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MECHANICAL BEHAVIOR OF COMPOSITE OF POLYURETHANE REINFORCED WITH COTTON FIBER AND ALUMINA TRIHYDRATE

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Abstract. This work aims to evaluate the mechanical behavior of the composite of polyurethane (PU) derived from a blend of vegetable oils with reinforcement of cotton fiber (CF) fabrics and added Alumina Trihydrate (ATH). For comparison and study, tests were performed for characterization of the pure PU, PU doped with different ATH contents (10%, 20% and 30%), of PU composite reinforced with cotton fiber and the PU composite reinforced with cotton fiber and ATH. The fibers were oriented at 0 °, ± 45 ° and 90 °. The mechanical properties obtained according to the tensile test for the laminated PU composite reinforced with cotton fiber and doped with 30% of ATH presented an elasticity modulus of 4.733 GPa and ultimate tensile strength of approximately 60 MPa for the samples oriented at 0°. The pure PU exhibited an elasticity modulus of 1.703 GPa and ultimate tensile strength of 39.715 MPa. When comparing the composite results with the pure polyurethane matrix, a significant stiffness and mechanical resistance enhancement was obtained.

Keywords: Composite, Polyurethane, Cotton fibers, Alumina trihydrate, Characterization.

1. INTRODUCTION

The use of raw materials from renewable sources for research involving the use of green polymers as substitutes for petroleum-based polymers and for the manufacture of bio-composites showed a great growth (Quirino, *et al.*, 2015; Milanese, Cioffi and Voorwald, 2012). The main reason of those researches is to decrease the risk of environmental damages caused by petro-based polymers and synthetic fibers (Machado, *et al.*, 2010; Sanjay, Arpitha and Yogesha, 2015, Alomayri, Shaikh and Low, 2014)

Among the numerous types of composites, there is a clear emphasis on polymer composites reinforced with fibers. The natural fibers are given special attention because they present: low cost, low density, good mechanical strength and also because they are derived from renewable raw materials.

In recent years, attempts have been made to reduce the use of synthetic fibers and still considerably reduce the weight of the structures, taking advantage of the lower density and cost that some natural fibers provide. In this sense, natural fibers were widely used as reinforcement in composites of interior parts of commercial vehicles (Koronis; Silva; Fontul; 2013; Holbery and Hoston, 2006).

In order to utilize polymeric composites reinforced with natural fibers in vehicle interiors, they must present certain safety precautions when exposed to fire situations, giving enough time to the rescue of the victims. Thus, researches involving the use of flame retardant additives in polymeric materials and polymeric composites have been necessary to allow the use of these materials according to existent standards.

Therefore, the main goal of this paper is the mechanical characterization of a bio-composite of polyurethane (PU) derived from a blend of vegetable oils reinforced with cotton fiber (CF) and doped with alumina trihydrate (ATH), according to the tensile test.

2. EXPERIMENTAL PROCEDURE

Four types of samples were made as describes the following procedures: pure PU, PU doped with ATH, PU reinforced with cotton fiber and finally PU reinforced with cotton fiber and ATH.

2.1 Pure Polyurethane

The polyurethane used was obtained by mixing two components, polyol (component A - AG201) and prepolymer or isocyanate (component B - AG201), provided by the company Kehl – Trade and Industry Ltd. The ratio used of the components is 1: 1, after homogenization the polymer was placed in the vacuum chamber to remove voids. Moreover, the mixture was poured into silicone molds for the production of test specimens in pure PU.

2.2 Polyurethane doped with ATH

The manufacture was based on two simple steps, the already sieved ATH was pre-mixed to the polyol (component A), after homogenization the prepolymer was added, the final blend was placed in a vacuum chamber for removal of voids, subsequently poured into silicone molds. The ratio of 1: 1 was used for polyurethane, and specimens with different amounts of ATH were manufactured, being 10%, 20% and 30% of the total mass.

2.3 Composite of PU reinforced with CF

The most suitable manufacturing method for the composite laminate of PU reinforced with cotton fiber was the vacuum bag. For the specimens manufacture with 0° and 90° oriented fibers, seven layers were stacked ($[0°]_7$). Subsequent cuts of the samples in the directions of 0° and 90° with respect to the fibers were made. Seven layers were stacked alternating the direction of the fibers between 0 ° and 90 ° ($[0°/90°/0°/90°/0°/90°/0°]$s) (Figure 1) for subsequent cutting at $\pm$ 45 °.
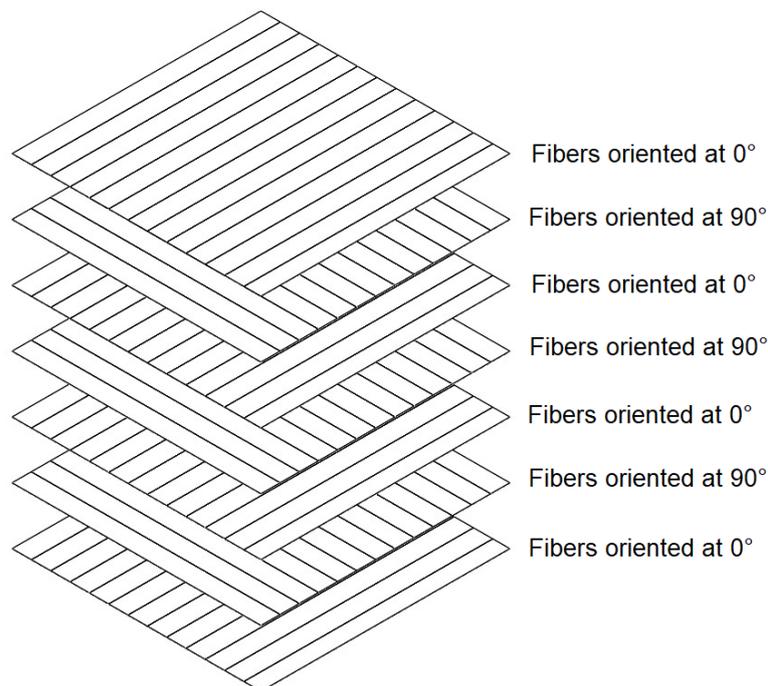

Figure 1 – Laminated composite configuration with 7 layers, alternating the direction between 0° and 90°.

2.4 Composite of PU doped with ATH and reinforced with CF

The same process of the composite of PU+CF, added with ATH, was used. The amount of ATH will be defined based on the results of the mechanical tests of the PU+ATH, analyzing the influence of the quantity of ATH on the mechanical properties of the material.

3. RESULTS AND DISCUSSION

Figure 2 shows the stress-strain curves of the respective pure PU specimens, according to ASTM D638-96. The mean value of the elasticity modulus and the maximum stress were 1.703 GPa and 39,715 MPa, Figure 2e.
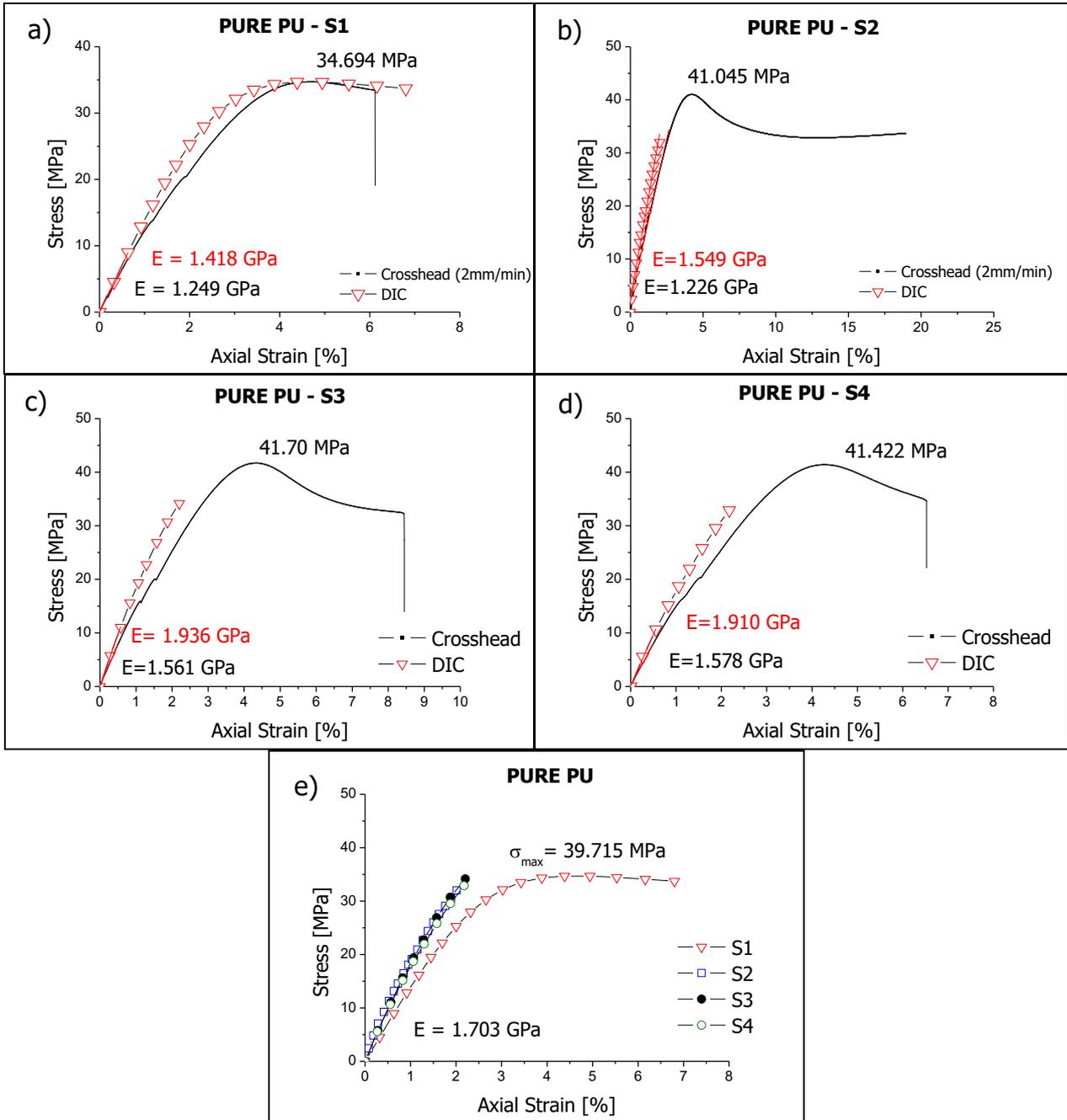

Figure 2 – a) Stress-strain curves of pure PU of S1 b) S2 c) S3 d) S4 and e) Stress-strain mean curves of pure PU specimens.

The mineral flame retardants, such as aluminum hydroxide, are widely used and very efficient decreasing the risk of fire propagation. However, a big amount of flame retardant must be incorporated to make the desired flammability properties achievable, and these additives may cause damages in the material, interfering on its mechanical properties (COSTES et al., 2017). Therefore, tensile tests were made in doped polyurethane with different proportions of ATH, 10%, 20%, and 30% of the specimen total mass.

In Figure 3 are represented all the stress-strain curves of the five PU+10% ATH samples (S1, S2, S3, S4 and S5) (Figure 3a), five PU+20% ATH samples (Figure 3b) and five PU+30% ATH (Figure 3c) specimens tested.

There was an improvement on the elasticity modulus when ATH represented 10% of the total mass, although, the maximum average bearable load (38.047 MPa) remained approximately the same if compared to the pure PU (39.715 MPa). The pure PU elasticity modulus is 1.703 GPa while the doped PU with 10% ATH showed an enhancement of 27% compared to the pure PU, achieving 2.162 GPa.

The doped PU with 20% ATH also revealed an increasement of its elasticity modulus (2.367 GPa), but with a maximum average bearable load (32.650 MPa) slower if compared to the pure polyurethane (39.715 MPa) and the doped PU with 10% ATH (38.047 MPa)

The maximum average stress presented by the 30% ATH doped PU was 31.630 MPa, which is the slowest number among all the tested polyurethanes. With its elasticity modulus being 2.607 GPa. It is possible to suppose that the higher the proportion of alumina trihydrate in the polymer, the higher will be the stiffness detected.
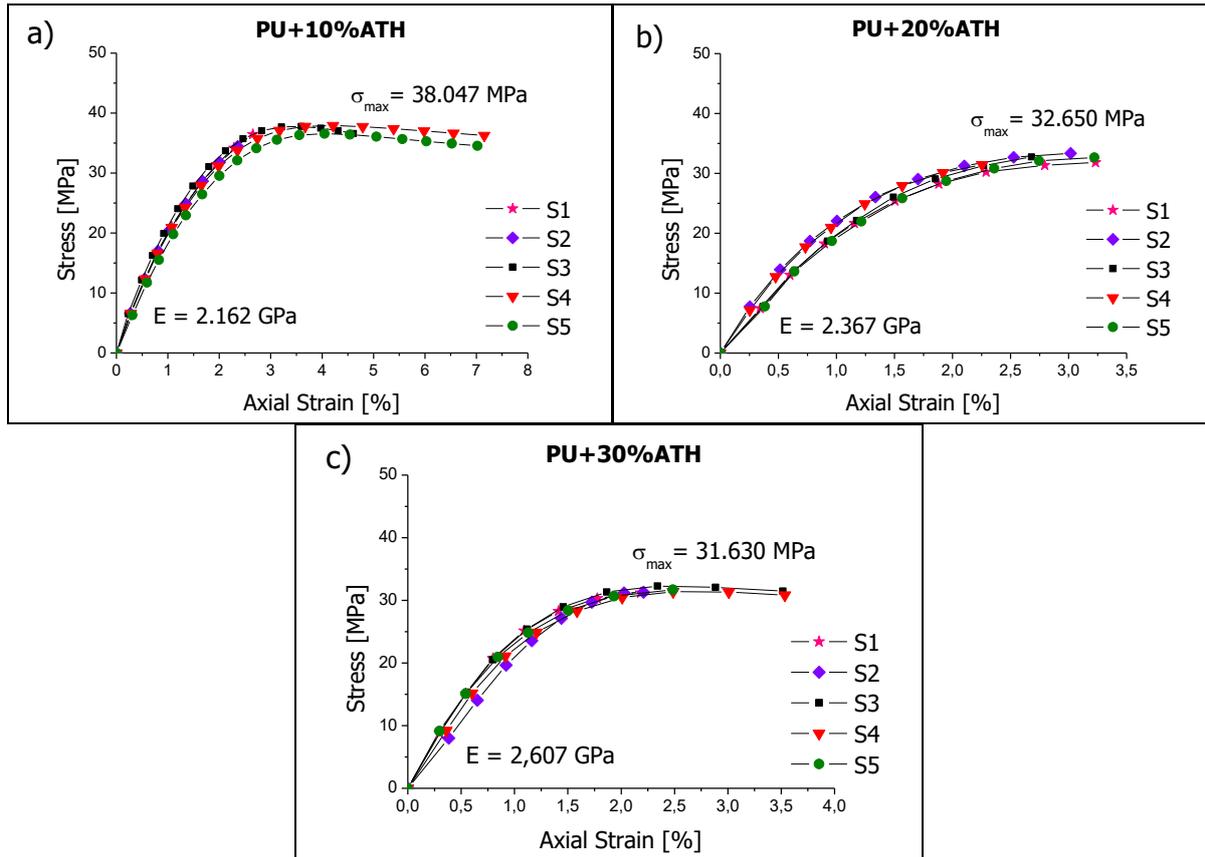

Figure 3 – a) Stress-strain curves of PU+10% ATH specimens. b) Stress-strain curves of PU+20% ATH specimens. c) Stress-strain curves of PU+30% ATH specimens.

Specimens of PU+7CF with orientation of 0 ° (PU+7CF-0 °) and 90 ° (PU+7CF-90 °) were tested according to ASTM D3039. As can be seen in Figure 4, comparing the results obtained from the composite with the pure PU, the maximum supported tension of the pure PU is on average of 40 MPa and for the composite of 79 MPa. The elasticity modulus presented by the composite (3,612 GPa) was almost double the pure PU (1.703 GPa).
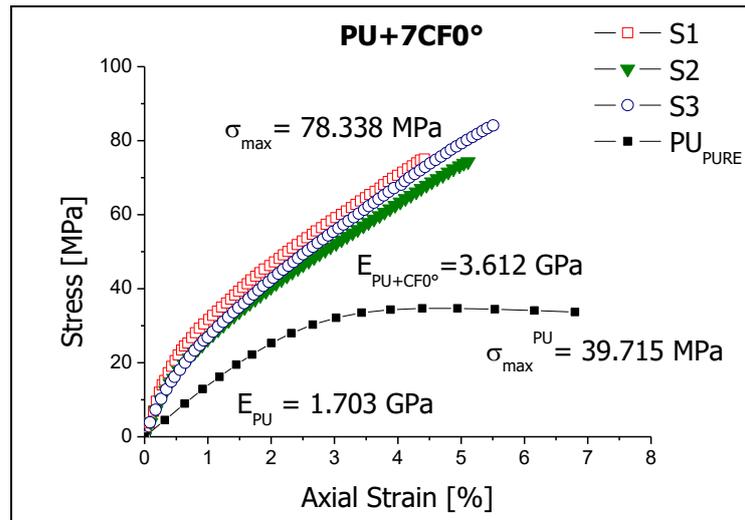
Figure 4 – Stress-longitudinal strain curves of composite PU+7CF-0°.

Misnon, *et. al.* (2014) listed many papers present in the licterature where natural fibers were used as reinforcement for resins, as shown in table 1, indicating mechanical properties obtained from the tensile test. As cited before, for cotton fiber fabrics oriented at 0°, the maximum tensile stress and elasticity modulus are approximately 80 MPa and 3.6 GPa respectivaly. Comparing the results presented in table 1, the maximum tensile stress of the composite PU+7CF showed compatible numbers with the linen fabric, although, the elasticity modulus was 50% smaller than the value presented by the PU+7CF -0° composite. The known material with the most similar mechanical behavior to the material in this study is the jute fabric, having the biggest mechanical resistance and stiffness. The only natural fabric composite that showed a Young modulus higher than 2 GPa was the jute fabric. Thus, the studied composite has singular characteristics when compared to the licterature.

Table 1. Mechanical properties of natural fabric fibers reinforced resins. (Adapted from Misnon, et al, 2014)

Types of Fibers	Tensile	
	Maximum Stress [MPa]	E Modulus [GPa]
Linen fabric	54.6 – 81.9	0.9 – 1.8
Jute fabric	22.6 – 92	2.23 - 7.2
Hemp fabric	63 – 69	3 – 4.3
Rami fabric	31 – 44	-
Bamboo fabric	48.72 – 77.58	0.983 – 1.75
Cotton fabric	80	3.6

For composite with fibers oriented at 90°, the results showed a large decrease in maximum stress and elastic modulus as compared with fibers that have the same direction of the applied force, as can be seen in Figure 5.
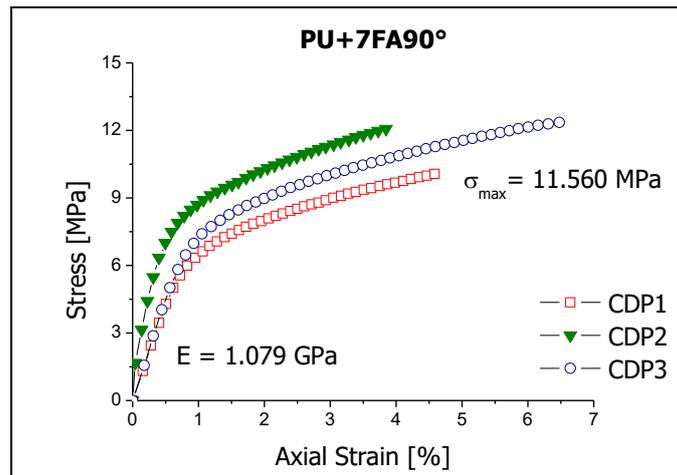
Figure 5 – Stress-longitudinal strain curves of composite PU+7CF-90°.

The uniaxial tensile tests of the laminated PU+7CF with orientation at ±45° were made according to the standard ASTM D3039 and ASTM D3518. Using expressions derived from the theory of laminated plates (fully described in the standard ASTM D35818), the shear strength at the plane in the material coordinate system was calculated directly from the axial load applied. The shear strength related was found from the normal longitudinal and transverse strain data obtained from the transducers of the machine or, as used in this paper, digital image correlation (DIC). These data were used to create the shear stress – shear strain curve in the plane.

Quasi-static tensile tests were made in 3 samples of PU with 7 layers of CF at 45°. These composite longitudinal stress-strain curves were represented in Figure 6, whit repetitive results for all tested samples. The maximum average achieved was 32.692 MPa and the tensile elasticity modulus was 2.127 GPa.
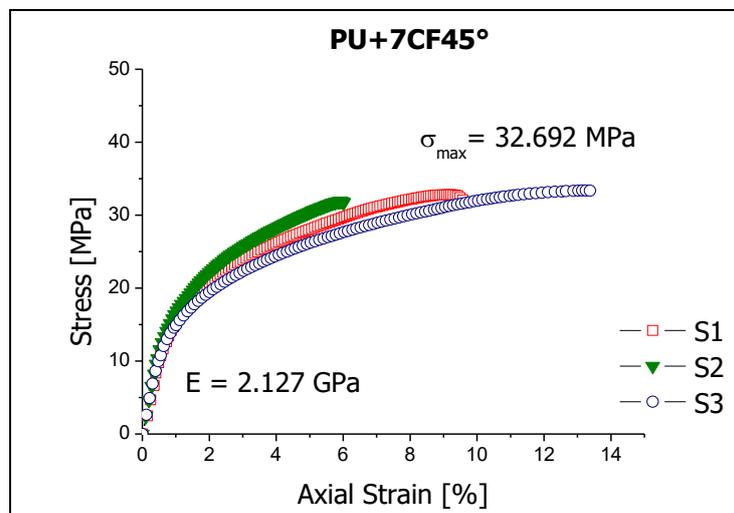

Figure 6 – Longitudinal stress-strain curves of the PU+7CF composite at ±45°.

The laminated composites with orientation at ±45° are used to find the shear material properties. The shear elasticity modulus or transverse modulus (G) obtained by the composite PU+7CF was 0.878 GPa and the maximum average shear strength observed was 16.348 MPa, these values can be perceived in Figure 7.
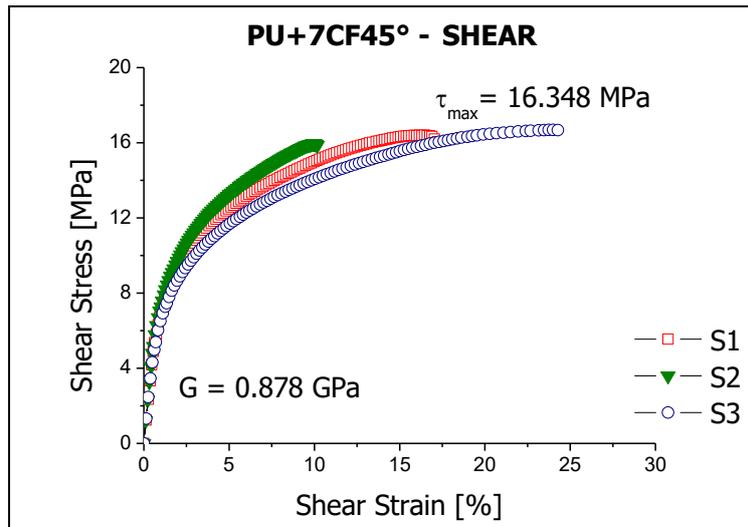
Figure 7 – Shear stress-Shear strain curves of the composite PU+7CF at ±45°.

Figure 8 shows the PU+7CF at ±45° specimen fracture, presenting the rupture in the direction +45°, indicating that the fibers were aligned properly.

Figure 8 – PU+7CF composite at ±45° specimen fracture.

Considering the analyses of the tensile mechanical properties obtained for the doped polyurethane with ATH at different proportions (10%, 20%, and 30%), the amount that most suits the application as composite matrix for PU+ATH+CF was 30%. The PU+30% ATH exhibited the higher elasticity modulus, indicating a more rigid material than the materials with other proportions. However, it showed a reduction on its ultimate tensile strength in relation to the pure polyurethane, but for the defined applications of this composite, these changes were rather irrelevant. Also, it would have a better efficiency when the flammability properties are required because it presents a considerable amount of flame retardant in its composition.

The laminated PU+ATH+CF composite was manufactured with a PU+30%ATH matrix and 7 cotton fabric layers. Two layers disposition were made, the first having all the layers being stacked with the same fiber alignment of 0°, and the second one with the layers being stacked with 0° and 90° alternately until the total number of 7 fabric layers. Specimens were made for the tensile test following the standard ASTM D3039/D3039M.

Quasi-static tensile tests were made in 3 specimens of doped PU with 30% ATH with 7 cotton fiber layers oriented at 0°, Figure 9 shows the representation of the stress-strain curves obtained for this composite. The average ultimate strength and the tensile elasticity modulus were 60.280 MPa and 4.733 GPa, respectively. The ultimate borne strength decreased nearly 25% the number observed for the composite PU+7CF

The results for doped PU with 30% ATH presented an enhancement on the tensile elasticity modulus (2.607 GPa) and a reduction in the borne maximum stress (31.630 MPa) when compared to the pure PU (1.703 GPa and 39.715 MPa). While it was used the doped PU matrix, the changes on the mechanical properties of the material followed the same behavior when compared to the pure PU as a composite matrix. Obtaining practically a twice higher value for the laminated composite PU+30%ATH+7CF elasticity modulus and ultimate strength when compared to the properties of the polymer.
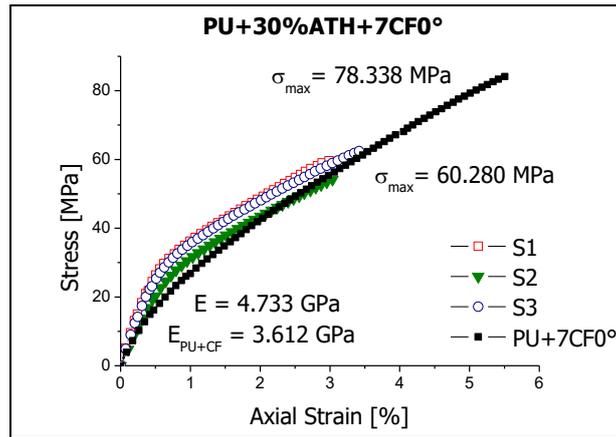
Figure 9 – Longitudinal stress-strain curve of the PU+30%ATH+7CF composite at 0°.

Tensile tests were made in 3 specimens of doped PU with 30% ATH reinforced with 7 layers of CF fabrics oriented at ±45°. Figure 10 represents the longitudinal stress-strain curves given by the composite. The average ultimate strength reached was 19.792 MPa and the tensile elasticity modulus was 2.425 GPa.
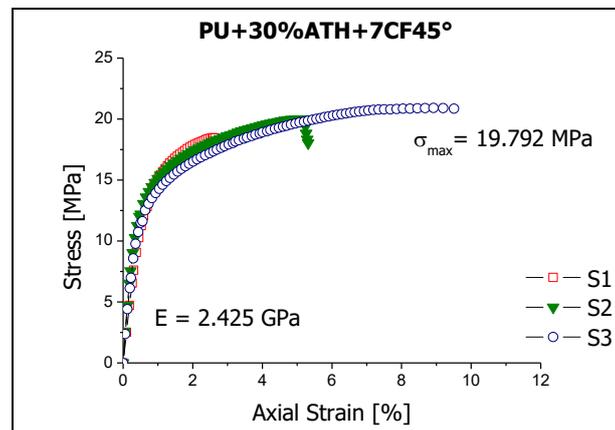

Figure 10 – Longitudinal stress-strain curves of the PU+30%ATH+7CF composite at ±45°.

The shear elasticity modulus or transverse modulus (G) obtained for the PU+30%ATH+CF composite was 0.923 and the average ultimate shear strength seen was 9.894 MPa as shown in Figure 11. Comparing these results with the composite PU+7CF (16.348 MPa) at ±45°, the PU+30%ATH+CF presented a decrement in its maximum shear strength and a little increment in its transversal modulus, indicating a smaller cutting strength resistance.
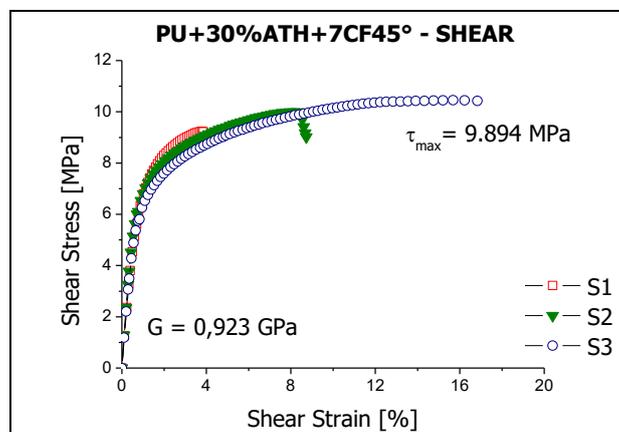

Figure 11 – Shear stress-shear strain curves of the PU+7CF composite at ±45°

The composite with 90° oriented fibers, similarly to the PU+7CF at 90° composite, demonstrated a decrement in its ultimate strength and elasticity modulus when compared to the composites with fibers oriented in parallel to the applied strength, as shown in Figure 12. All the three specimens exhibited approximately the same mechanical properties with the ultimate stress around 10.301 MPa.
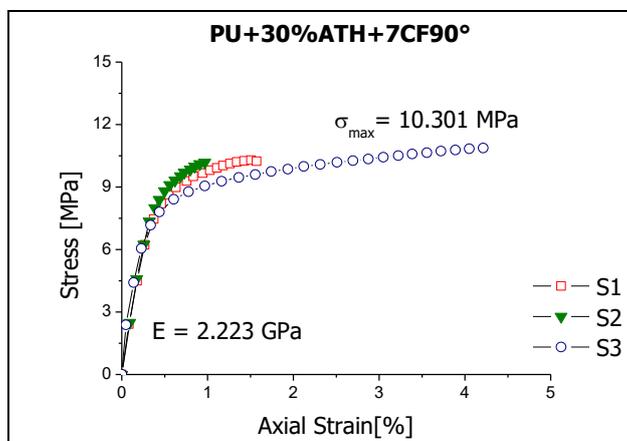

Figure 12 – Longitudinal stress-strain curves of the PU +30% ATH +7CF composite orientated at 90°.

4. CONCLUSIONS

Considering the results of this study, the pure PU exhibited an elasticity modulus of 1.703 GPa and an ultimate stress of approximately 40 MPa. When adding ATH to the mixture as flame retardant in different proportions (10%, 20%, and 30%), a higher value for the elasticity modulus (E) can be seen and a reduction of the ultimate tensile strength (σ_{max}) proportional to the increment of ATH, as shown in Table 2.

The PU reinforced with CF presented a considerable increase in the maximum supported tension (79 MPa), the elasticity modulus (3.6 GPa) was practically double in relation to the pure PU (1.7 GPa), this is true for fibers oriented in the same direction as the applied load, 0°. As expected, when a higher angulation among the fibers and the applied force (in an interval from 0 to 90 deegres) is used, a reduction in the σ_{max} was verified, once the 90° oriented fibers has a smaller value for E and σ_{max} than the pure polymeric matrix.

For the composite of PU+30% ATH+7CF with orietation of 0°, the maximum supported tension is 60 MPa and the modulus of elasticity (4,7 GPa) was practically double in relation to the PU+30%ATH (2,6 GPa), matrix used in this composite. Similarly to the PU+7CF composite, the higher is the angulation among the fibers and the applied strength, a reduction in the σ_{max} was verified as noticed when the 90° oriented fiber composite was tested, once it presented weaker mechanical properties than the polymeric matrix. Thus, the fiber showed no contribution as a material reinforcement.

The samples tested with fibers oriented at ±45° made possible the calculation of the shear modulus or transversal modulus (G) and the ultimate shear strength (τ_{max}). For the PU+7CF composite, the transversal modulus value was 0.888 GPa, the ultimate shear strength 16.399 MPa. The PU+30%ATH+7CF composite exhibited values for the transversal modulus and ultimate shear strength of 0.902 GPa and 9.233 MPa respectively. Therefore, the pure PU composite has a better behavior under cutting forces.

The mechanical properties according to the tensile test for PU laminated composite reinforced with cotton fabric fiber and doped with 30% of ATH revealed a higher stiffness and mechanical resistance than the pure PU, as shown in Table 2.

Table 2. Tensile mechanical properties of the tested materials.

Materials	E [GPa]	σ_{max} [MPa]	G [GPa]	τ_{max} [MPa]
PURE PU	1.703	39.715	-	-
PU+10%ATH	2.162	38.047	-	-
PU+20%ATH	2.367	32.650	-	-
PU+30%ATH	2.607	31.630	-	-
PU+7CF-0°	3.612	78.338	-	-
PU+7CF-45°	2.127	32.692	0.888	16.399

PU+7CF-90°	1.079	11.560	-	-
PU+30%ATH+7CF-0°	4.733	60.280	-	-
PU+30%ATH+7CF-45°	2.425	17.792	0.902	9.233
PU+30%ATH+7CF-90°	2.034	10.872	-	-

The main idea on the application of ATH as flame retardant is vinculated with the kind of application which the composite is exposed, one of them is the application in the manufacturing of vehicles interior coating. In future studies, the verification of the PU+30%ATH+7CF green composite flammability properties could be done, in order to evaluate and validate the considerations for applications made in this paper about the flame retardancy, fire propagation, and fire extinguishment.

5. ACKNOWLEDGEMENTS

6. REFERENCES

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