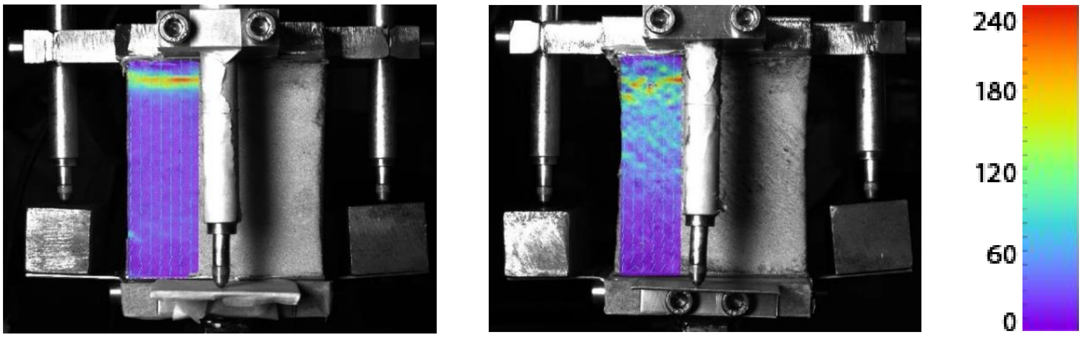
The stress-strain curves obtained in the flatwise tensile tests are illustrated in Figure 3a.



(a) (b)

Figure 3. Flatwise tensile test results: (a) stress-strain curves; (b) typical failure modes with tensile crack highlighted in red

All the specimens show a linear elastic behavior up to failure in tension. Slight strain-hardening may be noticed in the 50 kg/m^3 and 60 kg/m^3 specimens. The observed failure mode for all the densities is cohesive failure of the foam (see Figure 3b). This confirms the good quality of the foam-to-face sheet interface provided by the single-step production process. In Figure 4 the maximum principal strain field obtained from the DIC measurements prior to failure is illustrated for the 40 kg/m^3 and 50 kg/m^3 foams. The 40 kg/m^3 specimen shows a strain concentration in the top layer whereas the 50 kg/m^3 one shows a more distributed strain pattern in the middle and top layers. The 50 kg/m^3 and 60kg/m^3 foams show a similar tensile behavior.



(a) (b)

Figure 4. DIC measurements in terms of maximum principal strain at yielding of flatwise tensile tests: (a) 40 kg/m^3; (b) 50 kg/m^3. All units in micro strain

For what concerns compressive behavior, the 40 kg/m^3 specimens show a stress-strain curve with three distinct regions: i) a linear elastic part, ii) a plateau of deformation at constant stress due to cell buckling, and iii) a strain-hardening part at large strain due to crushing of the cell walls. On the other hand, in the 50 kg/m^3 and 60 kg/m^3 series the plateau region is replaced by a longer strain-hardening part (see Figure 5). This may suggest that the 50 kg/m^3 and 60 kg/m^3 foams microstructure present strong imperfection [17].

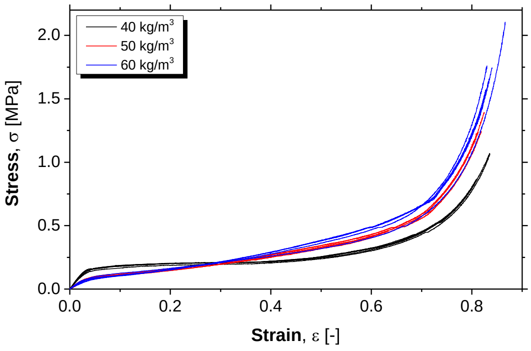
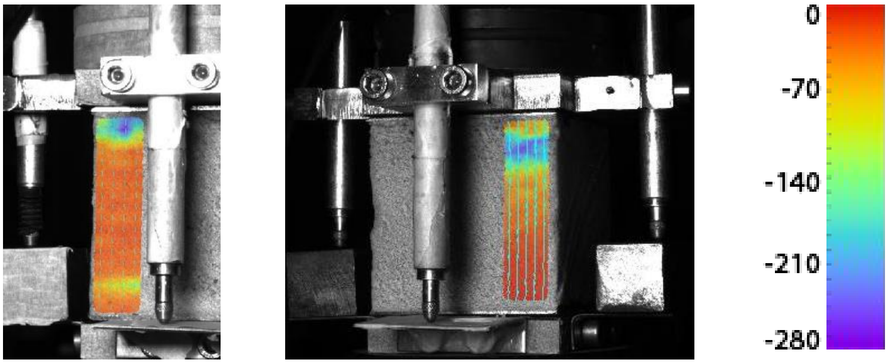


Figure 5. Flatwise compressive test results: stress-strain curves

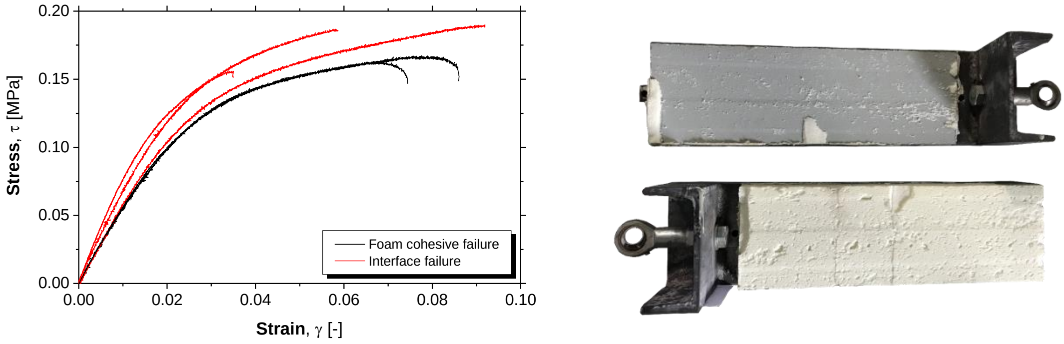
In Figure 6 the maximum principal strain fields obtained from the DIC measurements at yielding are illustrated for the 40 kg/m^3 and 50 kg/m^3 foams. In the 40 kg/m^3 the deformation is concentrated in the top and bottom layers of the foam. The middle layer present lower deformation, and thus higher compressive modulus in agreement with [18] that locates the level with the highest mechanical properties at mid height. The 50 kg/m^3 specimen presents strain concentration in the top layer of the foam and negligible deformation in the bottom layer similarly to the 60 kg/m^3 foam. It is important to note that the 40 kg/m^3 foam generally present higher tensile and compressive failure stress and Young's modulus values than the 50 kg/m^3 and 60 kg/m^3 foams. This result is contrary to the increase in mechanical properties with the density of the PUR foam. However, it is worth mentioning that the estimated density of the 50 kg/m^3 and 60 kg/m^3 foams were significantly lower than the nominal density, namely -6.7% and -14.9%. Thus, some differences in the chemical composition between the 40 kg/m^3 and the 50 kg/m^3, and 60 kg/m^3 are to be expected.



(a) (b)

Figure 6. DIC measurements in terms of minimum principal strain at yielding of flatwise compressive tests: (a) 40 kg/m^3; (b) 50 kg/m^3. All units in micro strain

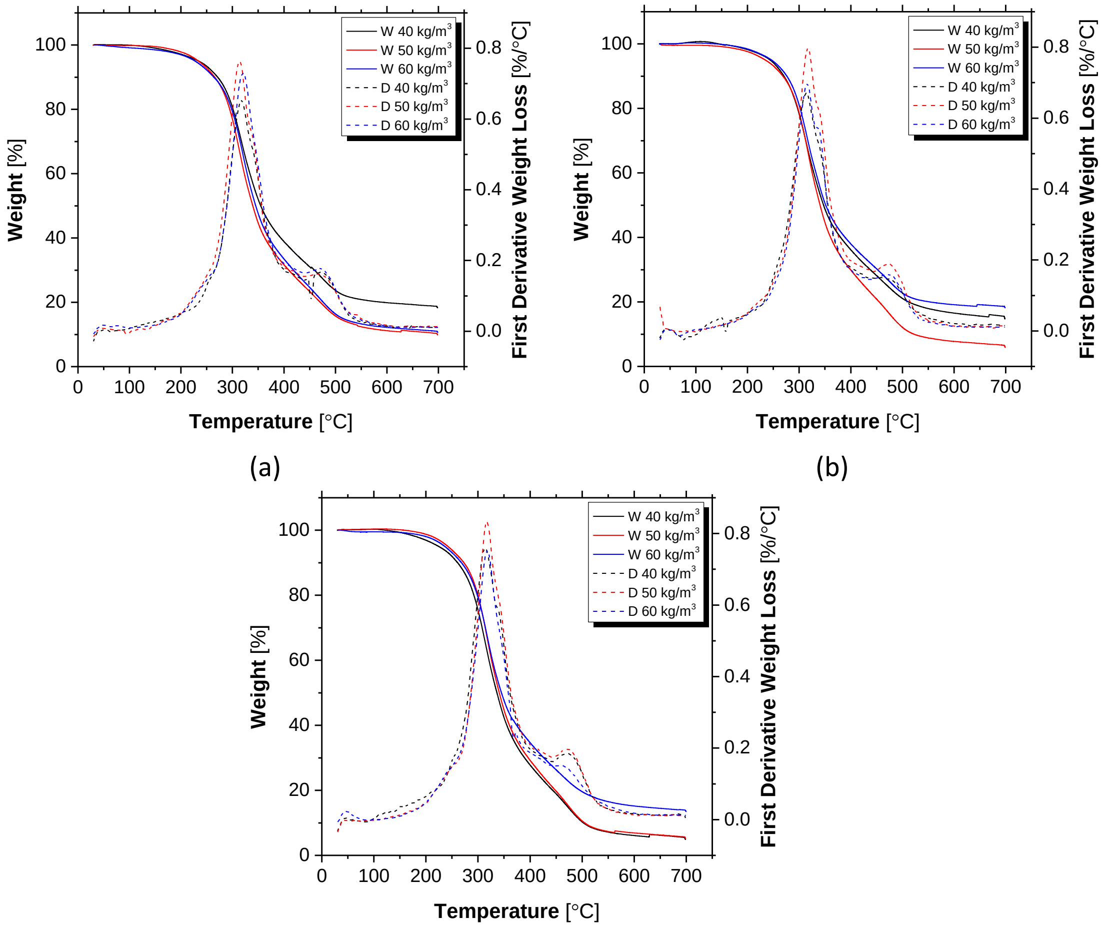
The stress-strain curves obtained in the shear tests are illustrated in Figure 7a. All the specimens present an initial elastic behavior followed by a non-linear stage. Two failure mode were identified: i) cohesive shear failure of the foam with the formation of cracks oriented at 45° and ii) adhesive shear failure at the foam-to-face sheet interface with cracks parallel to the loading plate. The latter failure mode occurred in specimens where the presence of macropores at the interface has been observed after testing (see Figure 7b).



(a) (b)

Figure 7. Sher test results: (a) stress-strain curves; (b) macropores at the interface foam-to-face sheet

The weight and derivative of the weight, both as a function of temperature, obtained from the TGA are plotted in Figure 8. All the layers of every foam density present a two-stage degradation process [19]: i) the first has a maximum rate loss at 316°C during which the mass is reduced by approximately 50% and ii) the second has its peak at 468°C during which the mass reduction is equal to 25%. The largest differences between the curves are found in the amount of residue at 700°C. The residue gives an indication about the cross-linked fraction of the polymer.



(a) (b)

(c)

Figure 8. TGA results: (a) top layer; (b) middle layer; (c) bottom layer

It is a critical aspect in the production of thermoset foamed product [20] such as PUR foam. Low crosslinking speed may delay gelation time and provoke the foam structure to collapse. The top layer of the 40 kg/m^3 is the largest value among all layers and foam densities. The residue of the middle layer of the 50 kg/m^3 is smaller than those of the other foam densities. Finally, the bottom layer of the 60 kg/m^3 foam is larger than those of the 40 kg/m^3 and 50 kg/m^3 foams. In the 40 kg/m^3 PUR foam a residue gradient is observed across the thickness, reaching its peak in the top layer. The density of crosslinking is related to large elastic deformation in polyurethane rubbers [21]. This may explain the large strain concentration found in the top layer of the 40 kg/m^3 foam in the flatwise tensile test (see Figure 4a). On the other hand, discrepancies may be found between the TGA and mechanical test results of the 50 kg/m^3 and 60 kg/m^3 PUR foams. Nevertheless, their scattered carbonized residue values may suggest that crosslinking and blowing processes might be imbalanced, and thus resulting in a foam with non-optimized microstructure.

4. Conclusions

In this work, an experimental campaign is carried out to assess the mechanical and thermophysical properties of PUR foams of various densities to be used as core material in a novel flooring system based on sandwich panels. Additionally, a qualitative assessment of the properties of the foam-to-face sheet interface is performed in terms of tensile and shear behavior. From the obtained results the following conclusions and a future topic of research are highlighted:

- The lowest density PUR foam (40 kg/m^3) generally exhibits the highest mechanical properties, i.e. a yielding tensile, compressive, and shear stress of 0.12 MPa, 0.15 MPa, and 0.15 MPa, respectively. It also shows the highest tensile, compressive, and shear modulus values, namely 5.7 MPa, 5.9 MPa, and 2.7 MPa, respectively.
- The DIC measurements provide insight on the mechanical behavior of the PUR foams. Two different strain fields are identified for the 40 kg/m^3 and the 50 kg/m^3 and 60 kg/m^3 foams: i) the former presents strain concentration at the top and bottom layers whereas ii) the 50 kg/m^3 and 60 kg/m^3 foams present a more uniform strain pattern.
- The foam-to-face sheet interface obtained through a single-step production process shows higher tensile strength than the PUR foam itself. On the other hand, the shear tests yielded both interface and PUR foam cohesive failure mode. This suggest that the presence of defects such as macropores is an influencing factor in the shear behavior of steel face sheet sandwich panel with PUR foam core.
- TGA measurements highlight the high heterogeneity of PUR foams produced continuously by injection on the bottom face sheet of sandwich panels. Additionally, the results suggest that other techniques, such as the scanning electron microscopy, may be required to further investigate the relation between mechanical behavior and foam microstructure.

Acknowledgements

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