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Investigation of Tensile Characteristics of an Epoxy Matrix Composite with Uni-Directional and Hybrid Tissue Natural Hemp Fibers

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ABSTRACT

Using natural hemp fibers to reinforce the tensile characteristics of polymer matrix composites is investigated in this article. The fibers were applied to the epoxy matrix in unidirectional and hybrid tissue forms. After preparation of standard tensile stress test specimens via manual layup, the standard tensile test was done. Young's modulus, ultimate tensile stress, and the amount of absorbed energy before fracture were obtained experimentally. A comparison is performed with respect to fibers posture. In all cases, the tissue fiber samples gave a higher strength in comparison with the unidirectional laminated fibers. An analytical model is finally presented to estimate the elasticity modulus of the tissue reinforced composites.

1. Introduction

Technically, the fiber reinforced composites are the most important composites in various applications. These composites are divided into two categories including the short fiber reinforced and the long fiber reinforced composites. The fibers are supposed to bear the imposed stress and the matrix is supposed to hold the fibers in place and carry the loads into the fibers. Beside the mechanical properties of the fibers, the posture of the fibers with respect to the direction of imposed loads is another effective factor influencing the tensile strength of the composite. In addition, in order to make efficient composite materials, it is necessary to achieve the best binding condition between fiber and matrix.

In the recent years, according to the environmental problems, the usage of recyclable or natural fibers for making the polymer matrix composites is deeply interested. Some natural fibers such as hemp and linen are known as adoptable fibers for reinforcement of thermoset polymers. The most interesting characteristics of these fibers are inexpensiveness, availability and recyclability. Recent investigations indicate that the natural fibers in comparison with the glass fibers could be used with the same performance and lower environmental impacts [1].

There are extensive studies conducted on applications and characteristics of polymer matrix composites with natural fibers as the state-of-the-art review about hybrid composites containing cellulosic/synthetic fibers for polymer reinforcement presented by Jawaid and Abdul Khalil [2]. Green composites with cellulosic fibers and natural resins

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were also reviewed focusing on development of cellulosic fibers in industrial applications [3,4].

The research efforts for processing the natural fibers to gain the epoxy based green composites were further discussed by Mittal et al. [5]. In addition, some different natural fibers were reviewed with respect to their mechanical properties and their applications in various industries by Alkabir et al. [6]. An overall review of the factors affecting the mechanical performance of natural fiber composites and the achieved capabilities and applications was also presented by Pickering et al. [7].

The ease of production process and the resulting properties are the main problems in using the natural fibers which was investigated by Bledzki and Gassan [8]. In their work, ordinary processing methods were discussed for manufacturing the natural fiber reinforced composites with high physical and mechanical properties.

The mechanical properties of natural fiber reinforced polymer composites could be improved by increasing the adhesion between the fibers and matrix. Increasing the adhesion value can be provided with chemical approaches as it was performed using silane coupling agent by Franco and González [9], and further studied by Xie et al. [10]. Another chemical approach for enhancement of natural fibers using sulfonic acid methodologies with lower environmental impactis was suggested by George and Bressler [11].

The placement of the fibers in the matrix can also affect the mechanical properties of the composite e. g. the mechanical properties of braided yarn fabric composites were compared with the conventional yarn fabric composite and random oriented intimately mixed short fiber composites by Pitchaimaniand Rajesh [12]. It wa shown that because of using braided yarn fabric reinforcement, the mechanical properties would be improved significantly.

Different natural fibers are available in every place on earth. A wide variety of natural fibers have been proposed and studied for reinforcement of the polymer matrix composites so far e. g. sisal, banana, jowar, bamboo, flax, coir, palm, ricinuscommunis and other fibers [13-18].

In order to investigate the mechanical performance of the natural fiber reinforced polymer composites, properties of such composites are widely studied by the researchers. A review on the tensile properties of natural fiber reinforced polymer composites for both thermoplastic and thermoset resin was presented by Ku et al. [19]. The elastic and post collapse compressive behavior of the natural fiber composites was studied by Węcławski et al. [20] for civil engineering applications. Adding hemp fibers were also investigated for improving the thermo-mechanical behaviour of gypsum plasters by Iucolano et al. [21]. Furthermore, for civil engineering purposes, Çomak et al. [22] studied the effect of adding hemp fibers on improving the general characteristics of cement based mortar.

Dynamic and mechanical properties of composites for hybrid and nano natural fiber reinforced polymer composites were reviewed by Saba et al. [23] providing a perfect dataset to explore the suitable materials for industrial applications.

Since the vibrational behaviors of the natural fiber composites are important for their applications, the vibrational characteristics of these materials have widely been studied. As a specimen, Rajesh et al. [24] studied the free vibrational characteristics of a natural fiber reinforced hybrid polymer composite beam with chemically prepared short and random banana/sisal fibers. Furthermore, the vibration and damping behavior of flax fiber reinforced composites with an interleaved natural viscoelastic layer was studied by Daoud et al. [25]. In their work, a parametric study was carried out using finite element analysis to investigate the effects of flax fibre direction, thickness, and Young's modulus of the natural viscoelastic layer. The effect of axial compression load on buckling and free vibration characteristics of natural fiber polymer composite beam was also analyzed experimentally by Rajesh et al. [26].

The usability of natural fiber composites for various applications dominantly depends on their tribological behavior. A general state of the art review on the tribologicalbehavior of natural fiber reinforced polymer composites was presented by Omrani et al. [27]. Based on the presented results in their work, the natural composites seem to have good potential to be employed in variety of applications e. g. due to the fatigue characteristics, natural fiber composites made of high density polyethylene and short birch fibers may replace high-performance thermoplastics [28].

Recent investigations on the microscopic structure and structural defects of the natural fibers give some encouraging results about the possibility of achieving high strength through use of natural fibers. Through a statistical investigation, conducted by Torres et al. [29], it was found that the mechanical properties of the long natural fiber laminates are similar to that of carbon fiber laminates.

In recent years, application of natural fiber reinforced composites in building structures, automobile parts and marine industries indicates the capabilities of these composites. As an example, a comprehensive experimental research on the physical and mechanical performance of natural fibers including flax, hemp, jute, sisal and coir fibers for the strengthening of masonry constructions was performed by Codispoti et al. [30]. Properties of natural fiber cement materials containing coconut coir and oil palm fibers for residential building applications was also studied by Lertwattanaruk and Suntijitto [31]. In order to improve the durability of sisal fiber in cement composites, the usage of rice husk ash was studied by Wei and Meyer [32]. In addition, Grubeša et al. [33] conducted a study investigating the use of hemp fibers for improving the fire resistance of concrete.

Topographical investigations of the hemp fiber sub structure show that these fibers are made of cellulose fibers reinforced via a half cellulose and half lignin erratic tissue. The mentioned half cellulose tissue has a set of scattered tiny fibers in it.

Advertent studies on hemp fibers indicate that each of these fibers is made of multiple sets of ten cells in a primary texture. Each primary texture has a multi-disciplinary structure. Every cell is consisted of three main parts including primary wall, secondary wall and the cell cavity (lumen). The tissue cells are also connected to each other via a middle layer. Every wall is composed of some tissue layers connected to each other via lignin. In the secondary wall, tiny cellulose tissues are arranged in spiral form connected to the half cellulose tissue. The constitutive layers of a hemp fiber are presented in Fig 1. A comprehensive study including experimental, analytical and numerical investigation of hemp fiber yarns was performed by Antony et al. [34] characterizing the properties and predicting the mechanical behavior of hemp fiber yarns under tensile loading. Dayo et al. [35] also conducted a study on mechanical, thermal and water absorption properties of hemp fiber/polybenzoxazine based green composites under influence of different chemical treatments.

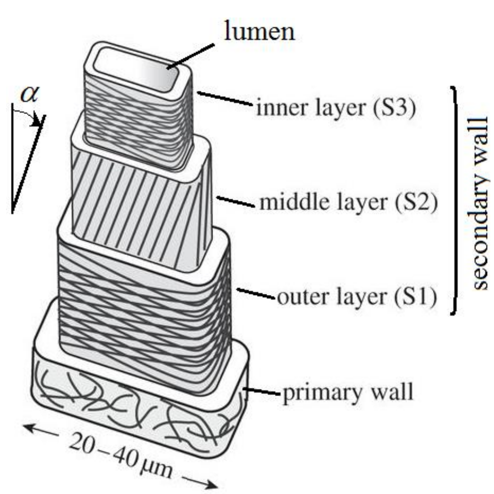

Fig. 1. Constituent layers of a hemp fiber

Since using the fibers for strengthening of polymer matrix composites is mainly done for increasing the tensile strength of the polymer resins, it is so important to investigate the tensile properties of such composites. Thus, in the present study, the effect of using natural fibers is investigated noting the tensile behavior of composite. In order to have a better assessment of the effect of fibers on the tensile properties of the composite, due to their orientation and distribution, the fiber volume fraction of all samples are set to be equal. Furthermore, because of the wide industrial applications of polyester fibers, hemp fibers are used beside the polyester fibers with different posture conditions, for making of test samples. This situation makes it possible to investigate the effect of fibers posture condition on tensile properties of the composite samples. Tensile tests are applied and the fracture behaviour of the composite is studied properly. Hemp and polyester fibers are used for polymer reinforcement as unidirectional laminates and woven tissue. The results show a much better performance for the woven tissue rather than the unidirectional laminated fibers with respect to the tensile properties of the composite. At last, an analytical formulation is derived for the first time to predict the mechanical properties such as modulus of elasticity for tissue fibre composites.

2. Methodology of the Experiments

At the first step, the composite structure would be introduced. Also, the specimen fabrication process and the experimental setup are presented as the methodology.

2.1. Materials

In this section, the materials utilized as fiber and matrix in the composite structure are introduced. The fibers are consisted of hemp and polyester fibers and an epoxy resin is used as the matrix. Material properties are described in the following.

2.1.1. Fibers

In this article, polyester and natural hemp fibers with equal diameters of 1 mm are applied for matrix reinforcement. The fibers are designed in the bulk as simple unidirectional laminate and simple hybrid tissues with 90 degrees angle between warp and woof. In the simple laminate case, for each layer only one type of fiber is put perpendicular to the beneath layer. The appearance of the used fibers is shown in Figs. 2 and 3. In addition, the physical and mechanical properties of hemp and polyester fibers are presented in Table 1.

Fig. 2. Appearance of the non-woven hemp fibers

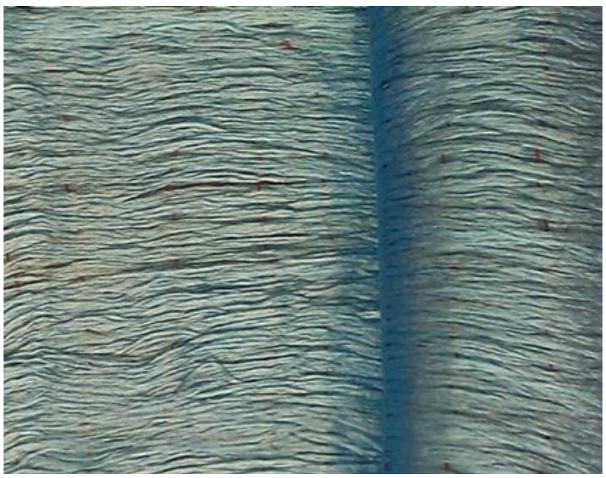

Fig. 3. Appearance of the non-woven polyester fibers

Table 1. Physical and mechanical properties of the used fibers

Parameter	Units	Hemp	Polyester
Density	gr/cm^3	1.2	1.3
Maximum strain per-	%	2	3
Tensile strength	MN/Tex	135	278
Mass per meter of	gr	0.903	1.011
Modulus of elasticity	GPa	3.2	3.6

2.1.2. The Matrix

An epoxy resin with commercial name of Shell Epikote 828 and density of 1.16 kg/Lit was used as the bulk material with an F205 hardener with density of 1.04 kg/Lit (Based on the standard of ASTM D4052). Due to the instructions of the resin producer company, the epoxy resin and the hardener are mixed with ratio of 4/1 and tempered up to 80^{o}C to obtain the desirable properties. The modulus of elasticity for the resulted bulk material is experimentally obtained and was equal to 1.02 GPa.

Epoxy resins in comparison to the other thermo set resins, have little shrinkage during the tempering process that causes less residual stress after tempering. Less residual stress leads to more accurate results in tensile test. Therefore, the effect of fibers on tensile behavior of the composite could be observed more accurately. The resin strength directly affects the strength of the composite, so it is necessary to compare the strength of the pure resin with that of the fiber reinforced resin. In order to perform such comparison, mechanical test was applied to the utilized epoxy resin. The test standards and results are shown in Table 2.

2.2. Preparing the Specimens

The process of the specimen preparation is explained at the following. The fibers were put into the matrix as woven tissue or laminates, based on ASTM standards.

2.2.1. Weaving the Fibers

As previously stated, in order to investigate the effect of fiber posture on the tensile properties of the composite, the fibers were put into the matrix as woven tissue and laminates. The tissue was woven using a traditional weaver machine in hybrid form. The hemp fibers were put on the machine as warp and the polyester fibers were put as woof. Woof fibers were passed through the warp fibers using a shuttle to produce the reinforcing hybrid tissue. The utilized weaver machine and the woven hybrid tissue with its pattern are shown in Fig. 4.

Table 2. The test standards and results for Shell Epikote 828

Parameter	Units	Value	Standard
Compressive strength	gr/cm^2	960	ASTM
Compressive modulus	gr/cm^2	9340	ASTM
Bending strength	gr/cm^2	940	ASTM
Bending modulus	gr/cm^2	36210	ASTM
Tensile strength	gr/cm^2	731	ASTM
Tensile modulus	gr/cm^2	27622	ASTM

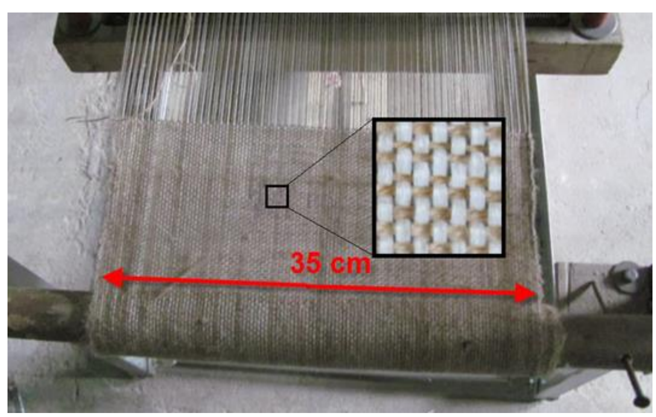

Fig. 4. The weaver machine weaving the hybrid tissue with the pattern

2.2.2. Tensile Test Specimens

In order to investigate the tensile characteristics of the composite, some specimens were made by hand lay-up method based on ASTM D3039 standard. In order to fabricate the hemp-polyester tissue reinforced samples, firstly, a woven hemp tissue was flattened over a waxed glass mould to be coated with resin. Resin and hardener were mixed together and be heated up to 80^{o}C, then they were poured into the mould to cover the tissue equably (Fig. 5-a). The operation was repeated putting another tissue on the previous layer and pouring resin into the mould. The produced composite plate that reinforced with two layers of the tissue was then picked up from the waxed mould and cut into the desired dimensions using a circular saw (Fig. 5-b). In fabrication of laminate samples, instead of woven tissues unidirectional sets of fibers were flattened over the mould. Therefore, there were four layers of hemp and polyester fibers on each other with 0 and 90 degrees angles.

The tensile test samples due to the ASTM D3039 standard should have 25 centimeters long and 2 centimeters width. Noting the instructions of the respective standard, the early made samples as trimmed and small 2×2 cm aluminium tabs were fixed to the ends of the specimens for mounting them in the fixtures of the tensile test devise to achieve a better accuracy in experiments. The aluminium tabs were fastened to the specimens under a hand mechanical press using the matrix resin as glue. The appearance and dimendions of specimens is shown in Fig. 6. The volume fraction of fibers for each b and p type specimens were set to be 25% and 30%, respectively. The utilized fibers in both b and p specimens were hemp and polyester with equal ratios. The b and p specimens were also different in posture of the fibers, as the fibers in b samples were set as a regular unidirectional laminate, but in p samples the fibers were applied as a hybrid woven tissue.

It should be noted that these volume fractions seem to be too high causing the composite to be too brittle. However, because of the considerable amount of trapped air among the fibers, these volume fractions were not much high. The mass fraction of the fibers in composite structures in all cases did not exceed 5%.

2.3. Instrumentations and Methodology of the Experiment

A multi-purpose devise, with commercial name of Hounsfield H25KS, was used to experimentally obtain the mechanical properties of the samples. Altering the fixtures of this devise made it possible to perform bending, tensile, compressive and shearing tests.

The tensile test was performed with the specified conditions of ASTM D3039 standard parameters that are tabulated in Table 3. In order to perform the tensile test, the proper fixture must be installed on the universal devise and the specimens are fixed in the fixtures via the fastened aluminum tabs. Because of the importance of ultimate strain measurement, the tensile test was followed up to the fracture point of the samples keeping the above mentioned settings. Eventually, the stress-strain curves were plotted for every sample and the experimentally obtained data from the tensile test were recorded.

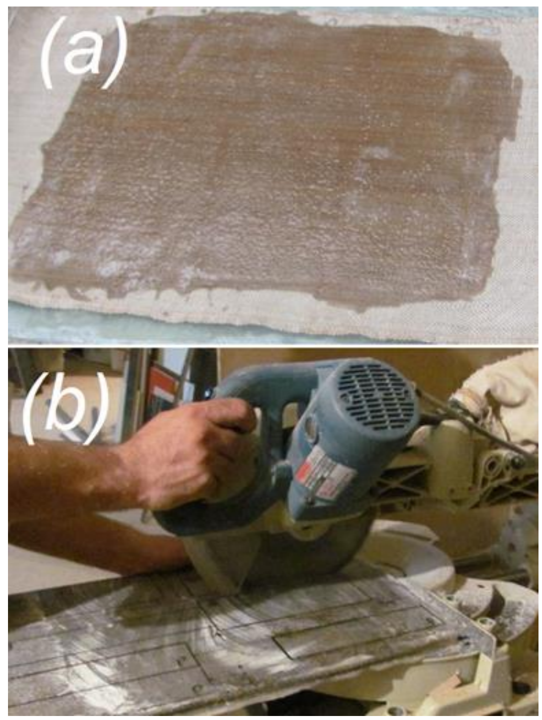

Fig. 5. Preparation of tensile test specimens a) coating tissue with resin b) cutting the composite plates

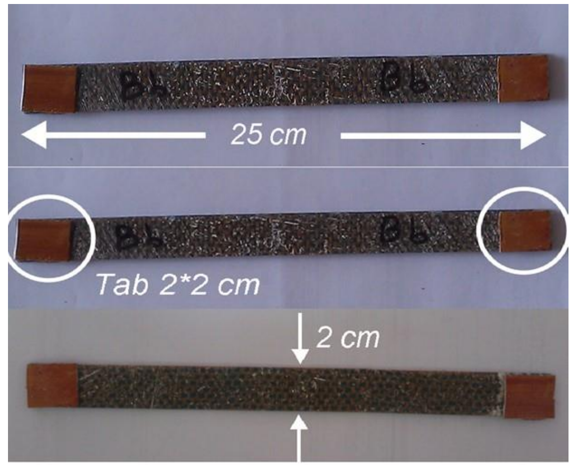

Fig. 6. The appearance and dimensions of some specimens

Table 3. The proposed parameters for tensile test due to the ASTM D3039 standard

Size parameter	Value
Tab angle (degree)	7 to 9
Tab thickness (mm)	1.5
Tab length (mm)	56
Thickness (mm)	3.5
Length (mm)	250
Width (mm)	20

3. Methodology of the Experiments

The experimental results including stress-strain diagrams, ultimate strength, fracture energy, and fracture modes of the samples are presented in this section.

3.1. Stress-Strain Diagrams of the Samples

Stress- strain diagrams of b and p specimens are respectively shown in Figs. 7 and 8. In order to perform a comparison between p and b specimens, the average of stress-strain diagrams in the elastic range for p and b specimens were calculated and plotted which can be seen in Fig 9. The slope of stress- strain diagram in the elastic range was taken as Young's modulus obtained via Eq. 1.

$$E_T = \Delta\sigma/\Delta\varepsilon \quad (1)$$

where E_T is the tensile Young's modulus in MPa, $\Delta\sigma$ is the difference of stress between two successive points on the elastic range of the stress-strain diagram in MPa and $\Delta\varepsilon$ is the difference of strains between those points.

In this research, the Young's modulus was set as a benchmark of stiffness for each group of samples. The obtained Young's modulus for *b* and *p* specimens is equal to 1.42 and 2.36 GPa respectively.

It was expected to have an increase in Young's modulus of composite materials by increasing the amount of fibers, but in this case, the increase is about 66% that is much more sensible. This extra increase in Young's modulus of p samples rather than b samples is because of using fibers as a woven tissue.

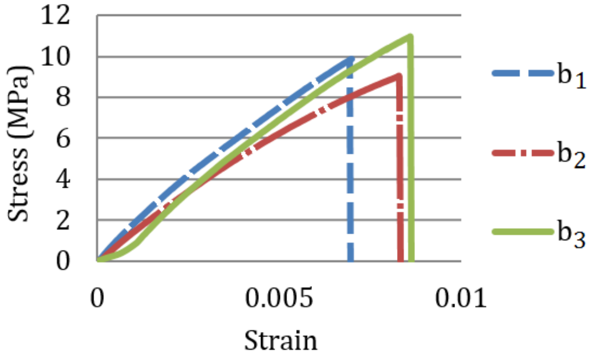

Fig. 7. Stress-strain diagrams of b samples

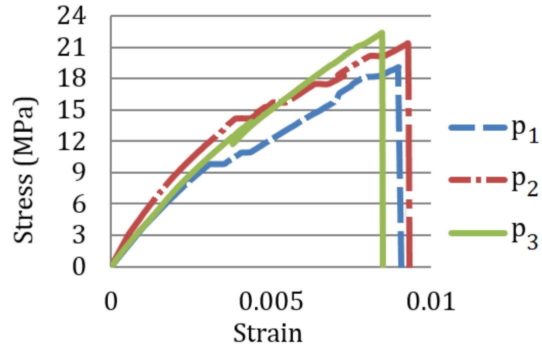

Fig. 8. Stress-strain diagrams of p samples

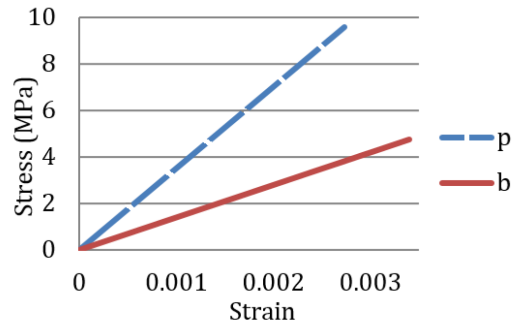

Fig. 9. A comparison between p and b samples in the elastic range

Having a better comparison, the modulus of elasticity of each set of specimens was devided to the average mass density so as to obtain the specific modulus of elasticity for each specimen. Fig. 10 gives a comparison between specific modulus of elasticity of b and p samples.

As it is seen in Fig. 10, the tissue samples have about 88% higher specific modulus of elasticity rather than the uni-directional samples. The reason is binding of fibers in tissue samples during the tensile test which causes the lateral fibers to directly strengthen the tissue in the tensile direction, beside the longitudinal fibers that are in the tensile direction. Whilst, in laminate samples only the longitudinal fibers can directly affect the strength of the material and the lateral fibers have no role in tensile strength.

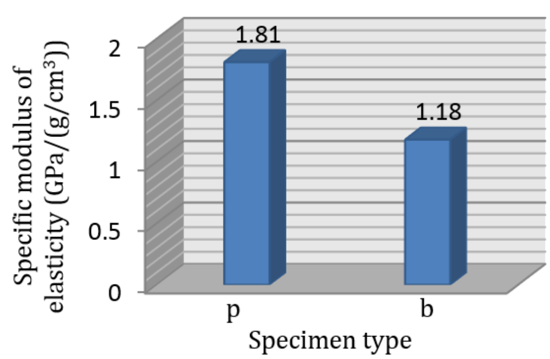

Fig. 10. Specific modulus of elasticity for p and b samples

3.2. Ultimate Strength

The stress value in the highest point on the stress-strain diagram for a material represents the ultimate strength value. Noting the experimental stress-strain diagrams for each type of specimens, the average of achieved ultimate strengths was taken as the ultimate strength of that type of specimens. The ultimate strength and the average ultimate strength values for tissue and uni directional specimens are respectively listed in Tables 4 and 5.

Noting the achieved averages, the tissue specimens gave about 106% improvement in the ultimate strength in comparison with the laminate specimens. The reason is that, during the tensile test, some amount of the tensile energy should be offtaken to break down the intertexture of the warp and woof fibers. Furthermore, in the tissue samples, the inter layer surfaces, because of having a retiaryform, give a better contact surface in comparison with the laminate samples. A comparison between the ultimate strength of specimens is available in Fig 11.

3.3. Fracture Energy of the Samples

The fracture energy of the samples is an important mechanical property. The fracture energy was primarily calculated by obtaining the area under the stress-strain diagram before occurance of the ultimate stress that gives the fracture energy parameter in Jouls (J). The other approach was to obtain the area under the stress-strain diagram before the ultimate stress point that gives the fracture energy in Jouls per cubic centimeters (J/cm^3). This parameter is the so called break specific energy. The break specific energy gives the toughness and the balance of energy for loading and deformation of a material up to fracture.

In this section, having the experimentally obtained force-displacement diagrams, the stress-strain diagrams are derived and the fracture energy of the samples during the average of tensile deformation is calculated. The obtained averages of the fracture energy for the samples are available for comparison in Fig. 12.

Table 4. The ultimate strength of b samples

Type of specimen	b_1	b_2	b_3
Ultimate strength (MPa)	10.3956	9.0593	10.9746
The average		10.1431	

Table 5. The ultimate strength of p samples

Type of specimen	p_1	p_2	p_3
Ultimate strength (MPa)	18.9661	21.3831	22.3708
The average		20.9066	

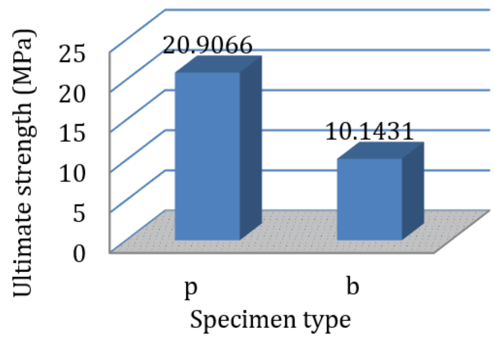

Fig. 11. Ultimate strength for p and b samples

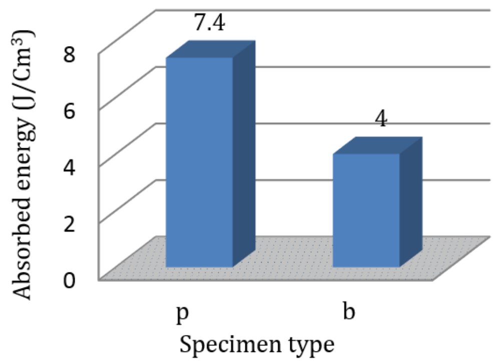

Fig. 12. The averages of the fracture energy for p and b samples

It can be seen that the fracture energy for tissue specimens is 85% higher than the laminate specimens. This is because of the amount of energy that consumed to tear down the tissue fibers. In the tissue samples, the frictional surfaces are larger than the laminated samples and overcoming this friction causes energy dissipation during the deformation.

3.4. Fracture Behaviour of the Composite

The fracture behaviour of the fabricated samples is discussed in this section noting the Scanning Electron Microscopy (SEM) micrograph of the fracture surfaces of the specimens.

The fracture modes of the composite are presented in Fig. 13 which shows the cracks in matrix, fiber rapture, fiber pull out, and debonding of matrix and composite. All regular fracture modes could be seen for the fabricated composite specimens.

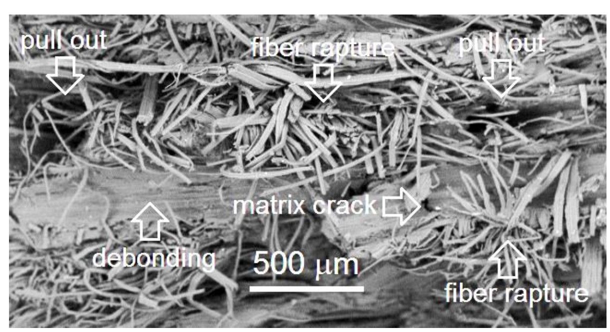

Fig. 13. The SEM micrograph of the broken composite surface

4. Analytical Formulation

In this section, the aim is to present a set of formulation to predict the mechanical properties of a hybrid tissue composite. There are some classical formulations to estimate the mechanical properties of uni-directional single layer composite laminates with respect to the volume fraction of fibers and mechanical properties of matrix and fibers as follows [36].

$$E_{c1} = v_f E_f + v_m E_m \quad (2)$$

Eq. 2 gives the Young's modulus for a unidirectional composite layer in direction of fibers (E_{c1}) based on mixtures law. Parameters E_f, v_f, E_m, and v_m, represent the modulus of elasticity and volume fraction for fibers and matrix repectively. It is obvious that $v_f + v_m = 1$. Index 1 deals with the direction of fibers which is called direction 1. For such composite layers, the Young's modulus in prependiclar direction of the fibers (E_{c2}) (also called direction 2) is obtained as follows:

$$1/E_{c2} = v_f/E_f + v_m/E_m \quad (3)$$

In order to extract the Young's modulus for a hybrid tissue composite, Fig. 14 shows that these composites are a hybrid of α fibers in direction x and β fibers in direction y. Directions x and y denote the global directions of the problem that are independent from direction of fibers.

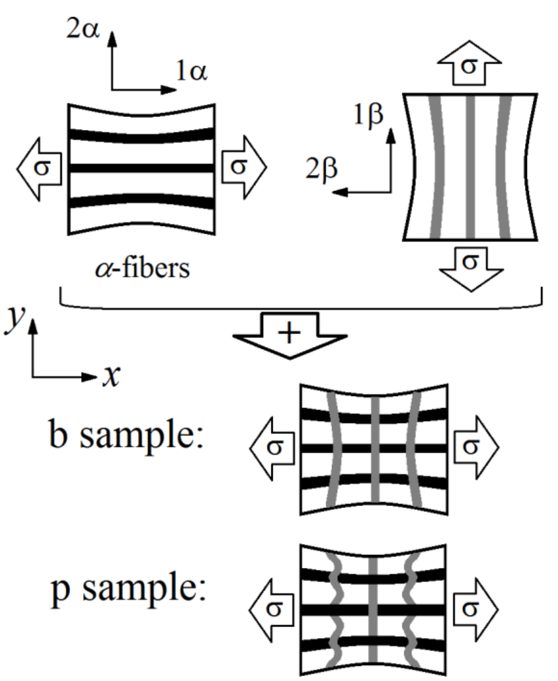

Fig. 14. The effect of fibers posture on matrix reinforcement

Based on classical models, β fibers (which are perpendicular to the tension direction) have no direct effect on tension, but experimental results for p samples in this study indicates their influence on tension. Therefore, the following equation is suggested to estimate the Young's modulus for a tissue composite in x and y directions (E_{xp} and E_{yp}).

$$E_{xp} = E_{1\alpha} + \delta E_{1\beta} \quad (4)$$

and

$$E_{yp} = \delta E_{1\alpha} + E_{1\beta} \quad (5)$$

in which, δ is the contribution of perpendicular fibers (β) which typically have a value between 0 and 1. Parameter δ depends on many conditions such as texture of tissue, quality of weaving, and cohesion among warp, woof and matrix. This parameter must be assigned experimentally and in this study, the value of $\delta = 0.7$ is suggested for the woven hybrid tissue. The values of $E_{1\alpha}$ and $E_{1\beta}$ are obtained as follow:

$$E_{1\alpha} = v_{f\alpha} E_{f\alpha} + (1 - v_{f\alpha}) E_m \quad (5)$$

and

$$E_{1\beta} = v_{f\beta} E_{f\beta} + (1 - v_{f\beta}) E_m \quad (6)$$

Note that, $1 - v_{f\alpha}$ and $1 - v_{f\beta}$ are used instead of v_m that is logically equal to $1 - v_{f\alpha} - v_{f\beta}$. This is because of avoiding loss of material in the structure.

For a p specimen with 30% fiber where $v_{f\alpha} = v_{f\beta} = 0.15$, it is obtained that $E_{1\alpha} = 1.41$, and $E_{1\beta} = 1.35$ GPa. Therefore, putting $\delta = 0.7$ in Eq. 4, Young's modulus for a tissue composite is obtained as E_{xp} =2.355 GPa that, having about 2% absolute error, has a good coincidence with the experimental result ($E_{xp} = 2.36$ GPa).

Similarly, the following equations are suggested to obtain the Poisson's ratio of a tissue composite (PR_{xyp} and PR_{yxp}) with respect to poisson ratios of α and β fiber layers.

$$1/PR_{xyp} = 1/PR_{12\alpha} + \delta/PR_{21\beta} \quad (7)$$

and

$$1/PR_{yxp} = \delta/PR_{21\alpha} + 1/PR_{12\beta} \quad (8)$$

5. Conclusions

In this article, two different types of specimens made by hybrid tissue and laminates of hemp and polyester fibers were investigated. Tensile tests were applied to both types of specimens. The results showed that using the fibers as a woven tissue would provide a great advantage in mechanical properties of the composite rather than using them as laminates. For example, having a tissue reinforced composite with just 5% higher volume fraction of fibers rather than a laminated composite, 66% increase in Young's modulus, 88% increase in specific modulus of elasticity, 106% improvement in ultimate tensile stress, and 85% improvement in amount of absorbed energy were observed.

In spite of classical theories on laminate composites, it could be seen that using the orthonormal fibers as a woven tissue can make them to be directly effective against both lateral and axial loads. Therefore, a novel mathematical formulation was proposed to estimate the Young's modulus of a tissue reinforced composite with 2% of absolute error. Another formulation was also proposed to estimate the Poisson's ratio of a tissue reinforced composite.

According to the obtained results from tensile tests, the mechanical properties for such composites might not be much more than the traditional composites, but a great advantage of using these composites is using natural fibers which are recyclable in the nature. Using stronger fibers like carbon fibers besides natural fibers could lead to higher mechanical properties.

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