PROCESSING AND PROPERTIES OF NATURAL FIBERS REINFORCED THERMOPLASTIC AND THERMOSSETING COMPOSITES

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Keywords: *natural fibers; composite materials; thermoplastic; jute; flax; sisal; polypropylene*

1 Introduction

During the past few decades, polymers have replaced, advantageously, many of the conventional materials, in various applications. This was possible because these materials have low density, are easy to process and, many polymers are low-cost. Traditional composite structures still use thermosetting matrices, like polyester or epoxy systems, but, more recently, thermoplastic matrices are being used in composite structures, because they allow shortening process cycle time, they have better impact behavior and are more ecological. However, the use of thermoplastic materials as matrices makes difficult and complex the impregnation of reinforcements and the consolidation tasks due to their very high viscosity [1-2].

Recently, because of their interesting properties, natural fibers are being studied as reinforcement material in composite components. They are low-cost fibers, combining very low density with high specific properties, are biodegradable and nonabrasive, unlike other reinforcing fibers, they can allow a high volume of filling in composites and are readily available [3-5].

In this work, three different natural fibers were studied and characterized, using optical and SEM microscopy. Woven fabrics of those reinforcement fibers were used to reinforce polyester and epoxy matrices and produce composite plates by vacuum lay-up. Also, using an experimental piston blender equipment [2, 6], long fiber reinforced PLA (LFT) composites were manufactured by hot compression molding. All different obtained composite plates were submitted to mechanical testing, in order to determine relevant mechanical proprieties.

2 Raw-materials

2.1 Natural fibers

Jute, sisal and flax fibers, chosen to be studied in this work, are between the most successfully used natural fibers as reinforcements in composite structures. Typical properties of those natural fibers can be seen in table 1.

2.2 Polymeric matrices

The different natural fibers were impregnated and consolidated with two different thermosetting resins: one orthophthalic polyester resin (Palatal P69 from DSM) and one epoxy system (SR 1500 SR resin with SD 2505 hardener from SICOMIN). Table 2 summarizes the relevant mechanical proprieties obtained from the manufacturers datasheets.

3 Experimental

3.1 Vacuum compression

Eight layers of each reinforcement fiber type were impregnated by hand lay-up with the polyester and epoxy resins. Then a vacuum bag was done, allowing establishing a controlled consolidation pressure. To obtain a good surface finishing, a glass plate was used as mould on both sides of the produced composite plate. Figure 1 shows two of the obtained composite plates.

The jute and flax fibers were acquired in the market in woven fabric form. Sisal fibers were processed from chopped mat raw-material.

3.2 Fiber characterization

In order to assess the shape and size of the used fibers, some samples of composites made from each fiber type were hot mounted in Bakelite resin and submitted to grinding with sandpaper and polished with diamond powder, in order to be observed under optical microscopy.

Figure 2 depicts a typical jute fiber cross section. As one can see, the shape of the fibers is approximately elliptical. The area of the fibers cross section was measured, from more than fifty measurements using different microscopic pictures and found to be 0.59 $mm^2 \pm 1$ μm^2.

Figures 3 a) shows typical sisal fiber shapes. As can be seen, two different types of fiber shapes can be found: one approximately elliptical (figure 3a)) and another with a heart like shape (figure 3b)).

The average area of the fibers cross section was measured and found to be approximately: 0.029 mm^2 $\pm$ 0.01 μm^2.

In figure 4 the cross section of a typical flax fiber can be observed. As can be seen, the shape of these fibers is approximately elliptical. The area of the fibers cross section was measured, and found to be approximately 0.38 mm^2.

The two woven fabrics reinforcements (jute and flax) were submitted to testing, according to NP EN 4105/91, NP EN 4115/91, NP EN 12127 and NP EN 4114/91, to determine their surface mass, fiber linear density, density, crimp, linear tensile strength and strain at break. The linear tensile strength is defined as the maximum force that a strip of woven fabrics can support, divided by the length (50 mm).

To characterize the mechanical properties of sisal fibers, single filament tests were conducted in a Instron 4505 universal testing machine using a 2.5 N load cell (having class 1 precision) and appropriated pneumatic grips. The test speed was kept constant at 0.5 mm/min. For each fiber length, more than 30 measurements were made.

The determination of the fibers density of was made using a precision balance and by comparing the weight of the sample with its weight immersed in pure water.

Table 3 summarizes the testing obtained results for the jute woven fabrics.

The jute density was measured to be: 1.33 ± 0.03 g/cm^3.

As can be seen in table 3, there are some differences between warp and weft fiber properties, especially in the strain at break and crimp. In order to minimize those differences, during the production of the composites with this reinforcement, the lay-up was done by alternating plies of fabrics in warp direction whit others in the weft direction.

Considering the well established values for the ultimate tensile unit strength (UTUS) of glass fiber reinforcements, (see BS 4994 [7] or EN 13121 [8]) one can get the value of 50 N/mm for the linear tensile strength of those fibers. Considering the specific values of the fibers strength, even if the glass fibers are more resistant (circa three times), jute fibers can be considered suitable materials for structural composite applications.

Fibers obtained from the sisal chopped mat reinforcement were used for determining their mechanical properties. Single filament tensile tests were performed, using three different fiber lengths: 20, 25 and 30 mm. Table 4 summarizes the obtained fiber mechanical properties.

As expected, the tensile strength tends to decrease with fiber length due to the higher probability of major defects occurrence on longer fibers. The tensile modulus follows the same behavior as the strength. The determination of this property needs further studies.

Sisal density was measured to be: 1.22 ± 0.4 g/cm^3.

Table 5 summarizes the obtained results for the flax fibers.

Flax density was measured to be: 1.52 ± 0.46 g/cm^3.

Again, as in the case of jute fibers, there are differences in the properties of warp and weft fibers, especially in crimp and linear tensile strength. The lay-up to produce the composite plates was done by alternating plies of fabrics in warp direction whit others in the weft direction.

3.3 Composite mechanical testing

3.3.1 Testing procedure

Flexure and tensile properties of the composites fabricated by the different technologies were obtained in accordance to ISO 14125 and ISO 527, respectively.

Tensile tests were done in four specimens with 25×200 mm^2, using a Shimadzu universal testing machine with a load cell of 100 kN. Those tests were conducted at the crosshead speed of 2 mm/min, and for accurately measure strain values, a strain gage with 50 mm of reference length was used. In all tensile specimens, tabs made from the same material of the specimens were bonded using an epoxy bonding system.

Flexural properties were determined using four specimens of each type of fiber reinforced composite plates. Three point bending tests were performed at room temperature in the fiber directions of the 100×20 mm^2 specimens using a Shimadzu universal testing machine with a load cell of 100 kN. The tests were conducted at the crosshead speed of 2 mm/min, using an 80 mm span-distance between supports.

3.3.1 Test results

Figure 5 shows typical flexural test curves of sisal fibers in polyester and epoxy matrices. As can be seen, the composite made from the epoxy matrix exhibits a more linear behavior until brittle break was obtained. Also, the flexural strength is higher for the epoxy based composites.

Figure 6 shows for the same reinforcement and matrices, typical obtained curve results for the tensile tests. As can be seen in this, again the composite made from the epoxy matrix exhibits a more linear behavior until break and a higher tensile strength. Before rupture to occur, one can see the strain at which the strain gauge was removed by the slightly decrease in stress values.

Figure 7 shows typical sisal/epoxy and sisal/polyester obtained in flexural tests. It can be seen that the behavior of the two composites is very similar. Also, the tensile strength and flexural modulus of the jute polyester composites are found to be slightly higher.

In the next figure 8, two typical curves of tensile test on jute/polyester and jute/epoxy composites are shown. Again, the behavior of the two curves is similar, but one can see that the epoxy matrix allows more a much higher tensile break strain.

Figure 9 shows typical flax/epoxy and flax/polyester curves obtained in flexural tests. The two cures are very similar.
Finally, in figure 10 are shown two typical tensile curves obtained from flax epoxy and polyester composites.

The observation of figure 10 allows concluding for the very different behavior of the two composites reinforced with flax. The flax epoxy composites have much higher tensile strength, elastic modulus and a much lower deformation at break. The flax polyester composite exhibits a creep behavior in most part of the test.

3.4 LFT production and processing

With this technology, the natural fibers were chopped to the desired length (one inch) and used to make LFTs by mixing with polymer material in the piston-blender (figure 11), which was specifically developed to promote their melting while maintaining fiber length. Due to the very low shear induced on the melt, fiber breakage is limited to a minimum, while accomplishing a sufficient level of mixing. After being mixed, the blend of natural fibers and polypropylene are quickly introduced into a hot plate press and immediately compressed into a composite plate. Until now, good quality composite plates obtained from the three different natural reinforcements were already produced and are being mechanically tested.

4- Results

The obtained tensile test results are summarized in table 6.

As can be observed, the use of an epoxy system as matrix in the produced composites led to an increase in the tensile strength but only with flax increases all mechanical properties. Considering that the epoxy system can be circa 10 times more expensive than polyester, it usage can be better justified if flax fibers were used as reinforcement. It should be noticed that if elasticity modulus is of relevance polyester matrix should be selected for sisal and jute fibers.

The obtained results for flexural tests are summarized in table 7. It can be observed that all values of the flexural strength are higher than those obtained in tensile tests. However, the flexural modulus values are lower than those obtained in tensile tests. Comparatively to the polyester matrix, the epoxy matrix leads to a decrease in the flexural modulus of the composites. If strength is considered, the use of an epoxy matrix increases this propriety only in the case of sisal fibers.

Table 8 allows comparing some produced natural fiber composites with more traditional engineering materials. It can be seen that specific module values for polyester jute composites are higher than those of more traditional LFT's, GMT's and Nylon. Also, the specific strength of the jute polyester composite is higher than the value of Nylon polymer.

5 Conclusions

It was possible to manufacture composites from thermoplastic and thermosetting resins reinforced with jute, sisal and flax. The composite plates were submitted to mechanical testing and the obtained experimental results allow concluding that enough good mechanical proprieties were obtained allowing the use of those materials as materials for structural and no-structural engineering applications.

In future, authors intend to study the processing of those natural by pultrusion and filament winding.

Acknowledgements

The authors wish to thank the Engineering School of the University of Minho, PIEP – Pole for Innovation in Polymer Engineering and the School of Engineering of the Polytechnic of Porto, for the support given to this work. They also acknowledge the Portuguese Foundation for Science and Technology for the financial support of IPC through project PEst-C/CTM/LA0025/2011 (Strategic Project–LA 25, 2011–2012).

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[8] GRP Tanks and Vessels for use Above Ground, EN13121 Standard, 2008.

Tables

Table 1. Typical natural fiber properties [3]

Fiber	**Specific gravity**	**Tensile strength (MPa)**	**Modulus (GPa)**	**Specific modulus (GPa)**
Jute	1.3	393	55	38
Sisal	1.3	510	28	22
Flax	1.5	344	27	50

Table 2. Properties of the used matrices from the manufacturers datasheets

Property	**Orthoftalic resin**	**Epoxy resin**
Density (kg/m^3)	1100	1130
Tensile modulus (GPa)	3.8	3.1
Tensile strength (MPa)	75	77
Elongation at break (%)	3.4	4.5
Viscosity at 25 ºC (mPa×s)	650-750	1550

Table 3. Jute fiber characterization

Mass (g/m^2)	204.0±7.0
Warp	
Linear density of the yarn (Tex)	140.5±9.5
Density (yarns/cm)	7.0±0.1
Crimp (%)	5.04±0.89
Linear tensile strength (N/mm)	8.62±1.18
Strain at break (%)	4.258±0.21
Weft	
Linear density of the yarn (Tex)	142.6±19.1
Density (yarns/cm)	6.6±0.5
Crimp (%)	2.44±1.24
Linear tensile strength (N/mm)	7.40±1.03
Strain at break (%)	8.58±0.12

Table 4. Sisal fiber characterization

Gage length (mm)	**Deformation at break** (%)	**Tensile strength** (MPa)	**Tensile modulus** (GPa)
20.00	3.22±0.28	760±114	28.1±0.97
25.00	2.81±0.70	763±92	19.4±0.66
30.00	2.64±0.42	461±185	14.7±0.13

Table 5. Flax fiber characterization

Mass (g/m^2)	624±10.5
Warp	
Linear density of the yarn (Tex)	255±30
Density (yarns/cm)	7.2±0.4
Crimp (%)	8.4±4.8
Linear tensile strength (N/mm)	4.2±1.84
Strain at break (%)	27.2±2.0
Weft	
Linear density of the yarn (Tex)	263±43
Density (yarns/cm)	8.0±0.7
Crimp (%)	6±4.1
Linear tensile strength (N/mm)	2.1±0.11
Strain at break (%)	34.2±1.2

Table 6. Tensile test results

Tensile properties	**Tensile strength (MPa)**	**Elasticity modulus (GPa)**	**Deformation at break (%)**
Jute-polyester	57.0±7.2	7.0±0.5	1.9±0.2
Sisal-polyester	24.8±3.9	5.4±0.3	1.5±0.3
Flax-polyester	22.4±2.3	3.4±0.6	5.7±0.8
Jute-epoxy	58.8±4.8	6.0±0.3	3.5±0.5
Sisal-epoxy	32.7±1.5	4.3±0.2	1.9±0.2
Flax-epoxy	78.9±1.8	6.9±0.4	4.3±0.5

Table 7. Flexural test results

Flexure properties	Flexural strength (MPa)	Elasticity modulus (GPa)	Deformation at break (%)
Jute-polyester	91.5±3.8	5.9±0.2	2.8±0.1
Sisal-polyester	54.8±1.9	3.9±0.2	2.4±0.1
Flax-polyester	123.3±9.1	3.1±0.2	6.3±0.7
Jute-epoxy	86.5±7.2	5.1±0.8	2.8±0.2
Sisal epoxy	68.3±6.7	3.0±0.4	3.0±0.3
Flax-epoxy	116.9±6.5	3.0±0.3	6.5±0.7

Table 8. Comparing properties of natural fiber composites with more traditional materials

Material	Density (kg/m^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Specific modulus (MN×m/kg)	Specific strength (kN×m/kg)
Polyester jute composite	1250	57	7.0	5.6	45.6
Polyester sisal composites	1200	25	5.4	4.5	20.8
Polyester flax composites	1300	22	3.4	2.6	16.9
LFT composites	1070	100	3.4	3.2	93.4
Mild steel	7850	400	210	26.8	50.9
Stainless steel	7850	500	184	26.6	63.7
Aluminium (pure)	2700	50	70	25.9	18.5
Aluminium (alloy)	2810	300	71	25.3	106.8
GMT (20% fiber weight)	1030	150	3.4	3.3	145.6
Nylon 66 (PA)	1060	45	2.8	2.6	42.4

Figures

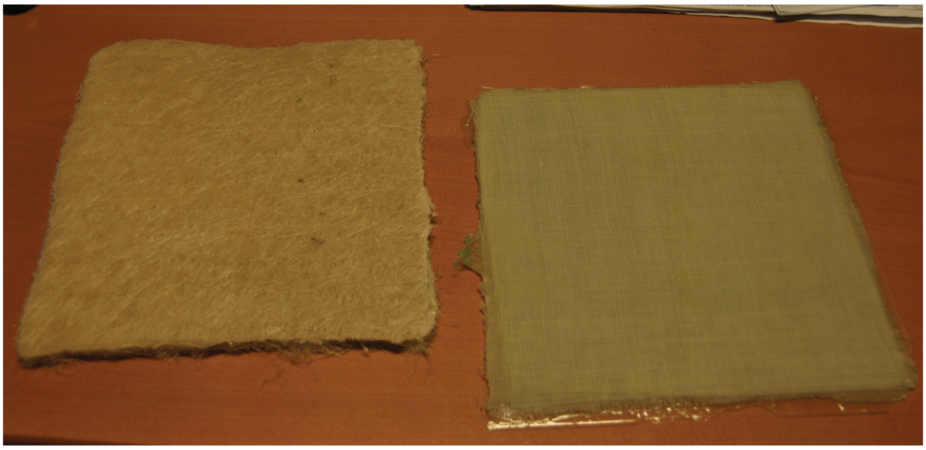
Figure 1. Sisal (left) and jute (right) plates produced by vacuum compression

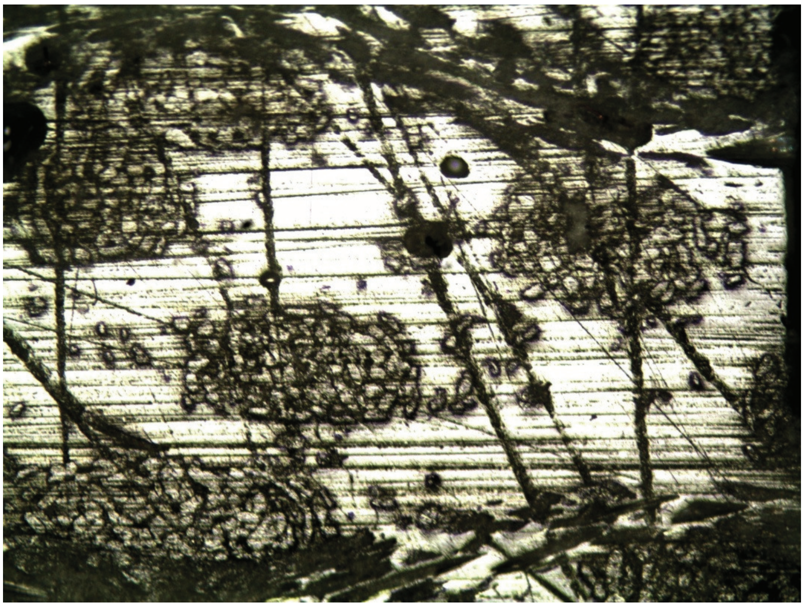
Figure 2. Jute fiber geometry (amplified 50×)

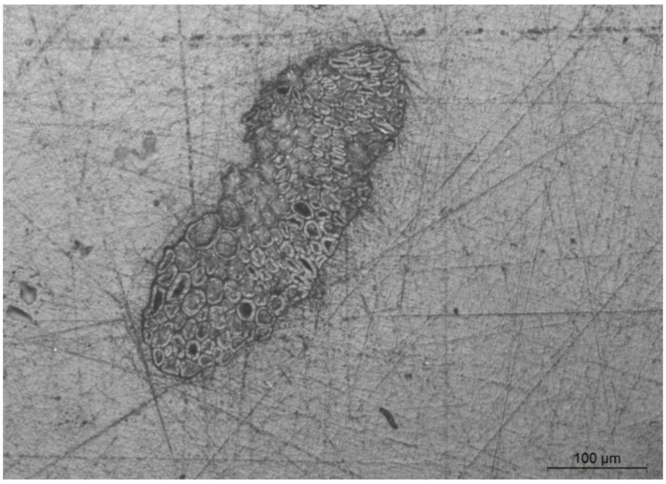

Figure 3a) Elliptical sisal fiber geometry (amplified 100×)

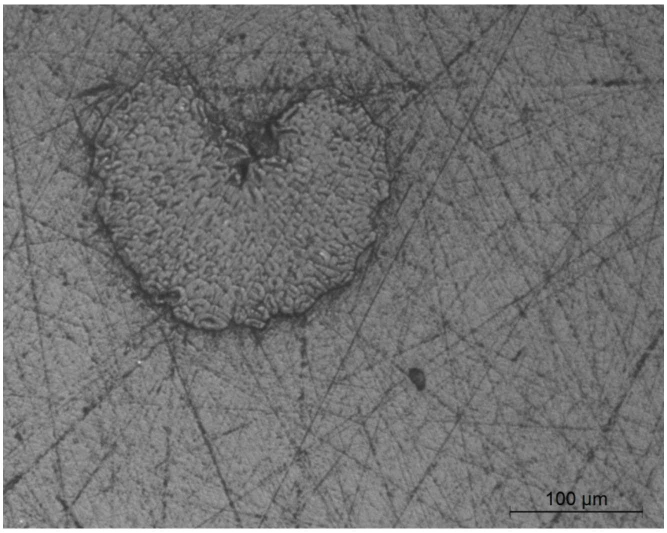

Figure 3b) Heart like sisal fiber geometry (amplified 100×)

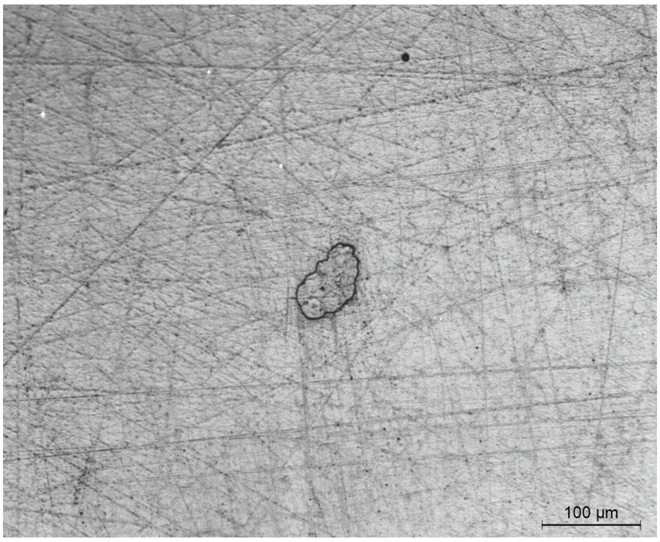

Figure 4. Typical flax fiber geometry (amplified 100×)

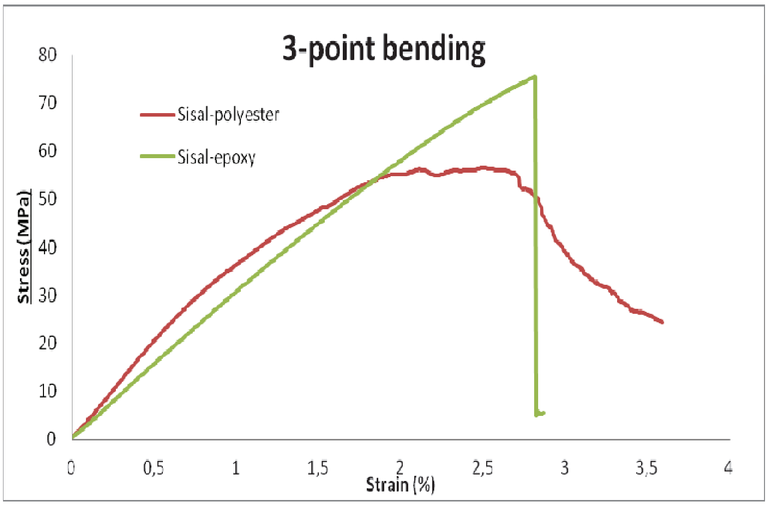

Figure 5. Typical sisal epoxy and polyester flexural test curves

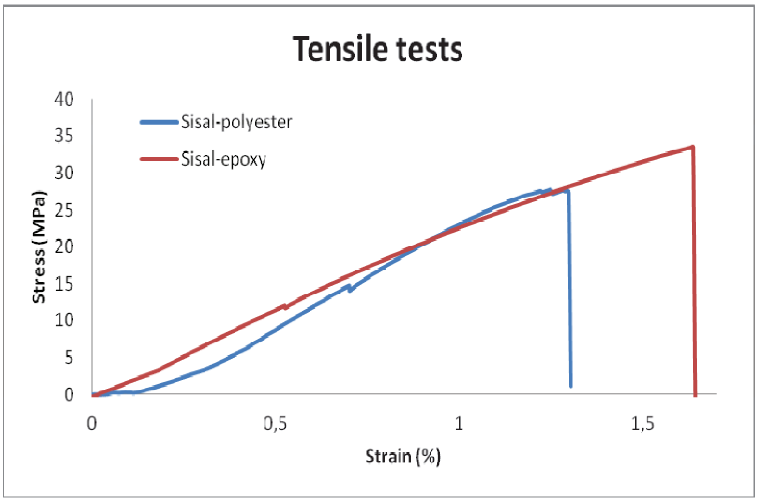

Figure 6. Typical sisal epoxy and polyester tensile test curves

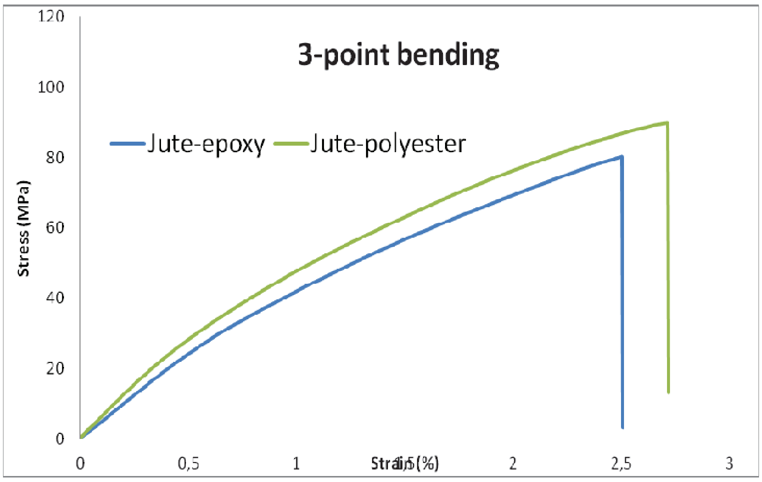

Figure 7. Typical jute epoxy and jute polyester flexural test curves

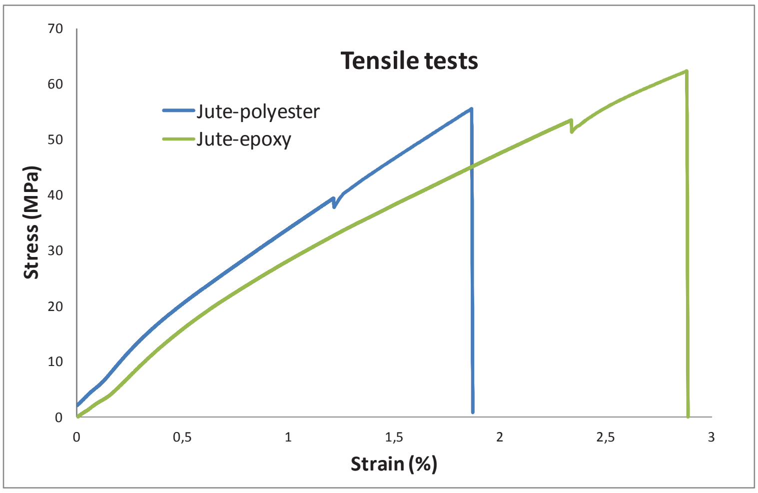

Figure 8. Typical jute epoxy and polyester tensile test curves

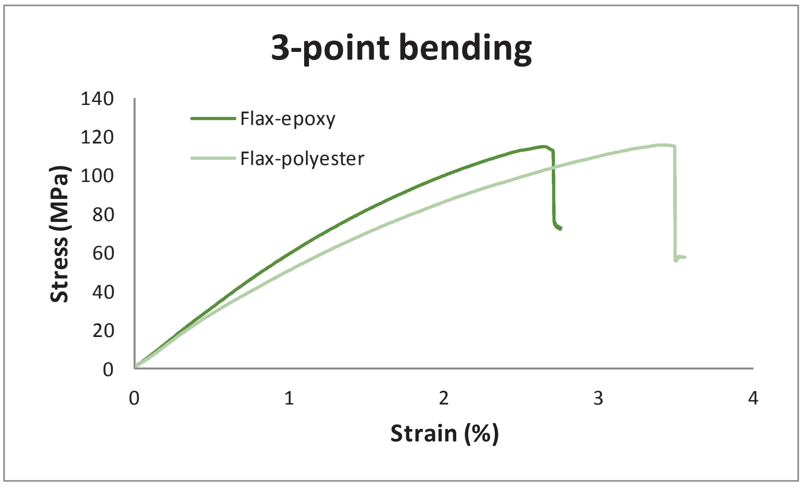

Figure 9. Typical flax epoxy and polyester flexural test curves

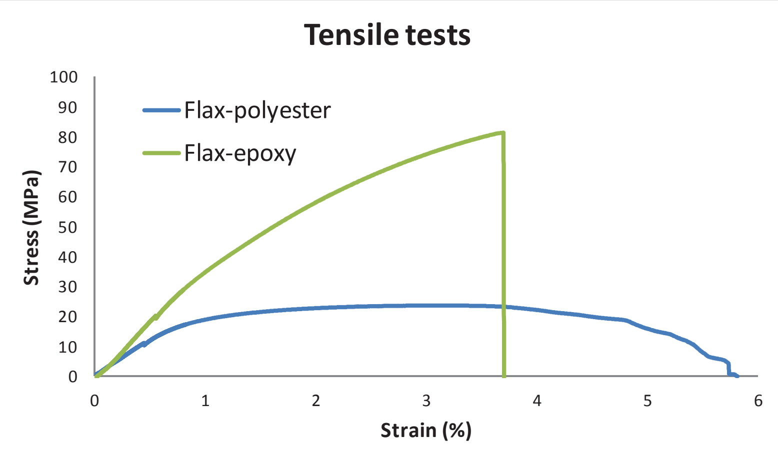

Figure 10. Typical flax epoxy and polyester tensile test curves

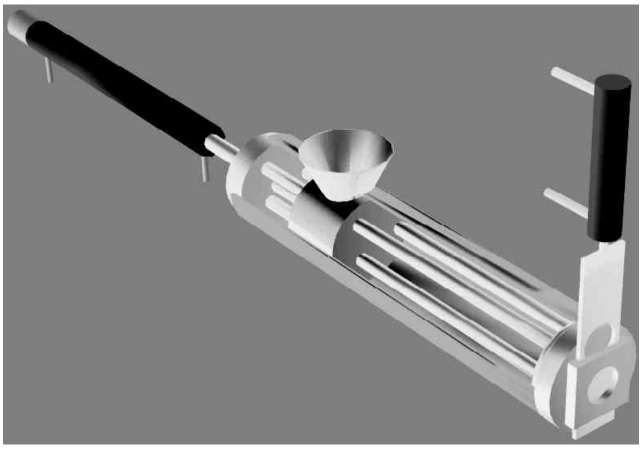

Figure 11. Schematic representation of the piston-blender [2, 6]