Assessments of Physical, Mechanical and Thermal Properties of Kenaf/ Cotton/ Polyester Fabric Reinforced Polyester Resin Composites: Differential Stacking Sequences

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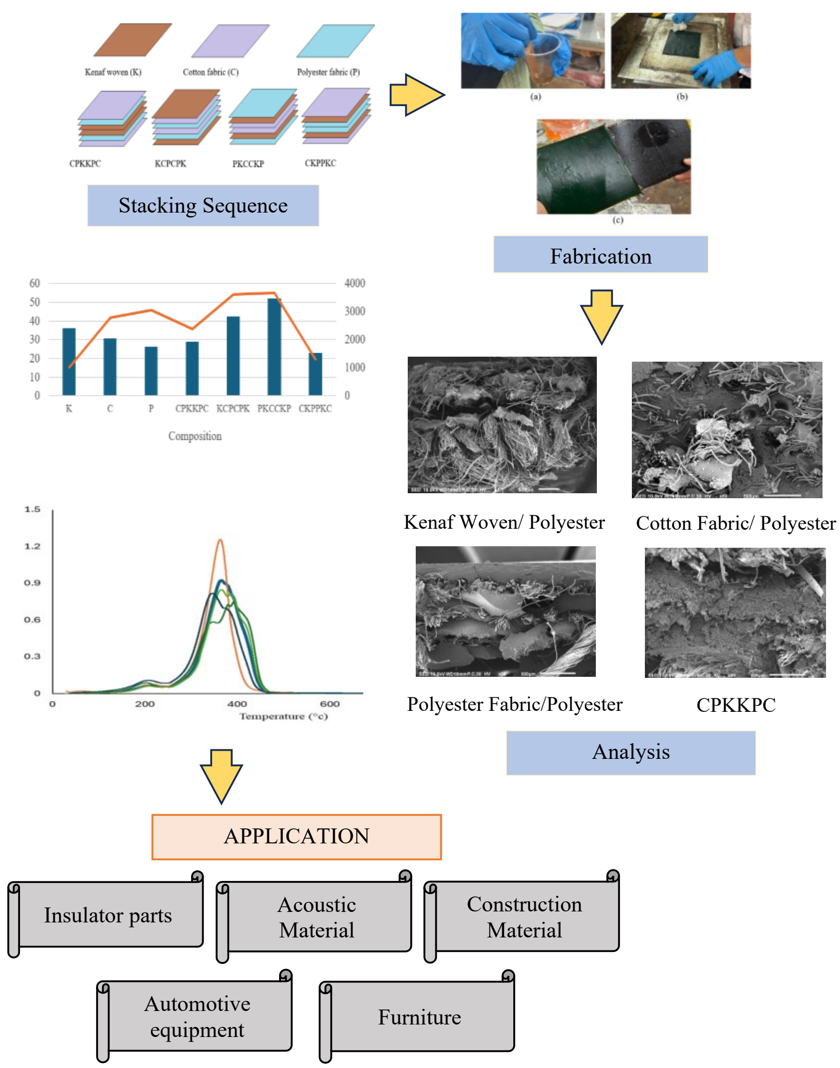
GRAPHICAL ABSTRACT



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A composite material was fabricated using a hand lay-up technique, incorporating layers of woven kenaf, cotton, and polyester fiber fabrics as reinforcement in a polyester resin matrix, arranged in a specific stacking sequence to enhance its properties performance. The composite material was compressed after the polyester resin was applied in the stacking sequence. Four stacking sequences were designed, and their influence on density, water absorption, moisture content, thickness swelling, tensile strength, flexural strength, and thermal stability was assessed. The PKCCKP sample also exhibited the lowest water absorption (1.99%), moisture content (1.42%), and thickness swelling (0.6%). Tensile and flexural strength attributes were enhanced when all three reinforcement materials were used together. The optimal stacking sequence for tensile, and flexural strength and modulus was with PKCCKP (52.1 MPa and 133.4 MPa). This improvement can be attributed to the excellent fabric adherence, with polyester fabric playing a significant role in the outside layer compared to the inside layer. All hybrid composite stacking sequences demonstrated good thermal stability, indicating their suitability for various eco-friendly applications. The choice of outer layers affected the durability and mechanical performance of composites for use in automotive, household, and structural applications.

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Keywords: Kenaf; Cotton; Polyester; Hybrid composites; Stacking sequence; Woven; Fabric

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INTRODUCTION

Natural fibers are increasingly being used as alternative reinforcements in composite production due to their comparable quality, ease of processing, wide availability, and low cost. Developments in natural and hybrid fiber reinforced composites highlight advances in hybrid stacking strategies and improved durability treatments, making them increasingly attractive for lightweight and sustainable applications. Natural fibers such as coconut, banana, kenaf, pineapple, sisal, and jute have been investigated for their suitability in composite polymer applications. The constant availability of this material has extended its application in the industrial business, including automotive, building insulators, and aerospace (Jawaid *et al.* 2022; Nadlene *et al.* 2016). Although this natural fiber material cannot always match synthetic fiber, it can be used in a wide range of applications. Natural sources that need surface treatment to get rid of the wax, lignin, hemicellulose, cellulose, and pectin compared to synthetic fiber do not need treatments. It is simple to make this type of fiber using woven, loose, and threaded fiber. In automotive manufacturing, natural fibers with various types of reinforced polymer have become among the essential components, notably in making door panels, seats, and car interiors. The automobile industry has conducted extensive studies on the usage of this natural material in vehicle parts (Kim *et al.* 2021; Zia *et al.* 2007). In several instances, using a single kind of natural fiber is insufficient to provide the necessary properties for the application (Jawaid *et al.* 2022; Madsen and Lilholt 2003). In such cases, hybrid composites made of two or three different types of fibers, such as natural fiber/natural fiber or natural fiber/synthetic fiber, need to be created.

Besides natural fibers, matrix materials such as biopolymers derived from renewable resources are also receiving growing interest in the manufacturing and research sectors as sustainable alternatives to conventional petroleum-based materials. Biopolymers are gaining traction across various applications due to their eco-friendly characteristics and potential to replace traditional plastics. Notable examples include biopolymers sourced from corn, starch-based materials like cellulose, and polyesters synthesized by bacteria (Mohanty *et al.* 2004; Miriţoiu *et al.* 2025; John and Bhattacharya 1999).

Consequently, researchers investigated the characterization of the composite hybrid's mechanical strength and physical properties using the composite hybrid method. The findings demonstrated that adding synthetic fibers to hybrid natural fiber composites can increase their potential (Bessadok *et al.* 2008; Ibrahim *et al.* 2015; Radzi *et al.* 2022). The adhesion of both materials between the fibers and the matrix polymer can be improved by combining these two types of fibers. Natural and synthetic fibers can be used together to create composite materials with the optimum qualities for a variety of goods, contributing to the development of more impactful and cost-effective composite technologies (Pramudi *et al.* 2021; Suhot *et al.* 2021; Das *et al.* 2021). Combining the two natural fiber materials often results in a weak effect and is not as commonly employed in practical applications. Rather, the use of some synthetic materials with natural resources has demonstrated remarkable performance. Using only half of the synthetic material as one of the fillers in the polymer matrix reduces cost, weight, and impact on the environment, which is the main problem with the overall use of this synthetic material (Rahman *et al.* 2024).

The research conducted by Ramesh *et al.* (2013) focused on sisal/jute/glass fiber reinforced epoxy hybrid composite and showed that the sequence of layers had a good impact strength. Furthermore, Prabhu *et al.* (2022) studied the mechanical characteristics of hybrid epoxy composites reinforced with glass, kenaf, and waste tea leaf fibers that had excellent results in terms of both mechanical and sound absorption. Combining natural and synthetic fiber hybridization techniques can lower the total material cost during product manufacturing while also enhancing the composite's physical characteristics (Jawaid *et al.* 2011, 2022; Soundhar *et al.* 2019). Therefore, the practical application of woven kenaf was the main topic of this study. Kenaf is becoming more and more popular in the manufacturing sector due to its excellent mechanical, physical, and thermal properties in composites. In fact, kenaf can be used to apply a variety of environmentally friendly items and can contribute to preserving a sustainable environment. Azlin *et al.* (2022) studied the stacking sequence and fiber content on the mechanical properties of woven kenaf-reinforced polyester hybrid composites. The results indicated that the properties of kenaf woven were enhanced by the addition of polyester fiber in the hybrid composites. The research results have shown that kenaf woven hybrid composites significantly affect the mechanical properties. Therefore, the study of stacking sequences revealed that the effect of different sequences can affect the properties of composite hybrids. The percentage of fibers depends on the thickness, size, weight and several layers because combining conventional fibers and polymers directly (individual fibers) is stronger than natural fibers. Apart from the study, Hanan *et al.* (2020) focused on the characterization of hybrid composites made from oil palm empty fruit bunch mats and kenaf woven fiber. According to these observations, since woven kenaf content in the composite is high, its application has a significant impact on mechanical qualities. This indicates that the woven kenaf's contribution will let it be utilized as a substitute for synthetic fiber. It is crucial to understand how the material performance varies with fiber orientation under specific loading conditions in order to select appropriate material attributes for a given application.

Different polymer matrices have been tested independently on woven cotton, polyester, and kenaf to produce a range of products. Regarding the three woven reinforced polyester hybrid composites in this study, there is still a great deal to learn. As a result, the creation of hybrid composites in different sequence layers for use in the transportation of materials such as automobiles and boats was the main goal of this work.

Overall, there has been limited research comparing natural and conventional composite fibers in terms of differential stacking sequences involving three types of woven fabrics kenaf, cotton, and polyester in hybrid composite systems. In particular, the role of more hydrophobic conventional fibers such as polyester, when positioned on the outer layers, compared to natural fibers, remains underexplored. This research aimed to fill this gap by systematically investigating the effects of different stacking sequences on the physical, mechanical, and thermal properties of kenaf/cotton/polyester fabric-reinforced polyester composites. It also sought to determine whether specific layer arrangements can enhance composite performance and provide optimized configurations suitable for lightweight, cost-effective, and semi-structural applications. The physical, mechanical, and thermal properties of woven kenaf, cotton, and polyester fabric-reinforced polyester hybrid composites have been investigated.

METHODOLOGY

Materials

The woven kenaf fiber (K) was purchased at Green Advantex Sdn. Bhd. (Malaysia) with a thickness of 0.57 mm, while the cotton (C) and polyester (P) fabrics, measuring 0.34 mm and 0.16 mm thick respectively, were obtained from Nagayo Textile and Fashion. Table 1 shows the stacking sequence of K, C and P hybrid composites.

Sample Preparation

The wet lay-up compression molding procedure was utilized to prepare samples of polyester hybrid composites. The polyester solution was created by combining polyester and hardener in a 10:1 ratio (Rajesh *et al.* 2016). The kenaf woven, cotton, and polyester fabrics were layered and impregnated with the polyester solution in the mold.

Table 1. Sequence of K, C and P Hybrid Composites

Composition	Designation
Kenaf woven	K
Cotton fabric	C
Polyester fabric	P
Cotton + Polyester + Kenaf + Kenaf + Polyester + Cotton	CPKKPC
Kenaf + Cotton + Polyester + Cotton + Polyester + Kenaf	KCPCPK
Polyester + Kenaf + Cotton + Cotton + Kenaf + Polyester	PKCCKP
Cotton + Kenaf + Polyester + Polyester + Kenaf + Cotton	CKPPKC

Each fabric layer kenaf, cotton, and polyester was individually wetted with polyester resin before placing the next layer to ensure even absorption and complete impregnation. This method was necessary to minimize the formation of air bubbles and to prevent weak interfacial adhesion between layers. The combination of K, C, P, and polyester resin was put into an aluminum mold (160 × 160 × 3mm), pressed with a cold press machine, and allowed to cure at room temperature for 24 hours. The hybrid composite designations and sample preparation for K, C, and P are shown in Table 1, and the stacking order is depicted in Fig.1 and Fig. 2.

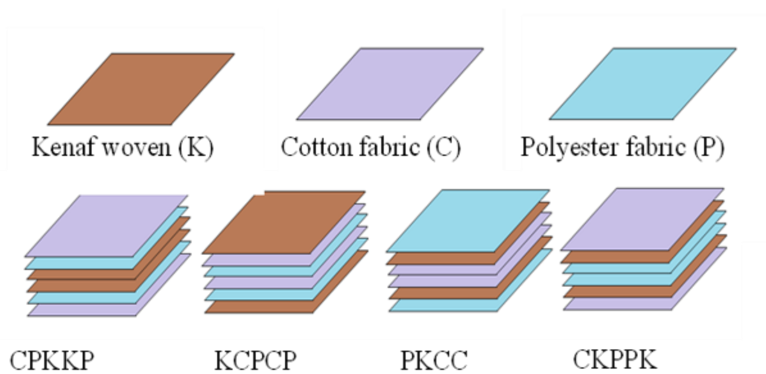

Fig. 1. Stacking Sequence of K, C and P hybrid composites

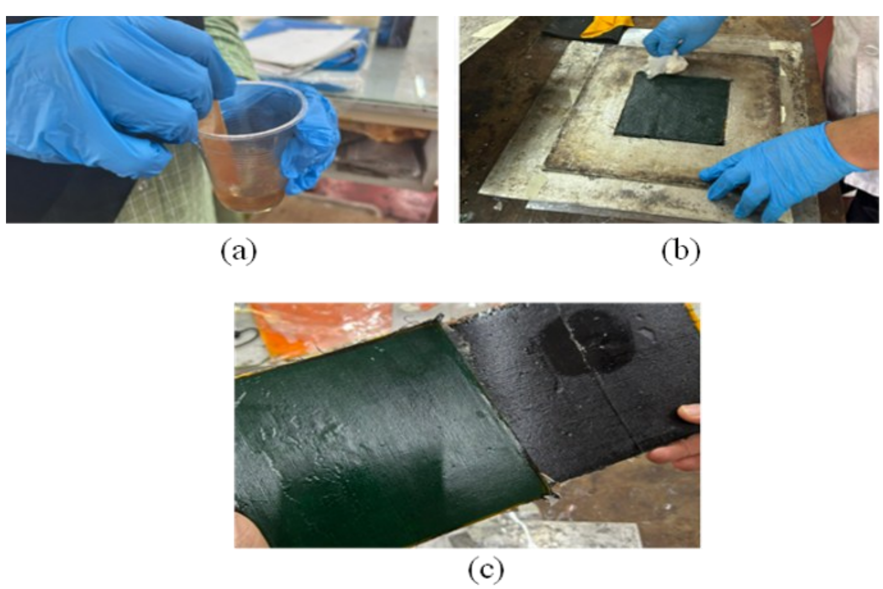

Fig. 2. Sample preparation of K, C and P hybrid composites

These specimens were cut from the cured composites into specific dimensions according to the standards for the density, water absorption, thickness swelling, moisture content, tensile, and flexural tests. Five samples for each composition were tested to calculate the mean value, with the standard deviation recorded to represent the error margin.

Density

The density of the polyester hybrid composites was measured according to the ASTM D792 (2007) using a Mettler Toledo balance. Five specimens were prepared for this assessment for each parameter of hybrid composites.

Water Absorption

The water absorption of the polyester hybrid composites was measured according to the ASTM D570 (1999) using a Mettler Toledo balance. The percentages of water absorption in kenaf/cotton/polyester woven reinforced polyester hybrid composites were calculated using Eq 1. Five specimens (10 × 10 × 3 mm) were prepared for this assessment for each parameter of hybrid composites. The samples were measured as W_0 and W_1 before and after a 24-hour immersion in water at room temperature:

$$Water\ Absorption, WA\ (\%) = \frac{W_1 - W_0}{W_1} \tag{1}$$

Thickness Swelling

All specimens were prepared following the procedures outlined in ASTM D570 standard method (1999). Five specimens (10 × 10 × 3 mm) were prepared for this assessment for each parameter of hybrid composites. The thicknesses of the samples were measured as T_0 and T_1 before and after a 24-hour immersion in water at room temperature using a Vernier caliper (Mitutoyo). The thickness swelling percentage was obtained using Eq 2.

$$Thickness\ Swelling, TS\ (\%) = \frac{T_1 - T_0}{T_1} \tag{2}$$

Moisture Content

The moisture content of the kenaf/cotton/polyester woven reinforced polyester hybrid composites was measured according to the ASTM D6980 using Shimadzi-MCO63u Balance. Five specimens (10 × 10 × 3mm) were prepared for this assessment for each parameter of hybrid composites.

Tensile Test

The tensile strength was determined using the INSTRON Universal Testing Machine. The tests were carried out in line with ASTM D638 standards (2001) using a crosshead speed of 5 mm/min (Das *et al.* 2021b). Five replicates' specimens were tested for each hybrid composite sample, and the mean value was reported.

Flexural Test

Flexural testing followed ASTM D-790 standards in the room (2002). The assessment was performed on the samples with 5 replications for each hybrid composite using a Universal Testing Machine (INSTRON 5556) with a 5 kN load; the crosshead speed was retained at 2 mm/min temperature (Thiagamani *et al.* 2022).

Field Emission Scanning Electron Microscopy (FESEM)

Morphological investigation of the composite fracture surface was carried out using Field Emission Scanning Electron Microscopy (TESCAN Brno.) The composite sample was coated with gold on the surface to obtain a clear image. This is to allow electrical charge to pass through the sample surface and avoid charge buildup due to electron firing that can distort the sample image. In addition, the working distance was set to 6.5 mm and the acceleration current used was 10 kV.

Thermogravimetric Analysis

Using a Q series thermal analysis machine model TA Instrument, thermogravimetric analyses (TGA) tests were conducted (TGA Q500) according to the ASTM E 1311 (2015). A temperature range of 30 to 600 °C and a heating rate of 10 °C were used for the analysis.

RESULTS AND DISCUSSION

Physical Test

Table 2 illustrates the density values of composite specimens and hybrid composites. The density average and corresponding standard deviation were determined from five samples for each composite composition. The polyester woven composites had the greatest density value (1.21 g/cm^3). This might explain why there was good compression pressure throughout the manufacturing process. Kenaf composites had the lowest density value of 1.14 g/cm^3 due to the matrix being merged in this form of composite specimen. In hybrid composites, KCPCP hybrid composites exhibited a maximum density of 1.23 g/cm^3. In contrast, the PKCCKP hybrid composites had the lowest density of 1.21 g/cm^3. This might be owing to greater adhesion between different fiber-stacking layers and the matrix.

Table 2. Density of Woven Kenaf, Cotton, and Polyester Composites and Various Stacking Sequences of Kenaf/cotton/polyester Hybrid Composites

Sample	Density (g/cm^3)	Standard Deviation
Kenaf woven	1.14	0.02
Cotton fabric	1.19	0.03
Polyester fabric	1.21	0.01
CPKKPC	1.15	0.01
KCPCPK	1.23	0.02
PKCCKP	1.21	0.01
CKPPKC	1.22	0.01

Figure 3 depicts the water absorption percentages of kenaf, cotton, and polyester, as well as different stacking sequences of kenaf-cotton-polyester woven reinforced polyester hybrid composites. The average water absorption and standard deviation were recorded from 5 samples for each composite composition. The water absorption of all composites had increased after 24 hours of immersion. In general, fiber reinforcing caused greater water absorption in polymer composites. Polyester woven composites had the lowest water absorption percentage, less than 1%. This was attributed to the nature of woven polyester, which was hydrophobic in these composites (Syafiq *et al.* 2020). Cotton composites had the lowest water absorption percentage of 6% among single-fiber woven composites compared to kenaf composites due to their excellent fiber-matrix bonding characteristics. Furthermore, the kenaf fiber as the outer skin layer of PKCCKP hybrid composites had the lowest water absorption percentage of 1.99%. The polyester matrix was well bonded throughout the polyester woven, kenaf fiber, and cotton fiber, preventing water molecules from accessing. However, the use of kenaf fiber as the outer skin of KCPCPK hybrid composites resulted in the highest water absorption percentage of 7.78% due to water molecules possessing the ability to quickly interact with the kenaf fiber surface and kenaf's hydrophilic characteristics (Al Rashid *et al.* 2020; Gwon *et al.* 2010; Mohamad Hamdan *et al.* 2019).

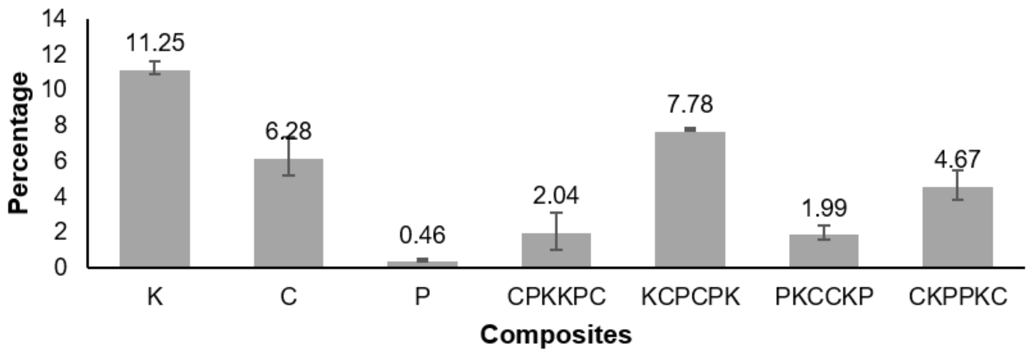

Fig. 3. Water absorption of K, C, and P composites and various stacking sequences of K/C/P hybrid composites

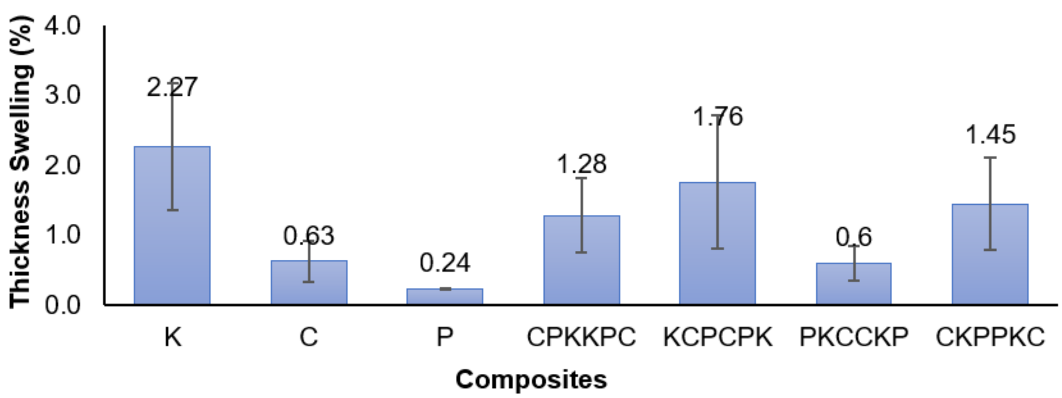

Fig. 4. Thickness swelling of woven kenaf, cotton, and polyester composites and various stacking sequences of K/C/P hybrid composites

Figure 4 shows the thickness swelling percentage of kenaf, cotton, and polyester woven composites, as well as the various stacking sequences of kenaf-cotton-polyester woven reinforced polyester hybrid composites. The average thickness swelling and standard deviation were recorded from 5 samples for each composite composition. The thickness swelling data revealed that the highest and smallest thickness swelling percentages of single fiber were recorded at kenaf composites (2.27%) and polyester woven composites (0.24%), respectively. For varied stacking, KCPCPK (1.76) had the greatest value, and PCKKCP (0.6%) had the lowest thickness swelling. This tendency was comparable to water absorption because it has very high fiber-matrix bond qualities. The disadvantage of the kenaf outer layer is that water molecules may interact fast with the surface of kenaf fibers due to the hydrophilic properties of kenaf (Mohammed *et al.* 2020; Siakeng *et al.* 2018). Table 3 shows moisture content of kenaf woven, cotton, and polyester fabrics and various stacking sequences of kenaf/cotton/polyester hybrid composites.

Table 3. Physical Properties (moisture content) of K, C, and P and Various Stacking Sequences of K/C/P Hybrid Composites

Sample	Moisture Content (%)	Standard Deviation
Kenaf	4.89	0.47
Cotton	2.54	0.39
Polyester woven	1.48	0.07
CPKKPC	1.53	0.36
KCPCPK	2.44	0.38
PKCCKP	1.42	0.18
CKPPKC	1.46	0.36

Tensile Test

Figure 5 shows the tensile strength and modulus of the difference in the stacking sequence of K, C, P, and hybrid composites. The tensile strength average and standard deviation were recorded from 5 samples for each composite composition. The highest value was recorded on the K composite of 36.4 MPa compared to the C and P composites. This strength was credited to the excellent adhesion between the filler and the matrix (Costa *et al.* 2017; Rihayat *et al.* 2018). In comparison to the C and P composites, the greatest value (36.4 MPa) was found on the K composite. The outstanding adherence of the filler to the matrix was the cause of this tensile strength.

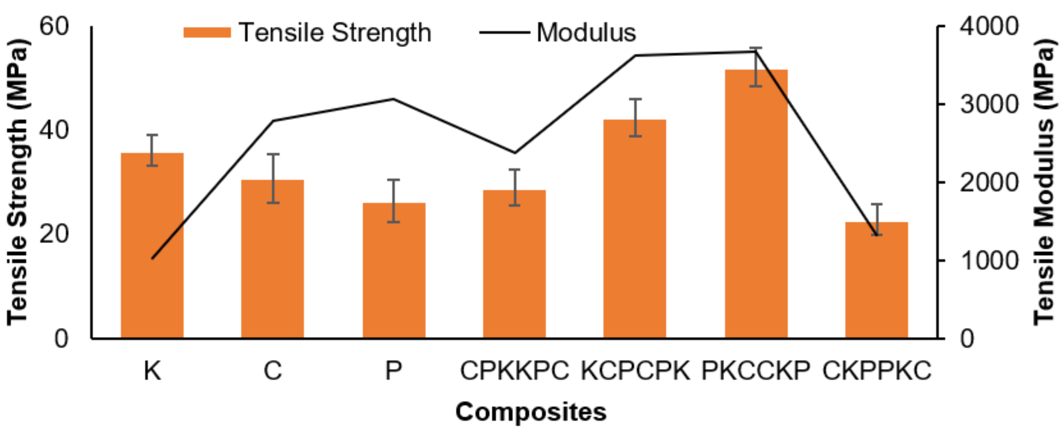

Fig. 5. Thickness swelling of woven kenaf, cotton, and polyester composites and various stacking sequences of K/C/P hybrid composites

As compared to other hybrid composites, the PKCCKP hybrid composite had a high tensile strength of 52 MPa upon observation of the hybrid composite sequence. The increase in tensile strength among the hybrid composites indicated that both adhesion and stacking sequence significantly impacted the performance of the composite hybrid.

Specifically, the increase in PKCCKP was attributed to the sequence arrangement, with P on the outer layers, followed by K and C in the middle. This stacking sequence of hybrid composite was a key factor contributing to the observed increase in tensile strength.

Thiagamani *et al.* (2019) stated that the strength of one type of fiber with the correct arrangement can compensate for the deficiency of another fiber to give the effect of enhanced properties. At 22.8 MPa, the CKPPKC hybrid composite had the lowest tensile strength. The second and fifth layers of K, supported by the outer layer P and the inner layer C, increased their adherence to one another and were responsible for the rise in tensile strength. In hybrid composites, the characteristics of one type of fiber can benefit other fiber to improve mechanical properties (Thiagamani *et al.* 2019). According to Azlin *et al.* (2022), the deficiency in mechanical strength due to surface adhesion, dimensional stability, and physical properties of a single fiber can be addressed by utilizing the composite hybridization technique. Therefore, Fig. 4 shows the tensile strength of hybrid composites increments when compared to single-fiber composites. The enhancement in tensile properties within the hybrid composite indicated that the integration of multiple fibers demonstrated a beneficial impact on the mechanical characteristics compared to the single-fiber composite. This figure also shows the modulus over K, C, P, and the hybrid composite stack sequence.

From observation, P-reinforced polyester composites had the highest recorded value compared to K and C composites, which was 3.1 GPa, and the K composite was the lowest at 2.8 GPa. This high modulus value was due to the adhesion compatibility of polyester woven reinforced with the same polymer as the matrix. The tensile modulus of K, C, and P, as well as the hybrid composite stack sequence, are also displayed in this figure. The P-reinforced polyester composites had the greatest recorded value of 3.1 GPa among K and C composites, while K composite had the lowest recorded value of 2.8 GPa. The adhesive compatibility of polyester fabric reinforced with the same polymer as the matrix contributed to this high tensile modulus. The PKCCKP layer was the highest in all hybrid composites with different layers compared to the other stacking sequence, which was 3.67 GPa. High tensile strength values in this layer sequence were similar to this pattern. This showed that PKCCKP hybrid composite had the potential to be used in various applications because its mechanical properties were very good and strong compared to other hybrid composites.

Furthermore, it demonstrated the excellent adherence and strength of the stacking sequence combination of these three materials (Hanan *et al.* 2020; Lee *et al.* 2021). At 1.3 GPa, CKPPKC had the lowest tensile modulus of the hybrid composite sequence layer. This composite hybrid's fragility was most likely caused by its unequal adherence. Additionally, cotton is comparatively softer than other materials, so the arrangement of cotton on the outside of the layer was inappropriate.

Flexural Test

Figure 6 displays the results of flexural tests for composites and hybrid composites. The flexural strength average and standard deviation were recorded from 5 samples for each composite composition.

According to the experiment's results, the C composites showed a strength value of 174 MPa, which was higher than the K and P composites. At 77 MPa, the K composite had the lowest tensile strength. Figure 6 displays the results of flexural tests for composites and hybrid composites. According to the experiment's results, the C composites had a strength value of 174 MPa, which was higher than the K and P composites. The K composite had the lowest flexural strength of 77MPa.

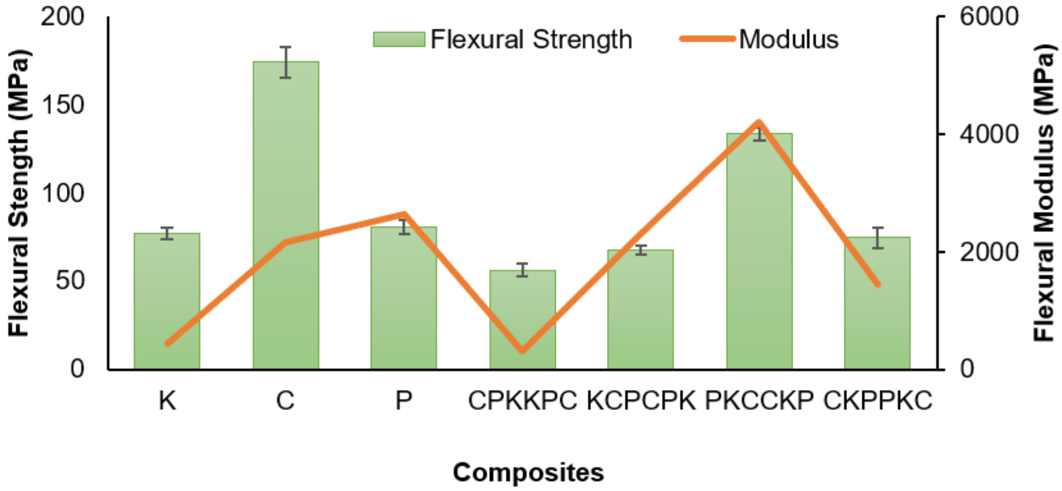

Fig. 6. Flexural strength and modulus of the difference in stacking sequence hybrid composites

For the stacking sequence of hybrid composites, PKCCKP was the highest for flexural strength, with a value of 133 MPa. This trend was similar to tensile strength, where this matching sequence had the highest value. The increase in flexural strength of the composite can be attributed to the matrix's ability to penetrate each layer, resulting in strong interlayer adhesion. Singh and Zafar (2022) reported that poor flexural strength occurs when the layers restrict matrix flow, leading to weak interfacial bonding and the formation of voids between the surfaces. In terms of flexural strength, CPKKPC had the lowest flexural strength, and its tensile strength was similarly quite low. The trend of the flexural strength element, which was great adhesion, and the outer layer's polyester fabric strength, which can withstand applied pressure, were the same factors that contributed to this growth (Chethan *et al.* 2019). The hybrid composite stacking sequence and the flexural modulus for each composite are also displayed in Fig. 6. Based on observations, the P composite had the highest modulus value (3.1 GPa), whereas the K composite had the lowest modulus (1 GPa). This trend showed similarities with the tensile modulus trend, where P composites were the highest, followed by C and K composites. Furthermore, the tensile modulus of all hybrid composites exhibited the same trend: PKCCKP had the highest flexural modulus (4.2 GPa), followed by KCPCPK (2.3 GPa), CKPPKC (1.4 GPa), and CPKKPC (0.3 GPa). The sample's outer layer determined how much the flexural modulus increments in value. Consequently, in comparison to other materials, the polyester fabric in the layer aids in improving the modulus (Baccouch *et al.* 2022; Shao *et al.* 2021). The core layer confirmed the significance of a composite stacking process. These two mechanical property tests revealed that the cotton fabric in the main core had a great influence, it has been shown in this study that cotton fabric was highly appropriate and had a favourable effect on the composite sample (Aruchamy *et al.* 2020; Zeeshan *et al.* 2021).

Morphology

Field Emission Scanning Electron Microscopy (FESEM) analysis was performed on the fractured tensile specimens to investigate the character of the hybrid composites.

The morphology difference between kenaf woven, polyester, and cotton fabrics needs to be investigated further to determine the effect of stacking sequence properties on the hybrid composite processability. Figures 7(a) and (b) show kenaf woven/polyester and cotton fabric/polyester, respectively. It was noted that in all stacking sequence composites, no delamination between layers was observed. Figure 7(b) further illustrates the impact of matrix cracking on the tensile strength of the laminates. Additionally, the interfacial bonding between the kenaf woven, cotton fabric, and polyester materials was found to be the strongest (Azlin *et al.* 2022). The woven kenaf/polyester composite failed due to fiber fracture, while the cotton fiber/polyester composite failed due to a combination of fiber pull-out, fiber fracture, and crack propagation into the matrix. The micrograph of the kenaf woven/polyester composite revealed a complex and convoluted course of crack propagation at the fiber/matrix interface. Additionally, numerous empty spaces can be observed following the fracture, indicating a significant occurrence of fiber pull-out. In Fig. 7(c), the crack in the polyester matrix extended to a polyester fabric, resulting in the separation of fibrils and a subsequent decrease in strength. This was judged to be the main cause of the decline in mechanical strength, where the transfer of stress from the matrix to the fibers becomes significantly weakened (Yahaya *et al.* 2016).

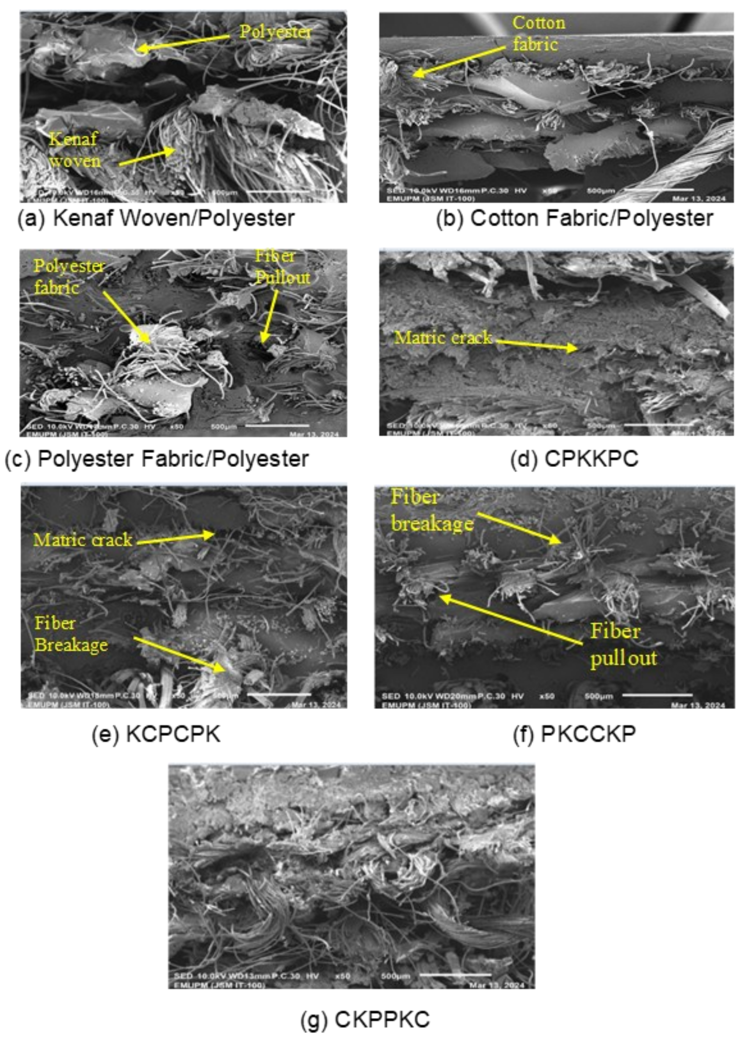

Fig. 7. Flexural strength and modulus of the difference in stacking sequence hybrid composites

Figure 7(d) depicts the extraction of kenaf fibers from the laminate. The fiber pull-out was clearly visible in Fig. 7(d) and 7(g) of the laminate. This is because the woven kenaf, which makes up a larger portion of the laminate, was unable to withstand the pulling force during the tensile test. The woven kenaf was a rigid material, and it exhibited the least elongation compared to the other laminates. Furthermore, laminates containing woven kenaf as the outer layer demonstrated a reduced tensile strength compared to other laminates, referring to Fig. 7(e).

Matrix cracking, fiber breakage, and fiber pull-out are the specific types of failure that can have a detrimental impact on the mechanical characteristics of composite materials. Nevertheless, Fig. 7(f) demonstrates the presence of sufficient interfacial bonding, which effectively transferred the stress generated in the hybrid laminated composites from the matrix to the fiber reinforcements.

The tensile strength of hybrid composites was significantly affected by the quality of interfacial bonding. Azlin *et al.* (2022) confirmed that optimizing fiber arrangement and enhancing interfacial adhesion are critical to improving mechanical performance and emphasized that further enhancements can be achieved through fiber surface treatments or matrix modifications to minimize fiber pull-out and control crack propagation. The tensile strength data was consistent with the micrograph shown in Fig. 7(f), which exhibited a higher tensile strength.

Thermogravimetric Analysis

One of the key procedures to determine the thermal resistance of composites is thermal stability testing using thermogravimetric analysis (TGA). Additionally, it is important to observe how the sample behaves at high temperatures and to verify that the composite can sustain a particular temperature during use. The presence of moisture, hemicellulose, lignin, and cellulose in K, C, and P composites and hybrids reinforced with polyester hybrid composites is a factor in this thermal evaluation. All sample composites were tested using temperatures between 27 and 900 °C with a 10 °C/min heating rate.

Figure 8 displays the thermogravimetric results of this experiment, whereas Fig. 9 displays the derivative thermogravimetric. The graph demonstrates the different phases of sample composite degradation, including the moisture evaporation phase, lignocellulosic decomposition, and the decompositions of cellulose, lignin, and ash. All composites exhibited moisture loss during the initial phase, known as moisture evaporation, which occurred between temperatures 27 and 100 °C (Azlin *et al.* 2022). Compared to other composites, kenaf composites had a relatively high moisture content loss during this phase because it is hydrophilic (natural) compared to other materials.

All composites underwent hemicellulose decomposition in the second phase between 150 and 220 °C (Arumugam *et al.* 2020). The exposure of the temperature range caused damage to the hemicellulose chain during this phase. The third degradation occurred between 310 and 400 °C (Abare *et al.* 2023; Azlin *et al.* 2022), where cellulose decomposition was followed by lignin and ash degradation. At this stage, the sample's weight loss was significantly lessened.

Overall, it is clear that the decomposition of each of these composites was quite complicated due to the influence of the test condition, the polymer's characteristics, and the thermal stabilities of different components.

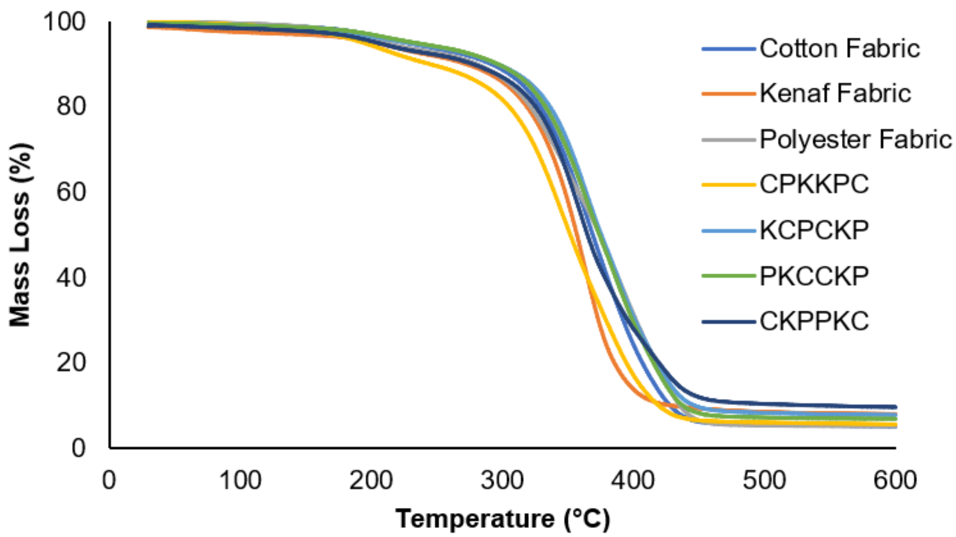

Fig. 8. TGA of woven kenaf, cotton, and polyester composites and various stacking sequences of K/C/P hybrid composites

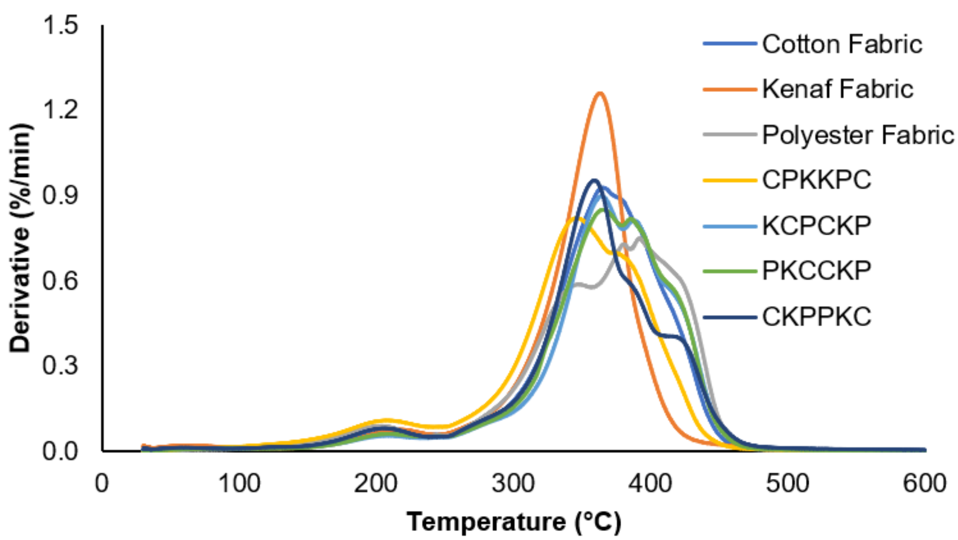

Fig. 9. TGA of woven kenaf, cotton, and polyester composites and various stacking sequences of K/C/P hybrid composites

Table 4. Thermal Degradation Analysis of Woven Kenaf, Cotton, and Polyester Composites and Various Stacking Sequences of K/C/P Hybrid Composites

	First degradation		Second degradation		
	T_{On} °C	T_{Max} °C	T_{On} °C	T_{Max} °C	Residue (%)
Cotton Fabric	157.23	207.27	326.46	363.31	5.059
Kenaf woven	184.97	215.13	327.23	364.14	7.565
Polyester Fabric	154.49	204.37	320.93	392.22	5.497
CPKKPC	150.63	207.91	309.63	345.37	5.428
KCPCKP	160.15	205.94	330.19	365.32	7.826
PKCCKP	162.54	206.72	326.5	366.07	7.198
CKPPKC	150.63	204.44	309.63	360.32	9.544

CONCLUSIONS

1. The study investigated the effects of combining kenaf, cotton, and polyester fabrics in various stacking sequences on the mechanical, physical, and thermal stability of composite materials. Among the configurations tested, the PKCCKP sequence—where polyester fabric formed the outer layers and natural fibers (kenaf and cotton) were positioned at the core—demonstrated the most favorable performance. This arrangement resulted in the lowest moisture content (1.42%), water absorption (1.99%), and thickness swelling (0.6%) among the hybrid composites. These findings can be attributed to the hydrophobic nature of polyester, which resists water uptake more effectively than the hydrophilic kenaf and cotton fibers. Additionally, the PKCCKP hybrid composite achieved the highest tensile and flexural strengths at 52.1 and 133.4 MPa, respectively. The enhanced mechanical properties were primarily due to strong interfacial adhesion between layers and the protective, structurally supportive role of polyester on the outer surfaces.
2. Morphological analysis indicated that the stacking sequence composite showed superior interfacial adhesion, particularly between kenaf, cotton, and polyester layers, contributing to enhanced mechanical properties. The presence of fiber pull-out, matrix cracking, and poor stress transfer especially in laminates with kenaf as the outer layer—was linked to reduced tensile strength.
3. The thermal analysis showed that the hybrid composite stacking sequence demonstrated good thermal stability. The decomposition behavior of the composites was influenced by several factors, including test conditions, polymer characteristics, and the thermal properties of the fibers. Differences in fiber type and layer arrangement led to varied degradation responses. Overall, the results indicate that the hybrid composites can withstand elevated temperatures, making them suitable for thermally demanding applications. The hybrid composites developed in this study are well-suited for automotive interior pares, household, furniture, and packaging applications. The incorporation of natural fibers also offers a more sustainable alternative to conventional synthetic materials.

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