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Dimensional Stability, Mechanical and Thermal Performance of Flax/Carbon/Kevlar Reinforced Bio-Phenolic/Epoxy Hybrid Composites

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ABSTRACT

This study explores the effects of hybridizing flax fabric (F) with carbon/Kevlar fabric (CK) on key material properties, including density, water absorption, void content, tensile properties, impact resistance, and thermogravimetric stability. The composites were fabricated using compression molding, employing different weight ratios of flax to carbon/Kevlar (F/CK): 100/0, 75/25, 50/50, 25/75, and 0/100, while keeping the fiber loading constant at 50 wt %. Bio-phenolic/epoxy polymer blends were used as the polymer matrix. The results indicate that as the amount of carbon/Kevlar fabric increases, the density of the hybrid composites also increases while the moisture absorption decreases. The analysis of void content in the composites suggests that the fabricated composites are well-prepared, with void content measuring less than 2%. Combining flax fiber with carbon/Kevlar fiber produces a composite with improved mechanical characteristics. Notably, the hybrid composite with a ratio of 25:75 (F: CK) demonstrated superior tensile modulus and impact strength, showing improvements of 25.96% and 16.05%, respectively, compared to the carbon/Kevlar composite. Moreover, the residue at 800°C of the composites increased with an increase in the carbon/Kevlar fabric and the highest was shown by hybrid composites with the ratio of 25:75 (F:CK), where the residue is 39.96%.

摘要

本研究探讨了亚麻织物（F）与碳/凯夫拉纤维织物（CK）杂交对关键材料性能的影响，包括密度、吸水率、孔隙率、拉伸性能、抗冲击性和热重稳定性. 复合材料是使用压缩成型制造的，采用不同重量比的亚麻与碳/凯夫拉尔（F/CK): 100/0、75/25、50/50、25/75和0/100，同时保持纤维负载恒定在50重量%. 生物酚醛/环氧聚合物共混物用作聚合物基质. 结果表明，随着碳/凯夫拉纤维织物用量的增加，杂化复合材料的密度也会增加，而吸湿性会降低. 对复合材料中孔隙含量的分析表明，所制备的复合材料制备良好，孔隙含量小于2%. 将亚麻纤维与碳/凯夫拉尔纤维结合，可以生产出机械性能得到改善的复合材料. 值得注意的是，比例为25:75（F:CK）的混合复合材料表现出优异的拉伸模量和冲击强度，与碳/凯夫拉尔复合材料相比，分别提高了25.96%和16.05%. 此外，复合材料在800°C下的残留物随着碳/凯夫拉纤维织物的增加而增加，比例为25:75（F:CK）的混合复合材料显示出最高的残留物，其中残留物为39.96%.

KEYWORDS
Epoxy; bio-phenolic; polymer blends; hybrid composite; mechanical properties; thermal properties; flax fabric; carbon/Kevlar fabric

关键词
环氧树脂; 生物酚; 聚合物共混物; 混合复合材料; 机械性能; 热性能; 亚麻织物; 碳纤维/凯夫拉纤维织物

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Introduction

Flax, scientifically known as Linum usitatissimum, is a plant cultivated for its unique fibrous qualities. The natural flax fibers, with properties akin to e-glass fibers, are a key focus of this research Fiore, Valenza, and Di Bella (2012). Short fibers from the flax plant, a byproduct of the textile industry, have been utilized as fillers in natural fiber-reinforced composites Fiore, Valenza, and Di Bella (2012); Jhala and Hall (2010). Flax, a rapidly maturing plant, is well-suited for cultivating and gathering its fibers, typically reaching maturity within 100 to 120 days. Fiber-reinforced polymer composites (FRPC) employ a variety of synthetic/natural fibers that are selected according to their intended uses. Industries requiring high performance, such as aerospace and military applications, often utilize synthetic fibers like carbon. Renowned for its lightweight and exceptional strength, carbon fiber surpasses steel in strength by a factor of five Bajpai (2021). Kevlar fiber, also known as polyamide fiber, has superior tensile strength and modulus at lower elongation than other synthetic fibers Agarwal, Broutman, and Chandrashekhara (2006); Matthews and Rawlings (1999); Pregoretti, Traina, and Bunsell (2009). Due to its excellent properties, Kevlar is used in industrial and military applications Singh and Samanta (2015). FRPC has become indispensable in displacing traditional materials like metal due to their lightweight nature, exceptional strength, and high rigidity. Many industries heavily rely on these materials, spanning the automotive, marine, aerospace, and defense sectors.

Researchers have directed their efforts toward exploring the potential of various types of fibers for high-performance applications. This investigation encompasses synthetic and natural fibers, each offering distinct advantages and drawbacks. Natural fibers, valued for their lightweight, renewable, cost-efficient, and high specific strength and modulus, have garnered attention Neto et al. (2022); Prasad et al. (2024); Sahu and Gupta (2022). Conversely, synthetic fibers boast superior mechanical attributes, minimal moisture absorption, and favorable thermal properties. However, the non-biodegradable nature of synthetic fibers, such as glass fibers, is challenging to dispose of, even through incineration Okubo, Fujii, and Yamamoto (2004). The utilization of petroleum-based polymer composites poses environmental risks. Researchers are exploring hybrid composites that combine natural and synthetic fibers to tackle environmental concerns. Studies are also looking into using bio-based polymers as matrix material, which could offer promising solutions to minimize environmental impact. Utilizing bio-based polymers and hybridizing composites with natural fibers can decrease reliance on petroleum-based materials.

Naveen et al. (2019) examined the impact of combining Kevlar and Cocos Nucifera, along with epoxy as a polymer matrix, on mechanical strength and moisture absorption. A decrease in tensile strength and modulus was observed when Kevlar was hybridized with Cocos Nucifera sheath (CS) in a 75:25 ratio (K: CS). Notably, hybrid composites with the same ratio exhibited improved flexural properties and comparable impact strength to Kevlar alone. Additionally, the moisture absorption of the composite decreased with the incorporation of synthetic fiber. This highlights that not all properties of the composite declined in the natural/synthetic hybrid composite. Instead, some properties could be maintained or even enhanced beyond those of the non-hybrid composite. In addition, Cheng et al. (2020) have studied carbon/flax-reinforced polypropylene hybrid polymer composites. Mechanical testing indicates that hybrid polymer composites exhibit significant improvement compared to flax composites. Cihan, Sobey, and Blake (2019) studied the mechanical properties of a hybrid polymer composite consisting of flax and E-glass reinforced epoxy were examined. Glass and flax fibers were laminated in different ratios and sequences. Hybrid composites demonstrated superior tensile characteristics to flax composites.

Audibert et al. Okubo, Fujii, and Yamamoto (2004) have studied hybrid composites with flax and Kevlar fiber as reinforcement. This study used both experimental and numerical simulations. It revealed that hybrid composites exhibited intermediate properties between flax and Kevlar composites. In the study by Wang et al. Naveen et al. (2019), flax and glass fibers were used as reinforcement, and epoxy was used for the matrix. The objective was to examine how adding glass fibers to flax influences the mechanical characteristics of the composite. Different arrangements of flax and glass fabrics were examined. The finding indicated that the tensile strength of the hybrid composites with various stacking patterns and the same flax-to-glass fiber ratio did not differ significantly. However, the flax/glass hybrid composites demonstrated substantially greater tensile strength than the flax composites. A comparative study was conducted by Yashas et al. (2021) on flax/basalt (natural/natural fibers) and flax/carbon (natural/synthetic fibers) hybrid composites using bio-epoxy and synthetic epoxy as the matrix. The research revealed that synthetic epoxy composites surpassed bio-epoxy composites regarding mechanical performance. Hybrid composites consisting of flax and carbon fiber reinforcement demonstrated superior tensile strength compared to those incorporating flax and basalt. However, unlike flax/carbon hybrid composites, the hybridization of basalt and flax composites showed enhanced impact strength. Additionally, when flax is combined with carbon fibers and basalt, the amount of water the composite material can absorb decreases compared to composites made solely with flax.

The researchers conducted studies involving hybrid composites incorporating three distinct fiber types for reinforcement within a single system. Chaudhary et al Maheshwari (2018) focused on hybrid composites of epoxy reinforced with jute, hemp, and flax fibers where six types of the composite were fabricated, which area jute/epoxy, flax/epoxy, hemp/epoxy, jute/hemp/epoxy, hemp/flax/epoxy and jute/hemp/flax/epoxy. In the study, it was discovered that a hybrid composite of jute/hemp/flax/epoxy demonstrated enhanced impact and tensile properties in comparison to other composite materials. Abd El-baky et al. (2020) conduct research on the mechanical characteristics of composites composed of flax, basalt, and glass fibers. The researchers found that incorporating flax with stronger fibers, such as basalt and glass, significantly enhanced the mechanical properties. Moreover, Petrucci et al. (2013) explored the development of hybrid composites containing three distinct types of fibers within a single system. The study focused on three types of hybrid composites: glass/flax/basalt, glass/hemp/basalt, and flax/hemp/basalt. The glass/flax/basalt composite performed superior to the other two hybrid composite combinations.

This study aimed to investigate the impact of hybridizing flax with carbon/Kevlar. Current literature indicates that no prior studies have examined hybrid flax/carbon/Kevlar with bio-phenolic/epoxy polymer blends matrix. The differences between this study and previous works are listed in Table 1. According to earlier studies, there is little research on hybrid composites with polymer blend matrices. Hybrid composites reinforced bio-phenolic/epoxy polymer blends were manufactured using flax and carbon/Kevlar as reinforcement. Different proportions of flax and carbon/Kevlar fibers were utilized. This study used a combination of bio-phenolic and epoxy polymers, with the bio-phenolic content set at 20 wt%. This percentage was determined to be the optimal formulation based on prior research Ismail et al. (2021, 2023).

This research conducted a series of tests, including physical, tensile, impact, morphological, and thermogravimetric analyses, to evaluate the performance of a hybrid composite material compared to flax composite and Carbon/Kevlar composite.

Materials and methods

Materials

The flax fabric utilized in this research was sourced from Dongguan Zhouma Textile Co. Ltd. in China. Additionally, the carbon/Kevlar fabric, Jointmine and 905-3S epoxy D.E.R * 331 were supplied by a Malaysian company located in Selangor, Tazdiq Engineering Sdn. Bhd. The bio-phenolic resin was acquired from Chemovate Girinagar, headquartered in Bangalore, India. Moreover, the Teflon sheet

Table 1. Current study on flax hybrid composites.

Fibers	Matrix	Remarks	ref
Flax Carbon Kevlar Hybrid Carbon/ Kevlar	Epoxy	• Weaving types of flax, Carbon, and Kevlar are plain weaves, while hybrid Carbon/Kevlar is a twill weave. • 7 different types of composites were fabricated: • Flax epoxy composite (1) Carbon epoxy composite (2) Kevlar epoxy composite (3) Carbon/Kevlar hybrid composite (4) Flax/Carbon hybrid composite (5) Flax/Kevlar hybrid composite (6) Flax/Carbon/Kevlar hybrid composites (7) Seven layers of the laminated composite were created, with fiber loading ranging from 30% to 40% by weight.	TG et al. (2022)
Flax (F) Carbon (C)	Epoxy	• Bidirectional flax fabric and unidirectional Carbon fabric were used in this study. • This research was done to find out how the stacking order affected the properties of flax/Carbon hybrid composites. Two different flax/Carbon Kevlar layering sequences were created: FCFCF and CFFFC. Neat flax and Carbon composite were fabricated as a control. • Each composite consists of five layers of fibers and the volume fraction of Carbon to flax is 29:71.	Wang, Wang, and Xian (2020)
Flax/Kevlar	Epoxy	• A balanced plain weave hybrid flax/Kevlar fabric was used. • One composite type was fabricated consisting of hybrid flax/Kevlar as reinforcement and epoxy as the matrix. • The result was compared with published work for neat flax/epoxy and neat Kevlar/epoxy composite. • The sample was tested in three orientations: 0°, 90°, and ±45°.	Audibert et al. (2018)
Flax Carbon/ Kevlar	Bio-phenolic/epoxy polymer blend (20wt% bio-phenolic)	• The weaving type for both fibers is plain weave. • Study the different ratios of flax and carbon/Kevlar (25/75, 50/50 and 75/25) and pure flax and Carbon/Kevlar were fabricated as a control. Fiber loading was maintained at 50 wt%	Current study

was provided by Evergreen Sdn Bhd, a supplier based in Malaysia. Figure 1 illustrates the materials utilized in the study.

Fabrication of composites

Fabrication of the composites utilizing the conventional method i.e., hand layup technique, to ease the process for commercialization, followed by a hot-press procedure for curing. Flax and carbon/Kevlar fabric were prepared with 150 mm x 150 mm dimensions and oven-dried for 24 hours at 60°C. The polymer blends comprising 20 wt% bio-phenolic were prepared by blending epoxy with bio-phenolic. To ensure thorough mixing, the mixture was stirred for

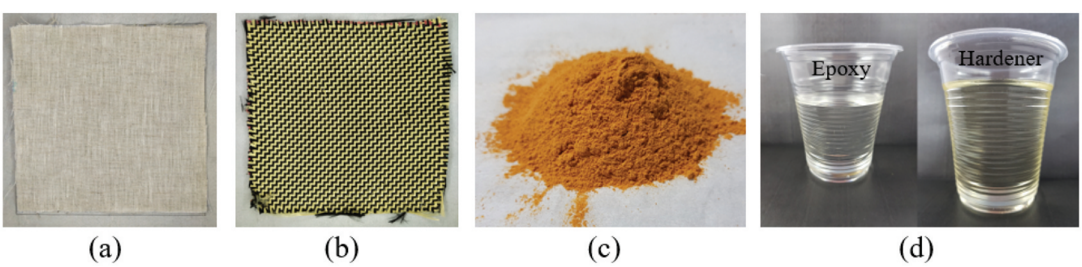

Figure 1. a) Flax fabric, b) carbon/Kevlar fabric, c) bio-phenolic, d) epoxy and hardener.

approximately 10 minutes. Following an even distribution of the bio-phenolic in the epoxy resin, a 2:1 ratio of epoxy to hardener was added, and the mixture was agitated for a further 2–4 minutes. A Teflon sheet was used to prevent the sample from sticking to the steel place by placing it between the steel plate and the mold. A tiny layer of the polymer blend was applied to inhibit adhesion on the Teflon sheet, followed by carbon/Kevlar. The carbon/Kevlar and flax fabrics were then layered atop each other, separated by a thin layer of polymer blend. The composites were fabricated while maintaining the fiber loading at 50 wt%. The mold underwent hot pressing at 150°C and a pressure of 30 tons for 15 minutes. Table 2 delineates the composite compositions, while Figure 2 illustrates the layering sequence. The composites produced are depicted in Figure 3.

Characterization

Density test

The density of the fabricated composites was determined using the ASTM D 792–20 standard. The sample density was measured using a densimeter from Mettler Toledo XS205 Dual Range Analytical Balance. Distilled water was used in this test. The average of three samples was taken.

Void content

Estimating the presence of voids within the composites becomes feasible by employing both theoretical and experimental densities. Equation 1 was employed to derive the theoretical density, whereas the experimental density was measured using a densimeter. Equation 2 facilitated the calculation of the void content in the composites. ASTM D 2734–70 standard was used as the guideline for calculating void content.

$$\text{Theoretical density, (DT)} = \frac{100}{\left(\frac{\mathrm{R}}{\mathrm{D}} + \frac{\mathrm{r}_F}{\mathrm{d}_F} + \frac{\mathrm{r}_{CK}}{\mathrm{dCK}}\right)} \quad (1)$$

Table 2. Formulation of flax, carbon/Kevlar and, flax/carbon/Kevlar composites.

Composites	The weight ratio of flax/carbon/Kevlar	The weight ratio of bio-phenolic/epoxy	Number of layers (F/CK)
F-50	100/0	20/80	10/0
75F25CK	75/25	20/80	8/2
50F50CK	50/50	20/80	5/4
25F75CK	25/75	20/80	3/6
CK	0/100	20/80	0/8

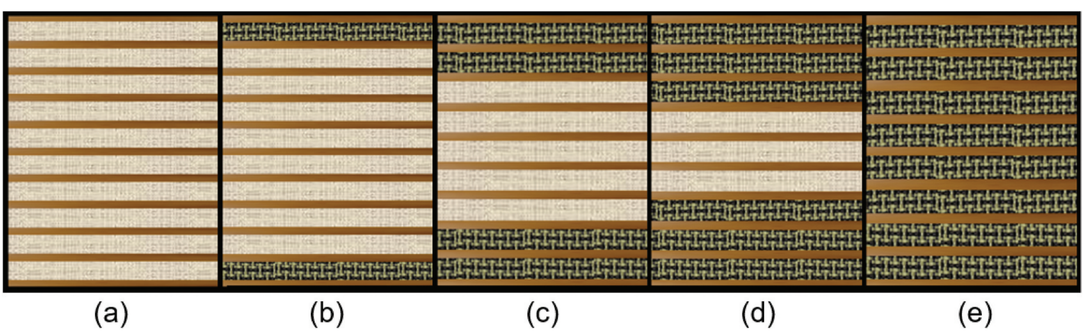

Figure 2. The layering sequence of fabricated composites, a) F-50, b) 75F25CK c) 50F50CK, d) 25F75CK and e) CK.

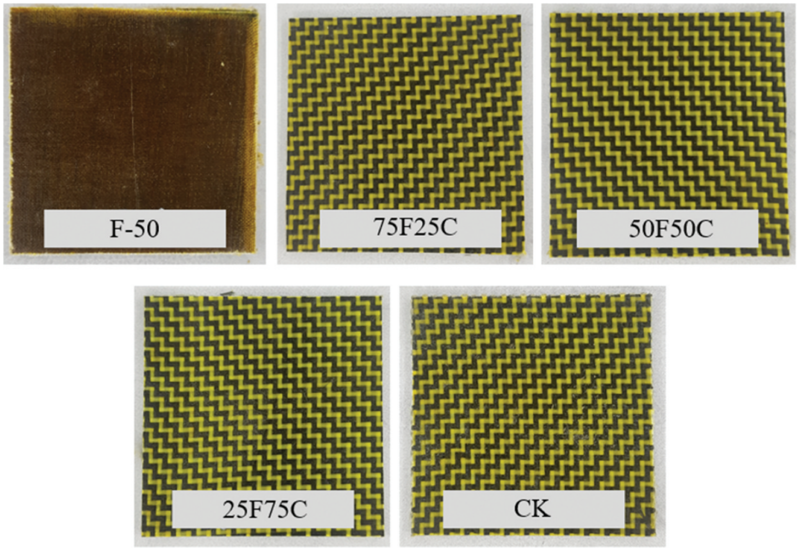

Figure 3. Fabricated composites.

$$\text{Void Content} = \frac{D_{T-}D_E}{D_T} \times 100 \tag{2}$$

The variables in the equation are as follows:

R : weight percentage of the matrix
r_F : weight percentage of the flax fabric
r_{CK}: weight percentage of the Carbon/Kevlar fabric
D: density of the resin
d_F: represents the density of the flax fabric
$d_{CK:}$ represents the density of the Carbon/Kevlar fabric
D_T: theoretical density
D_E: experimental density.

Water absorption study

The testing was conducted in accordance with ASTM D570–98 (2010) standard, utilizing samples with dimensions of 20 mm × 20 mm × 3 mm. The specimens were oven-dried for 24 hours at a temperature of 50°C, then allowed to cool in a desiccator before being weighed. The initial weight (Wd)(g) was recorded, and its weight (Wn)(g) was monitored every 24 hours while immersed in water. Equation 3 was applied to estimate the sample's absorption. The average of three samples was reported.

$$\text{Water absorption}(\%) = \frac{W_{n-}W_d}{W_d} \times 100 \tag{3}$$

Tensile testing

The tensile study on the composite samples was carried out in accordance with the ASTM D 3039 standard, utilizing a universal testing machine (30 kN Bluehill, INSTRON 5567). The testing parameters, including the gauge length and speed, were configured to 60 mm and 2 mm per minute, respectively. Before testing, the samples were conditioned at 23 ± 3°C and 50 ± 10% relative humidity within a chamber for 24 hours. Five samples were tested, and the results were reported by averaging the collected test data.

Izod-impact test

The composite's impact testing was conducted according to the ASTM D 256 standard using a Ray Ran advanced universal pendulum impact tester (RR/IMT). The sample was prepared with a size of 63.5 mm × 12.7 mm × 3 mm. A V-notch was made on the sample using a motorized notch-vis machine. The average of the results from five samples is recorded.

Scanning electron microscopy (SEM)

The SEM of fractured tensile composite samples involved coating the sample's surface with a thin layer of gold via sputtering before observation. The samples were then examined using a Vega 3 scanning electron microscope. The acceleration voltage used is 15 kV.

Thermogravimetric analysis (TGA)

The composites' thermal degradation characteristics were analyzed using Mettler Toledo 851e following ASTM E1131–03 (2003) guidelines. The was weighed approximately 45 ± 3 g and placed in an alumina crucible. The sample underwent pyrolysis at a 50 mL/min flow rate in a nitrogen atmosphere. The testing temperature gradually increased from 30°C to 800°C at a heating rate of 10°C per minute.

Results and discussion

Dimensional stability

The physical characteristics of the composites are tabulated in Table 3. The theoretical and experimental densities display a consistent trend, indicating lower void content values in the developed composites. It has been noticed that the experimental and theoretical densities increase with an increase in Carbon/Kevlar fabric content. This is primarily because of the higher Carbon/Kevlar fabric density than flax fabric. It is a noteworthy fact that natural fibers generally possess lower density than synthetic fibers An et al. (2022). Table 4 illustrates the densities of both synthetic and natural fibers. The findings reveal that the composites exhibit less than 2% void content, indicating good sample preparation. The void formation could be due to the entrapments while mixing resin with hardener, residual solvents, and moisture content present in the fibers Mehdikhani et al. (2019); Norizan et al. (2017). Achieving a low void content in composites necessitates meticulous material preparation and precise manufacturing parameters. Composites boasting excellent mechanical properties typically exhibit minimal void content, as the presence of voids significantly compromises their strength. Higher void content correlates with decreased composite strength. The observed low void content in the study suggests thorough wetting of fibers within the composites and minimal bubble formation during manufacturing, resulting in high-quality composite materials.

Water absorption behavior in composites depends on several factors, such as resin viscosity, fiber type, voids, temperature, and humidity. In Figure 4, the water absorption of the fabricated composites is highlighted, showing the influence of incorporating carbon/Kevlar fabric into flax fabric. It was noted that an increase in the ratio of carbon/Kevlar fabric resulted in reduced water absorption. This is due to the hydrophobic nature of carbon/Kevlar fabric, which contrasts with the hydrophilic nature of flax fabric. The high hydrophilicity of flax fiber arises from its composition, primarily cellulose, hemicellulose, and lignin. Cellulose and hemicellulose contain hydroxyl groups, naturally attracting

Table 3. Physical properties of the composites.

Sample code	Experimental Density (g/cm^3)	Theoretical density (g/cm^3)	Void content (%)
F-50	1.23	1.25	1.42
75F25CK	1.25	1.27	0.08
50F50CK	1.28	1.29	0.21
25F75CK	1.30	1.31	0.45
CK	1.33	1.33	0.31

Table 4. Density of natural and synthetic fibers.

Fiber	Density (g/cm^3)	References
Natural Fibers		
Flax fabric	1.38	Current study
Flax	1.4–1.5	Bhadra and Dhar (2022)
Kenaf	1.19–1.5	Bhadra and Dhar (2022)
Jute	1.38–1.46	Bhadra and Dhar (2022)
Hemp	1.45–1.5	Bhadra and Dhar (2022)
Synthetic Fibers		
E-Glass	2.5	Binoj et al. (2016)
Carbon	1.7	Binoj et al. (2016)
Kevlar	1.4	Binoj et al. (2016)
Carbon/Kevlar	1.6	Current study

water and promoting water absorption Karimzadeh et al. (2020); Khalil, Jawaid, and Bakar (2011). When natural fibers absorb water, it increases the cell wall of the fibers to saturation Ghani et al. (2022). Substituting some of the natural fiber with synthetic fiber can significantly reduce water absorption in composites. Research conducted by Ng, Yahya Ng, Muthukumar (2022) demonstrated that the water absorption of composites reinforced with glass fiber and pineapple fiber reduces as the glass fiber content increases. Additionally, findings from another researcher showed that combining synthetic fibers with natural fibers reduces water absorption by composites Nuryanta, Sentanuhady, and Muflikhun (2022).

Tensile properties

Figure 5 depicts the outcome of the tensile tests conducted on the composites. CK composite (434.34 MPa) exhibits significantly higher tensile strength than the F composite (105.04 MPa). The tensile strength of the composites showed substantial improvement when some of the flax fabric was replaced with carbon/Kevlar fabric. Specifically, the tensile strength improved from 105.04 MPa to 182.79 MPa when 25% of the flax fabric was replaced with carbon/kevlar fabric. Furthermore, the composite material’s tensile strength increases as the carbon/kevlar fabric proportion increases. This behavior is attributed to synthetic fibers’ higher tensile strength than natural fibers, as illustrated in Table 5. The

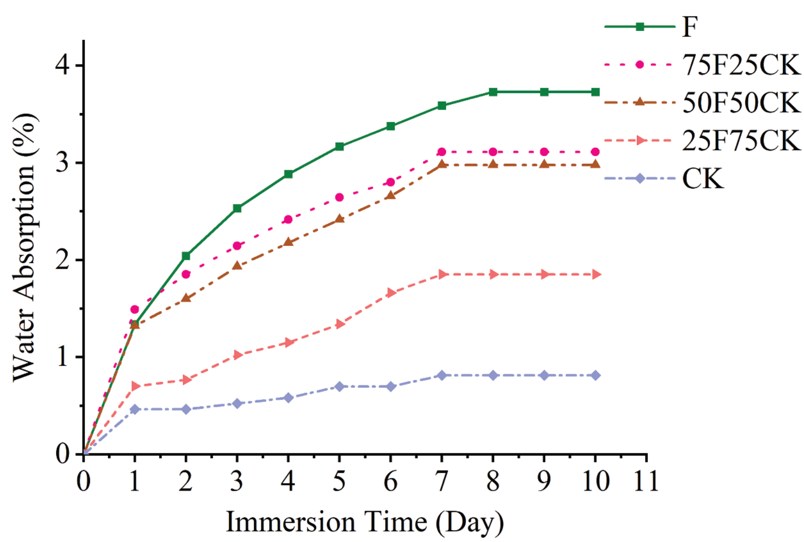

Figure 4. The water absorption of the composites.

tensile strength of the composite with a 25:75 ratio of flax to carbon/kevlar is 29.22% lower than that of the CK composite and 192.13% higher than that of the F composite. Recent studies conducted by Abd El-Baky et al. (2022) demonstrated that adding flax and basalt fibers to glass fiber composites significantly enhanced mechanical properties. Meenakshi and Krishnamoorthy (2018) research indicated that combining flax fibers with synthetic fibers resulted in a remarkable 87.44% increase in the tensile strength of the composite, from 44.68 MPa to 83.75 MPa. Additionally, Devaraju, and Harikumar (2021) observed that the tensile strength of the composite material increased with higher loading of synthetic fibers.

The graph in Figure 6 shows the tensile modulus of the composites. The findings reveal that the CK composite exhibits a higher tensile modulus than the F composite, with values of 13.01 GPa and 9.1 GPa, respectively. Incorporating carbon/Kevlar fabric and flax fabric improves the tensile modulus. Notably, the tensile modulus of the 75F25CK and 50F50CK composites is comparable to that of the CK composite, while the 25F75CK composite surpasses the tensile modulus of the CK composite. The results are consistent with the outcomes reported by Zhang, Li Zhang et al. (2013) and Kim and Song (2020), highlighting the enhancement of composite tensile modulus by reinforcing synthetic fibers Zhang et al. (2013). The lower tensile modulus of the F composite compared to the CK composite can be attributed to differences in chemical structure, molecular weight, and crystallinity between flax fiber and synthetic fiber. Flax fiber, a natural material primarily composed of cellulose, tends to have lower molecular weight and crystallinity than synthetic fiber. Consequently, natural fibers exhibit reduced

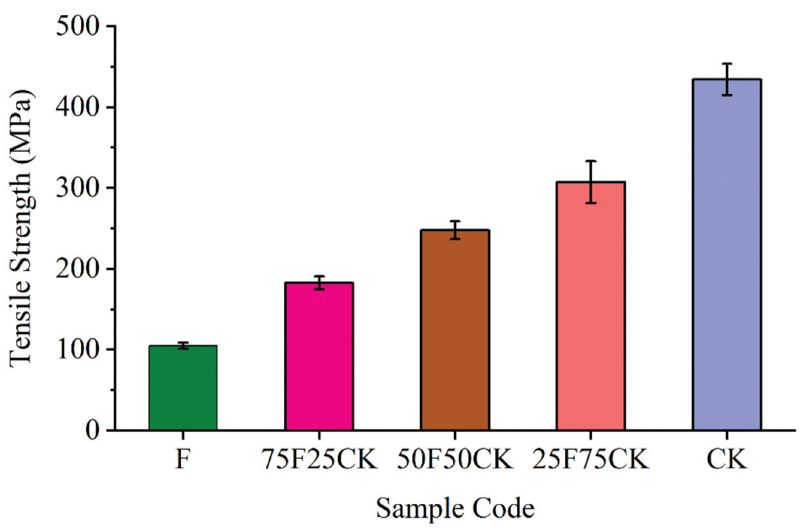

Figure 5. Tensile strength of the composites.

Table 5. Tensile strength of synthetic and natural fiber Bhadra and Dhar (2022); Binoj et al. (2016).

Fiber	Tensile strength (MPa)
Natural Fibers	
Flax	345–1035
Kenaf	930
Jute	393–773
Hemp	690
Synthetic Fibers	
E-Glass	200–3500
Carbon	2400–4000
Kevlar	3000–3150

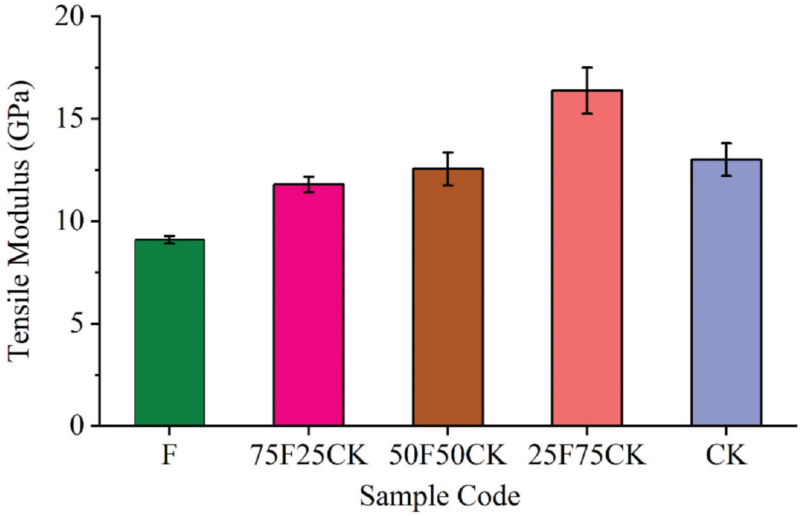

Figure 6. Tensile modulus of the composites.

stiffness and lower tensile modulus compared to synthetic fibers. It's important to note that the tensile modulus of a composite is not simply an average of the individual fiber modulus. Factors such as fiber-matrix interaction and fiber distribution within the matrix play crucial roles. The hybrid composite 25F75CK exhibits a higher tensile modulus than the CK composite, providing clear evidence of this phenomenon. The improved tensile modulus of the hybrid composite might be due to the enhanced bonding between the fiber and matrix, leading to a better ability to transfer stress. Moreover, the lower stiffness of natural fibers leads to deformation during loading, which facilitates better stress distribution.

Scanning electron microscopy (SEM)

Figure 7 illustrates the SEM images in the F composite, F/CK hybrid, and CK composite. In the SEM image, the tensile fracture of the F composite (Figure 7(a)) reveals longitudinal fiber break and transverse direction fiber pulling out. The adhesion between fibers and matrix significantly influences the mechanical characteristics of composites, with carbon/Kevlar fabric demonstrating superior fiber-matrix adhesion compared to flax fabric. In the case of the flax composite, the fiber is pulled out from the matrix along the longitudinal direction and the fiber breaks inside the matrix, indicating weaker adhesion between the fiber and matrix. On the other hand, the CK composite exhibited substantial stress transfer during the tensile test due to fiber breakage, indicating excellent adhesion at the fiber-matrix interface and leading to higher tensile strength. The SEM showed that the middle section of the hybrid composites consists of flax fabric, while the top and bottom sections are made of carbon/Kevlar fabric.

Impact strength

The data in Figure 8 demonstrates the impact strength composite from combining flax fabric with carbon/Kevlar. The study reveals the impact strength of the F composite is 11.94 kJ/m^2, whereas the CK composite exhibits a significantly higher impact strength of 69.03 kJ/m2. The CK composite demonstrates significantly greater impact strength than the F composite, with the CK composite being 5.8 times stronger than the F composite. The lower impact strength of the F composite is due to the inferior mechanical properties of flax fiber as well as insufficient adhesion between the fiber and

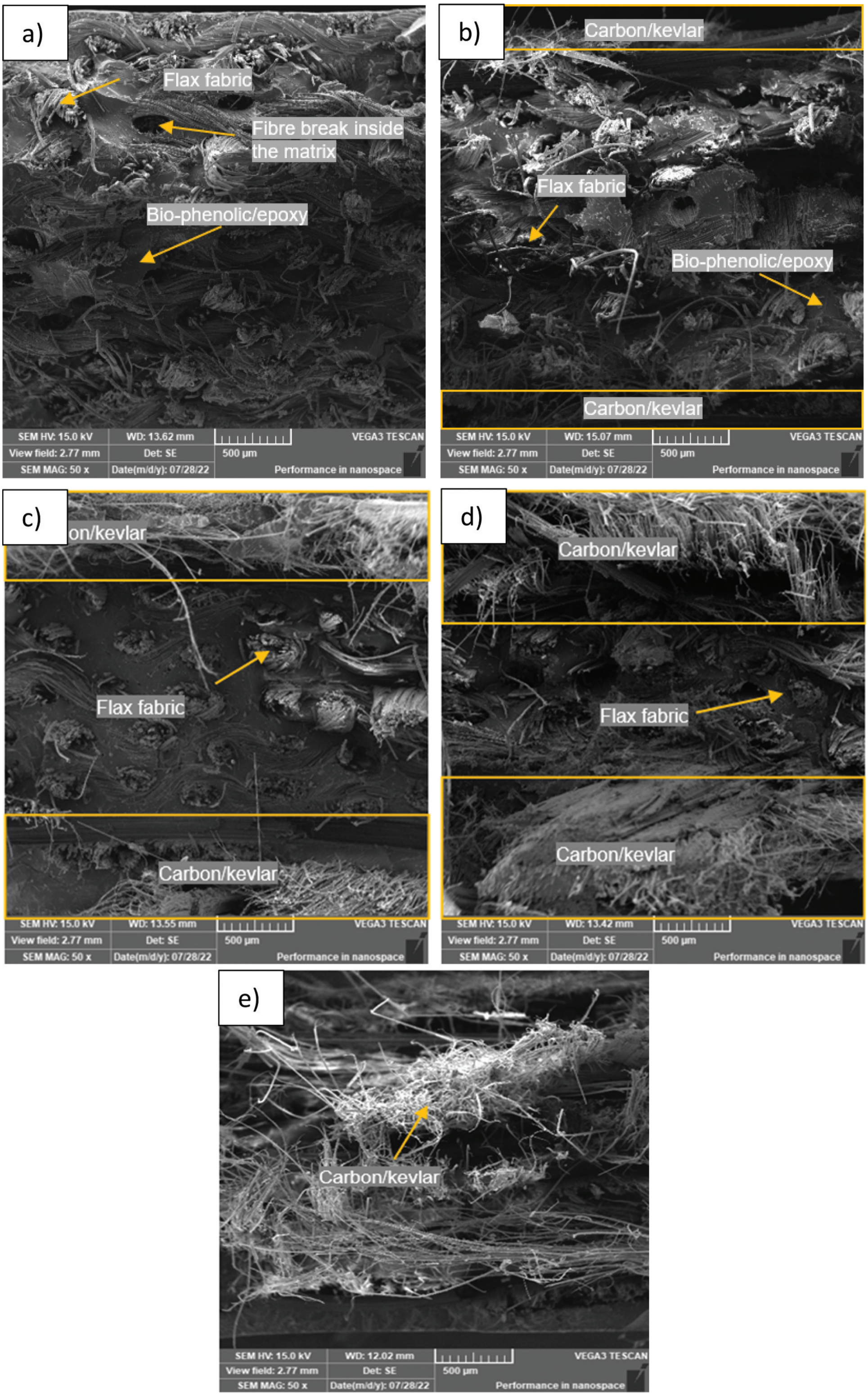

Figure 7. SEM of the tensile fracture surface of the composites: a) F, b) 75F25CK. (c) 50F50CK, (d) 25F75CK, (e) CK.

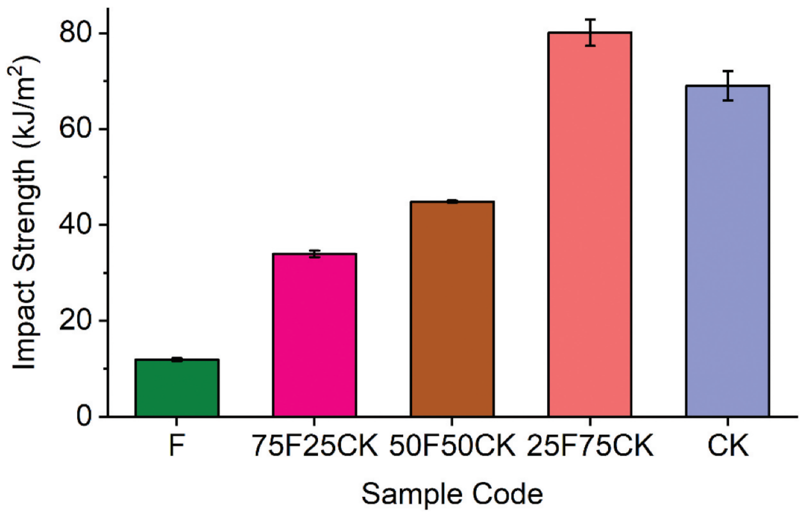

Figure 8. Impact strength of the composites.

matrix. The impact strength of the composite substantially increased with the introduction of carbon/Kevlar fabric into flax fabric due to the addition of stronger fibers.

Interestingly, when the ratio of flax fabric to Carbon/Kevlar fabric is set at 25:75, the impact strength exceeds that of the CK composite. The hybrid composite with a 25:75 ratio (F: CK) demonstrates an enhancement of approximately 16.05% compared to the CK composite. This improvement can be attributed to the incorporation of carbon/Kevlar fiber, which provides greater strength than flax fiber. The heightened impact strength of the 25F75K composite, surpassing that of CK, showed a positive hybrid effect. The relatively lower mechanical properties and weaker adhesion of flax fiber result in improved energy dissipation during impact. In contrast, the Carbon/Kevlar fiber prevents catastrophic failure of the composite, ultimately leading to increased impact strength. In addition, the lower stiffness of natural fibers helps dissipate energy and resist crack growth. When a crack starts to form, natural fibers can deform and absorb energy, which slows the crack's propagation. According to Flynn et al Flynn, Amiri, and Ulven (2016), breaking and pulling the fibers out of the matrix helps dissipate the energy during impact. Umapathi et al. Devaraju, and Harikumar (2021) discovered that increasing the glass fiber percentage of flax/glass composites enhances its impact strength. Meanwhile, Flynn et al and Ulven (2016) found that adding carbon fibers to flax composites significantly enhanced their impact strength. These studies indicate that the selection of fibers can substantially impact composites' impact strength. The superior impact strength of the hybrid composite 25F75CK results from the enhanced interfacial bonding between the fiber and matrix components.

Thermogravimetric analysis (TGA)

TGA provides valuable information about the relationship between a material's weight change and variations in temperature or duration. TGA quantifies mass loss under controlled temperature ramps, enabling assessment of thermal stability, material composition, and examination of physical, structural, and chemical changes that occur with increasing temperature Kalia, Kaith, and Kaur (2009). The influence of hybridizing flax fabric with carbon/Kevlar fabric on the thermal stability of the composites is demonstrated in Figure 9. The weight loss of the F composite occurs in two stages, while the hybrid composites and the CK composite display weight loss in three stages, as depicted by the DTG curve in Figure 10. The DTG curve of the F composite displays two peaks, whereas the hybrid composites and the CK composite exhibit three peaks. The weight loss process for the composites begins at temperatures between 100°C and 250°C. It's important to note that weight loss within this temperature range

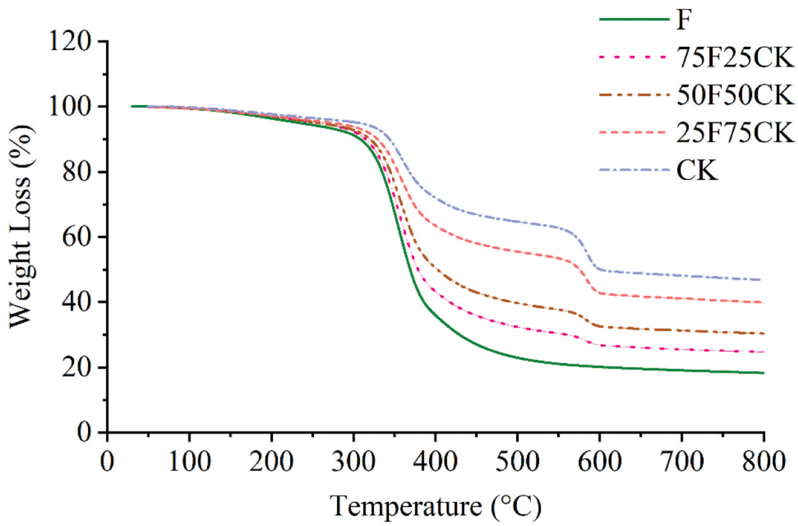

Figure 9. Weight loss versus temperature of the composites.

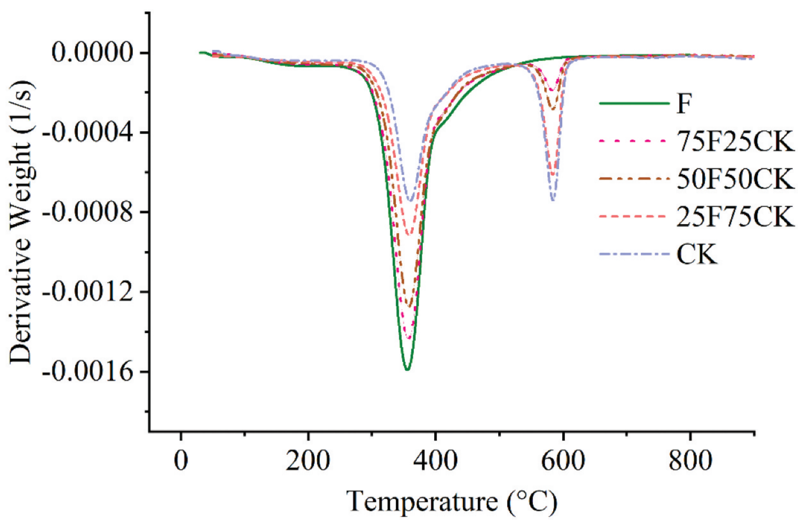

Figure 10. Derivative weight loss of the composites.

decreases as the Carbon/Kevlar fabric ratio increases. This phenomenon is attributed to the moisture and volatile content present in the composites during this temperature range Azhary et al. (2022); Dhakal et al. (2013); Monteiro et al. (2012). The presence of flax fabric, a natural fiber predominantly consisting of cellulose, hemicellulose, and lignin, is responsible for the moisture content in the composites. The cellulose and hemicellulose content particularly contribute to the higher moisture content in composites. Despite oven drying the fibers before manufacturing, completely removing moisture from the fibers is unattainable. It has been demonstrated that oven-dried flax fabric retains a higher moisture content than carbon/Kevlar fabric, registering at 7.20% and 2.33%, respectively. This was measured before the composites were fabricated. This aligns with the finding that the composite's moisture content decreases with increased carbon/Kevlar loading. In a study by Chee et al. Chee, Jawaid, and Sultan (2017), a similar trend was observed in weight loss for kenaf/epoxy composites and bamboo/epoxy composites at temperatures below 250°C. This weight loss was attributed to the

Table 6. Decomposition temperature for 5%, 25% and 50% of total weight loss of the composites and the residue at 800°C.

Type of composites	T (°C) at 5%	T (°C) at 25%	T (°C) at 50%	Residue at 800 °C (%)
F	235.83	341.68	383	18.45
75F25CK	258.83	346.68	378.83	24.77
50F50CK	257.67	352.17	402.5	30.44
25F75CK	275.50	363.33	575.5	39.96
CK	307.50	384.17	601.5	46.86

* Temperatures are given based on total weight lost at 5%,25% and 50%.

evaporation of moisture and volatiles. Similarly, Nurazzi et al (2020) documented a slight but discernible weight loss below 250°C, primarily attributed to moisture in the fibers.

The weight loss occurring in the composites between 250°C and 400°C is due to the decomposition and pyrolysis of the polymer matrix and fiber reinforcement, marking the second stage of weight loss Kumar et al. (2021); Saba et al. (2017). According to Thakur, Thakur, and Gupta (2014), natural fibers exhibit a decomposition temperature similar to that of polymer matrix. The finding indicates that raising the carbon/Kevlar ratio in the composite has led to a decrease in weight loss of the composites during the second stage. This outcome stems from the higher decomposition temperature of carbon/ Kevlar fabric than that of flax fabric. The hybrid composites and CK composite exhibit a tertiary weight loss stage at a temperature range of 525°C to 625°C. This corresponds to the decomposition of the Carbon/Kevlar fabric, with a proportional increase in weight loss observed with higher ratios of Carbon/Kevlar fabric.

The decomposition temperatures of the composites at different weight losses are presented in Table 6. As the ratio of carbon/Kevlar fabric increases, the decomposition temperature of the composites shows a corresponding increase at various weight losses. These results indicate that the carbon/Kevlar fabric ratio influences the thermal stability of hybrid composites. It is observed that the carbon/Kevlar fabric has a higher thermal degradation temperature than the flax fabric. Furthermore, an increase in the carbon/Kevlar fabric ratio within the composites leads to higher thermal stability of the materials, as evidenced by the higher residue at 800°C with increasing carbon/Kevlar fabric ratio.

Conclusion

In conclusion, this study demonstrates that combining flax with carbon/Kevlar in bio-phenolic /epoxy composites significantly enhances material properties. All fabricated composites' void content was less than 2%, indicating well-prepared composites. As the carbon/Kevlar content increased, the composites exhibited higher density, reduced water absorption, and improved tensile properties, impact strength, and thermal stability. Among hybrid composites, those with a 25:75 ratio of flax to carbon/Kevlar demonstrated the highest performance. When compared to carbon/Kevlar composites, the 25F75CK hybrid composites showed a 29% reduction in tensile strength. However, they exhibit notable improvements in tensile modulus and impact strength, with increases of 25.96% and 16.05%, respectively, compared to carbon/Kevlar composites. These findings suggest that a balanced combination of natural and synthetic fibers can optimize hybrid composites' mechanical and thermal properties, making them suitable for advanced applications requiring high performance and stability.

Disclosure statement

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