J MATER RES TECHNOL. 2019;8(1):1308–1318

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Journal of Materials Research and Technology
www.jmrt.com.br

Original Article

Mechanical and moisture diffusion behaviour of hybrid Kevlar/*Cocos nucifera* sheath reinforced epoxy composites

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ARTICLE INFO

Article history:
Received 4 May 2018
Accepted 16 July 2018
Available online 9 November 2018

Keywords:
Hybrid composites
Laminated composites
Kevlar fibre
Cocos nucifera sheath
ANOVA

ABSTRACT

The aim of this research is partial replacement of plain woven Kevlar 29(K) with naturally woven cocous nucifera sheath (CS) waste. Laminated K/CS reinforced epoxy hybrid composites were fabricated by hand lay-up method followed by hot compression moulding with 105 °C temperature at 275 bar pressure for 1 h. The total fibre loading of the hybrid composite was maintained 45 wt.% and the ratio of Kevlar and *Cocous nucifera* sheath varies in weight fraction of 100/0, 75/25, 50/50, 25/75, and 0/100. Mechanical (tensile, flexural, impact), moisture diffusion and morphological behaviour of the laminated composites were evaluated. The results showed that the hybrid composites (75/25) declined the tensile strength by 19% compared to Kevlar fabric reinforced epoxy composites. But, the hybrid composites (75/25) exhibited highest flexural strength (175 MPa) and flexural modulus (18 GPa) than pure Kevlar reinforced epoxy composites. Moreover, the impact toughness of hybrid composites (86 kJ/m^2) at 75/25 wt.% showed good agreement with the pure Kevlar fabric reinforced polymer composites (90 kJ/m^2). From the moisture diffusion analysis, hybrid composites (75/25) exhibited better moisture resistance. Statistical analysis of the results has been carried out using one way-ANOVA (analysis of variance) and it shows that there is a statically significant difference between the obtained mechanical properties of the laminated composites. Morphology of the tensile fractured laminates showed the delamination's, matrix cracking and fibre/matrix adhesion. From the results, it has been concluded that naturally woven *Cocos nucifera* sheath has the potential to replace Kevlar fabric in the polymer composites exclusively for defence applications.

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https://doi.org/10.1016/j.jmrt.2018.07.023

1. Introduction

Now a days, fibre reinforced polymer (FRP) composites are widely used in aerospace, automobile, marine and defence applications because of their higher specific strength and stiffness [1]. Fabrics having outstanding mechanical properties are used in aerospace structures and in protective clothing. In particular polymer composites reinforced with carbon, Kevlar, glass, dyneema are used in ballistic applications [2]. Even though these synthetic fibres had higher mechanical properties, thermal resistance and corrosion resistance, they are not biodegradable and it affects the environment. Kevlar 29 fabrics are manufactured from petroleum based resources. Depletion of petroleum based resources and an increase in awareness towards utilization of eco-friendly manufacturing process and products, it is essential to find a sustainable replacement. According to Wambua et al. the following natural fibres can become an alternate materials to synthetic fibres such as kenaf, coir, jute, flax, etc. [3]. However, compared to synthetic fibre composites natural fibre composites exhibited lower mechanical strength [4] and poor moisture resistance [5].

Reddy et al. evaluated the mechanical and physical properties of naturally woven agro waste "*Cocos nucifera* sheath", and concluded that *Cocos nucifera* sheath is a suitable reinforcement with polymer matrix and for making green composites [6]. Yahaya et al. and Jawaid et al. proved that woven natural fibre composites have superior mechanical properties than unidirectional or chopped fibre based polymer composites [7,8].

Hybrid composites contains more than two discontinuous phases and one continuous phase. Continuous phase of the hybrid composite is matrix and the discontinuous phase is termed as reinforcement [9]. The main advantage of hybrid composites lie in the ability to combine the properties of their individual constituents, and it provides superior properties which cannot be obtained from the single fibre based polymer composites. Kumar et al. studied tensile properties of hybrid banana/*Cocos nucifera* sheath reinforced polymer composites and reported that hybridization increases the tensile strength [10]. Siva et al. evaluated the tensile strength of hybrid glass/*Cocos nucifera* sheath reinforced polyester composites with different fibre weight ratios and reported that hybrid composites showed higher tensile strength than pure glass fibre reinforced polyester composites [11]. Rajini et al. studied the mechanical properties of *Cocos nucifera* sheath/glass fibre reinforced nano clay modified polyester composites and they have suggested that the *Cocos nucifera* sheath can replace the glass fibre [12,13]. Addition of nanoclay with *Cocos nucifera* sheath in the polymer composites improved the dynamic mechanical properties [14]. Chemically modified *Cocos nucifera* sheath enhanced the fibre/matrix adhesion [15].

Yahaya et al. studied the impact of layering sequence on the mechanical behaviour of hybrid Kevlar/kenaf woven fibre reinforced epoxy composites. They found that the samples which contains outer Kevlar fabric showed higher mechanical properties [16]. Jambari et al. investigated the tensile properties of Kevlar/kenaf fibre reinforced epoxy composites with different fibre weight ratios and reported that replacement of Kevlar with 30 wt.% woven natural fibre (kenaf) shows acceptable range of decrement in tensile properties[17]. Layering sequence is an important factor which affects the mechanical properties of the laminated composites [18]. Ahmed et al. evaluated the effect of layering arrangement on the mechanical properties of glass/jute/polyester composites. From the results, they have concluded that the laminates which contains outer glass fabric showed higher mechanical properties than other laminates [19]. Mashouf Roudsari et al. statistically correlated the mechanical properties of bio composites using ANOVA [20]. Koronis et al. carried out an ANOVA test, based on the obtained experimental data to find the significant effect of input parameters [21].

The present research focussed on evaluating the tensile, flexural, impact, moisture diffusion and microstructural behaviour of hybrid Kevlar 29/*Cocos nucifera* sheath reinforced epoxy composites. *Cocos nucifera* sheath is an agro waste which can be collected from the coconut tree [22]. Naturally woven *Cocos nucifera* sheath was chosen for hybrization because of its fibre architecture, low cellulose content (21%), allowable mechanical properties, cost and availability. Low cellulose content decline the hydrophilic nature of the natural fibre and forms a rough and hard surface which is suitable to absorb impact energy. Recently identified *Cocos nucifera* sheath has a naturally woven architecture. The weaving nature of the *Cocos nucifera* sheath is that the outer fibres are randomly interlaced around the core fibre. Hybridization of Kevlar fabric with *Cocos nucifera* sheath will increase the mechanical interlocking which results in superior properties. Also, the moisture diffusion and permeability analysis has been conducted to evaluate the moisture absorption behaviour. In this study, statistical analysis of the results has been performed using one way-ANOVA to find the statistically significant difference between the mean of individual mechanical properties of different laminated composites and it has been validated with normal probability plots.

2. Materials and method

2.1. Materials

The *Cocos nucifera* sheath is a naturally woven material which contains core and outer fibres. Generally, the diameter of core fibre is higher than the outer fibre. Fig. 1 shows the naturally woven *Cocos nucifera* sheath. The weaving nature of the *Cocos nucifera* sheath is that the outer fibres are randomly interlaced around the core fibre. Chemical composition, mechanical and physical properties of the *Cocos nucifera* sheath are listed in Table 1. The average density of *Cocos nucifera* sheath is 1.37–1.50 g/cm^3. The *Cocos nucifera* sheath is a bio-waste which is available everywhere. The *Cocos nucifera* sheaths were collected manually from Serikembangan, Malaysia.

The aramid fibre utilized in this study is Kevlar 29. The properties of Kevlar 29 fabric were taken from the suppliers data which are listed in Table 2. Fig. 2 shows the 2D plain Kevlar 29 fabric with warp and fill. The matrix used in this study was D.E.R.331 liquid epoxy resin with joint amine type (905-3S) curing agent supplied by Tazdiq Engineering Sdn. Bhd. (Selangor, Malaysia). The density of the epoxy matrix is 1.08 g/cm^3.

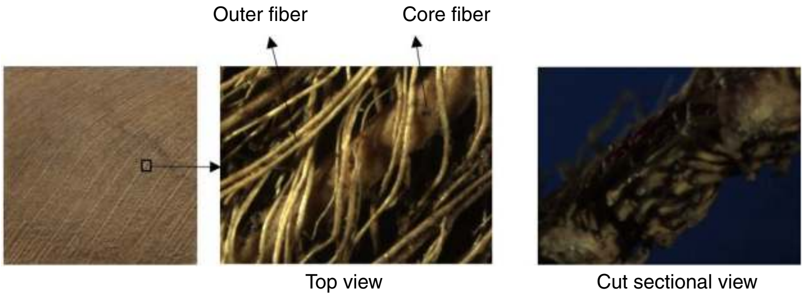

Fig. 1 – Naturally woven *Cocos nucifera* sheath.

Table 1 – Chemical composition, physical and mechanical properties of core fibre and outer fibre of the *Cocos nucifera* sheath.

Properties		Core fibre	Outer fibre
Chemical composition	Cellulose	22.25	21.99
	Hemicellulose (%)	42.01	43.44
	Lignin (%)	33.32	31.98
	Extractive (%)	2.05	2.42
	Others (%)	0.37	0.17
Physical and mechanical properties	Diameter (μm)	2111.6	308.08
	Tensile strength (MPa)	169.64	69.67
	Tensile modulus (GPa)	5.7	3.3
	% of Elongation	15.5	21.32

2.2. Extraction of naturally woven *Cocos nucifera* sheath

The *Cocos nucifera* sheath wastes were collected manually from the coconut tree. The sheaths were immersed in the water for 1 week and then they were thoroughly washed with both tap water and distilled water. After complete removal of debrises the sheaths were dried in the hot sun for 1 week. Finally, the sheaths were cut into the required size for fabrication. Fig. 3 shows the *Cocos nucifera* sheath extraction process.

Table 2 – Properties of Kevlar 29 [23].

Properties	Kevlar 29
Diameter (μm)	12.00
Density (g/cm^3)	1.44
Tensile strength (MPa)	3000
Tensile modulus (GPa)	60
Elongation at break (%)	3.30
Thickness (mm)	0.30

2.3. Fabrication of composites

Laminated hybrid composites were fabricated by using simple hand lay-up method followed by hot pressing. A stainless steel mould of dimensions 150 mm × 150 mm × 3 mm was used. The mould was first cleaned and applied with a releasing agent (Silicone spray) to prevent the adhesion of laminated composites with stainless steel mould. After curing it improved the surface finish of the composites. Epoxy resin and the curing agent were mixed for 15 min with 2:1 ratio respectively. The overall fibre/matrix weight ratio was kept as 45/55. The laminated composites were fabricated with different Kevlar/*Cocos nucifera* sheath fibre weight ratios such as S1 (100/0), S2 (75/25), S3 (50/50), S4 (25/75) and S5 (0/100). The detailed description and the layering sequences are shown in Table 3 and Fig. 4. For each laminates, the woven mats were kept inside the mould according to the layering sequence. Then the resin and curing agent mixture was poured into the mould. Hand roller was used to remove the air bubbles which may present inside the laminae. Then the mould was closed and kept inside the hot press at 105 °C for 1 h. The pressure applied over the mould was 275 bars and it squeezed out the excess resin which is present inside the mould. Eventually, in order to prevent the

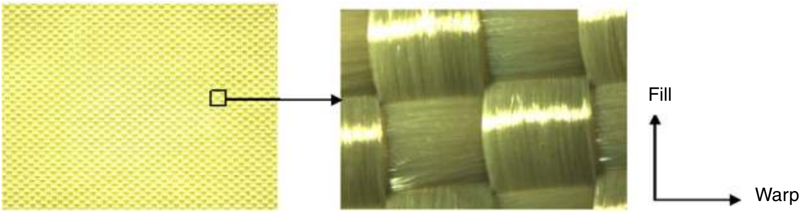

Fig. 2 – Plain 2D Kevlar fabric.

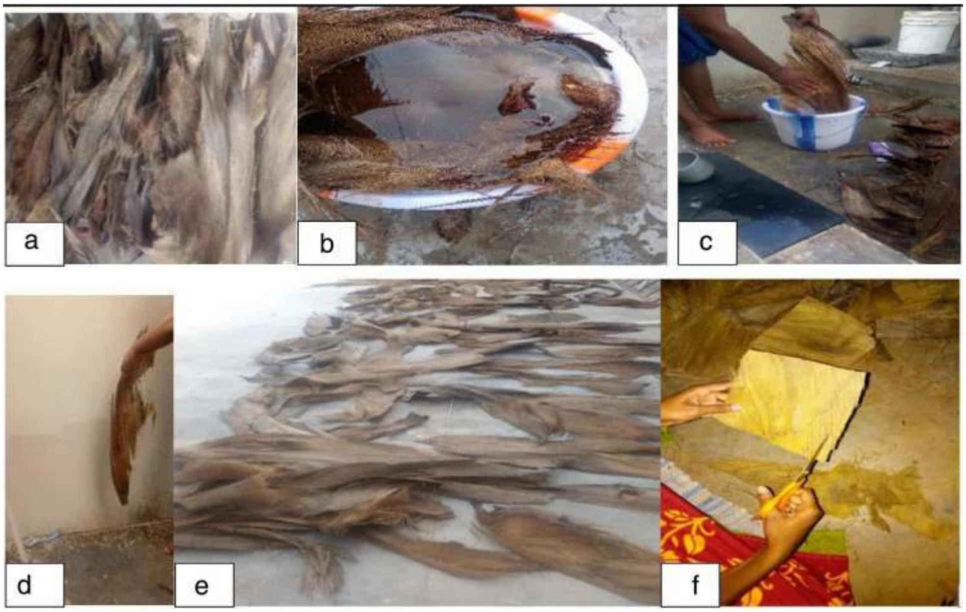

Fig. 3 – Extraction of *Cocos nucifera* sheath (a) waste *Cocos nucifera* sheath, (b) dipped sheath, (c) tap water cleaning, (d) distilled water cleaning, (e) drying process, and (f) cutting the sheath to the required size.

Table 3 – Stacking sequence and fibre weight percentage.

Symbol	Stacking sequence	Weight percentage (wt.%)	
		K	CS
S1	K/K/K/K	100	0
S2	K/CS/K/K	75	25
S3	K/CS/CS/K	50	50
S4	CS/CS/K/CS	25	75
S5	CS/CS/CS/CS	0	100

K, Kevlar; CS, *Cocos nucifera* sheath.

warpage failure the composites were kept inside a cold press for 15 min at a constant pressure of 275 bars.

2.4. *Characterization*

2.4.1. *Tensile test*

Tensile test was conducted as per ASTM D 3039 standards. The specimens for tensile testing were cut from the laminated composites using band saw with a sample size of 120 mm × 20 mm × 3 mm. Accurate surface finishing could be obtained using emery paper. Tensile strength and modulus were measured by using an INSTRON 5566 Universal Testing

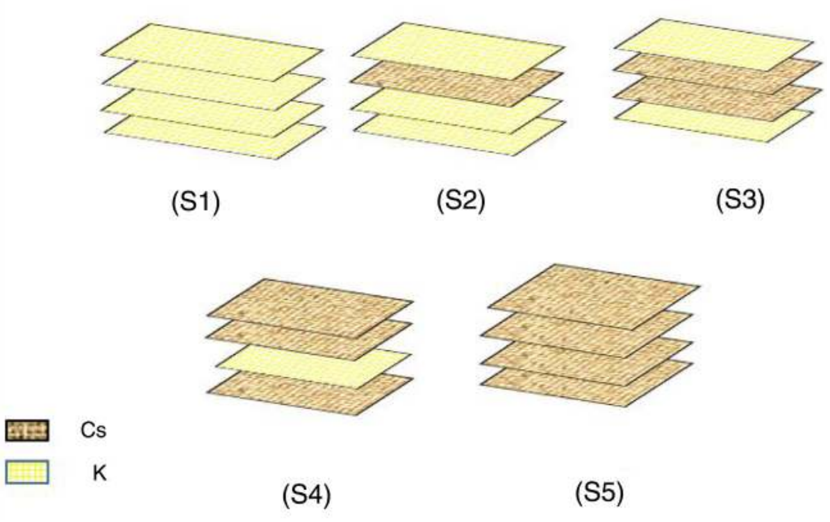

Fig. 4 – Stacking sequence of laminates.

machine. The magnitude of load and the rate of loading were 10 kN and 5 mm/min. In each group five identical test samples were tested and the mean value has been tabulated.

2.4.2. *Flexural test*

The flexural test was carried out according to ASTM D 790 with a specimen size of 120 mm × 20 mm × 3 mm through three point bending test using an INSTRON 5566 Universal Testing machine (UTM). The standard span to depth ratio of 16:1 was considered. The magnitude of load and the rate of loading were 10 kN and 2 mm/min. Five identical samples were tested for each layering sequence and the average results were reported.

2.4.3. *Impact test*

The Izod impact test was conducted as per ASTM D 256 standards by using Gotech GT-7045-MD model impact tester. Five identical samples with dimensions of 70 mm × 15 mm × 3 mm were tested for each layering sequence and the average results were reported.

2.4.4. *Moisture diffusion*

Moisture diffusion coefficient is an important parameter in the Fick's model which shows the capability of water molecules to penetrate into the polymer composites. The percentage of moisture absorption can be calculated by using the following relation

$$\%\text{ of moisture absorption} = \frac{(m_t - m_i)}{m_i} \tag{1}$$

m_t and m_i are the weight of the sample at time t and initial weight respectively.

The diffusion coefficient D (mm^2/s) can be calculated by using the following relation:

$$D = \pi\left(\frac{t\theta}{4Q_s}\right)^2 \tag{2}$$

where θ is the slope of the moisture absorption curve, t is the initial thickness of the sample, Q_s is % of moisture absorption at saturation.

The permeability of the polymer composites depends upon the sorption of the fibre. The sorption coefficient (S) is a key element to calculate the permeability coefficient. The sorption coefficient is calculated using the following relation:

$$S = \frac{Q_s}{Q_t} \tag{3}$$

where Q_s and Q_t are the molar percentages of water absorption at saturation and at time t.

The combined effect of sorption and diffusion can be calculated using the permeability coefficient P (mm^2/s) which is given by the following relation:

$$P = D \times S \tag{4}$$

Moisture absorption test was conducted according to ASTM570 to evaluate the kinetics of moisture absorption. Initially, the samples were dried in an oven for 24 h. Then the specimens were immersed in the distilled water at room temperature. The samples were weighed periodically using 4 digit weighing balance.

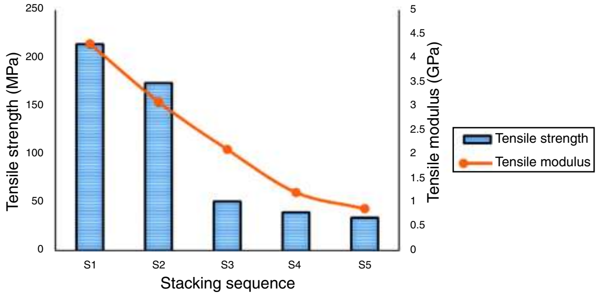

Fig. 5 – Tensile strength and modulus of the laminated composites.

2.4.5. *Scanning electron microscopy (SEM)*

Morphology of the tensile fractured laminated composites were studied using a Scanning electron microscope (Hitachi S-3400N). Fractured specimens were mounted on an aluminium stub. For better visualization the samples were sputter coated with gold.

3. Results and discussion

Mechanical properties of woven fabric based laminated composites depends on the layering sequence, weaving nature or fibre architecture, fibre density and fibre matrix adhesion [24–26]. In order to understand the hybridizing effect of *Cocos nucifera* sheath with Kevlar fabric reinforced epoxy composites tensile, flexural, Impact, moisture diffusion and microstructural behaviour were analyzed. Statistical analysis was done using one way analysis of variance with Minitab 18 software to identify a statistically significant difference between the mean properties of different laminates.

3.1. *Tensile properties*

Tensile properties of the laminated composite are mainly depends on the fibre strength, modulus, adhesion between the fibre and matrix, fibre geometry and the type of weave [19]. Fig. 5 shows the tensile strength and modulus of different laminated composites. Pure Kevlar fabric reinforced polymer composites (S1) exhibited maximum tensile strength and modulus among the five different laminates. This is because of the tensile properties of Kevlar single fibre is much higher than the *Cocos nucifera* sheath single fibre. Replacement of Kevlar with 25 wt.% of *Cocos nucifera* sheath (S2) reduces the tensile strength by only 19%. Yahaya et al. found that hybridization of kenaf with Kevlar fabric reduces the tensile strength by 50% [16]. Jambari et al. concluded that hybridization of kenaf with Kevlar fabric declined the tensile strength by 30% [17]. Hence, from the previous research it is evident that reduction in tensile strength is acceptable for hybrid composites (S2). Equal weight percentage of Kevlar and *Cocos nucifera* sheath (S3) had 27% higher tensile strength then S4 laminates. Pure *Cocos nucifera* sheath reinforced epoxy composites (S5) showed

Table 4 – ANOVA test results of tensile strength.

Source	DOF	SS	MS	F-value	P-value
Between group (BG)	4	10,309	2577.4	14.59	0.000
Within group (WG)	20	3533	176.7		

DOF, degrees of freedom; SS, sum of square; MS, mean square.

Table 5 – ANOVA test results of tensile modulus.

Source	DOF	SS	MS	F-value	P-value
Between group (BG)	4	11.886	2.97143	32.69	0.000
Within group (WG)	20	1.818	0.09089		

DOF, degrees of freedom; SS, sum of square; MS, mean square.

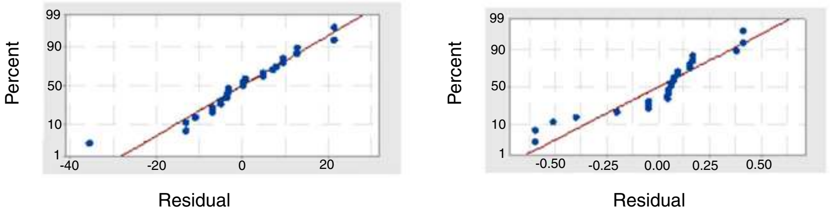

Fig. 6 – Normal portability plot for tensile strength and modulus.

the lowest tensile strength (34.71 MPa) and modulus (0.88 GPa) among the five laminates. Compared to S4 laminates, S3 laminates showed 72% higher tensile modulus. Almost similar trend was found in the tensile modulus whereas replacement of Kevlar with 25 wt.% of *Cocos nucifera* sheath (S2) reduces the tensile modulus by only 27%. Yahaya et al. found that hybridization of kenaf with Kevlar fabric reduces the tensile modulus by 42%. Jambari et al. reported that hybridization of kenaf with Kevlar fabric declined the tensile modulus by 32.2% [17]. Hence, from the previous research it is evident that reduction in tensile modulus is also acceptable for hybrid Kevlar/*Cocos nucifera* sheath composites (S2).

Tensile test results have proven that the addition of 25 wt.% naturally woven *Cocos nucifera* sheaths showed acceptable range of decrement. Generally, cellulose content of the natural fibre is attributed to its tensile strength and modulus. Even though the cellulose content of the *Cocos nucifera* sheath (22.25%) is lower than the other natural fibre due to its naturally woven dense architecture and different fibre diameters (major fibre diameter –2111.6 μm and minor fibre diameter –308.08 μm) enhances the mechanical interlocking and makes the structure more unique. Hence, it can act as a most promising natural alternative to Kevlar fabric.

Statistical analysis was performed using one way ANOVA to find a statically significant difference between the mean tensile strength and modulus of different laminated composites (S1, S2, S3, S4 and S5). Tables 4 and 5 show the ANOVA results of tensile strength and modulus. Total number of laminated composites are five (S1–S5). Five replicates were tested in each laminate. The variance of the tensile strength has been divided into two categories such as between the groups (BG) and within the groups (WG). *F*-value is the ratio between the mean square (BG) to the mean square (WG). The *P*-value of the *F*-test is less than 0.05 in Tables 4 and 5, which rejects the null hypothesis. Hence, it has been concluded that there is a statically significant difference between the mean tensile strength and modulus among the laminated composites (S1–S5) with 95% confidence level.

Fig. 6 shows the normal probability plot. These plots evaluates the goodness of fit of the model in the ANOVA [20]. There is a minimal deviation from the normalization line, in both the normal probability plot of tensile strength and modulus and it follows a linear pattern with normal distribution. The points are almost close to the normalization line. In general, the points follow the straight line for both tensile strength and modulus.

3.2. *Flexural properties*

The flexural property is specifically important among the mechanical properties because bending induces combination of different stresses consisting of compressive and tensile, i.e. top layer of the hybrid composite is subjected to compression while the bottom layer is in tension. The position of the woven layers and fibre properties plays a vital role to improve the flexural properties of the laminated composites [27].

The flexural strength and modulus of different layering sequence are shown and compared in Fig. 7. Interestingly, it was found that the hybrid laminate S2 (K75/CS25) possess the highest flexural strength (175 MPa) and flexural modulus (18 GPa) than pure Kevlar fabric (S1) reinforced epoxy composites. This is mainly be due to the dense, tight fibre architecture and higher lignin content of *Cocos nucifera* sheath compared to other natural fibres. Lignin act as a chemical bond in the natural fibres. Higher lignin content of the *Cocos nucifera* sheath improved the bending resistance of the S2 and S3 hybrid

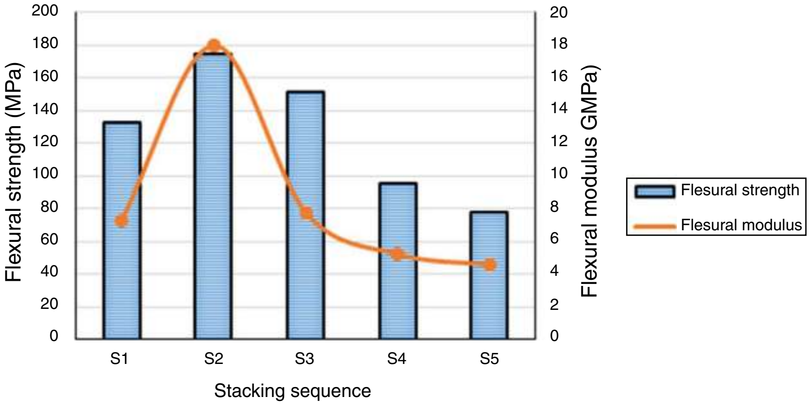

Fig. 7 – Flexural strength and modulus of the laminated hybrid composites.

composites compared to pure Kevlar/epoxy composites (S1). The increase in flexural properties of hybrid woven composites (S2) is also because of the combined advantage of its 2D plain architecture of Kevlar fabric, dense architecture of *Cocos nucifera* sheath [28] and moderate fibre matrix adhesion [8]. According to Munikenche Gowda the flexural strength is controlled by the outer layer of reinforcement [8]. It can be justified that the laminate which contains outer Kevlar fabric (S1, S2, and S3) exhibited highest flexural properties than the laminate which contains outer layer as *Cocos nucifera* sheath (S4, S5). But while comparing the flexural strength and modulus of S1 (K/K/K/K) and S2 (K/CS/K/K) it is clear that the flexural properties also depends upon the individual lamina. Compared to S4 (K25/CS75), the laminate S3 (K50/CS50) had higher flexural strength (57%) and modulus (48%). The laminate S5 (K25/CS75) has shown poor flexural strength (78 MPa) and modulus (4.6 GPa) among all the laminated composites. Khalil et al. reported that lack of fibre/matrix adhesion declined the flexural properties [27]. The laminate S4 showed slightly higher flexural strength and modulus than S5 laminate.

Flexural modulus is a measure of bending resistance of the materials. From the results, it is clear that the S2 laminate had the highest bending resistance than the other laminated composites (S1, S3, S4, and S5). Also, it was observed that hybridization of naturally woven *Cocos nucifera* sheath with Kevlar fabric results in improved flexural properties which could not be achieved by using either pure synthetic or pure natural fibre reinforced polymer composites. Enhanced flexural properties plays a vital role while designing the body armour which makes the structure more flexible and rigid.

Statistical analysis was conducted using one way ANOVA to find the statically significant difference between the mean flexural strength and modulus of different laminated composites (S1, S2, S3, S4 and S5). Tables 6 and 7 show the ANOVA test results of flexural strength and modulus. The variance of the flexural strength and modulus has been decomposed into two categories such as between the groups (BG) and within the groups (WG). *F*-value is the ratio between the mean square (BG) to the mean square (WG). The *P*-value of the *F*-test is less than 0.05, in Tables 6 and 7 which rejects the null hypothesis. Hence, it was concluded that there is a statically significant difference between the mean flexural strength and modulus among the laminated composites (S1 to S5) with 95% confidence level. Fig. 8 shows the normal probability plot of flexural strength and modulus. All the data points are almost nearer to the normalization line and it confirms the goodness of fit of the model in the ANOVA.

3.3. *Impact strength*

Izod's impact test was conducted to investigate the effect of cocos-nucifera sheath hybridization on the impact energy

Table 6 – ANOVA test results of flexural strength.

Source	DOF	SS	MS	F-value	P-value
Between group (BG)	4	48,818	12204.5	33.32	0.000
Within group (WG)	20	7325	366.2		

DOF, degrees of freedom; SS, sum of square; MS, mean square.

Table 7 – ANOVA test results of flexural modulus.

Source	DOF	SS	MS	F-value	P-value
Between group (BG)	4	672.627	168.157	425.17	0.000
Within group (WG)	20	7.910	0.395		

DOF, degrees of freedom; SS, sum of square; MS, mean square.

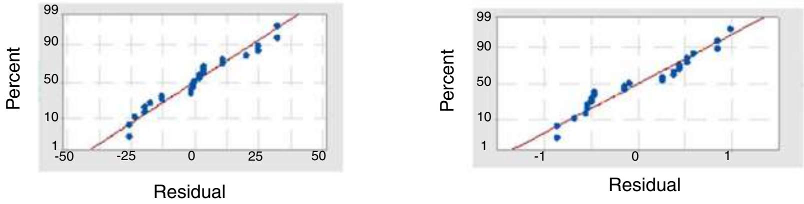

Fig. 8 – Normal probability plot of flexural strength and modulus.

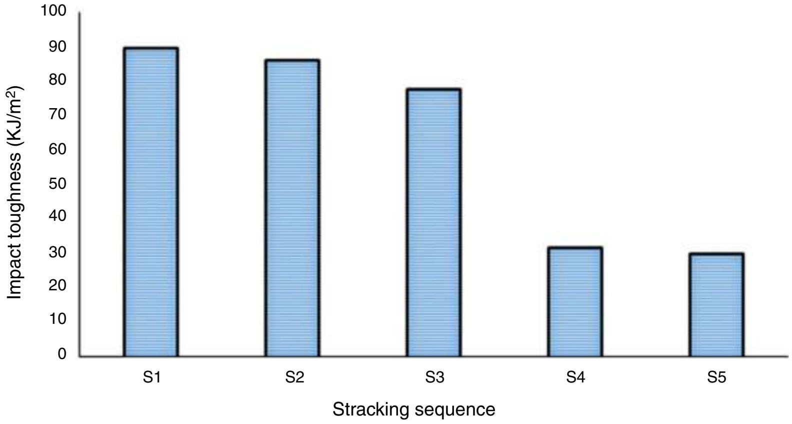

Fig. 9 – Impact toughness of the laminated composites.

absorption capability of Kevlar fabric reinforced epoxy composites. The absorbed energy is the amount of energy required to fracture the specimen completely. The impact toughness or impact strength (kJ/m^2) of the hybrid composites was calculated using the following relation.

$$\text{Impact toughness} = \frac{\text{Absorbed impact energy}}{\text{Cross sectional area (kJ/m}^2\text{)}}$$

Impact toughness of the material is the most important factor in case of personal body armour applications. The material which is having highest impact toughness can efficiently dissipate the kinetic energy of the projectile rapidly away from the impact zone. Moreover, in the fibre reinforced polymer composites the moderate fibre/matrix bonding is essential to achieve higher energy absorption [29].

The results from the Izod's impact test of hybrid Kevlar/*Cocos nucifera* sheath reinforced epoxy polymer composites are shown in Fig. 9. The impact toughness of the S1 laminates (K100/CS0) possess the highest impact toughness among the laminates. Addition of *Cocos nucifera* (25 wt.%) sheath with the Kevlar fabric (70 wt.%) reinforced epoxy composites declined the impact toughness only by 4.4%. In case of S3 (K50/CS50) hybrid composites the decrement in impact toughness compared with S1 (K100/CS0) laminate was 13.3%, Both S4 (K75/CS25) and S5 (K0/CS100) laminates showed almost similar impact toughness.

All the natural fibres contains cellulose which is the main reason for its hydrophilic nature. Each anhydro-D-glucose element of cellulose contains three alcohol hydroxyls. These hydroxyls forms hydrogen bonding in between the cellulose macromolecules and with the hydroxyl groups which is present in the air [30]. Low cellulose content of the *Cocos nucifera* sheath produce a rough fibre surface and it forms a hydrogen bond with the adjacent cellulose and hydrophobic polymer matrix rather than atmospheric air molecules. In addition to that, the most important chemical composition of a natural fibre is 'lignin' which significantly affects the bonding of distinct cells of hard natural fibre. Also lignin act as a cementing material. Due to this the impact toughness of S2 hybrid composites shows good agreement with the pure Kevlar fabric reinforced polymer composites (S1). It could be further validated with the SEM microstructure, whereas the S2 hybrid composites showed moderate fibre/matrix bonding which is required to absorb the impact energy. Moreover, S4 and S5 laminates shows almost equal impact toughness which exhibited the potential of *Cocos nucifera* sheath to be used in armour applications. From the impact test results, it is clear that *Cocos nucifera* sheath/Kevlar hybrid composites can replace the pure Kevlar fabric reinforced epoxy composites.

Statistical analysis was performed using one way ANOVA to study the significant difference between the mean impact toughness of different laminated composites. Table 8 shows the ANOVA test results of impact toughness. The variance of the impact toughness has been decomposed into two categories such as between the groups (BG) and within the groups (WG). *F*-value is the ratio between the mean square (BG) to the mean square (WG). The P-value of the *F*-test is less than 0.05, as shown in Table 8 which rejects the null hypothesis. Hence, it has been concluded that there is a statically significant difference between the mean impact toughness among the laminated composites (S1–S5) with 95% confidence level. Fig. 10 shows the normal probability plot of impact toughness. All the data points are almost nearer to the normalization line and it confirms the goodness of fit of the model in the ANOVA.

Table 8 – ANOVA test results of impact toughness.

Source	DOF	SS	MS	F-value	P-value
Between group (BG)	4	16737.4	4184.34	175.29	0.000
Within group (WG)	20	477.4	23.87		

DOF, degrees of freedom; SS, sum of square; MS, mean square.

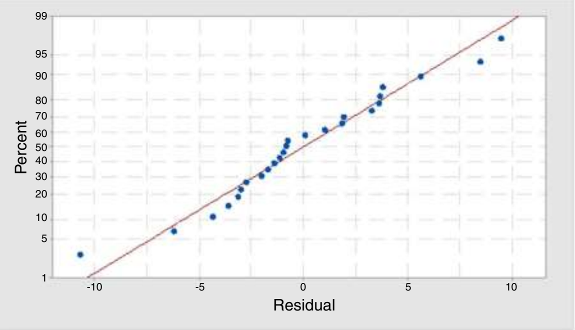

Fig. 10 – Normal probability plot of impact toughness.

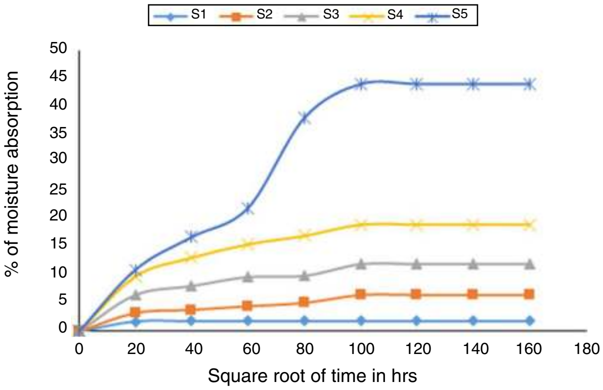

Fig. 11 – Moisture absorption behaviour of Kevlar/*Cocos nucifera* sheath hybrid composites.

3.4. *Moisture diffusion analysis*

The moisture absorption curve was plotted with the percentage of moisture uptake against the square root of time (hours) as shown in Fig. 11. From the graph it is clear that the Kevlar/epoxy composites (S1) shows very less water uptake due to its hydrophobic nature. Whereas, *Cocos nucifera* sheath/epoxy composites (S5) shows the highest moisture absorption due to its hydrophilic nature. From Table 9 it was understood that the hybrid composites S2 has less diffusion coefficient and permeability coefficient than the other hybrid composites (S3, S4) which indicates that the S2 hybrid composites possess good moisture resistance behaviour.

3.5. *Microstructural analysis (SEM)*

Microstructural analysis of the tensile fractured specimens were studied using scanning electron microscope. Fibre and matrix bonding plays a vital role in the mechanical properties of the composites. Generally, fibre or reinforcements could bear the stress or it act as a load carrying member, whereas matrix transfers the load to the fibre. Moreover, resin bonds the fibre together.

From Fig. 12a it is clear that there are delamination's between the Kevlar fabrics and shows moderate fibre/matrix adhesion. Even though single Kevlar fabric had higher tensile strength, the poor fibre matrix adhesion and delamination affects the tensile properties of the Kevlar composites. Fig. 12b shows the pulled out Kevlar and *Cocos nucifera* sheath after tensile testing. Fig. 12c clearly compares the fibre–matrix adhesion of Kevlar fabric and *Cocos nucifera* sheath and it shows that *Cocos nucifera* sheath have better adhesion with the matrix than Kevlar fabric. But delamination occurs in between the Kevlar fabric and *Cocos nucifera* sheath (Fig. 12d). From Fig. 12e it is understood that though the *Cocos nucifera* sheath have better bonding with the matrix and it has some voids which affects the mechanical properties of the composites. Generally, the woven fabric contains fibres both in warp and in fill directions and they are interlaced with each other. While applying the tensile load the fibres in the transverse direction will also tend to straighten which creates stress concentration at the interface of the fibre and matrix. As a result, micro cracks has been initiated (as shown in Fig. 12c) in the matrix which propagates in the transverse direction causing fibre fracture. This continues, until the specimen has been fractured completely.

Table 9 – Diffusion and permeability analysis.

Weight percentage of Kevlar/*Cocos nucifera* sheath	Percentages of water uptake at saturation time, Q_S (%)	Sorption coefficient, S	Diffusion coefficient, D (mm^2/s)	Permeability coefficient, P (mm^2/s)
100/0	1.84	1.00	0.01E−05	0.01E−05
75/25	6.51	1.20	1.92E−05	2.3E−05
50/50	12.12	1.23	2.04E−05	2.5E−05
25/75	19.13	1.44	4.89E−05	7.04E−05
0/100	44.12	2.00	8.25E−05	16.4E−05

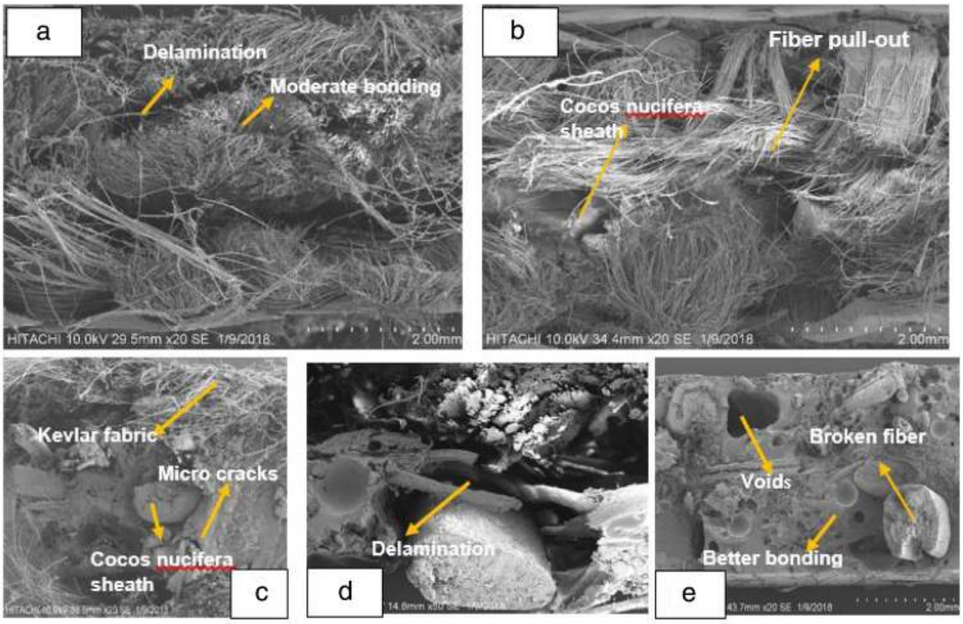

Fig. 12 – Scanning electron microscope of tensile fractured specimens (a) S1 (K100/CS0), (b) S2 (K75/CS25), (c) S3(K50/CS50), (d) S4(K25/CS75), and (e) S5(K0/CS100).

4. Conclusion

Effect of hybridizing naturally woven *Cocos nucifera* sheath waste with Kevlar fabric/epoxy composites on tensile, flexural, impact and moisture diffusion properties were studied.

- From the results, it is clear that replacement of Kevlar with 25 wt.% *Cocos nucifera* sheath declined the tensile properties by only 19%.
- Highest flexural strength and modulus of were observed in the hybrid laminates (K75/CS25) than other laminated composites due to the dense fibre architecture and mechanical interlocking.
- The impact toughness of hybrid composites (75/25 wt.%) showed good agreement with the pure Kevlar fibre reinforced polymer composites. This indicate that hybridization of 25 wt.% *Cocos nucifera* sheath can absorb and efficiently dissipates the impact energy.
- From the moisture diffusion analysis, hybrid composites S2 (75/25) exhibited better moisture diffusion and permeability coefficient which indicates that the S2 (75/25) hybrid composites had better moisture resistance behaviour.
- From the ANOVA test results, it was found that there is a statistically significant difference among the mean of individual mechanical properties. The residual plots proved the goodness of fit of the ANOVA.
- From the results, it is concluded that the laminated composites S2 (K75/CS25) can efficiently replace the pure Kevlar composites S1 (K100/CS0).

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

We are thankful to Ministry of Higher Education for Providing HICOE Grant No: 6369108 to INTROP, UPM for doing this work.

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