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ORIGINAL PAPER

Experimental Investigation of Mechanical and Morphological Properties of Flax-Glass Fiber Reinforced Hybrid Composite using Finite Element Analysis

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Abstract The use of cellulosic fibers as reinforcing materials in polymer composites has gained popularity due to an increasing trend for developing sustainable materials. In the present experimental study, flax and glass fiber reinforced partially eco-friendly hybrid composites are fabricated with two different fiber orientations of 0° and 90°. The mechanical properties of these composites such as tensile, flexural and impact strengths have been evaluated. From the experiments, it has been observed that the composites with the 0° fiber orientation can hold the maximum tensile strength of 82.71 MPa, flexural strength of 143.99 MPa, and impact strength of 4 kJ/m^2. Whereas the composites with 90° fiber orientation can withstand the maximum tensile strength of 75.64 MPa, flexural strength of 134.86 MPa, and impact strength of 3.99 kJ/m^2. Morphological analysis is carried out to analyze fiber matrix interfaces and the structure of the fractured surfaces by using scanning electron microscopy (SEM). The finite element analysis (FEA) has been carried out to predict the resulting important mechanical properties by using ANSYS 12.0. From the results it is found that the experimental results are very close to the results predicted from FEA model values. It is suggested that these hybrid composites can be used as alternate materials for pure synthetic fiber reinforced polymer composite materials.

Keywords Hybrid composites · Fiber orientation · Mechanical properties · Finite element analysis (FEA) · Morphological properties · Flax-glass fiber composites

1 Introduction

In many engineering applications the use of composite materials can offer significant weight reduction, which can have a positive influence on the life cycle of a component or system through energy saving effects [1]. Today the need to achieve environmental sustainability in engineering has spurred the development and creation of new engineering materials incorporating bio-derived materials [2]. Increasing environmental concerns and depletion of petroleum resources has forced researchers to find new green materials [3]. There are many naturally occurring fibers that can be used as reinforcing materials in polymer matrix composites; some of these fibers are obtained by processing agricultural, industrial, or consumer waste [4]. The reinforcement of natural fibers in polymer matrix composites has been increasing for developing low-cost, eco-friendly composites with acceptable properties [5]. An important characteristic of plant fibers is their ability to absorb moisture from the atmosphere, because these fibers are hygroscopic in nature. Moisture has no immediate negative effect on the mechanical properties of natural fibers, but deterioration will happen after fungus starts to grow in the fibers [6]. Plant fibers with small diameter generally possess high mechanical properties, while their permeability is relatively low compared to those with large diameter. By hybridizing these two kinds of fibers, a composite with both high permeability and good mechanical properties can be achieved [7].

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It is inevitable that the inherent detriments of flax, including moisture adsorption and incompatibility with some polymeric systems due to high hydrophilicity, present many challenges with respect to composite design and applications. To improve the mechanical properties, the natural fibers are hybridized with synthetic fibers to make the composite hybrid and these composites are playing a vital role in many engineering applications [8–12]. Layering sequence significantly affects the mechanical properties and the hybrid composite with two extreme glass plies has better strength and modulus [13]. Flax is one of the most widely utilized bio-fibers to be extracted, spun and woven into fabrics [14]. Flax is primarily cultivated for its seeds from which oil is obtained and stems were often considered as waste material. But the fibers extracted from stems can be used as reinforcement in fiber reinforced composites and possess good mechanical properties. The production of flax fibers requires little energy and the plant needs little fertilizer and pesticides, so its cultivation offers a positive environmental impact which can be used to maintain soil quality and biodiversity [15].

Flax fibers have gained the attention of many researchers and are used as reinforcement in polymer matrix composites due to their ease of handling and good mechanical properties [16, 17]. Flax fibres are composed of cellulose (70–82%), hemicellulose (15–18%), pectin (2–5%), lignin (3–5%), waxy substances (2–3%) and dust (1%) [18, 19]. Flax fibers are also known as “technical fibers” in the textile industry, which consist of a number of ultimate or single cell fibers that are bundled together by gummy matters (i.e., hemicellulose, pectin, lignin and etc.) [20]. The mechanical properties of the flax fibers with cement mixtures were assessed and showed an improvement in the properties of the fibers as well as in the properties of the composites [21]. According to Guen et al. [22] the damping coefficient of flax fiber reinforced epoxy composites was found to increase considerably with the addition of glycerol and polyglycerol. The specific flexural strength and stiffness, inter-laminar shear strength and specific impact strength of silk fiber reinforced polymer composites was slightly higher than that of flax and glass fiber composites, and more comparable to, but lower than that of pure glass fiber reinforced polymer composites [23].

The tensile performances of flax fibers with epoxy and polyester matrices have been investigated and showed satisfactory results [24]. The impact behaviour of flax/epoxy composites subjected to transverse impact loading has been analyzed by Liang et al. [25]. It was found that the stiffness of the impacted structure was controlled by the contact time and the increase in contact time leads to damage growth in the specimen. The flax/glass fiber reinforced epoxy composites were subjected to quasi-static loadings and it was found that the compression strength of the composite was comparable to a glass/epoxy composite [26]. The effect of ultraviolet radiation and water spraying on the tensile and flexural properties of flax fiber reinforced epoxy composites was investigated and found that the tensile and flexural strengths of the composites decreased 29.9% and 10.0% respectively due to radiation and spraying [27]. The stiffness of the flax fiber reinforced epoxy composites was increased along the direction of fiber orientation [28]. The effect of hybridization on mechanical behavior of flax/glass fiber reinforced hybrid composites has been investigated and it was found that there is significant improvement in tensile properties with the increasing of glass fiber content [29].

A review has been made on the thermal conductivity, absorbing acoustic coefficient, and hydric properties of a flax fiber reinforced green composite by Hajj et al. [30]. The use of fine flax-tows leads to extraction of more organic substances of the inner fibers during the microwave treatment which improves the mechanical performance and reduces the thermal conductivities of these materials. The effects of stacking sequences and hybridization on the properties of flax–carbon fiber reinforced epoxy composites have been investigated by Assarar et al. [31]. The results showed that the flax layers played a major role in their bending stiffness and damping properties. Flax fiber composites have the potential to be the next generation materials for structural application for infrastructure, automotive industry and consumer applications, filtration industry, packaging such as biodegradable bags and covers, manufacturing of lightweight sports equipments etc [14]. In this experimental study, flax and glass fibers are reinforced with epoxy resin and the hybrid composites are prepared with two different fiber orientations of 0° and 90°. The mechanical and morphological properties of these have been evaluated and analyzed. The results are compared with the results obtained from the finite element analysis by using ANSYS 12.0 software.

2 Experimental

2.1 Materials

In this experimental study, the composites employed for the characterization were made from flax and glass fibers by using epoxy resin. The flax fiber was supplied by Chandra Prakash & Co., Jaipur, Rajasthan, India. The glass fiber, epoxy resin (Type: Araldite LY 556), and the hardener (Type: Araldite HY951), were purchased from M/s. Sakthi Fiber Glass Ltd., Chennai, India. The properties of fibers

Table 1 Properties of flax and glass fibers [23, 32, 33]

Property	Flax fiber	Glass fiber
Density (g/cm^3)	1-1.5	2.5-2.7
Elongation at break (%)	4.5- 6.5	3-5
Young's modulus (GPa)	60-80	70
Microfibrillar angle (Deg.)	11	–
Lumen size (mm)	5	–
Fiber diameter (μm)	160-230	–
Fiber length (cm)	33	33 (continuous)
Tensile stiffness (GPa)	30-80	70-85
Tensile strength (GPa)	0.4-1.5	2-3.7
Tensile modulus (GPa)	–	68-75
Toughness (MJ/m^3)	5-35	40-50

used for composite fabrication are presented in Table 1. The properties of the epoxy resin are given in Table 2.

2.2 Methods

2.2.1 Composite Preparation

The choice of fabrication process is dependent on many factors, such as type of reinforcement and matrix materials, size, shape, quantity and cost. There are many specialized processes available, but the most commonly used commercial process is the hand lay-up technique. In this process the reinforcing fibers are cut and laid in the mold, then the resin is catalyzed and added to the fibers. The hardener HY 951 is added with the resin 1-1.5% for easy mixing and quick setting. The volume fractions of the glass and flax fibers are in the ratio of 60:40. The main difference between the two types of specimen is directional orientation. In the 0° orientation specimen all the layers of the specimen are arranged in the same direction whereas in the 90° orientation specimen the alternate layers of the laminate are arranged in the transverse direction (i.e., perpendicular to each other). The fabrication of the composite in this experimental study is explained in three simple steps which are presented in Fig. 1. Step 1: The wooden mold was prepared, cleaned with thinner solution and kept over the base plate. Then the resin was applied over the cleaned surface and the surface was allowed a few minutes to set for the mold lay-up. Step 2: The glass fibers were placed inside the mold and the resin was applied over them. Then the roller is used for even distribution of resin throughout the fiber surface. The air gaps formed between the layers were squeezed out by means of the roller. Then the flax fibers were placed over the glass fiber layer and the resin applied again. Step 3: The process was repeated for all five

Table 2 Properties of epoxy resin [14]

Property	Range
Density (g/cm^3)	1.1-1.4
Glass transition temperature (°C)	120 -130
Tensile strength (N/mm^2)	35-100
Tensile modulus (N/mm^2)	10,500
Elongation at break (%)	0.8-6
Flexural strength (N/mm^2)	112
Impact strength (J/m)	0.3
Flexural modulus (N/mm^2)	10,000
Elastic modulus (GPa)	3-6
Compressive strength (N/mm^2)	100-200
Water absorption - 24 hours at 23 °C (mg)	5-10 (0.06-0.068%)

Fig. 1 Processing steps of the composite samples

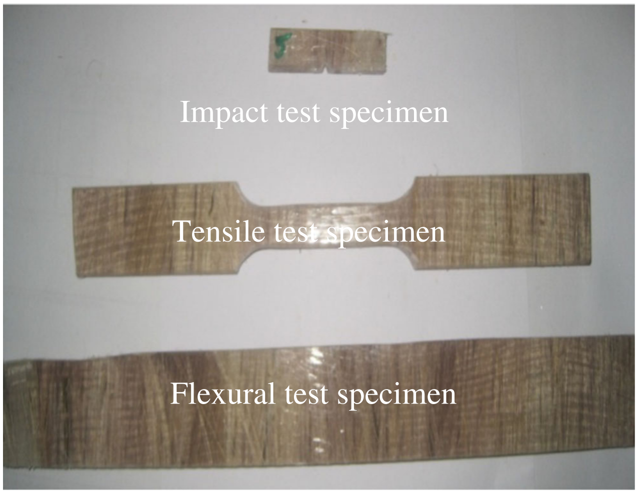


Fig. 2 Mechanical test specimens

layers and the fabrication of the composite material was completed. The fabricated composite samples are kept for solidification under room temperature (32 °C) for 24 hours. The processing of composites is carried out with the surrounding temperature of 32±2 °C and the average relative humidity of 65%. In each case (both 0° and 90° orientation) three samples are tested and the average values are used for the detailed analysis.

2.3 Characterization of Composites

The objective of the characterization is the determination of parameters such as strength and stiffness. The specimens used for mechanical testing are presented in Fig. 2. The experiments are carried out with the surrounding temperature of 32±2 °C and the average relative humidity of 65%. The thickness of the specimen used for mechanical testing in this experimental study is 3.2 cm.

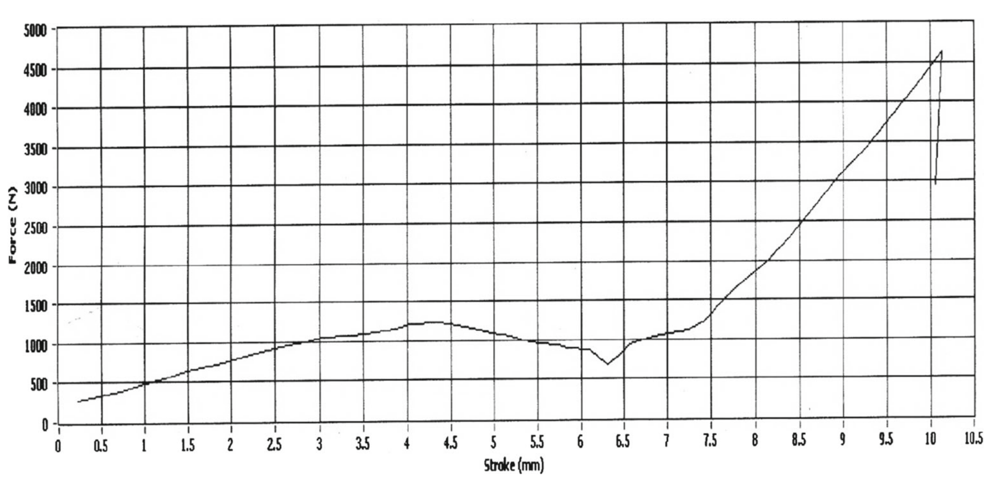
2.3.1 Tensile Strength Test

The tensile strength of the composite depends on how well the stress can be transferred from the broken to the surviving fibers through shear in the resin at the interface and the amount of stress a sample can withstand before failure occurred [32]. A tensile test is conducted as per ASTM D638 standards for plastics and polymeric materials. The material was loaded in the universal testing machine (Make FIE; Model: UTN 40, S. No. 11/98-2450), then the load was applied at increasing rate at the cross-head speed of 5 mm/min, until the breakage of the material has taken place. The load at this point is used to calculate the maximum tensile strength of the composite material. The experiment was repeated for three samples and the average values are used for the detailed analysis.

2.3.2 Flexural Strength Test

Flexural strength is defined as the capability of laminated composites to withstand the bending before reaching the breaking point [32]. The flexural strength represents the highest stress experienced within the material at its moment of rupture. When a material is bent only the extreme fibers are at the largest stress so, if those fibers are free from defects, the flexural strength will be controlled by the strength of those intact fibers. Therefore it is common for flexural strength to be higher than tensile strength for the same material. In this experiment, the flexural test has been conducted as per ASTM D 790 standards by using the same universal testing machine. The three point static flexural test is the most common flexural test and is used in this experiment. The load was applied at the cross-head speed of 5 mm/min, and at the gauge length of 100 mm. The experiment was repeated for three samples and the average values are used for the detailed analysis.

Fig. 3 Typical load vs. displacement curve generated directly from the machine during tensile loading



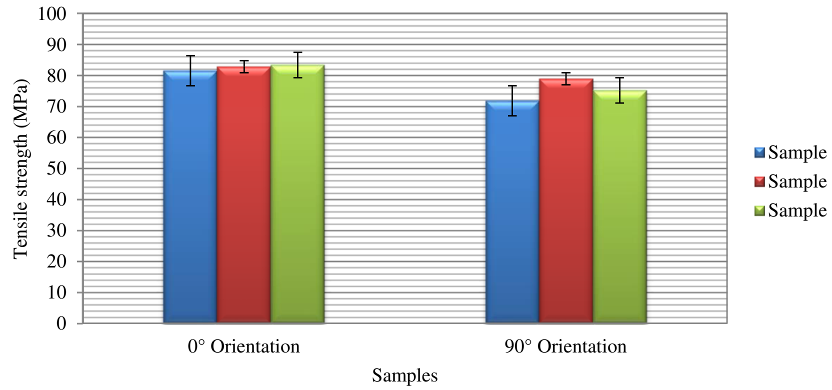


Fig. 4 Experimental tensile strength comparison

2.3.3 Impact Strength Test

This test is designed to give information on how a material will respond to a suddenly applied load and ascertains whether the material is tough or brittle. The Charpy impact test is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture and has been carried out in this experimental study. The samples were prepared for the Charpy impact test according to ASTM D6110 standards. The tests were carried out, using a Charpy impact-testing machine (Model: KL-300, S. No. 96/1054, and Make: Krystal Elmec). This absorbed energy is a measure of a given material's toughness and acts as a tool to study the brittle-ductile nature of a material. The experiment was repeated for three samples and the average values are used for the detailed analysis.

2.3.4 Finite Element Analysis (FEA)

To study the elastic behavior of the composites and predict the mechanical properties, a finite element analysis was carried out. Although most of these properties can be obtained through experimentation, the elastic-plastic transition behavior in composites is not easy to study under experimental conditions; hence a need for FEA modeling is essential. In addition to validating experimental findings, the theoretical prediction of these properties can shorten the cycle time for determining optimum filler quantities that will maximize the resulting composite properties. In this experiment, a finite element model of the specimens was created using ANSYS 12.0 software. In ANSYS 12.0, laminate composite ply results for transient dynamics solutions outputs stress/strain information for an individual laminate. In the present analysis the composite plate is modeled with five layers of hexahedral elements with the element size of 5 mm. The Young's modulus and Poisson ratio of the glass fiber is 2.8 GPa and 0.33 respectively [34] whereas for the flax fibers they are 2.01 GPa and 0.22 [31, 35]. The composite plate is constrained (all six DOF arrested) at a point where the two symmetrical axes are intersecting each other. The loads were applied on both sides along the length of the components. Failure modes of the composites include elastic

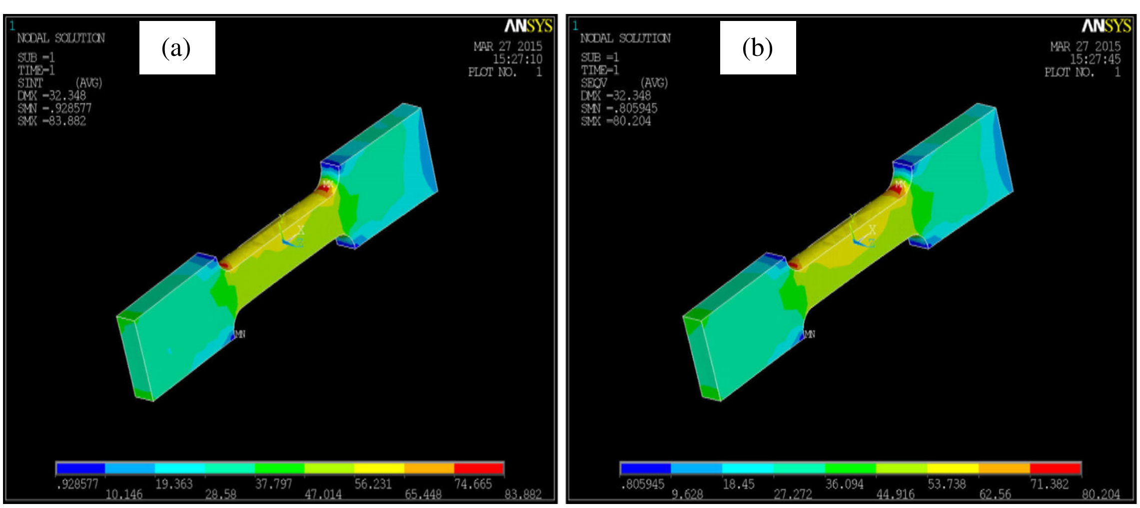


Fig. 5 FEA simulation plots of tensile test specimen with (**a**) 0° fiber orientation and (**b**) 90° fiber orientation

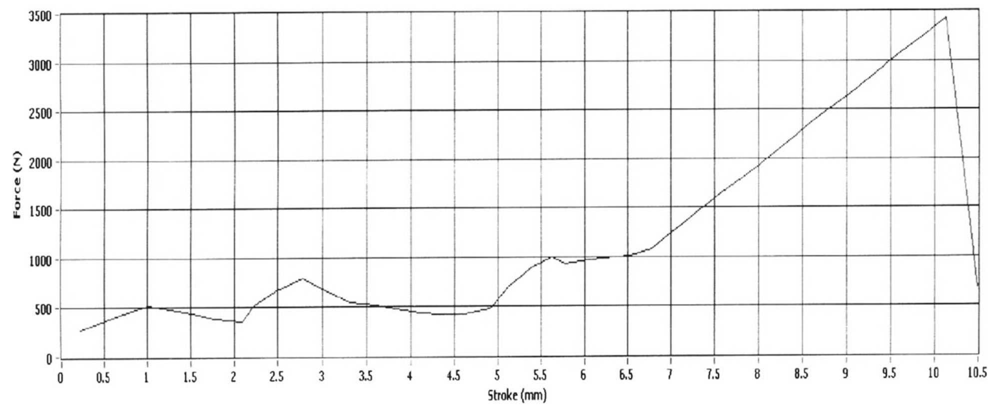


Fig. 6 Typical load vs. displacement curve generated directly from the machine during flexural loading

deformation, plastic deformation, strain hardening, necking and fracture. Unfortunately we cannot capture these processes in numerical simulations, because software follows a different stress-strain curve which is not the actual one. The results from tensile, flexural, and impact tests indicated that the composite material was very brittle but exhibited linear deformation in its elastic state.

2.3.5 Morphological Studies

The instrument, (Model: JEOL JSM-6480LV) is used to analyze the morphological properties of flax-glass fiber reinforced hybrid composites. In most applications, data are collected over a selected area of the surface of the sample, and a two-dimensional image is generated that displays spatial variations in these properties. The SEM can analyse selected locations on the sample; this approach is especially useful in qualitatively or semi-quantitatively determining the chemical composition, crystalline structure, and crystal orientations. To prepare specimens for the SEM, they are first fixed with Karnovsky's fixative, and then taken through a graded alcohol dehydration series. Once dehydrated, the specimens are placed in a critical point dryer, and then in a gold coater. After the gold coating is complete, the specimens are ready to be viewed on the SEM. Images may be scanned on a digital imaging system by computer enhancement, or polaroid pictures may be taken using an attached camera. The samples are prepared at different thicknesses of 0.1 cm, 0.3 cm, and 0.5 cm and the morphology of surfaces observed at an accelerating voltage of 2 kV at room temperature. The results are at the form of black and white images with our interpretation of their meaning.

3 Results and Discussion

In this experimental study, flax and glass fibers reinforced hybrid epoxy composites were fabricated and their mechanical properties are evaluated and the results are compared with values obtained by using ANSYS 12.0.

3.1 Tensile Strength Analysis

3.1.1 Experimental Result Analysis

The typical load vs. displacement curve generated directly from the universal testing machine during tensile loading is presented in Fig. 3. From the figure it can be observed that there is a slight variation in the load up to the displacement of 8 mm in the load vs. displacement curve. This is because

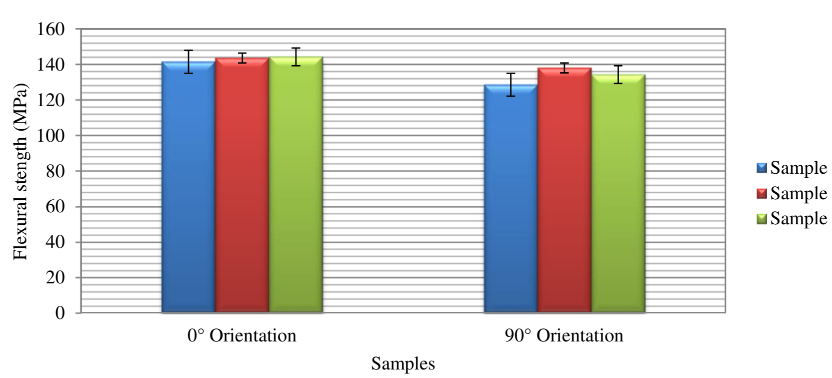


Fig. 7 Experimental flexural strength comparison

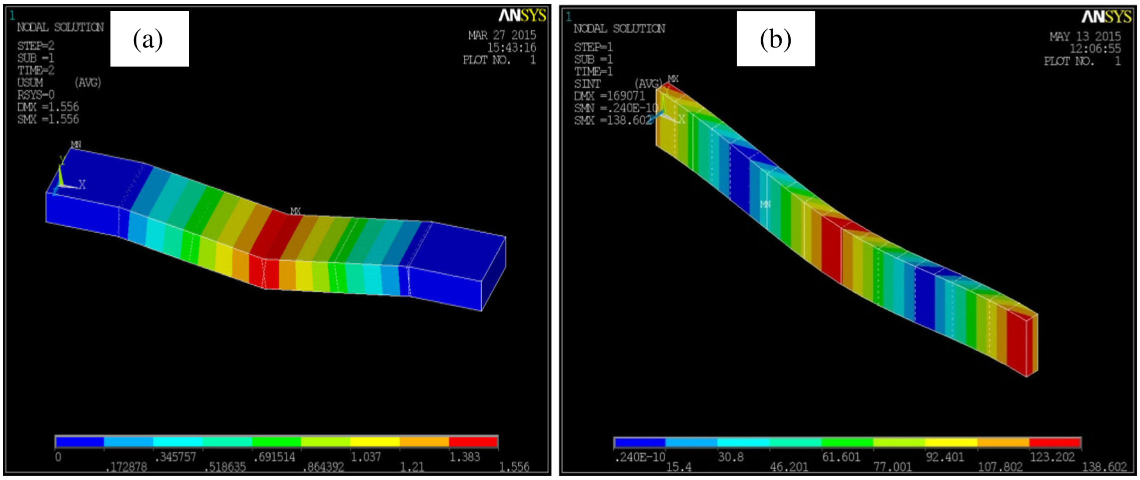


Fig. 8 FEA simulation plots of flexural test specimen with (**a**) 0° fiber orientation and (**b**) 90° fiber orientation

of the initial displacement in the specimen due to the applied load. After that there is the drastic increase in the displacement when the applied load increases and there is a sudden decrease in the curve after the material breaks. The tensile strength comparison of the composites is presented in Fig. 4. The figure reveals that the tensile strength of the 0° fiber orientation composites is greater than the 90° fiber orientation composite samples. This may be due to the load acting along the direction of fiber orientation. As expected, the tensile strength of the hybrid composite laminate is slightly lower than that of pure glass and comparable with glass-flax fibers reinforced composite laminates which already exist [23, 29, 36].

3.1.2 Analysis of Tensile Strength by Using FEA

The FEA simulation plot for the tensile test specimen is presented in Fig. 5. The simulated stress distribution for tensile properties of flax-glass fiber hybrid composites was obtained under different loading conditions. From the plots it is observed that the 0° fiber orientation specimen can withstand the maximum tensile strength of 83.882 MPa and the 90° fiber orientation composite can hold the maximum tensile strength of 80.204 MPa. This is located approximately at the middle portion of the specimen where the maximum stress occurs which is observed from Fig. 5a and b. Results from tensile tests indicated that the composites are very brittle but exhibited linear deformation in their elastic state. It is found that the results from FEA analysis are very close to the experimental results.

3.2 Flexural Strength Analysis

3.2.1 Experimental Result Analysis

The typical load vs. displacement curve generated directly from the universal testing machine during flexural loading is presented in Fig. 6. From the figure it can be observed that there is a gradual increase in the displacement when the applied load is increasing and there is a sudden decrease in the curve after the material breaks. There are some variations in the curve; this is due to void formation inside the composite laminate, air bubbles formed between the layers and insufficient bonding between the fiber and the matrix. The flexural strength comparison of the composites is presented in Fig. 7. The figure reveals that the flexural strength

Fig. 9 Experimental impact strength comparison

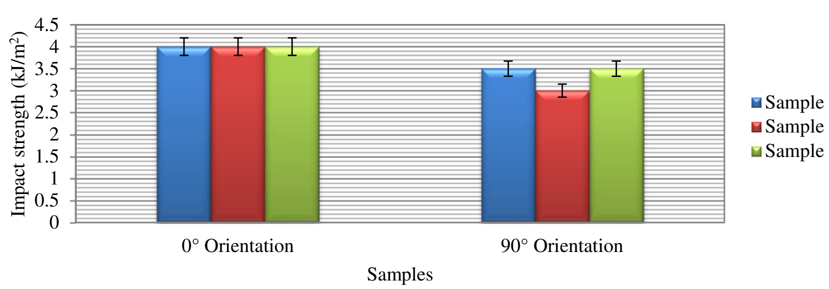


Table 3 Experimental and ANSYS 12.0 predicted results of the flax-glass fiber reinforced hybrid composite samples

Fiber orientation (Deg.)	Experimental/ ANSYS 12.0.	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (kJ/m^2)
0	Experimental	82.71	143.99	4
	ANSYS 12.0.	83.882	155.60	5.42
90	Experimental	75.64	134.86	3.99
	ANSYS 12.0.	80.204	138.602	3.13

of the 0° and 90° fiber orientation composite samples are performing almost at the same level, this is due to the loading acting perpendicular to the direction of fiber orientation. Therefore fiber orientation has not much influence on the flexural properties. As expected, the flexural strength of the hybrid composite laminate is slightly lower than that of the glass/flax fiber reinforced the hybrid composite laminate with more layers [23].

3.2.2 Analysis of Flexural Strength by Using FEA

Figure 8 shows the FEA simulation result plots of the sample subjected to flexural loading. The maximum flexural stress acting on the 0° fiber orientation specimen is 155.6 MPa which is located at the middle portion of the specimen where the maximum stress occurs as shown in Fig. 8a. From Fig. 8b, it is found that the maximum flexural stress acting on the 90° fiber orientation composite specimen is 138.602 MPa, which is also located at the middle portion of the specimen. The result from the flexural test further indicated that the composites are very brittle but exhibited linear deformation in the elastic state. It is also observed that the results obtained from FEA are very close to the experimental results.

3.3 Impact Strength Analysis

3.3.1 Experimental Result Analysis

The experimental impact strength comparison of the composites is presented in Fig. 9. From the results, it is observed that flax-glass fiber composites with 0° fiber orientation have more impact strength than 90° fiber orientation composites. It can be seen that for the two types of hybrid composite, their absorbed energies are slightly less than that of the published results [31]. The energy absorbed by the hybrid composite materials is low when compared with the results obtained by [23].

3.3.2 Analysis of Impact Strength by Using FEA

Figure 10 shows the FEA simulation result plots of the samples subjected to impact loading. The simulated strain energy distribution for impact properties of the hybrid composites was obtained under different loading conditions. The maximum strain energy observed on the 0° fiber orientation specimen is 5.42 kJ/m^2 as located at the middle of the specimen where the maximum stress occurs as shown in Fig. 10a. The maximum strain energy observed on the 90° fiber orientation

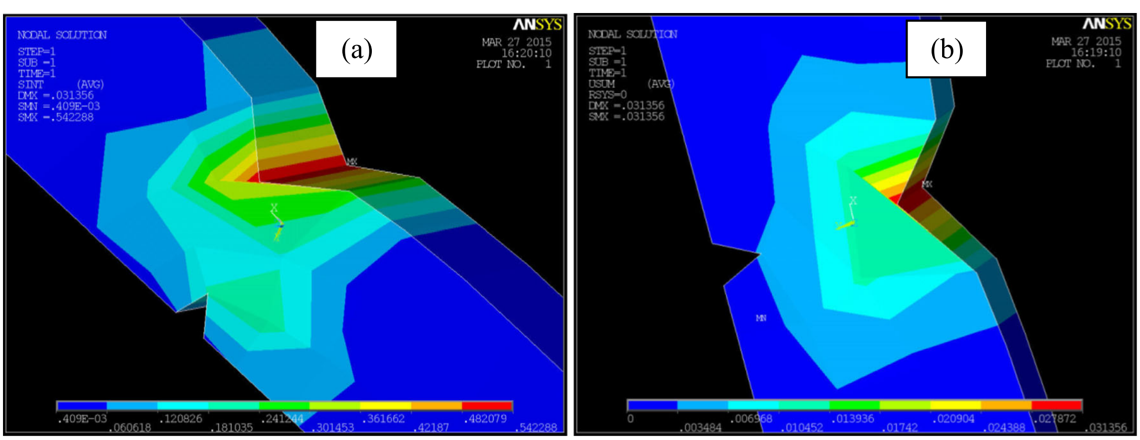


Fig. 10 Strain energy distribution of impact test specimen with (**a**) 0° fiber orientation and (**b**) 90° fiber orientation

specimen is 3.13 kJ/m^2 which is also located at the middle of the specimen as shown in Fig. 10b. Results from impact tests indicated that the composites are very brittle but exhibited linear deformation in their elastic state. It is also found that the FEA analysis results are very close to the experimental results

3.4 Comparison of Experimental and Numerical Results

Table 3 shows the experimental and finite element model predicted results related to the mechanical properties of the flax-glass fiber reinforced hybrid composites. The comparison between the experimental and numerical results of mechanical properties is presented in Fig. 11. From the figures it is clearly observed that the experimental values are slightly lower than the numerical value for tensile and flexural strengths. Whereas the numerical value for impact strength of the composites with 90° fiber orientation is lower than that of the experimental one. From this it has been concluded that the experimental strengths for all the composite samples are lower than that of the strengths predicted from numerical analysis. This is because of the void formation inside the laminate, uneven distribution of the resin, uniformity in fiber layer etc.

3.5 Morphological Property Analysis

Morphological property analysis has been carried out to study the interfacial characteristics, structure of the fractured surfaces due to mechanical loading, fiber orientation etc. Improvements in strength by hybridizing flax and glass fibers significantly depended on the fiber bridging between glass fibers and the flax fibers which was mainly caused by the structure and surface roughness of the flax fiber compared to the glass fibers, and was explained through SEM images [29]. The rough surface of the flax fiber and the fiber structure played vital roles on the adhesion between flax and glass fiber plies. The SEM studies of natural and glass fibers reinforced hybrid composites has been observed by various researchers [9–12, 37]. From their studies, they mainly observed the quality of the fractured surface, method of fiber breakage, structure of the fractured fiber, fiber and matrix interface etc. The SEM micrographs of the flax-glass fiber reinforced composite samples subjected to mechanical testing is presented in Fig. 12. The images clearly show the orientation of flax-glass fibers, the general arrangement of fibers and the distribution of resin into the reinforcements. Fiber pullouts are the predominant mode of failure in the case of 90° fiber orientation composite samples. The images

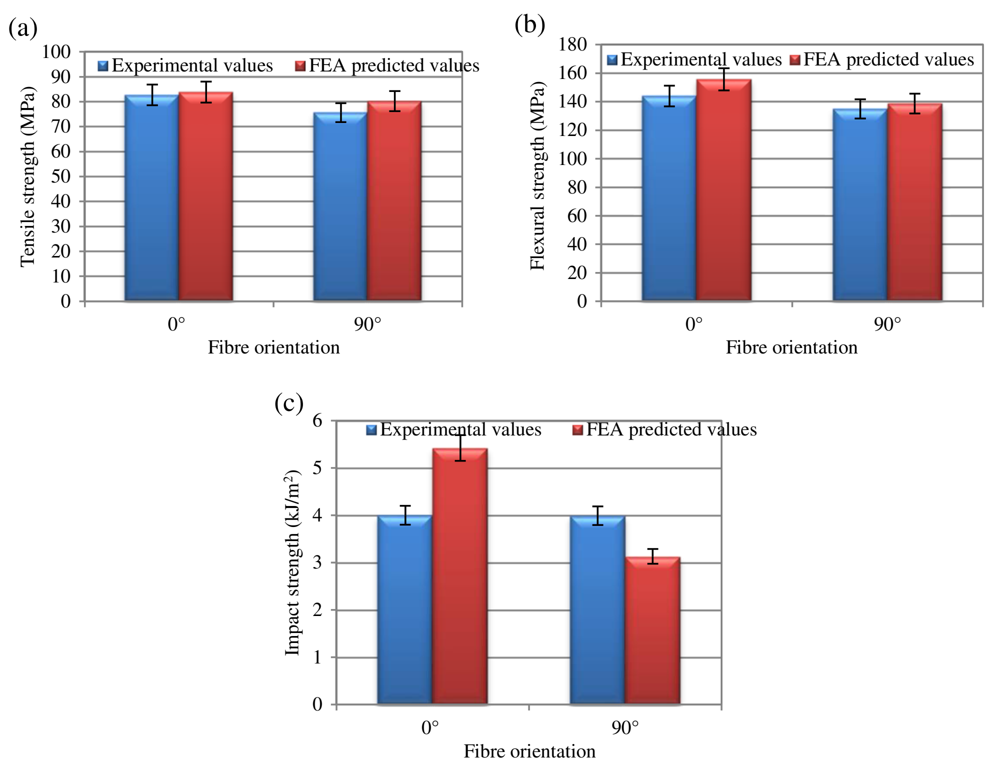


Fig. 11 Comparison between experimental and numerical results for (**a**) tensile testing, (**b**) flexural testing and (**c**) impact testing

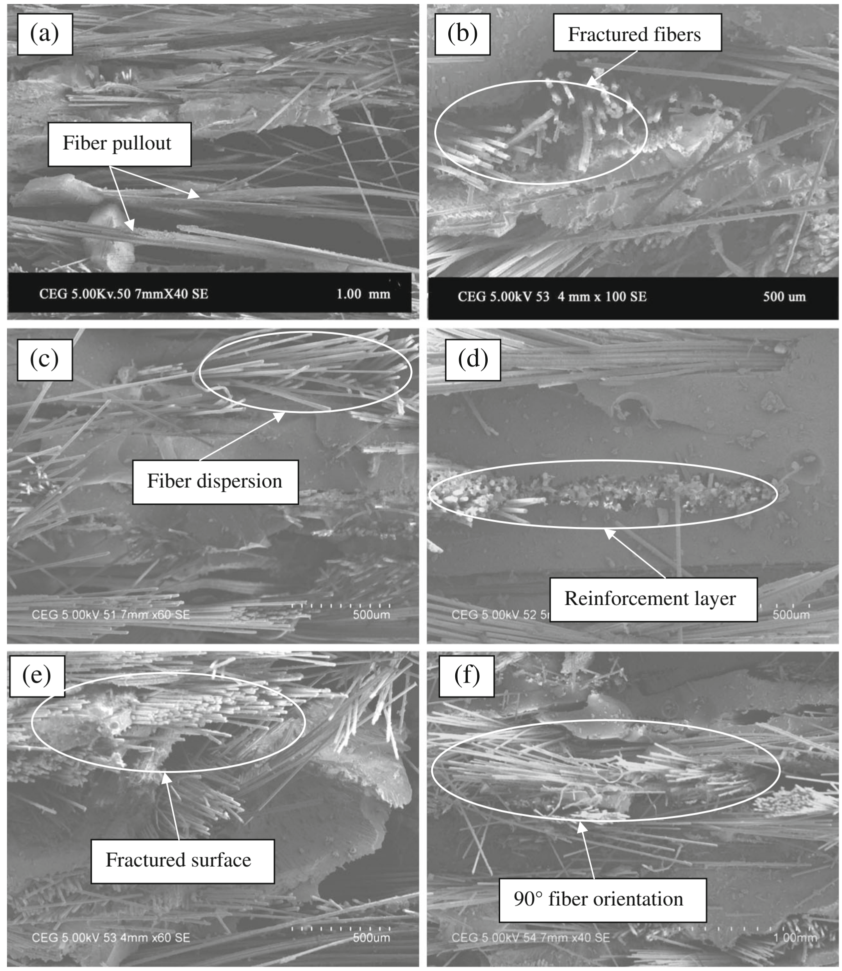


Fig. 12 SEM micrographs for flax-glass fibers reinforced composite specimens subjected to (**a**) tensile loading (0° orientation), (**b**) tensile loading (90° orientation), (**c**) flexural loading (0° orientation), (**d**) flexural loading (90° orientation), (**e**) impact loading (0° orientation) and (**f**) impact loading (90° orientation)

are well correlated and a similar pattern with the morphology analysis of plant fiber reinforced composites was done by Li et al. [38].

4 Conclusion

In this experimental study, the flax-glass fibers reinforced hybrid composites have been prepared with two different fiber orientations of 0° and 90°. The mechanical properties of these composites such as tensile strength, flexural strength and impact strength have been evaluated. The FEA analysis has been done to validate the results by using the simulation software ANSYS 12.0. The SEM analysis is carried out to observe the interfacial characteristics and internal surface of the fractured specimen. From the results, the following conclusions have been arrived at:

- The composites with the 0° fiber orientation can hold the maximum tensile strength of 82.71 MPa, flexural strength of 143.99 MPa, and impact strength of 4 kJ/m^2.
- The composites with 90° fiber orientation can with stand the maximum tensile strength of 75.64 MPa, flexural strength of 134.86 MPa, and impact strength of 3.99 kJ/m^2.
- According to the fiber orientation, 0° orientation composite samples perform better than the 90° fiber orientation composite samples.
- The simulated stress distribution for mechanical properties of these composites under different loading conditions was obtained by using ANSYS 12.0.
- It was found that the FEA model predicted results are very close to the experimental values.
- From the SEM analysis, the interfacial relationship between the fiber and matrix, orientation of fiber, fiber dispersion into the matrix and the internal cracks of the fractured surfaces are clearly observed.
- This study provides evidence that the ability of flax fibers can be tailored by a proper hybridization with glass fibers in order to find a suitable cost-performance balance, meanwhile reducing the environmental impact of the material.

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