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Full Length Research Paper

Influences of a novel henequen fabric structure on the mechanical properties of a polymeric composite

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This study discusses the effect of quantity and stacking sequence of two different woven henequen fabrics on the mechanical performance of henequen/epoxy composites. Tensile and flexural properties of the composites were improved when the modified woven fabric was used, which is ascribed to the increase in adherence between fiber-matrix at the knots of fibers in this fabric, providing a mechanical anchoring at the knot with the matrix and creating a strong bond which prevents fiber slip and pull-out. Hence, by tailoring and designing the fabric structural geometry, improvements on the mechanical properties of polymer composites can be achieved.

Key words: Polymer composite, woven henequen fabric, tensile and flexural properties, mechanical anchoring.

INTRODUCTION

Natural fibers (bio-fibers) became more attractive in the last decade since they are reasonably strong, biodegradable, economical production with few requirements for equipment, low specific weight and free from health hazards (Maya et al., 2008; Ahmed et al., 2007). However, when they are compared with synthetic fibers their main limitations are low thermal stability, tendency to form aggregates during processing, low resistance to moisture and seasonal quality variations (Bismarck et al., 2006; Kim et., 2006), lower modulus of elasticity and low strength (Velmurugan and Manikandan, 2007). The use of bio-fibers like sisal, henequen, jute, hemp, banana, oil palm, wood pulp as a reinforcement in polymer matrix is reported in the literature (Pothan and Thomas, 2003, Sreekala et al., 1997; Aziz and Ansel, 2004; Herrera and Valadez, 2004).

One approach to improving the toughness of natural fibre composites is to more precisely control the reinforcement architecture by the use of fabrics (Liu and Hughes, 2008). These fabrics have advantages in the control of fiber dislodgment and ease of handling, better dimensional stability and reduction of labour costs in manufacture of composite materials (Alpyildiz et al.,

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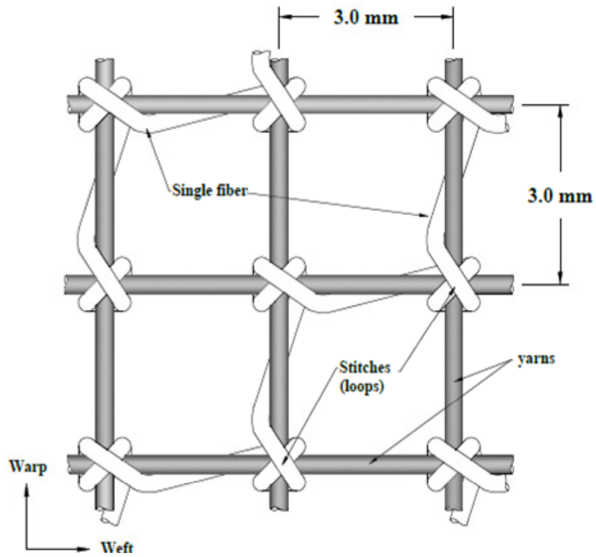

Figure 1. Novel woven henequen fabric.

2009; Kim et al., 2005; Huang and Liya, 2008). Moreover, fabrics provide composite materials with improved mechanical performance, interlaminar strength, fracture toughness and impact resistance (Hearle and Du, 1990).

Failure mechanisms of textile reinforced composites depend on the textile type (woven, braided, stitched) and the weave style (plain, twill, satin) along matrix properties (Daniel et al., 2008). The aim of this paper was to study the effect of a modified plain woven henequen fabric as reinforcement for epoxy based composites. The impact of quantity and stacking sequence of two woven fabrics on the tensile and flexural properties of the composite was analyzed.

MATERIALS AND METHODS

Yarns and woven henequen fabrics

Continuous henequen fibers supplied by Desfibradora Yucateca S.A. (DESFIYUSA Co.) of Mérida, Yucatán, México were employed here. The average diameter and length for single fibers were 180±5.8 µm and 350±60 mm, respectively. All yarns (warp and weft) used in the preparation of woven henequen fabric were composed of two unentangled fibers. Two different types of woven fabric for the reinforcement of henequen-epoxy composites were designed and manually manufactured. The plain woven henequen fabric labeled as "PWHF" was the reference fabric (no-modified) where each warp (0°) yarn passes alternately under and over each weft (90°) yarn, forming an interlacing regular pattern. On the contrary, the modified woven henequen fabric (MWHF) was obtained by tying a single fiber (stitch) at all intersections yarns of the plain woven fabric (PWHF), Figure 1.

To promote adhesion between the fibers and epoxy matrix, all fabrics were treated chemically. In the first stage, the fabrics were immersed in a NaOH aqueous solution (2% w/v) for an hour at 25°C, then were washed with distilled water until all the sodium hydroxide was eliminated. After drying the fabrics at 60°C for 24 hrs, these were treated with a vinyltriethoxysilane (Sigma-Aldrich) solution. Treatment consisted of immersed the fabrics in the solution under stirring for 1 hr. and then dried at 60°C for 24 h (Valadez et al., 1999). The solution consists of 1% w/w of the silane weight percentage with respect to the fiber, which was dissolved for its hydrolysis in a mixture of ethanol water (90/10 w/w) at 25°C. The pH of the solution was adjusted to 3.5 with acetic acid.

Composite preparation

Henequen-epoxy composites were manufactured using the woven henequen fabric, mentioned above, with different number of layers and an epoxy resin. The resin (matrix) used in this study was a EPOLAM 2015 and a EPOLAM 2014 hardener in the proportions 4:1 (resin: hardener). The wet hand lay-up process was used, which involved brushing the woven henequen fabric with liquid resin and then stacking the fabric/resin layers to the required thickness (Mouritz, 2008). The henequen composites were cured in an oven at 40°C for 24 h.

For M1 and M2 specimens tested under bending loads, the reinforcing fabric was placed at the bottom area, with the purpose of reinforcing the area where maximum tensile stresses were induced (Figure 2a). On the other hand, three fabric layers were distributed along the thickness of specimens M3 to M6 that is one at the top, one at the center and another at the bottom. In groups M7 to M10 the stacking sequence of previous groups were kept, however the fiber content was increased, additionally all the layers were stacked with the same orientation. The stacking sequence and overall fiber content (% vol.) are shown in Table 1.

Mechanical properties

Both, tensile and flexural tests were carried out on a ZWICK/ROELL universal testing machine equipped with a 5000 N load cell. The cross-head speed used for tensile specimens was 5 mm/min and the tests were carried out at standard laboratory atmosphere of 23±2°C and 50±5% relative humidity. According to the recommendation of ASTM standard D3039, the specimen dimensions for the tensile tests were 250 mm length and 25 mm width, moreover the distance between the tabs (gage length) was 150 mm.

Flexural tests were performed according to the ASTM D6272 standard, and the specimen dimensions were 127×12.7 mm with a thickness between 3.2 to 6.0 mm; The required depth dependent on the number of layers of woven henequen fabric. For each stacking sequence, five identical specimens were tested and average result was obtained. A schem of the beam is shown in Figure 2.

In addition, a Philips environmental scanning electron microscope (ESEM) model XL 30 to observe the micro structural characteristics of samples were used.

RESULTS

Tensile properties

The results of tensile strength and modulus of elasticity for the composites are shown in Figure 3 (a) and (b). It

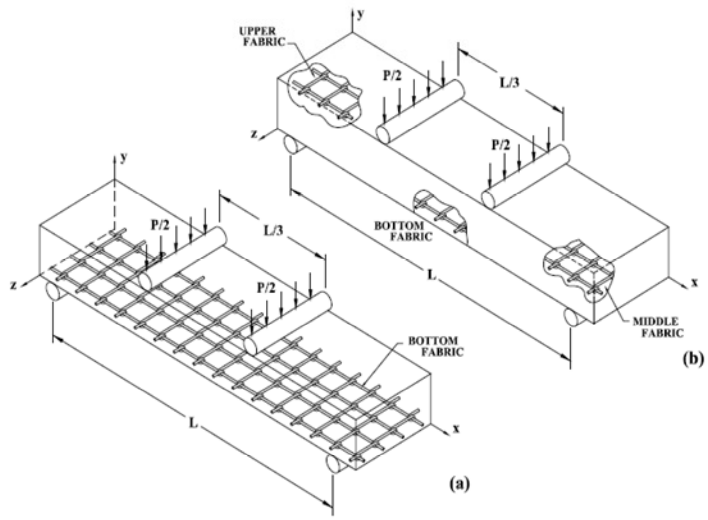

Figure 2. Flexural test for: (a) samples with single woven henequen fabric, (b) samples with three or nine layers of woven henequen fabric.

Table 1. Composite stacking sequence.

Sample series	No. of woven layers	Stacking sequence	Overall fibre content (% volume)
M1	1	h	2
M2	1	m	5
M3	3	hhh	7
M4	3	hmh	10
M5	3	mhm	13
M6	3	mmm	16
M7	9	hhhhhhhhh	18
M8	9	hmhmhmhmh	32
M9	9	mhmhmhmhm	35
M10	9	mmmmmmmmm	47

h (PWHF fabric), m (MWHF fabric).

can be observed that the tensile strength and elastic module of the reinforced specimens with one (M1), three (M3) and nine layers (M7) of PWHF reinforcement fabric, had lower values that the corresponding specimens reinforced with MWHF reinforcement fabric (M2, M6 and M10).

Based on the tensile results, it is clear that these properties are influenced mainly by the woven fabric structure. High values were obtained for groups M4, M5, M6, M8, M9 and M10, while the best were for those groups where only MWHF were employed (M6 and M10). It can be seen that the tensile strength increases, as the number of layers of MWHF fabrics increases, Figure 3 (a) and (b).

Flexural properties

The effect of the MWHF reinforce fabric on the flexural strength of the henequen-epoxy composites analyzed in the present work is evident when comparing the results of the samples MI and M2. On the other hand, comparing results of M2 and M3, it can be observed that better results were obtained for M2 specimens. Therefore, it is clear that with the layer of MWHF fabric placed at the area of maximum tension stress, good mechanical properties could be obtained. Hence, the fiber content (or fiber volume percent) does not always contribute to improve the flexural strength, instead the reinforcement architecture showed to be more important.

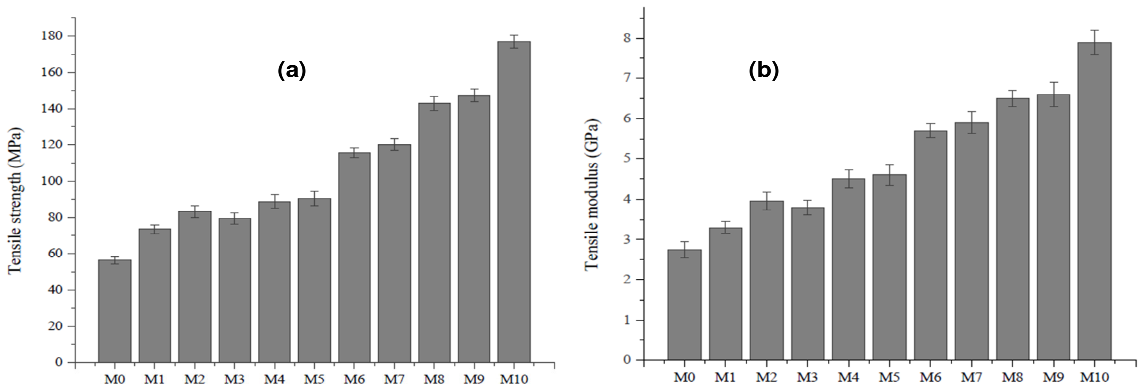

Figure 3. Tensile properties of the composites. (a) Strength, (b) Elastic modulus, M0-unreinforced specimen.

In general, there is an increase in flexural properties with increasing number of layers of MWHF reinforcement fabric (Figure 5). Best results for specimen M5, M6, M9 and M10 were obtained in relation to the corresponding specimen M4, M7, M8. This is because the former have a layer of MWHF reinforcement fabric at top and bottom of the beams specimens. Hence, the type of henequen woven fabric had more influence on the mechanical behavior of the composites proposed in the present work, due to an improvement in the adherence fiber-matrix and absence of fiber slip.

Also, according to the results it can notice that the specimens that were reinforced with both types of fabrics (M4, M5 and M8, M9), the mechanical behavior was improved by both: the increase in the number of layers of MWHF (along the fiber content) and the type of woven fabric.

Figure 6a and b present SEM micrographs of fracture surfaces corresponding to specimens M4. It can be observed that the anchorage induced by the knots reduces the extraction of the fiber (pull-out) transferring the tension loads more appropriately toward the fiber. Figure 7 shows the load-displacement graphic corresponding to test specimens under a four-point loading system applied to a simply supported beam. All the curves showed a no-linear tendency up to failure and they presented a break point without a yield point. It is also observed that an improvement in groups M5 and M9 compared with groups M4 and M8, associated to the presence of the MWHF fabrics at bottom area.

DISCUSSIONS

Relation between woven fabric structure and tensile strength

The increment of the tensile properties of samples with MWHF fabrics could be attributed to the fact that the knots of the MWHF increase the mechanical anchorage and the adherence. The increase in these mechanical characteristics is associated with several facts. Firstly, it can be due to the non-linear geometry of individual yarns induced by the fabric structure, there are better anchorages and the reinforcement increases the load capacity. These knots also help to neutralize the adverse effect of areas of stress concentrators induced by the fibers in the weft direction, as it has been reported elsewhere (Peled et al., 2008). The stress gradient in these areas could be attributed to the difference between the mechanical properties of the fiber and epoxy matrix.

Secondly, to the knots which allow the matrix penetration (Figures 4a and b). The matrix penetrability provides mechanical anchoring of the knot within the epoxy matrix, creating a strong bond (Munikenche et al., 1999) and, in consequence, a minimization of fiber straightening, cross fiber shortening, fiber slip or the transverse displacement of cross fibers. In addition, the anchorage increases the ability of the yarns to carry load.

Relation between woven fabric structure and flexural strength

The mechanical properties of the beam specimens under four-point loading system (pure flexion) were also enhanced by the effect of the mechanical anchorage induced by the knot of the MWHF. It is thought that this effect is similar to the anchorage induced by the corrugate bars in the reinforced concrete. The mechanical adherence induced by the knots counteracts the pull-out and debonding process, getting a ductile failure in the specimens, even after matrix cracking by tension stress.

For the composite obtained in the present work, the fiber content (or fiber volume percent) does not always

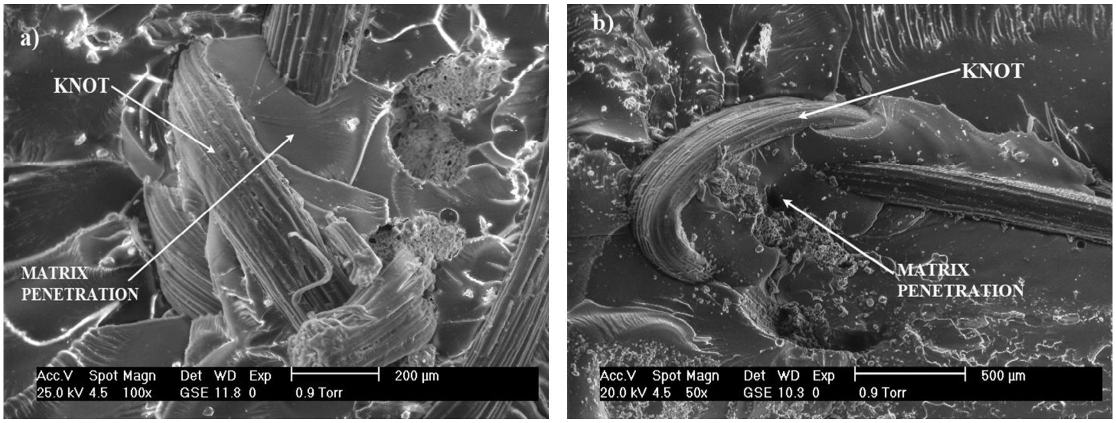

Figure 4. Matrix penetration inside knots in MWHF. (a) Tension test specimen, (b) Flexural test specimen.

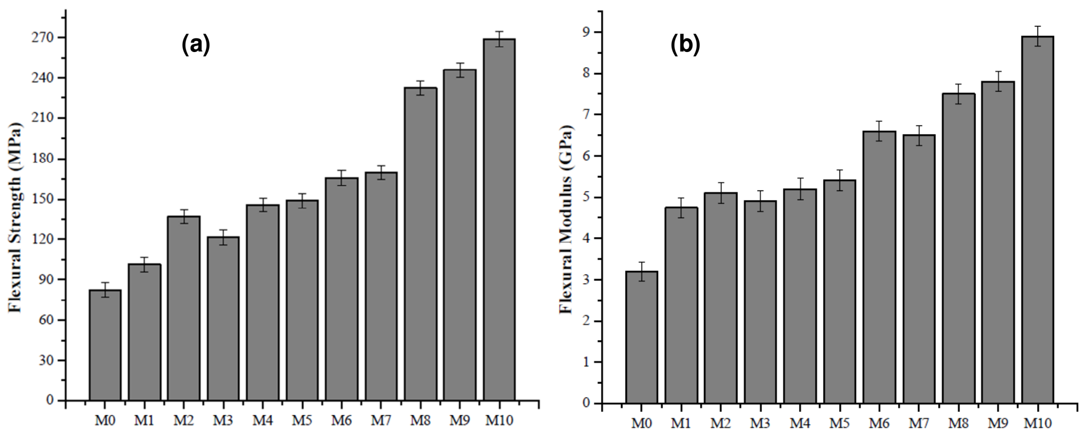

Figure 5. Flexural properties of the composites. (a) Strength, (b) elastic modulus, M0-unreinforced specimen.

contribute to improve the flexural strength, instead the reinforcement architecture showed to be more important. Flexural strength and stiffness of a laminate composite are controlled by layers of reinforcement placed at the top and bottom of the specimen beam. Due to the reinforcement in such surfaces usually contributing to support the compressive or tension stress maximum.

Therefore, woven fabric structure is the main fact governing the flexural and tensile strength in the composites with MWHF reinforcement fabric.

Conclusions

The properties of the composite are influenced by the geometry of the fabric and the bond developed between the fabric and the epoxy matrix and less by fabric strength. In addition, layering sequence (altering the position of the MWHF) significantly affects the flexural strength.

Overall comparison between the properties of all the laminates revealed that the MWHF enhances the mechanical properties due to an improvement in the adherence fiber-matrix ascribed to the anchorage induced by the knot which prevents fiber slip and pull-out. It is considered that the present results allow the use of this new woven fabric geometry in composites with hybrid reinforcement (natural and synthetic fibers) to design reinforced composites with higher properties and/or lower cost.

In this case, the chemical treatment used to modify the fiber surface was very important in two aspects: a)

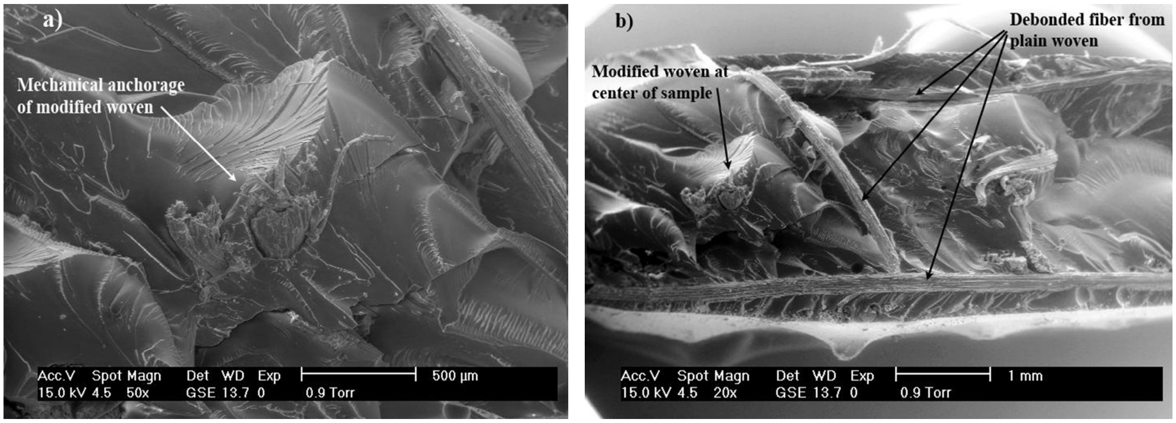

Figure 6. Mechanical anchorage a) Magnification of a knot b), Test specimen of group M4 with modified (MWHF) and (PWHF) plain henequen woven fabric.

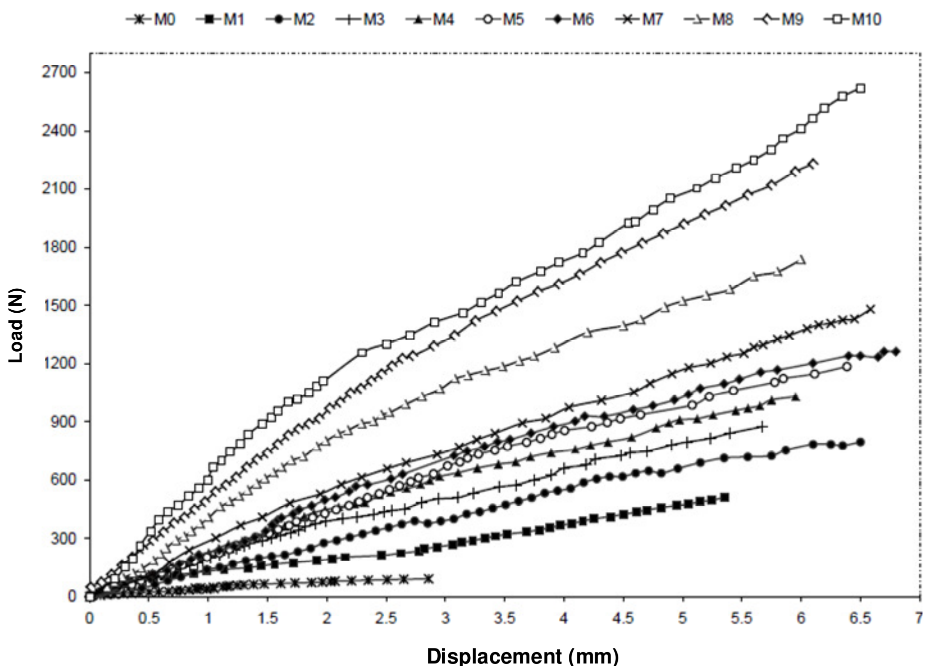

Figure 7. Flexural load-displacement graphic, M0-unreinforced specimen.

Protect against degradation at the fiber-matrix interface region, which can be induced by the moisture absorbed by the polymer matrix, b) Improve the adhesion between henequen fiber and epoxy matrix. However, when comparing the mechanical properties of specimens with both types of fabrics it was observed that the knots of MWHF reinforcement fabric contributed greatly in increasing the mechanical adherences.

Further investigation is needed to quantify the contribution of the MWHF reinforcement fabric proposed in this study on impact strength of henequen-epoxy composites. However, in the broader context, assessing the impact resistance of a composite material is always difficult since the damage manifests itself in different forms such as delamination at the interface, fibre breakage, matrix cracking and fibre pulls out (Mitrevski et al., 2006). Industries such as the aerospace, auto, and maritime where in addition to carrying static and cyclic loads, structural components are expected to perform well under impact.

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