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Effect of fiber length on the mechanical properties of high dosage carbon reinforced

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Abstract

Short fibers are effective reinforcements in strengthening and toughening polymer materials. It is reported that even small amounts of fibers drastically increased composite strength. However, for high fiber dosage the dispersion and interface adhesion is quite poor reaching to lower stiffness and strength efficiency. The effects of fiber length on mechanical properties of low content of short fiber reinforced composites is usually associated with a gain with the increasing of fiber length, but for high dosage this statement is not entirely consensual. This paper intends to contribute for the better understanding of the effect of the fiber length on the mechanical performance of high dosage fiber reinforced composites. Composite plates were manufactured by compression moulding, using short carbon fibers reinforcements (2, 4 and 6 mm in length) with 60% wt fiber fraction and the Biresin®CR120 resin as matrix. The specimens were machined from the plates for desired dimensions to the tensile and DMA tests. High dosage composites exhibits very low efficiency parameters both in stiffness and particularly in tensile strength. Stiffness increases in order of 25% when fiber length increases from 2mm to 4mm, but afterwards decreases for 6mm fiber length composites. The same tendency was observed for the tensile strength meaning that poor fiber dispersion and disorder was achieved for 6mm fiber length. The results of DMA indicate, however, that modulus storage increases when fiber length increases from 2mm to 6mm.

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Keywords: Composites, Mechanical properties, Short fibber composites.

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1. Introduction

Short fiber-reinforced exhibits some advantages in comparison with the continuous fiber-reinforced composites, like: lower cost, quasi-isotropic mechanical properties and easier manufacturing processing, which leads to their widely use in automobile and other industries. Short fiber reinforced composites are designed to occupy the gap corresponding to the large difference between mechanical properties of continuous fiber laminates used as highly charged primary structures and unreinforced polymers used in non-load-bearing applications, Fu et al. (2000), Gordeyev et al. (2001) and Kuriger et al (2002). Epoxy resins have high modulus, excellent thermal performance and chemical resistance, Jin et al. (2011). Short carbon fibers have high length to radius ratio (L/D ratio), showing complex failure mechanisms, like fiber pullout, debonding and fiber breakage, Zhang et al. (2011). Literature reports the use of carbon fibers (CFs) as reinforcement for high the performance of reinforced composites using matrix thermoplastic, like polyamide, Botelho et al. (2003) and PPS, Jiang et al (2008).

Short carbon fibers composites are easily manufactured by using conventional techniques, like extrusion compounding and injection moldingor the compression moulding, which is an inexpensive process. Factors like fiber dispersion, fiber length and volume fractions play important role to enhance the mechanical properties of short fiber polymer composites. Shao Fu and Lauke (1996) predicted analytically the effect of fiber length on the tensile strength of short fiber reinforced polymers showed significant increasing of the strength with the increase of the mean fiber length. Literature reports the increasing of composite mechanical performance with increasing fiber content for low and medium dosage. However, for high dosage fiber dispersion and disorder is quite difficult becoming poor fiber enhancement and complex failure mechanisms, which need better understanding. In that case, the improvement of the composites performance depends of its capacity to obtain good fiber dispersion.

Tiesong Lin et al. (2008), studied the effects of fiber length on mechanical properties and fracture behavior of short carbon fiber reinforced geopolymer matrix composites, and obtained important gains on flexural strength, which reached the maximum values for the fibber length of 7 mm. F. Rezaei et al. (2009), used DMA to measure the damping properties of short carbon fiber reinforced polypropylene composites, and shown that an increase in fiber length can enhance the thermal stability and improve the damping properties as well.

Current investigation intends to study the effect of the fiber length on mechanical and thermos-mechanical properties of short carbon fibers composites, using 2, 4 and 6 mm fibers length to reinforce an epoxy resin matrix. Mechanical properties were obtained by conventional tensile tests and dynamic mechanical analysis (DMA). DMA was used to determine the viscoelastic properties of the composites.

2. Materials and testing procedure

The composite plates were manufactured using short carbon fibers reinforcements (2, 4 and 6 mm in length) with 60% mass fraction. The matrix was the Biresin®CR120 resin, formulated by bisphenol A - epichlorhydrin epoxy resin 1,4 - bis (2,3-epoxypropoxy) butane, combined with the hardener CH120-3, both supplied by Sika, Stuttgart, Germany. The short carbon fibers were supplied by the company, Sigrafil, SGL Group, Germany.

Carbon fibers were dispersed in closed erlenmeyer adding 150 ml of dichloromethane solvent to 1 g of fibers. Therefore, the mixture was immersed in an ultrasonic bath for 7 min, which globally improve the dispersion of the fibers. Afterwards, it was filtered through a qualitative filter 202 moderate speed, Ø90mm and the solvents were recovered. Finally, the mixture was subjected to a process of evaporation for about 40 hours at room temperature. Fig. 1 shows de aspect of the mixture after evaporation.

The composites were processed by compression using a metal mold specially manufactured for this study. The resin was previously prepared and placed under vacuum. Then it was added a desired amount of short carbon fibers. Afterwards, the materials were mixed slowly, and the mixture were placed in the mold cavity. A compression force of 1500 kg was applied (as shown in Fig. 2), which corresponds to a pressure processing of about 60 MPa. The produced plates were then subject to a cure and post cure processes. The cure was at room temperature for 8 hours in the mold, and the post cure was carried out as follows: 55 ºC for 16 hours, 75 ºC for 3 hours and finally 120 ºC for 12 hours.

Fig. 1. Fibber dispersion aspect after ultrasonic bath and evaporation.

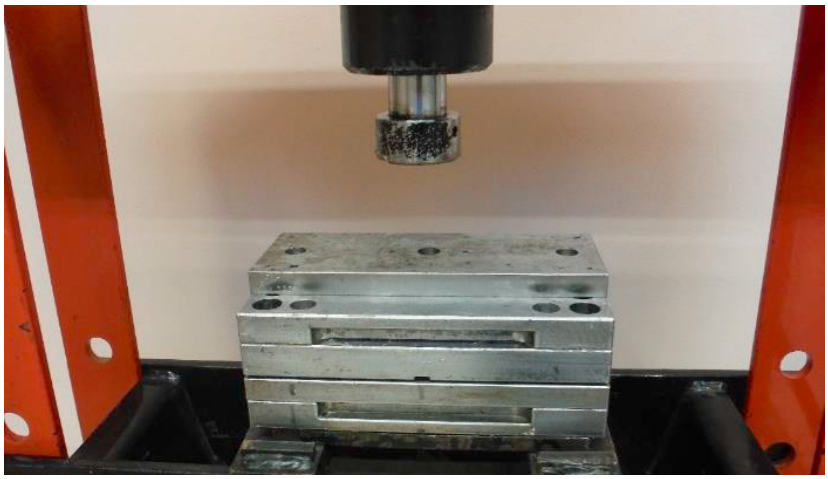

Fig. 2. Molding apparatus and compressing process.

Table 1 summarizes the mass fraction and the fibber length of the different composite batches produced for present work.

Fig. 3a) shows a plate after post cure process, with dimensions about 150x100x5 mm. From these plates, the tensile specimens were machined with geometry and dimensions indicated in Fig. 3b). The cutting parameters used in milling plates process were: spindle speed of 1500 rpm, cutting speed of mm/min and feed rate milling of 0.2 mm/rot.

Tensile tests were performed at room temperature using an electromechanical Instron Universal Testing machine (Instron, High Wycombe, UK), model 4206, with a displacement rate of 1 mm/min. Four specimens were tested for each test condition until the final failure. Specimen elongation was measured using a strain gauge extensometer with 25 mm reference length (Instron, model A1439-1007). After tensile tests, the fracture surfaces in some specimens were gold sputtered and then observed with a scanning electron microscope (Philips XL30) in order to understand the fiber dispersion and adhesion, and also the failure mechanisms.

Thermomechanical properties were obtained by using dynamic mechanical analysis (DMA). Dynamic elastic modulus and viscous modulus were obtained, for different temperatures. The tests were carried out in a Triton Technology TRITEC 2000 machine and the specimens with 40×4×3 mm were bi-supported inside the thermal

chamber. Three samples were tested for each condition and the results will be discussed in terms of their average values. The materials were tested for a displacement of 0.05 mm, at 1 Hz and 10 Hz, and a temperature range between 20 to 180 ºC. In all tests, the heating rate was 2 ºC/min.

Table 1. Mass fraction, fibber length and mechanical properties of different batches.

Fibber length [mm]	Mass fraction, wt [%]	Ultimate strength [MPa]	Young`s modulus [GPa]	Strain at failure [%]
2	60	64.6±6.9	14.1±0.4	0.41±0.08
4	60	74.2±5.7	18.1±1	0.49±0.06
6	60	66.9±5.7	16.7±0.7	0.59±0.01

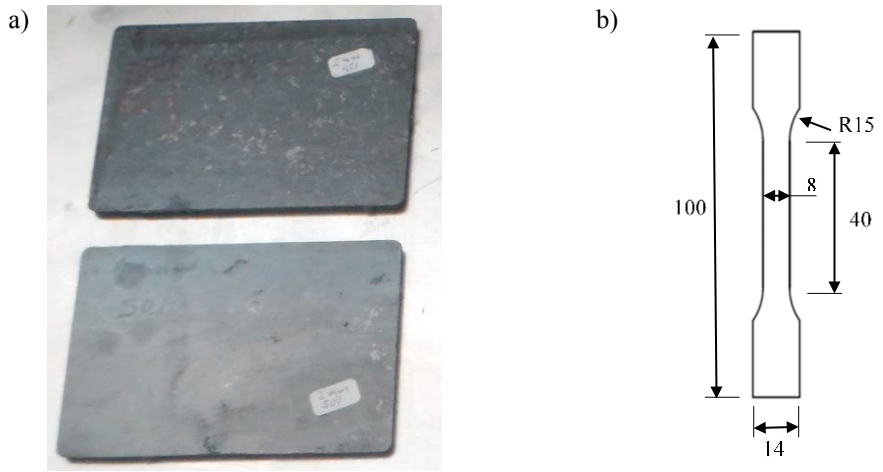

Fig. 3. Specimens preparation: a) Molded plate; b) Geometry and dimensions.

3. Results and discussion

The curves of the tensile stress versus strain, were obtained, showing a nearly linear until final failure and clearly show that the specimens fail immediately at maximum load. The tensile strength was assumed as the value of peak load divided by cross section area. The Young`s modulus was obtained by linear regression of the stress–strain curves considering a straight segment starting from the origin (0,0). To standardize the analysis was always considered the largest range that guarantees a correlation factor greater than 99.5%. Tensile strength, Young`s modulus and strain at failure of the composites were collected and statistical analyzed. Mean values and standard deviation are indicated in Table 1. Figs. 4a) and b) show the tensile strength and Young`s modulus with respect to the fibers length, respectively. This figure shows that, tensile strength and Young`s modulus increases when fiber length increases from 2 to 4mm, but afterwards tends to decrease, consequence of the poorer distribution quality of the longer fibers.

The stiffness of SFRP composites is usually, estimated based on the rule of mixture. According to this theory; Young`s modulus of a composite is predicted by using equation (1), Houshyar et al. (2005);

$$E_c = \alpha_E V_f E_f + V_m E_m \quad (1)$$

where, α_E is an efficiency factor for the composite stiffness taking into account the effects of fiber length and orientation, E is the tensile Young`s modulus, V is the volume fraction and subscripts c, f and m represent composite, fiber and matrix, respectively, Fu and Lauke (1996), Karsli et al. (2012).

Using the same rule to predict tensile strength, we have the equation (2)

$$\sigma_c = \alpha_{UTS} V_f \sigma_f + V_m \sigma_m \tag{2}$$

where: α_{UTS} is an efficiency factor for the composite strength, σ_c, σ_f and σ_m are the tensile strength of the composite, the fiber and the matrix, respectively.

In current study, they were also obtained the matrix properties, to be: E_m=3.16 GPa, σ_m =58 MPa. Using, according with manufacturer, E_f=230 GPa and σ_f=3500 MPa, the efficiency factors α_E and α_{UTS} were obtained from equations (1) and (2), respectively, for each composite batch. The values obtained for and α_{UTS} and α_E, are superimposed against the fiber content in Figs. 4a) and b), respectively.

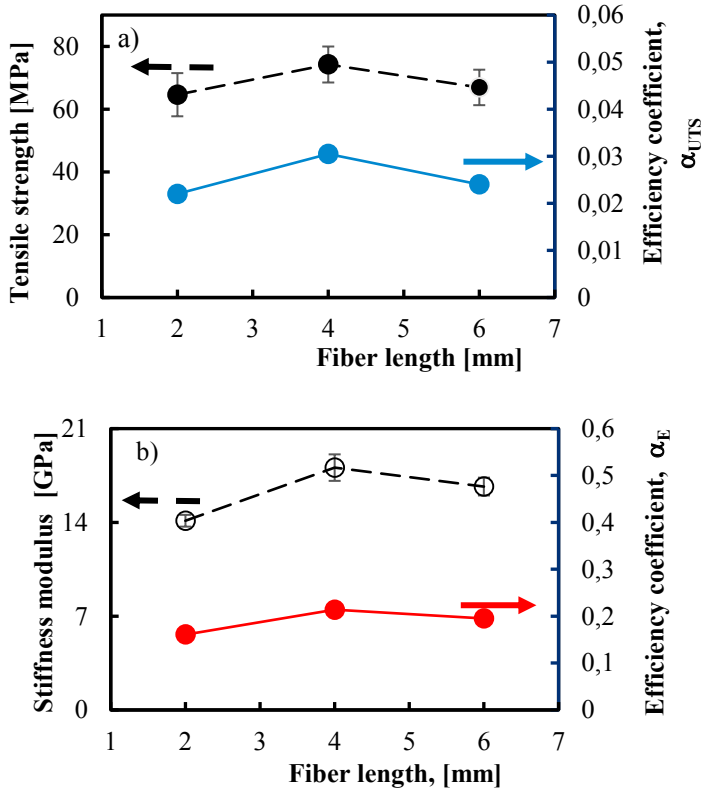

Fig. 4. Mechanical properties against fiber length: a) Tensile strength and efficiency coefficient; b) Young´s modulus and efficiency coefficient.

Both efficiency factors exhibit low values, generally, lower than those obtained by Fu S.Y. et al. (2000), in polypropylene matrix composites and with volume content up to 24%. In any case, the values obtained can be considered in line with those obtained by S.Y. Fu et al. (2000), since the percentage of fiber used is much higher, so a much lower efficiency is expected, as a result of the poor distribution and wetting of the fibers by the resin.

Liang (2011) developed a model to predict relative Young's modulus (E_r= E_c/E_m) of short inorganic fiber reinforced polymer composites, introducing an interfacial strength factor, given by equation (3)

$$E_r = 1 + (16\pi)^{1/3} \left(K \frac{l}{d} - 0.25 \right) V_f^{2/3} \tag{3}$$

where V_f is the fiber volume fraction, l and d, are the length and diameter of the fiber, and K is the interfacial strength factor.

Fig 5 shows experimental values of E_r and predicted interfacial strength factor K against the fiber length. These results confirm the low efficiency, which decreases significantly with the fiber length.

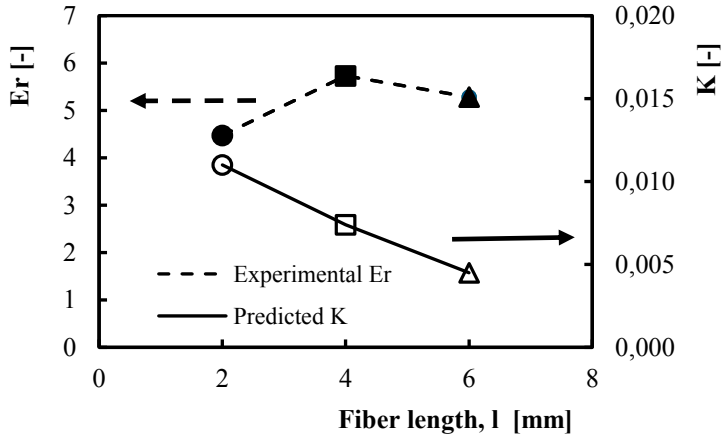

Fig. 5. Influence of fiber length on E_R and K factor.

DMA analysis was performed at 1 and 10 Hz for the batches indicated in Table 2. The DMA thermograms at 1 and 10Hz, are typically quite similar, but they have a small gap between them. The increasing of the frequency slightly increases the measured storage modulus and the glass transition temperature.

The data of the storage modulus, loss modulus and tan δ, were collected. The data presented in current paper are reported to 1 Hz analysis. Elastic modulus at 25 and 80 ºC, viscous modulus at 80 ºC and glass transition temperature (which was assumed as the temperature for tan δ peaks) are summarized in Table 2. Fig. 6 presents the DMA thermograms showing the effect of the fiber length. The analysis of table 2 and Fig. 6 show that DMA elastic modulus values (dynamic values obtained in bi-supported bending) are lower than static elastic modulus obtained from tensile tests. Showing some similarity to the results of the tensile tests, DMA elastic modulus in bending increases when fiber length increases from 2 to 4mm, but afterwards tends to increase until 6mm fiber length.

Table 2. Mechanical properties obtained from DMA tests (1Hz).

Fibber length [mm]	Mass fraction, wt [%]	***E'***, Elastic modulus at 25 ºC (GPa)	***E'***, Elastic modulus at 80 ºC (GPa)	***E'***, 'Viscous modulus at 25 ºC (MPa)	Tg (ºC)
2	60	8.2	7.2	14.2	102.7
4	60	9.3	8.2	13.9	114.5
6	60	10.0	8.3	16.3	113.3

After tensile tests it was performed a SEM analysis in order to investigate fiber distribution, fiber/matrix adhesion and failure mechanisms. Fig. 7 shows representative images of that analysis. Figs. 7a) and b) show the fracture surface of composites with 2 and 4mm fiber length, respectively. In both cases, the dispersion is only reasonable, showing poor disorder exfoliation, especially for 4mm fiber length. The dispersion becomes worse when fiber length increases, appearing some regions with lack in resin. The predominant failure mechanism is the fiber/resin decohesion.

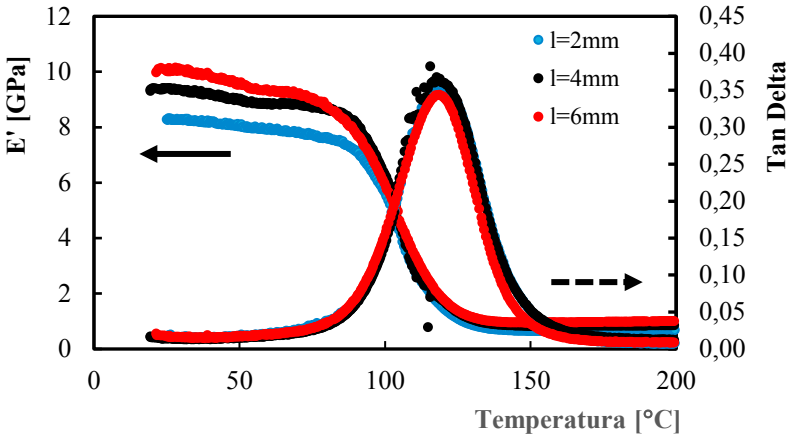

Fig. 6. Influence of fiber length on DMA thermograms at 10Hz.

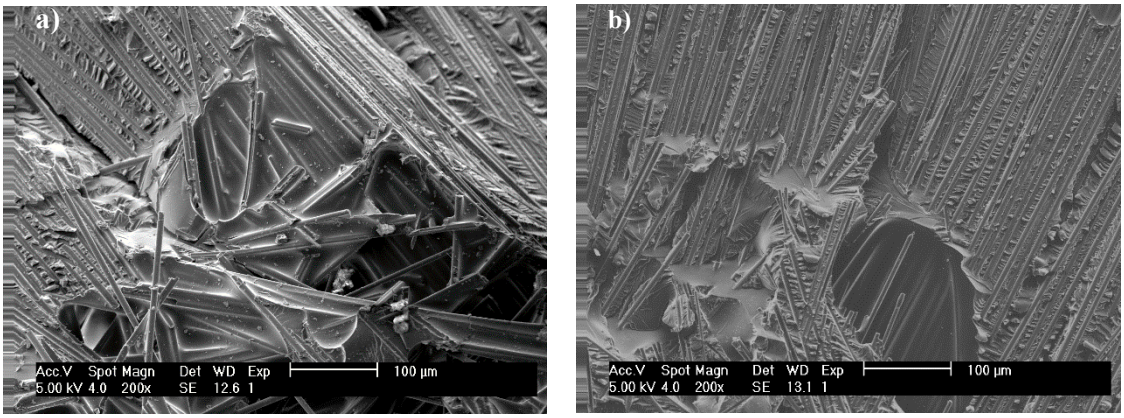

Fig. 7. SEM observations: a) 60% mass fraction of 2mm fibers; b) 60% mass fraction of 4mm fibers.

4. Conclusions

The effects of the fiber length on mechanical properties of high dosage short fiber carbon composites was studied using tensile and DMA tests. The main conclusions were drawn:

- High dosage composites exhibits very low efficiency parameters both in stiffness and particularly in tensile strength. Stiffness increases in order of 25% when fiber length increases from 2mm to 4mm, but afterwards tends to decrease for 6mm fiber length composites. The same tendency was observed for the tensile strength.
- For high fiber dosage composites poor fiber dispersion and disorder was achieved, particularly for 6mm fiber length.
- DMA analysis showed bending elastic modulus lower than static tensile elastic modulus obtained. DMA elastic modulus increases when fiber length increases from 2 to 4mm, and still increases slightly when fiber length increases from 4mm to 6mm.

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