MECHANICAL PROPERTIES OF WOVEN NATURAL FIBER REINFORCED COMPOSITES

A. Pozzi[1*], R. Sepe[2]

[1]*A-Technology S.p.A., Zona Industriale Ex Indesit Stab. 15 - 80131 Gricignano di Aversa, Italy;*
[2]*Dept. of Materials and Production Engineering - University of Naples Federico II - P.le V. Tecchio, 80 - 80125 Naples, Italy;*
[*]*e-mail: angela.pozzi@a-technology.it.*

Keywords: Natural fibers, Mechanical properties, SEM.

Abstract
Epoxy matrix composites reinforced with woven natural fiber were studied. Composites having fiber volume fraction greater than 55% were prepared by hand lay-up technique. For reinforcement, three different natural fibers were used, jute, flax and silk. The tensile and flexural properties were investigated and the influence of the orientation of fibers on the stiffness were analyzed. It was observed that the tensile and flexural strength of silk composites is almost equal to that of flax composite and 1.98 times that of jute composite. Moreover the stiffness of the silk composites isn't influenced by orientation of fibers. Morphological examinations were carried out using scanning electron microscopy (SEM). All specimens were coated with a thin layer gold alloy prior to SEM observations. A high voltage of 20 kV was used for making the micrographs. The SEM investigation was used to study the fracture surface of the tensile specimens of the composites samples. The results of this study indicate that using silk fiber as reinforcement could successfully develop a composite material in terms of high strength and stiffness to produce a bio-composites for light applications compared to conventional composites.

1 Introduction
Environmental and economical concerns are stimulating research in design and production of innovative materials for aeronautic, railways and automotive industries. Particularly attractive are new materials in which a good part is based on natural renewable resources, preventing further stresses on the environment. Among these materials, Natural Fibers-Reinforced Composites (NFRC) are finding much interest as a substitute for glass or carbon reinforced polymer composites. In fact they are used in technical applications such as the automotive industry, where mechanical properties have to be combined with low weight.
Natural fibers have several advantages if compared with other synthetic fibers, glass, or carbon fibers: they are available in abundance and inexpensive compared to other relatively advanced man-made fibers reinforcing factors, including low weight, low cost, low density, high specific properties, nonabrasive processing characteristics, and lack of residues upon incineration. Moreover natural fibers sequester CO_2 from the atmosphere, hence providing an advantageous contribution to the global carbon budget. The easy disposal of natural fiber composites is also important, since they can be easily combusted or composted at the end of their product life cycle. The disadvantages are lower impact strength, higher moisture

absorption which brings to local or seasonal dimensional changes thus leading to micro-cracking and poor thermal stability.
Natural fibers are subdivided based on their origins, coming from plants, animals or minerals.
Generally, plant or vegetable fibers are used to reinforce plastics. Plant fibers may include hairs (cotton, kapok), bast (flax, hemp, jute, ramie) and hard-fibers (sisal, henequen, coir).
The availability of large qualities of such fibers with well-defined mechanical properties is a general prerequisite for the successful use of these materials and the lack of this is one of the drawbacks at the moment.
In the past decade, natural fiber composites have been developed, in which several fibers such jute, flax sisal, bamboo, silk and banana are used as reinforcements in place of glass or carbon fibers [1-12].
Prasad et al. [13] have investigated the behavior of new composites made by reinforcing jowar into polyester resin matrix changing the volume fraction fiber. This material presents high strength and rigidity compared to conventional sisal and bamboo composites.
Lin et al. [14] studied the effects of varying textile yarn linear density, textile weave configuration and stacking sequence of the textile, on the fracture behavior of the composites. It was found that the addition of woven textile improves the fracture toughness of the composites.
Franco et al. [15-16] studied the mechanical behavior of high density polyethylene (HDPE) reinforced with continuous henequen fibers. It was found that the use of the silane coupling agent improved the degree of fiber-matrix adhesion and then the strength and stiffness of the composites. In [16-17] the effect of the fiber treatments and matrix modification on mechanical properties of composites were analyzed.
In this paper are reported the results of a study to investigate the potential use of natural fiber to produce bio-composites. The mechanical properties of composites made by epoxy matrix reinforced with natural fibers are evaluated and the influence of the orientation of fibers on the stiffness is analyzed.

2 Experimental

2.1 Materials

For reinforcement three different natural fibers were used:
Jute: woven jute fabric with specific weight of about 300 g/m^2.
Flax: woven flax fabric with specific weight of about 178 g/m^2.
Silk: woven silk fabric with specific weight of about 75 g/m^2.
For all composites a commercially available epoxy resin EC138 produced by Elantas with a density of 1.15 g/ml and a tensile strength of 55 MPa was used as matrix. This was used in conjunction with W341 hardening agent, the weight ratio between mixing resin and hardener being 10:3. All composites were produced at 60% fibre weight fraction. The fibers were dried in oven at 100° C for 2 h.

2.2 Laminates fabrication materials

All laminates were prepared by simple hand lay-up technique in a mould at room temperature. The mould used for preparing laminates is made from two rectangular stainless steel sheets having dimensions of 400 x 300 mmxmm. The function of these plates is to cover and compress the fibers after the epoxy has been applied.
Each layer of reinforcement was pre-impregnated with matrix material and placed one on the other in the mould, taking care to keep practically achievable tolerances on fabric alignment. The layers were compression-molded by vacuum bag for 24 h at 500 mmhg. Then the laminates were post-cured 7 h at 90÷100 °C in oven. The stacking sequences of the laminates were reported in table 1.

Symbol	Fiber	Test	N° ply	Stacking sequence	Thickness (t_h) [mm]
S1	Jute	Tension and flexural testing	4	$[0/90]_{1s}$	3.2
S2	Flax	Tension and flexural testing	12	$[0/90]_{3s}$	3.2
S3	Silk	Tension and flexural testing	16	$[0/90]_{4s}$	2.7
S4	Jute	Tension testing for in-plane shear response	8	$[-45/45]_{2s}$	6.3
S5	Flax	Tension testing for in-plane shear response	8	$[-45/45]_{2s}$	2.2
S6	Silk	Tension testing for in-plane shear response	8	$[-45/45]_{2s}$	1.4

Table 1. Laminate stacking sequences.

2.3 Mechanical characterization

2.3.1 Flexural testing

Three point bend tests were performed in accordance with ASTM D 790 to measure flexural properties. The tests were carried out using a universal mechanical testing machine INSTRON 8500 with load cell of 5 kN. The specimens of 80 mm length and 12.5 mm wide were cut from the laminates such that warp yarns were oriented along the length of the specimen. The specimen is placed onto two supports with a span to depth ratio of 16:1 and the speed of the jaws was set to 0.023 mm/min. A three point bending test is chosen instead of a four point bending one because it eliminates the need to accurately determine center-point deflections with test equipment. The flexural modulus and maximum flexural stress were calculated by (1) and (2).

$$E = \left(mL^3\right)/\left(4bh^3\right); \tag{1}$$

$$\sigma_{\max} = \left(3P_{\max}L\right)/\left(2bh^2\right); \tag{2}$$

where:

P_{max} is maximum load at failure in [N];
L is span in [mm];
b is width of the specimen in [mm];
h is thickness of the specimen in [mm];
m is initial slope of the load-displacement curve.

2.3.2 Tension testing

Specimens for tension test were carefully cut from laminates using diamond wheel saw; the specimens were cut with fabric warp yarns oriented in the loading direction. The geometry of the specimens is shown in figure 1.

The tensile tests of the composites were performed on a universal testing machine INSTRON 8502 according to ASTM D 3039/M. The tests were carried out using a load cell of 250 kN and the strain is measured by strain rosette with three legs disposed at 0°-45°-90° (type CEA-13-250UR-350). The specimens were tested without tabs and to ensure proper gripping and failure in the gauge length, a folded strip of medium grade (80 grit) emery cloth between the specimen faces and the grip jaws was used, mounting at grip pressure of 1 MPa. The crosshead speed was 2 mm/min at room temperature.

Five samples were tested for each composites to evaluate the mechanical properties. All data (load, displacement and strains) were acquired by National Instrument system. Stress-strain curves were obtained from these tests and Young's modulus and tensile strength values were evaluated.

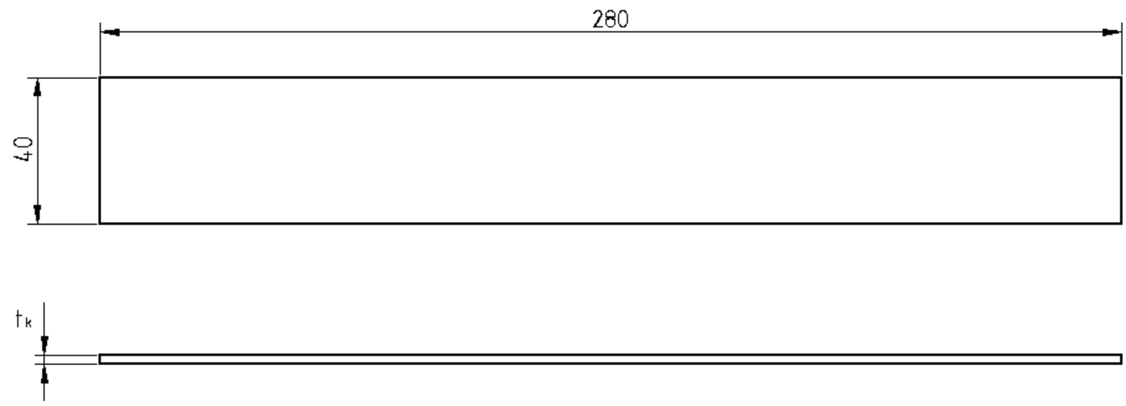

Figure 1. Tension test specimen.

2.3.3 Tension testing to determine the in-plane shear response

This test method in according to ASTM D 3518 is designed to produce in-plane shear property data. Using expressions derived from laminated plate theory, the in-plane shear stress in the material coordinate system is directly calculated from the applied axial load, and the related shear stress is determined from longitudinal and transverse normal strain data obtained by a sensor.

This data is used to create an in-plane shear stress-shear strain curve. Specimens for this test were carefully cut from laminates using diamond wheel saw and they were cut with fabric warp yarns oriented at 45° respect to the loading direction. The geometry of the specimens is shown in figure 1 and thickness (t_h) is reported in table 1. The tests of the composites were performed on a universal testing machine INSTRON 8502 according to ASTM D 3039/M.

2.3.4 Scanning electron microscopy

Morphological examinations were carried out using scanning electron microscopy (SEM). All specimens were coated with a thin layer gold alloy prior to SEM observations. A high voltage of 20 kV was used for making the micrographs. The SEM investigation was used to study the fracture surface of the tensile specimens of the composites samples.

3 Results and discussion

3.1 Flexural testing

The load-deflection and strength-strain diagrams for all composites are shown in figures 2 and 3. The specimens show a non linear behavior because the crack initiates on the tension side of the beam and slowly propagates in an upward direction. The flexural modulus and strength values obtained are shown in figures 4 and 5, respectively.

Flax fiber composites show the highest modulus value (5226 MPa) while jute fiber ones show the lowest (3381 MPa). Flax fiber composite is found to have both modulus and flexural strength 35% and 50% respectively higher than that of jute fiber composite. Instead flax and silk fiber composites show the highest strength value (119 MPa) but the modulus of silk composite is 41% lower than that of flax composite.

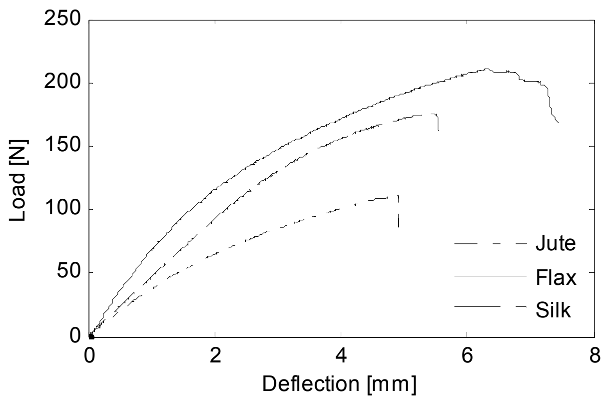

Figure 2. Load-deflection.

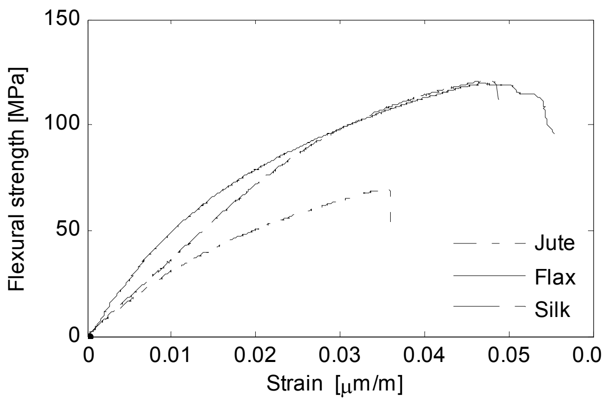

Figure 3. Strength-strain.

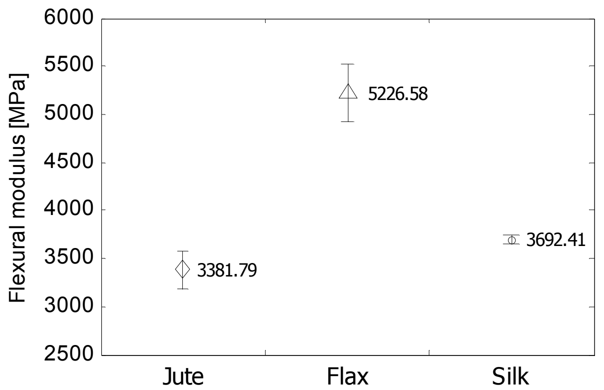

Figure 4. Flexural modulus of the composites.

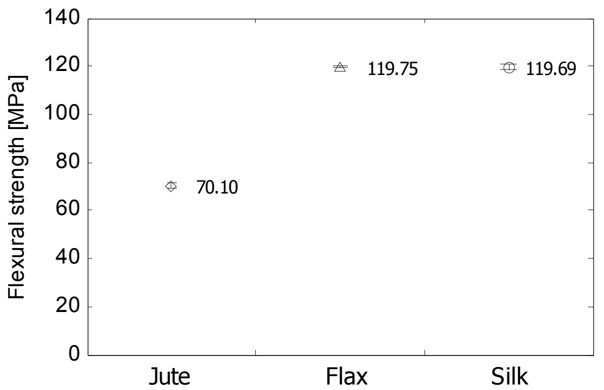

Figure 5. Flexural strength of the composites.

3.2 Tension testing and in-plane shear response

The tensile strength-displacement and shear strength-displacement diagrams for all composites are shown in figures 6 and 7. All composites exhibited stress-strain curves with some degree of non linearity before maximum load as a result of the development of incipient damage such matrix cracking, fiber failure or fiber pull-out. Moreover the curves evidence in all samples brittle fracture due to simultaneous fracture of fibers and matrix.

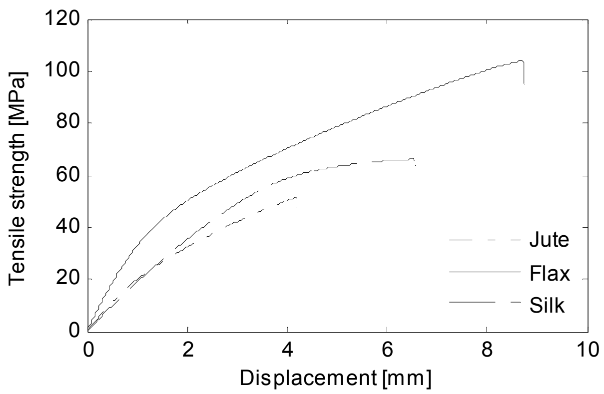

Figure 6. Tensile strength-displacement.

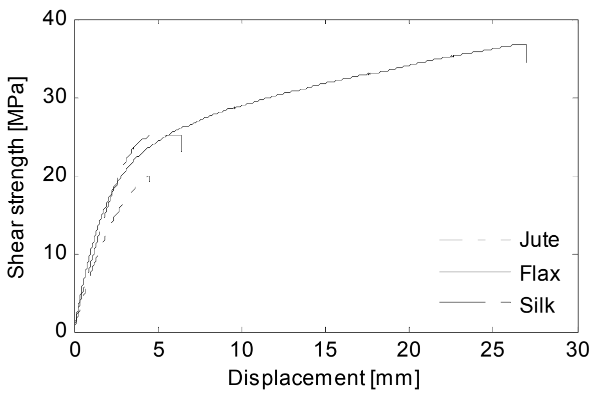

Figure 7. Shear strength-displacement.

The tensile modulus and strength values obtained are shown in figures 8 and 9, respectively. All composites with [0/90] stacking sequence have the tensile modulus and strength higher than composites with [-45/45]. Flax fiber composite displayed the highest (103 MPa) tensile strength while jute showed the lowest (49 MPa). The strength of silk composite was approximately 66 MPa. Flax fiber composites show the highest tensile modulus value (7882

MPa) while silk fiber show the lowest (4149 MPa). Flax fiber composite is found to have tensile modulus 34% and 47% higher than that of jute and silk fiber composite respectively. Moreover figure 8 shows that tensile modulus of the flax and jute fiber composites is strongly dependent on fiber orientation. In fact flax and jute fiber composites with [0/90] orientation are found to have the modulus 39% and 32% higher than that of composites with [-45/45] whereas the tensile modulus of silk composites is not dependent on fiber orientation. The tensile modulus of silk composite with [0/90] fiber orientation is only 12% higher than that of composites with [-45/45].

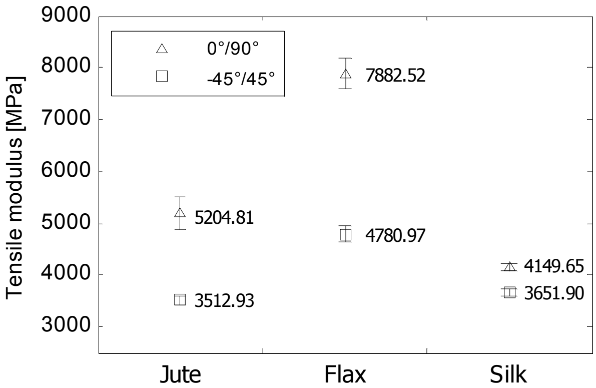

Figure 8. Tensile modulus of the composites.

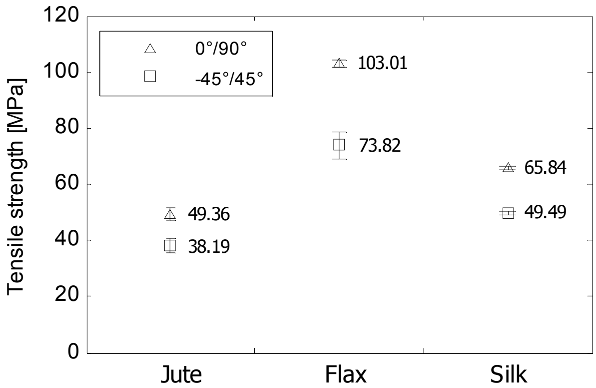

Figure 9. Tensile strength of the composites.

Figure 10 shows the Poisson's ratio of the composites tested. All composites with [-45/45] stacking sequence have the Poisson's ratio higher than composites with [0/90].The figure 10 shows also that Poisson's ratio for flax and jute fiber composites depends on fiber orientation. Flax and jute with [-45/45] fiber orientation are found to have Poisson's ratio 52% and 39% higher than that of composites with [0/90] whereas the Poisson's ratio of silk composite with [-45/45] fiber orientation is only 8% higher than that of composites with [0/90].

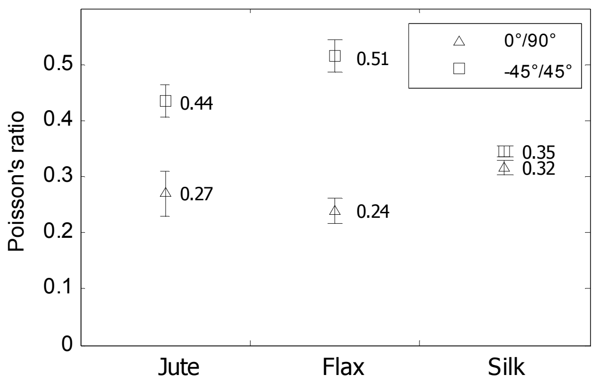

Figure 10. Poisson's ratio of the composites.

The shear strength and tangential modulus values obtained from in plane shear testing are shown in figures 11 and 12, respectively. Flax fiber composite displayed the highest (37 MPa) shear strength while jute showed the lowest (19 MPa). The shear strength of silk composite was approximately 25 MPa. Flax fiber composites show the highest tangential modulus value (3054 MPa) while jute fiber show the lowest (2365 MPa). Flax fiber composite is found to have tangential modulus 23% and 12% higher than that of jute and silk fiber composite respectively.

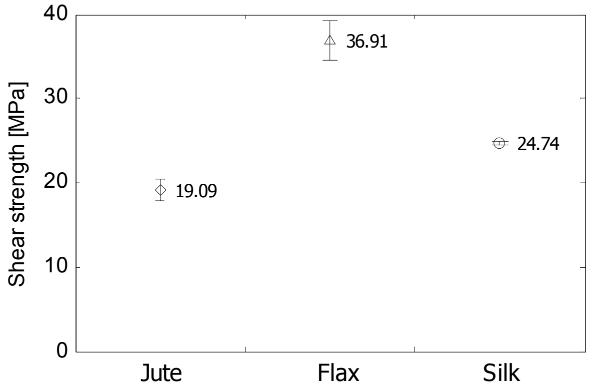

Figure 11. Shear strength of the composites.

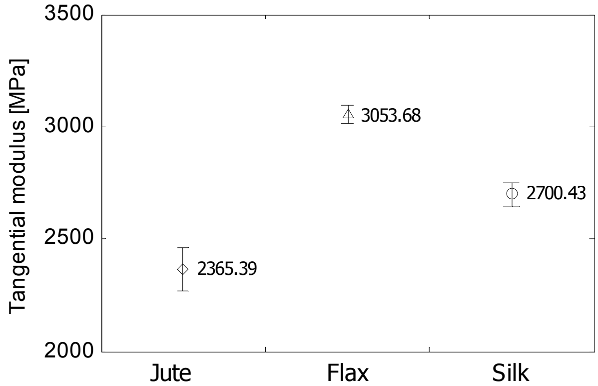

Figure 12. Tangential modulus of the composites.

3.3 SEM analysis

Figures 13-15 show SEM micrographs of fracture surface of jute fiber composites subjected to tensile stresses. The surfaces of fibers are completely devoid of matrix material. This is a clear indication of fiber-matrix interfacial failure followed by extensive fiber pull-out from the matrix. Furthermore, the matrix also shows many voids, thus indicating a no-contact between fiber and matrix and worse wetting of the fibers. This is also an indication that the matrix wasn't able to fully penetrate among the fibers.

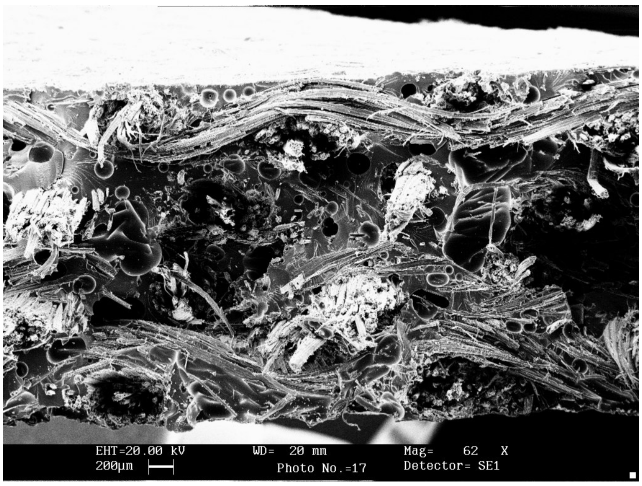

Figure 13. Photo-micrographs of jute fiber composite fracture surfaces of a sample subjected to tensile stresses.

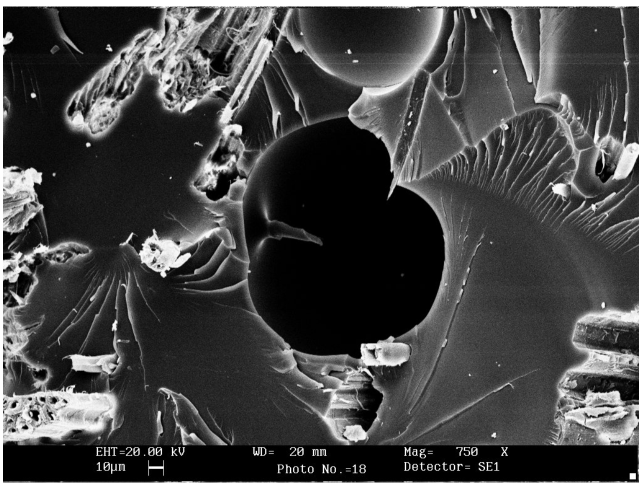

Figure 14. Photo-micrographs of jute fiber composite fracture surfaces of a sample subjected to tensile stresses.

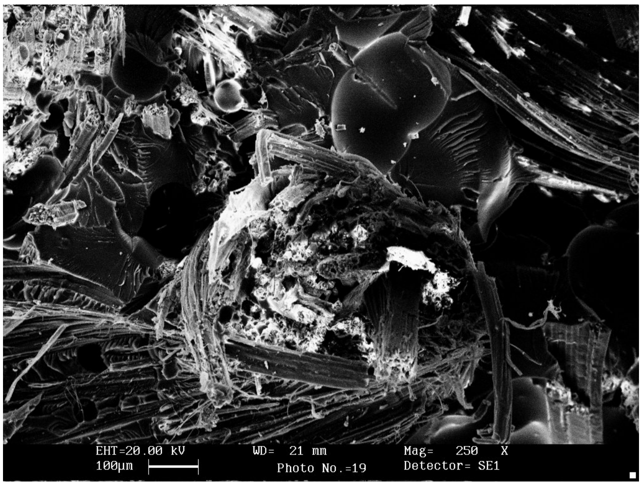

Figure 15. Photo-micrographs of jute fiber composite fracture surfaces of a sample subjected to tensile stresses.

Figures 16-18 show SEM micrographs of fracture surface of flax fiber composites subjected to tensile stresses. There aren't voids, this is an indication that the matrix was able to fully penetrate among the fibers but also in this case the surfaces of fibers are completely devoid of matrix material indicating worse wetting of the fibers and bed interaction fiber-matrix.

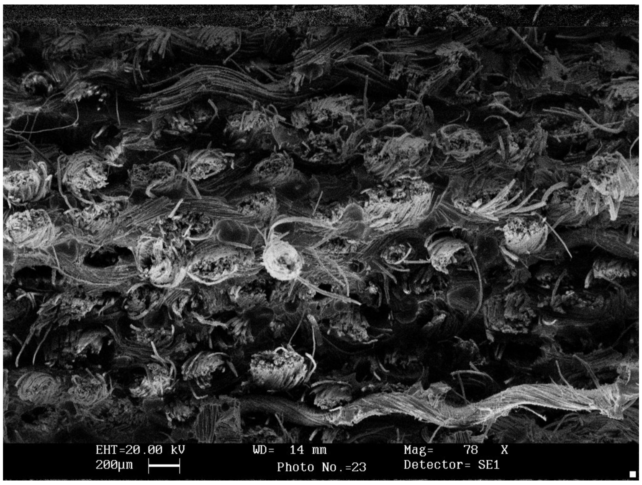

Figure 16. Photo-micrographs of flax fiber composite fracture surfaces of a sample subjected to tensile stresses.

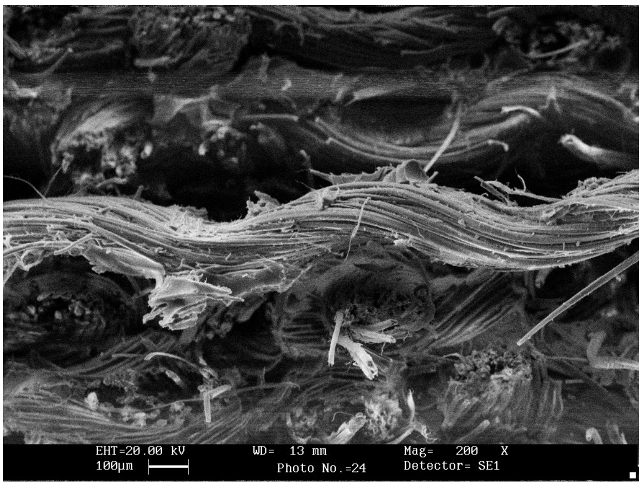

Figure 17. Photo-micrographs of flax fiber composite fracture surfaces of a sample subjected to tensile stresses.

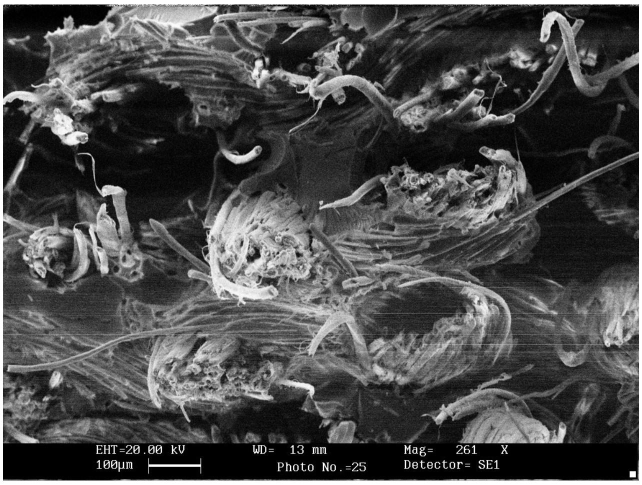

Figure 18. Photo-micrographs of flax fiber composite fracture surfaces of a sample subjected to tensile stresses.

Figures 19-21 show SEM micrographs of fracture surface of silk fiber composites subjected to tensile stresses. The failure mode observed on the fibers shows fiber splitting and tearing and it is attributed to a better interaction with the matrix and better wetting of the fibers. The failure surfaces show there were many traces of matrix material still surrounding the fibers surfaces.

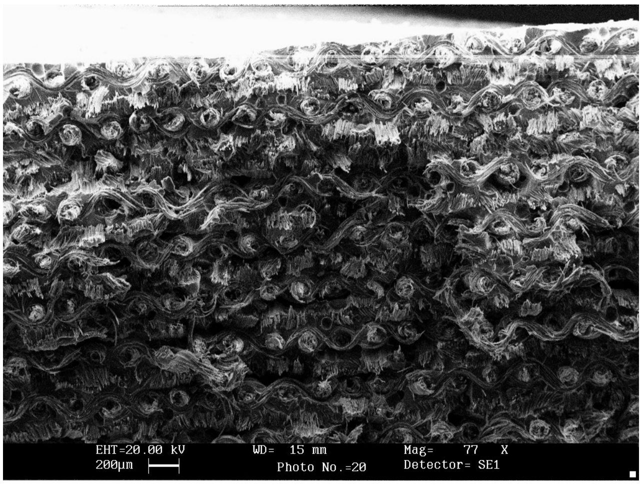

Figure 19. Photo-micrographs of silk fiber composite fracture surfaces of a sample subjected to tensile stresses.

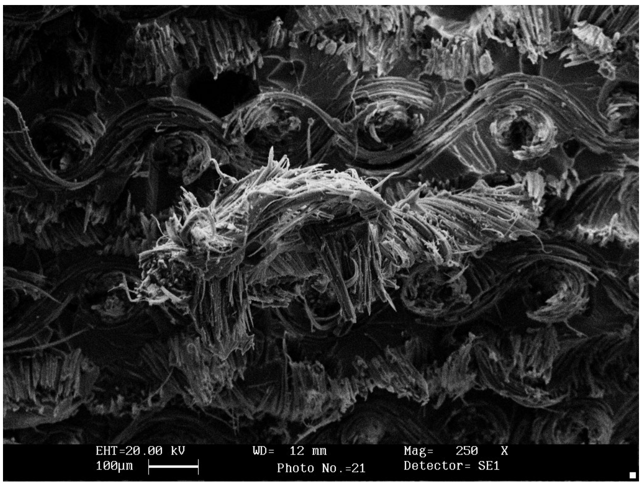

Figure 20. Photo-micrographs of silk fiber composite fracture surfaces of a sample subjected to tensile stresses.

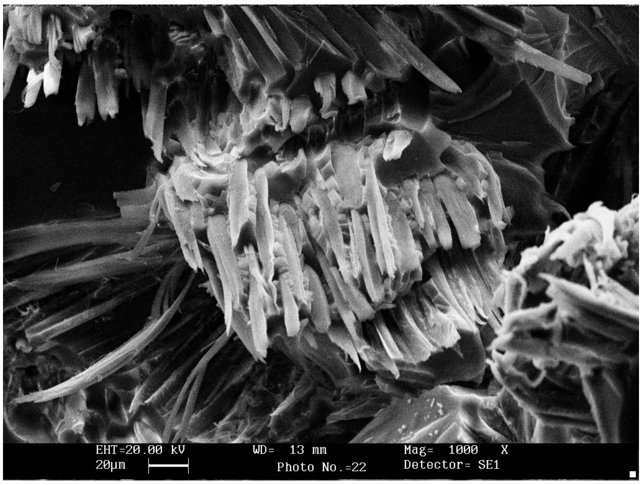

Figure 21. Photo-micrographs of silk fiber composite fracture surfaces of a sample subjected to tensile stresses.

4 Conclusion

Some mechanical behaviour of the epoxy matrix composites reinforced with jute, flax and silk fiber has have been experimentally evaluated. From the results of this study, the following conclusions are drawn.

1. The tensile and flexural strength of silk composites is almost equal to that of flax composite and 1.98 times that of jute composite.
2. Flax fiber composite displayed for both stacking sequence [0/90] and [-45/45] the highest tensile strength while jute showed the lowest. The tensile strength for [-45/45] fiber orientation decreases about 25% for all composites.
3. Flax fiber composites show the highest tensile modulus value for both fiber orientation while silk fiber show the lowest. The tensile modulus of the flax and jute fiber composites strongly depends on fiber orientation, whereas the tensile modulus of silk composites does not depend on it. In fact the tensile modulus of silk composite with [0/90] fiber orientation is only 12% higher than that of composites with [-45/45].
4. All composites with [-45/45] stacking sequence have the Poisson's ratio higher than that of composites with [0/90]. Flax and jute with [-45/45] fiber orientation are found to have Poisson's ratio 52% and 39% higher than that of composites with [0/90], whereas the Poisson's ratio of silk composite with [-45/45] fiber orientation is only 8% higher than that of composites with [0/90].
5. Flax fiber composite displayed the highest (37 MPa) shear strength while jute showed the lowest (19 MPa). Flax fiber composite has tangential modulus 23% and 12% higher than that of jute and silk fiber composite respectively.
6. From SEM analyses the surfaces of jute fibers are completely devoid of matrix material. Furthermore, the matrix also shows many voids, thus indicating a no contact between the fiber and matrix and worse wetting of the fibers. The fracture surface of flax fiber composites does not present voids; this suggests that the matrix is able to fully penetrate among the fibers but also in this case the surfaces of fibers are completely devoid of matrix material indicating worse wetting of the fibers and bed interaction fiber-matrix. The failure mode of the silk fiber composites shows fiber splitting and tearing and this is attributed to a better interaction with the matrix and better wetting of the fibers.

The results of this study indicate that the mechanical properties of the composite reinforced by silk fiber are interesting and they are few affected by orientation of fibers. Moreover the silk fibers have better interaction with the matrix and better wetting.

So this study indicates that using silk fiber as reinforcement could successfully develop a composite material in terms both of high strength and stiffness to produce by bio-composites for light applications compared to conventional composites.

References

[1] Ku H., Wang H., Pattarachaiyakoop N., Trada M. A review on the tensile properties of natural fiber reinforced polymer composites, *Composites: Part B*, 42 pp. 856–873 (2011).

[2] Singleton A.C.N., Baillie C.A., Beaumont P.W.R., Peijsc T. On the mechanical properties, deformation and fracture of a natural fibre/recycled polymer composite, *Composites: Part B*, 34 pp. 519–526 (2003).

[3] Bledzki A.K., Jaszkiewicz A. Mechanical performance of biocomposites based on PLA and PHBV reinforced with natural fibres – A comparative study to PP, *Composites Science and Technology*, 70 pp. 1687–1696 (2010).

[4] Harish S., Peter Michael D., Bensely A., Mohan Lal D., Rajadurai A. Mechanical property evaluation of natural fiber coir composite, *Materials Characterization*, 60 pp. 44–49 (2009).

[5] Hoi-Yan Cheung, Kin-Tak Lau, Mei-Po Ho Mosallam A. Study on the mechanical properties of different silkworm silk fibers, *Journal of Composite Materials*, 43 N. 22 pp. 2521-2531 (2009).

[6] Sabeel Ahmed K., Vijayarangan S. Tensile, flexural and interlaminar shear properties of woven jute and jute-glass fabric reinforced polyester composites, *Journal of Materials Processing Technology*, 207 pp. 330–335 (2008).

[7] Symington M.C., Banks W.M., West O.D., Pethrick R.A. Tensile testing of cellulose based natural fibers for structural composite applications, *Journal of Composite Materials*, 43 N. 9 pp. 1083-1108 (2009).

[8] Graupner N., Herrmann A.S., Müssig J. Natural and man-made cellulose fibre-reinforced poly(lactic acid) (PLA) composites: An overview about mechanical characteristics and application areas, *Composites: Part A*, 40 pp. 810–821 (2009).

[9] Wollerdorfer M., Bader H. Influence of natural fibres on the mechanical properties of biodegradable polymers, *Industrial Crops and Products*, 8 pp. 105–112 (1998).

[10] Athijayamani A., Thiruchitrambalam M., Natarajan U., Pazhanivel B. Effect of moisture absorption on the mechanical properties of randomly oriented natural fibers/polyester hybrid composite, *Materials Science and Engineering A*, 517 pp. 344–353 (2009).

[11] Arbelaiz A., Fernández B., Cantero G., Llano-Ponte R., Valea A., Mondragon I. Mechanical properties of flax fibre/polypropylene composites. Influence of fibre/matrix modification and glass fibre hybridization, *Composites: Part A*, 36 pp.1637–1644 (2005).

[12] Wambua P., Ivens J., Verpoest I. Natural fibres: can they replace glass in fibre reinforced plastics?, *Composites Science and Technology*, 63 pp. 1259–1264 (2003).

[13] Ratna Prasad A.V., Mohana Rao K. Mechanical properties of natural fibre reinforced polyester composites: Jowar, sisal and bamboo, *Materials and Design*, 32 pp. 4658–4663 (2011).

[14] Liu Q., Hughes M. The fracture behaviour and toughness of woven flax fibre reinforced epoxy composites, *Composites: Part A*, 39 pp. 1644–1652 (2008).

[15] Herrera-Franco P.J., Valadez-González A. Mechanical properties of continuous natural fibre-reinforced polymer composites, *Composites: Part A*, 35 pp. 339–345 (2004).

[16] Herrera-Franco P.J., Valadez-González A. A study of the mechanical properties of short natural-fiber reinforced composites, *Composites: Part B*, 36 pp. 597–608 (2005).

[17] Stocchi A., Lauke B., Vázquez A., Bernal C. A novel fiber treatment applied to woven jute fabric/vinylester laminates, *Composites: Part A*, 38 pp. 1337–1343 (2007).