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ORIGINAL RESEARCH

Hybridization of woven kenaf and unidirectional glass fibre roving for unsaturated polyester composite

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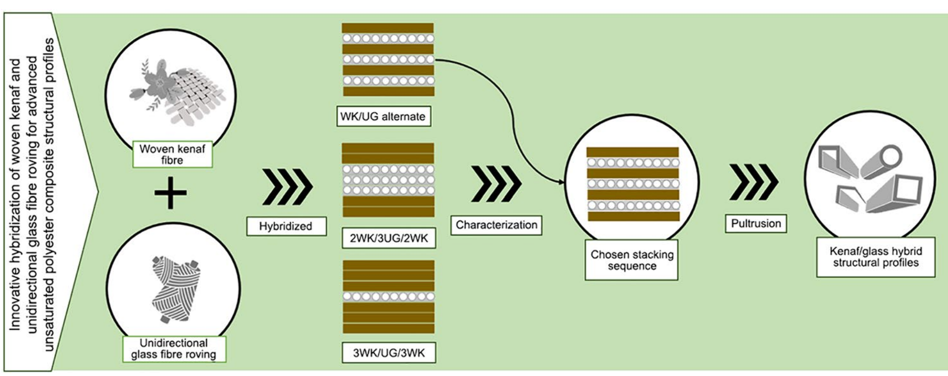
Abstract

This is a study on the mechanical properties of kenaf/glass-reinforced polyester composites intended for use in structural profiles with a wall thickness by max. 6 mm. Mechanical properties such as tensile, compression, bending and interlaminar shear stress were investigated by comparing the hybrid variants with the pure fibreglass variant. According to the study, woven kenaf/unidirectional glass roving (WK/UG) alternate recorded the highest tensile properties among hybrid samples. It demonstrated a decrement of about 8.2% of the tensile strength (404.54 MPa) and 10.7% of tensile modulus (24.54 GPa) compared to conventional fibreglass samples. Alternating WK/UG samples demonstrated higher compressive strength (417.15 MPa) compared to other hybrid specimens, recording a slight decrease at 6.09% compared to pure fibreglass composites. The highest bending properties were also observed in hybrid alternate WK/UG samples among other hybrid laminates with only a decrement of 4.13% in modulus of rupture (456.33 MPa) and 1.9% in modulus of elasticity (14.49 GPa) when compared to the control specimen. The ILSS of hybrid composites 2WK/3UG/2WK (30.97 MPa) and WK/UG alternate (34.90 MPa) showed good agreement with the pure fibreglass (42.33 MPa) composites. Using SEM images, tensile fractured specimens were examined to comprehend composites' failure mechanism and interfacial adhesion. Overall, woven kenaf/unidirectional glass roving alternate sequence is chosen as a potential alternative in developing structural profiles for moderate load-bearing structural applications. In contrast, 3WK/UG/3WK with a higher kenaf to glass ratio demonstrate potential in low load-bearing structural profile applications.

Graphical abstract



Keywords Plant fibre composites · Fibreglass composites · Hybridization · Structural profiles · Mechanical properties

Extended author information available on the last page of the article

Introduction

Throughout history, structural profiles have found their foundations in various materials, including stalwarts like steel, aluminium, wood, and fibreglass composites (Fig. 1) [1, 2]. These versatile materials have played pivotal roles in shaping beams, columns, trusses, and other load-bearing components across diverse sectors encompassing construction, aerospace, marine, and automotive industries. Extrusion and pultrusion manufacturing processes have traditionally shaped these profiles [3–5]. However, the mounting concerns about current materials, such as cost, weight, and ecological sustainability, have spurred a compelling shift in research and industry circles. For instance, wood may be prone to decay, insect infestation, and has limited load-bearing capacity; aluminium and steel can be heavy, prone to corrosion, and require extensive energy for production; fibreglass composites may face challenges in recyclability and can be relatively expensive compared to traditional materials in certain applications, limiting their cost-effectiveness. This shift has driven a compelling exploration into innovative alternatives, particularly by embracing the inherent benefits of plant fibres like kenaf, flax, jute and hemp [6]. As these plant fibres progressively emerge as viable contenders, they offer the potential to redefine structural profiles, infusing a new era of lightweight, efficient, and sustainable materials into sectors that have traditionally relied on established materials and processes.

Recent research has focused on advancing plant fibre-based composite materials, exploring innovative approaches to enhance their mechanical properties. For instance, Thimmaiah et al. [7] research has focused on hybridizing fibre-reinforced composites using Kenaf and Kevlar fabrics in unsaturated polyester matrices with varying proportions. The study has employed Taguchi's method and artificial neural networks to analyze and predict the tribological behaviour of the laminates, offering insights into wear rates and microstructural changes under different operating conditions. Shariff et al. [8] have introduced an epoxy-based hybrid composite incorporating Millettia pinnata leaf powder, alumina/boron nitride particles, and glass sheets, improving mechanical properties. Optimal composition, with 6 g each of boron nitride and Millettia pinnata leaf powder, demonstrated superior tensile strength (312.21 MPa), flexural strength (19.53 MPa), impact strength (53.68 kJ/m^2), and hardness (103.25 HRL), offering valuable insights for industrial applications. Arpitha et al. [9] have developed hybrid epoxy-based composites using banana and glass fibres, utilizing banana fibres as a cost-effective and eco-friendly reinforcing material. The composite with alternating layers of banana and glass fibres, along with 1% (by weight) charcoal, exhibits superior mechanical properties, including the highest tensile strength (80.9 N/mm^2), flexural strength (145.4 N/mm^2), impact strength (3.5 kJ/m^2), and hardness (56 VH), making it a promising candidate for lightweight applications in automobile and structural domains. According to Khandaker et al. [10], jute caddies, a by-product of jute spinning industries, were successfully transformed into dry fibre preforms for thermoplastic composites. The resulting composites, composed of 40% jute fibres and 60% polypropylene matrix, exhibited significantly improved flexural properties, particularly when chemically modified with binders such as polyvinyl alcohol, demonstrating a sustainable and effective approach for repurposing jute industry solid waste in semi-structural composite applications.

Kenaf fibres, industrially grown in Malaysia, have proven their potential to be an eco-friendly alternative to synthetic fibres in developing composites for various applications [11, 12]. Compared to other natural fibres, kenaf fibres have greater stiffness, strength, and availability, which is why they were used in composite production [13]. Water absorption, strength degradation, and lack of thermal stability are just a few of the major disadvantages of natural fibre composites over synthetic ones. As a result, it has been discovered that hybridization with either natural or synthetic fibre can improve and overcome these issues. Hybridizing kenaf fibre with glass fibres has become a potential solution to overcome the limitations through the advantages that the fibres can offer independently, such as mechanical properties and economic value [14–16]. Chetan et al. [17] investigated the tensile and bending strength of hybrid composites prepared from E-glass, woven jute and kenaf as epoxy resin reinforcements. The results indicated that hybrid laminates made from kenaf and glass fibres have superior mechanical properties to those made from jute and glass fibres and that the number of glass plies could further enhance these properties. Another study was conducted on the mechanical properties of hybrid composites with chicken eggshell powder

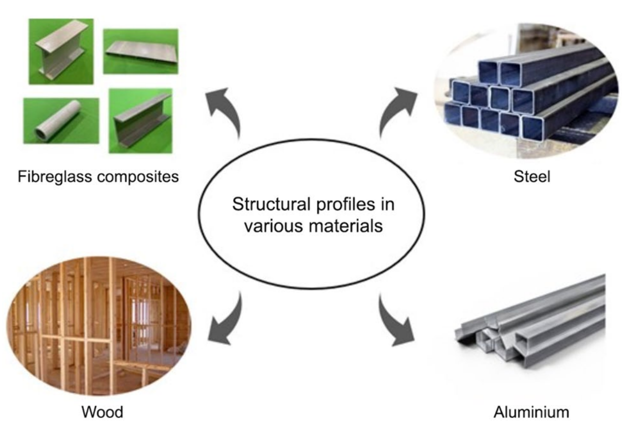


Fig. 1 Stacking sequence of kenaf/glass hybrid composites and pure fibreglass composites

as a filler and alternate layers of glass and kenaf fibres in epoxy resin [18]. The mechanical properties were compared by varying the weight percentage of kenaf and eggshell filler while maintaining the weight fraction of E-glass at 5%. Better tensile and bending properties were obtained in the composition of 5% (by weight) glass fibre, 15% (by weight) kenaf fibre, and 9% (by weight) eggshell filler among other samples. In a study conducted by Mohapatra et al. [19], the tensile strength of the kenaf and palmyra palm leaf stalk fibres increased when glass fibres were added, but the composites bending strength decreased. In addition, compared to palmyra palm leaf stalk/glass fibre hybrid composites, the glass fibre hybridized kenaf fibre composites have demonstrated superior tensile properties.

Unsaturated polyester composites are a class of versatile and widely used materials combining unsaturated polyester resin with reinforcing fibres such as fibreglass, offering excellent strength, durability, and corrosion resistance for various applications, including construction, automotive, and marine industries. Few research works have been reported on the properties of hybrid kenaf/glass-reinforced unsaturated polyester (UPE) composites. The studies on hybridization of kenaf and glass fibres as reinforcements of unsaturated polyester are highlighted in this literature. Atiqah et al. [20] studied the bending, tensile and Izod impact strength of kenaf/glass-reinforced UPE composites. The researchers found that hybrid composites with 15/15 v/v kenaf-glass fibres underwent a three-hour mercerization treatment with 6% sodium hydroxide to improve their mechanical strength. Zhafer et al. [21] stated that higher tensile properties were achieved at fibre loading up to 10% kenaf/10% glass fibre in kenaf/glass-reinforced UPE composites. The study highlighted that a higher volume fraction of glass fibres significantly improved the tensile properties of hybrid laminates due to the high strength and modulus of glass fibres compared to kenaf fibres. According to Zakaria et al. [22], hybridized kenaf/glass-reinforced UPE composites have shown better bending strength and bending modulus when compared to pure kenaf-reinforced composites. Mohaiman et al. [23] stated that increasing kenaf fibre to woven kenaf/glass fibre-reinforced UPE composite reduces tensile strength. However, the compressive strain of hybrid composites was increased by adding kenaf layers to hybrid composites. Jamal et al. [24] hybridized kenaf fibres with recycled glass fibres as reinforcements in UPE composites. The recycled glass/kenaf fibre composites recorded a higher tensile strength than pure kenaf composites, with a slight decrease in value compared to virgin glass/kenaf composites. However, the highest bending strength is observed in the recycled glass/kenaf hybrid with respect to pure kenaf and glass/kenaf composites.

Salleh et al. [25] investigated the water absorption effects on the mechanical properties of long kenaf/woven glass fibre-reinforced UPE composites. The study highlighted the decrement of fracture toughness of the composites due to moisture absorption. Similarly, Ghani et al. [26] investigated the tensile properties of long kenaf/woven glass fibre-reinforced UPE composite immersed in distilled water, seawater, and rainwater (acidic solution) at room temperature. The study revealed that the hydrogen bonds between the water molecules and the cellulose fibre deteriorated the tensile properties. Bassam et al. [27] mentioned that the dielectric strength of kenaf/glass-reinforced UPE composites was higher than that of pure glass fibre-reinforced UPE composites. The burning effect demonstrates that natural fibres have superior insulating properties, so bundled kenaf close together increased dielectric strength. Moreover, the researchers also conducted another study analyzing the effect of moisture absorption on the bending properties of kenaf/glass/UPE rods [28]. The study revealed that when the hydrophilic fibre was concentrated at the centre of a cross-section of the composite rod, the arrangement of the fibre in the composite preserved the bending strength of pultruded hybrid composites. A study was conducted by analyzing the vibration-damping factor of glass/kenaf/UPE hybrid composites, and the findings indicated that increasing kenaf fibre content increases the vibration-damping factor and decreases the elastic modulus and stiffness of the hybrid composite [29]. Generally, as the percentage of glass fibre increased, the vibration-damping factor decreased proportionally.

During the manufacturing process or the useful life of the material, defects are created in composite structures. As a result, when designing structures, failure mechanisms must be considered. Some common failures that generally appear inside the plies are transverse cracking and fibre breakages between the plies, which is delamination [30]. A significant loss in mechanical properties is seen in delamination, which causes the layers to separate to form a mica-like structure [31]. Atiqah et al. [20] conducted impact testing on kenaf/glass UPE composites and analyzed the failure modes. Defects like fibre tearing, pulling out, debonding, and cracking were observed on the fracture surfaces. The researchers also claimed that the mercerization process enhances the fibre-matrix adhesion and significantly improves the hybrid composites mechanical properties. Additionally, Verma et al. [32] stated their findings on glass/kenaf hybrid composites where fibre breakage, debonding and fibre pull-out were identified as the primary fracture mechanisms of hybrid composites.

The study is driven by the aspiration to explore and establish the feasibility of woven kenaf fibres as an alternative to conventional fibreglass mats in structural profile manufacturing. The over-arching motivation lies in advancing sustainable materials for structural applications, aiming to enhance eco-friendliness, reduce production costs, and provide a lighter and more environmentally conscious option for diverse structural products. The identified gap in the existing research lies in the limited exploration and characterization of woven kenaf/unidirectional glass fibre-reinforced hybrid unsaturated polyester composites, specifically in the context of structural profile applications. While previous studies have touched upon various aspects of plant fibre and glass fibre-reinforced composites, there is a noticeable scarcity of literature addressing the mechanical properties and failure modes of this hybrid combination, particularly for wall thicknesses up to 6 mm. This preliminary research aims to bridge this gap by conducting a comprehensive investigation, systematically varying stacking sequences of woven kenaf and unidirectional glass-fibre rovings to develop open and closed-section structural profiles. According to industrial experts, fibreglass structural profiles primarily consist of two key components, woven glass fibres and unidirectional glass-fibre rovings. Woven fibres are used as the outer layers, while unidirectional rovings serve as the core of structural profiles to ensure dimensional stability. The application of woven kenaf fibres as a potential substitute for conventional fibreglass mats in structural profile manufacturing introduces a novel approach to enhance sustainability, reduce manufacturing costs, and offer a lighter alternative for various structural products. Through this work, we aim to provide practical insights into the mechanical performance of these hybrid composites, contributing valuable knowledge to the field of sustainable materials for structural applications.

Experimental

Materials

Kenaf mats (WK) were purchased locally in Lembaga Kenaf danTembakau Negara (LKTN), Kota Bharu, Malaysia, and glass-fibre bobbins and glass-fibre mats were purchased from Shandong Fibreglass Group Co., Ltd., Linyi, China. The matrix material used for the study was selected as an unsaturated polyester resin, which is curable at room temperatures. Unsaturated polyester resin is well known for economical composite manufacturing while offering good mechanical, electrical and chemical properties [33]. It is highly affordable and easily handled compared to other thermoset resins like vinyl esters and epoxies. The resin and hardener were mixed in the weight ratio of 10:1, per the manufacturer's specification.

Composite fabrication

Woven glass fibres (WG) and unidirectional glass rovings (UG) are conventionally used to manufacture fiberglass structural profiles. The expensive and highly dense woven fiberglass is used by industrial players with the stacking sequence of WG/UG alternate. Therefore, this research has used woven kenaf fibres as a substitute for woven glass fibres to develop lighter, cheaper, and sustainable hybrid composites for structural applications. However, this preliminary study used hand layup followed by compression moulding to prepare the samples instead of pultrusion to reduce the manufacturing cost and time. Hence, three different stacking sequences of woven kenaf/unidirectional glass fibre composites were fabricated considering the traditional pultrusion setup (Table 1 and Fig. 2). In Fig. 2, WK is represented by brown filling while grey filling with circle embedded and solid grey filling represent UG and WG respectively. The overall best-performing hybrid sequence will be used to develop structural profiles for further investigation. Kenaf fibres were chemically treated with a 5% sodium hydroxide (NaOH) solution to enhance the fibre-matrix adhesion. The fibres were treated at room temperature for 8 h, washed in clean water, and dried under hot sun for 48 h. The overall fibre/matrix ratio was fixed at 55/45. Calcium carbonate and aluminium hydroxide were used as fillers at 40% of the total resin weight to improve the composites' mechanical properties. All the samples were controlled with seven layers of plies and a thickness of about 6 mm.

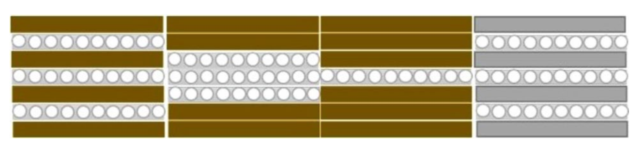


Fig. 2 Schematic showing stacking sequence of different composites

Table 1 Stacking sequence of kenaf/glass hybrid composites and pure fibreglass composites

Samples	Stacking sequence	Weight percentage (% by weight)	
		Kenaf content	Glass content
WK/UG alternate	WK/UG/WK/UG/WK/UG/WK	45	55
2WK/3UG/2WK	WK/WK/UG/UG//UG/WK/WK	45	55
3WK/UG/3WK	WK/WK/WK/UG/WK/WK/WK	81.7	18.3
WG/UG alternate	WG/UG/WG/UG/WG/UG/WG	0	100

Tensile and compression tests

Tensile and compression tests were carried out for the kenaf/glassfibre reinforced hybrid composites and glass-fibre composites (control). The procedures were conducted for the tensile test following the ASTM D-638, and the crosshead speed was set at 5 mm/min. The ASTM D-695 standard was used for the compression test, and the crosshead speed was 1.3 mm/min. Tensile tests were performed using a universal testing machine, Zwick/Roell Z400. The tensile specimen dimension was 165 mm × 19 mm × 6 mm. Compression tests were carried out using the universal testing machine Instron 5582. The specimen dimension for compression testing was 79.4 mm × 19 mm × 6 mm. Five samples from each composite were tested in each test, and the average value was determined and recorded. The tensile strength and tensile modulus were recorded from the tensile test, whereas the compressive strength and compressive modulus data were obtained from the compression test.

Bending test

The bending test was conducted utilizing INSTRON 5567 (Institute of Tropical Forestry and Forest Products (INTROP)'s Biocomposite Laboratory, Universiti Putra Malaysia, Malaysia). The samples were subjected to a three-point bending test using the ASTM D 790 standard. At 2.5 mm/min, the crosshead speed remained constant. The standard specimen length is 120 mm for a thickness of approximately 6 mm, and the standard specimen width is 25 mm, with the specimen length being approximately 20% longer than the support span. The standard span-to-thickness ratio is 32:1.

Interlaminar shear strength test

Interlaminar shear strength properties of the composites were tested using ASTM D-2344. The crosshead speed was set at 1 mm/min. The samples were prepared with dimensions of 40 mm × 13 mm × 6 mm. The test was conducted using the universal testing machine Instron 5967.

Interlaminar shear strength was calculated as per the following equation [34, 35]:

$$F^{sbs} = 0.75 \times \frac{P_{max}}{b \times h} \quad (1)$$

where F^{sbs} is the short-beam strength (MPa), P_{max} is the maximum load observed during the test (N), b is the measured specimen width (mm), and h is the measured specimen thickness (mm).

SEM analysis

A scanning electron microscope was used to examine the laminated tensile fractured composites morphology. The tested 3–4 mm samples were cut from the fractured zone. The specimens were subjected to high-resolution scanning electron microscopy (SEM) analysis on the fracture surface using a COXEM EM-30AX PLUS with a 20 kV voltage acceleration from the Institute of Tropical Forestry and Forest Products (INTROP) Biocomposite Laboratory at Universiti Putra Malaysia, Malaysia. In order to enhance sample imaging, a gold coating was applied to the samples.

Results and discussion

Tensile properties

Parameters such as fibre strength, modulus, adhesion between fibre and matrix, fibre geometry, and weave type significantly impact laminated composites tensile properties. Figure 3a shows the tensile strength and modulus of different laminated composites. Pure fibreglass/reinforced laminates have shown the highest tensile strength (440 MPa) and modulus (28 GPa) among four different laminates. Similar values have been recorded for hybrid WK/UG alternate and 2WK/3UG/2WK laminates. The hybrid laminates recorded

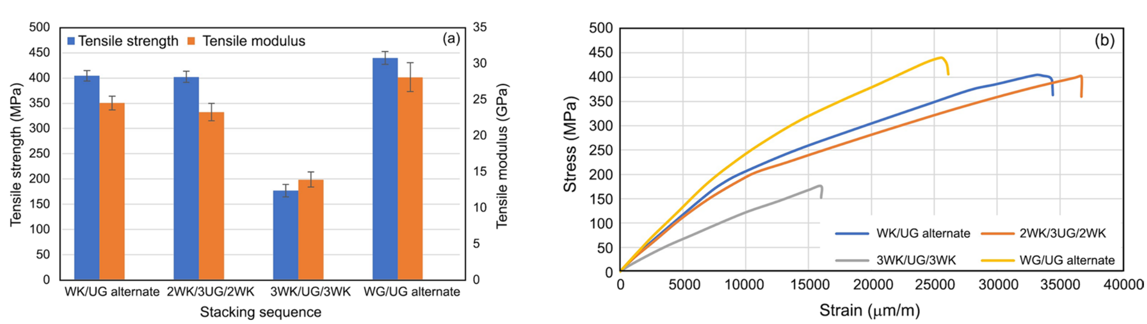


Fig. 3 **a** Tensile properties, and **b** tensile stress–strain profile

slightly lower tensile strength and tensile modulus than pure fibreglass composites. This is due to the higher tensile properties of individual glass fibres compared to the kenaf single fibre. However, hybrid specimen 3WK/UG/3WK has recorded the lowest tensile strength and tensile modulus at 177 MPa and 14 GPa, respectively.

As shown in Fig. 3b, comparable curvature of stress–strain profiles is observed in tensile behaviour. The graph shows a linear increment up to failure. The brittle behaviour of the composites is explained when the plot suddenly drops once the samples achieve ultimate tensile strength. When the peak load is achieved, all the samples are fractured in a brittle behaviour. The plot also identifies that pure fibreglass composite attained the highest stiffness compared to the hybrid specimens. However, among the hybrid samples, WK/UG alternate laminates showed better stiffness than 2K3UG2K and 3KUG3K laminates. The load is applied in the direction of fibres, and the properties of single fibres determine the composites tensile strength and modulus. The experimental results indicate a trend of decrease in tensile strength and tensile modulus as the volume percentage of glass fibres decreases and is replaced with kenaf fibres. However, satisfactory values of tensile properties have been recorded by WK/UG alternate and 2WK/3UG/2WK laminates at around 404 MPa and 25 GPa, respectively. The results indicate that the fibre volume fractions assigned for kenaf and glass rovings for the laminates are adequate for tensile applications with only 8.2% strength degradation compared to pure fibreglass composites. Tensile modulus determines the ability of samples to resist deformation with respect to the load applied.

Besides that, tensile modulus is also used to evaluate the stiffness of the composites. From the results, hybrid specimens (WK/UG alternate) recorded a slight decrease in tensile modulus at 10.7% from fibreglass specimens. Hence, the kenaf and glass composition at 41.7% and 58.3%, respectively, is suitable for moderate load-bearing structural profile application with satisfactory mechanical strength and stiffness. The outcome has proven that woven glass fibres can be effectively replaced with woven kenaf fibres in the conventional pultrusion setup for low and moderate load-bearing applications.

The failure modes for tensile specimens are evaluated through visual inspection. All the samples resulted in fibre breakage and delamination upon failures (Fig. 4). However, none of the samples broke into two pieces during the tensile test. The WK/UG alternate and WG/UG alternate samples have shown similar failure modes. The kenaf mats and glass mats used in the samples have gone through fibre breakage. However, transverse cracking has only happened to the mats as the glass roving plies have resisted the crack growth through the composites. This is due to the higher strength properties of the unidirectional glass roving against transverse loading compared to bidirectional fibre mats. The direct roving plies that prevent the crack from growing from one end to the other ensure the stress is well distributed in the alternating sequences in WK/UG and WG/UG samples. Fibre breaking, fibre pull-outs and transverse cracking were observed in kenaf mats in 2WK/3UG/2WK samples and 3WK/3UG/2WK samples. However, there is no delamination observed between the kenaf-kenaf interface. In all the samples, delamination only occurred between the kenaf-glass interface. This might be due to the different tensile properties of the kenaf and glass fibres, which caused differences in elongation during tensile loading, resulting in delamination between them.

Compressive properties

A compressive test was carried out to study the effect of stacking sequences on the compressive properties of the hybrid composites, and the results are presented as shown in Fig. 5. Compressive property is attributed to fibres in the composites, which provide more excellent load-bearing capability and resistance to the applied compression load. Besides fibre strength, the compressive properties of composites are also influenced by the matrix strength, the fibre/matrix interface and stacking sequences.

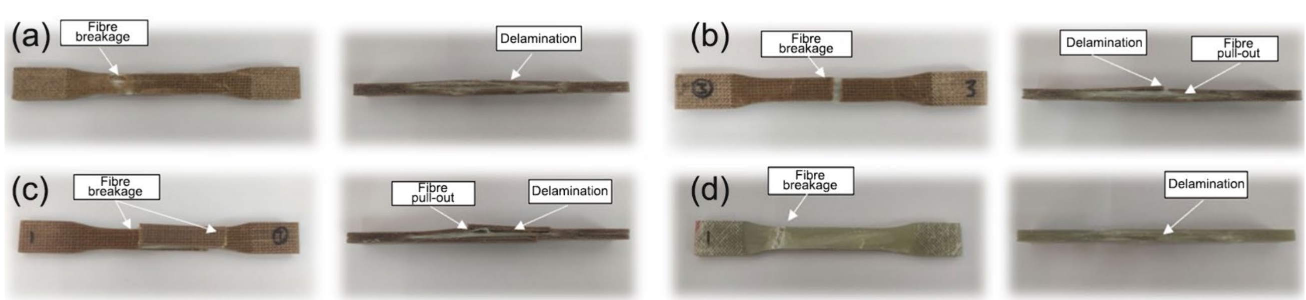


Fig. 4 **a** WK/UG alternate tensile coupon, **b** 2WK/3UG/2WK tensile coupon, **c** 3WK/UG/3WK tensile coupon, and **d** fibreglass tensile coupon (WG/UG alternate)

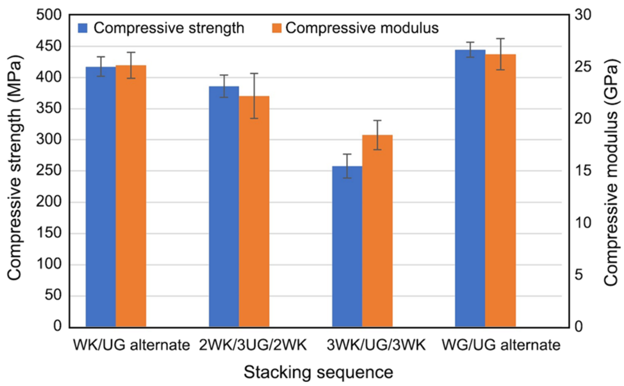


Fig. 5 Compressive properties

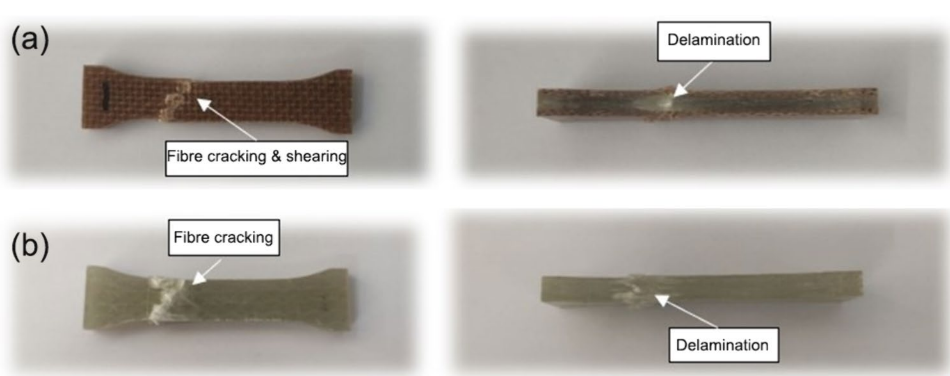
Woven kenaf/unidirectional glass alternate samples have recorded the highest compressive strength (417.15 MPa) among other hybrid specimens. The alternating sandwich specimen recorded a slight decrease in strength value at 6.09% compared to the control WG/UG specimen (444.21 MPa). The high values of the non-hybrid composites are supported by a study conducted by Rajpurohit et al. [36], where the glass fibre samples acquired a thickness of 1.2 mm and recorded compressive strength of 316 MPa. According to Batu et al. [37], among the hybrid false banana/glass fibre reinforced epoxy composites, ones with alternate stacking sequences recorded higher compressive strength when compared to the 2 glass/3 banana/1 glass stacking sequence. This is possibly due to the good interfacial adhesion and fibre interlocking between the plant and glass fibres in the hybrid composites. Plant fibre composites generally exhibit lower compressive properties compared to fiberglass composites due to the inherent characteristics of plant fibres [38]. The woven kenaf fibres have lower stiffness and strength compared to the high-performance glass fibres commonly used in fibreglass composites. Additionally, the plant fibres may have irregularities and structural variations, leading to less uniform stress distribution within the composite, thereby reducing compressive strength.

On the other hand, the highest compressive modulus is achieved by WG/UG alternate at about 27 GPa, followed by WK/UG alternate and 3WK/UG/3WK hybrid specimens at about 25 GPa. The lowest tensile modulus is recorded by 3WK/UG/3WK, which alternates at 18.45 GPa.The compressive strength and modulus are reduced as the composites' kenaf to glass fibre ratio increases. Kenaf fibres have a less ordered and densely packed atomic structure than glass fibres, leading to lower stiffness and strength. However, when kenaf fibres are hybridized with high-stiffness material glass fibres, the resulting composite exhibited improved mechanical properties compared to kenaf fibres alone. Based on the visual inspection, the damage induced in WG/UG alternate samples is lower than in other samples. This is explained by the highest tensile modulus recorded by the samples, as shown in Fig. 5. Hence, both samples are better at resisting deformation at high compressive loads. However, failure modes such as fibre cracking, fibre micro buckling, local fibre micro buckling with an elastic matrix, and shear failure are observed in 2WK/3UG/2WK and WG/UG alternate samples (Fig. 6). The failure modes correlate with the composites' fibre/matrix adhesion [39].

Bending properties

Bending properties are vital in designing structural profiles. Structural profiles are subjected to bending force, which combines compressive and tensile stresses. The stacking sequence heavily influences the laminated hybrid composites' bending properties, typically involving the positioning of woven kenaf mats and direct roving glass fibres. Figure 7 depicts the modulus of rupture and modulus of elasticity of various stacking sequences. Pure fibreglass non-hybrid laminates (control) recorded the highest modulus of rupture (476 MPa) and modulus of elasticity (14.77 GPa) compared to other specimens. The hybrid sample WK/UG alternate yielded the highest modulus of rupture (456.33 MPa) and modulus of elasticity (14.49 GPa) among other hybrid laminates. The alternate specimens varied with only a 4.13% modulus of rupture and 1.9% modulus of elasticity reduction

Fig. 6 **a** 2WK/3UG/2WK compressive coupon, and **b** fibreglass compressive coupon (WG/UG alternate)



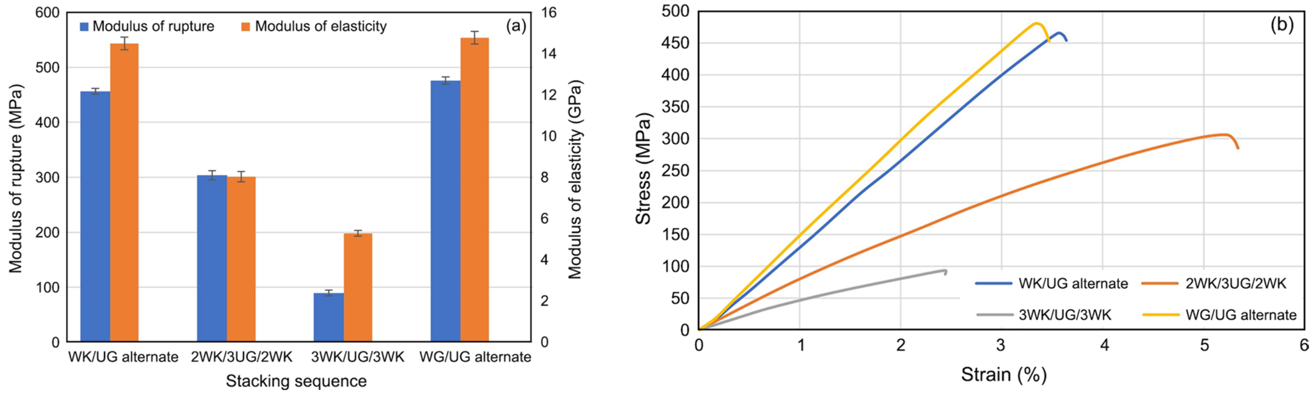


Fig. 7 **a** Bending properties, and **b** bending stress–strain profile

with respect to pure fibreglass composite. The woven kenaf mats' dense, tight fibre architecture and lignin content improved the composites' bending strength and resistance. The hybrid laminate, 3WK/UG/3WK, recorded the lowest modulus of rupture and modulus of elasticity among all the laminated composites. The experimental results indicate that the stacking sequence is essential in determining the bending properties of hybrid laminates. Hence, alternate woven kenaf/unidirectional glass laminates will be a potential candidate for bending applications by effectively replacing conventional pure fibreglass laminates in structural profile applications.

The failure modes observed in the composite samples are fibre breakage and delamination (Fig. 8). All the samples demonstrated failure at the tensile region. This is because the higher compressive modulus of kenaf fibres in hybrid composites (Fig. 5) has reduced deformation at the compressive region. Similar damage modes are observed in WK/UG alternate and WG/UG alternates where fibre breakage happens in the first ply at the tensile region of the composite samples. Delamination was observed in WG/UG alternate between the first ply (woven glass mat) and second ply unidirectional glass rovings. In 2WK/3UG/2WK hybrid samples, fibre breakage was displayed by the first two plies of woven kenaf mats at the tensile region. The samples also experienced delamination in the unidirectional glass rovings, which served as the core of the hybrid composites. Similarly, the first three plies of kenaf mats experienced fibre breakage in 3WK/UG/3WK samples.

Interlaminar shear strength

The short beam bending test determined the hybrid and control samples' interlaminar shear strength (ILSS). The short beam is subjected to bending and shear stress during the three-point bending test when a load is applied in the thickness direction. Another crucial mechanical test that provides information about the quality of the resin-fibre bond is the interlaminar shear strength (ILSS). Yahaya et al. [40] claimed that interlaminar shear cracking, micro buckling, fibre rupture, and a combination of the failure modes lead to ILSS.

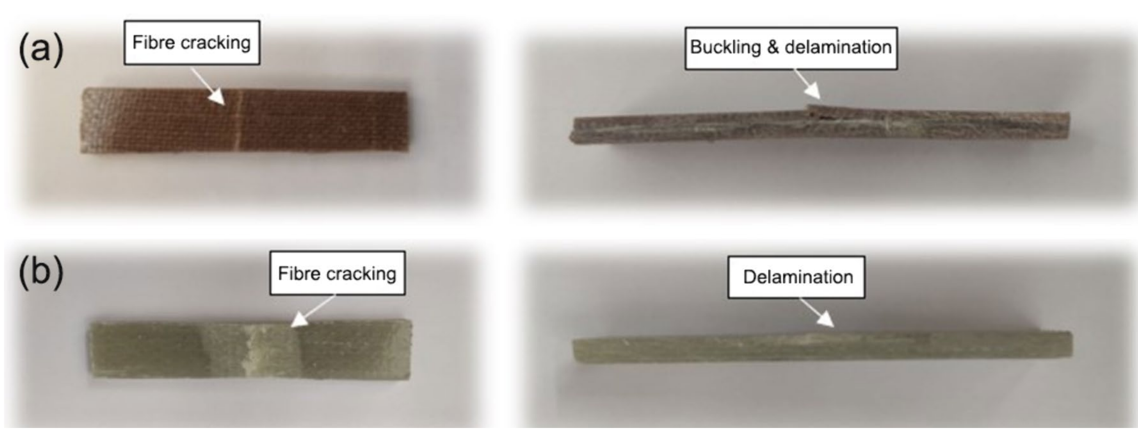


Fig. 8 **a** 3WK/UG/3WK bending sample, and **b** fibreglass bending sample (WG/UG alternate)

As shown in Fig. 9, the highest ILSS is recorded in the non-hybrid control sample, the alternate WG/UG (42.33 MPa). The higher ILSS of the composite with higher glass fibre content is attributed to the better wetting of the glass fibres by the polyester matrix, leading to better fibre/matrix adhesion in the composites than hybrid samples. However, among the hybrid samples, WK/UG alternate (34.9 MPa) scored the highest ILSS, followed by 2WK/3UG/2WK samples (30.97 MPa) with a minor value difference. However, the ILSS is significantly reduced for hybrid 3WK/UG/3WK (13.97 MPa) composites. The results demonstrate a comparable range of values compared to the ILSS results of other plant fibre compositesin the most recent studies. Some examples are bamboo-reinforced epoxy (20.4 MPa) recorded by Rajabipour et al. [41]; jute/glass-reinforced epoxy (26 MPa) recorded by Alves et al. [42]; and jute/banana reinforced phenol formaldehyde (5.21 MPa) by Prashanth et al. [42]. From the previous investigations, plant/glass fibre-reinforced hybrid composites show higher ILSS values when compared to composites hybridized between two different plant fibre reinforcements. Notably, ILSS is significantly reduced as the volume fraction of kenaf increased in 3WK/UG/3WK. This is probably due to the poor wetting between the kenaf-kenaf region with more than one ply thickness in the composites. Hence, separating the kenaf mats and direct roving with a single layer of kenaf mats improved the interlaminar shear properties in the WK/UG alternate. This modification likely addresses the challenges associated with poor wetting and enhances the uniformity of matrix infiltration into the kenaf layers, leading to improved fibre-matrix adhesion. Alves et al. [43] reported similar work, where they studied the ILSS of jute/glass-reinforced hybrid epoxy composites. The researchers reported that fracture occurred between jute layers due to the lower shear strength between the jute-jute interface. This finding aligns with the current study, emphasizing the critical role of interlayer interfaces in determining the interlaminar shear properties of hybrid composites. It further underscores the importance of thoughtful design in layer arrangement to optimize the overall mechanical performance of the composite material. The higher ILSS values suggest improved resistance to interlaminar shear forces, indicating a more robust interfacial bonding between the plant and glass fibres and the matrix. The effective load transfer and stress distribution achieved through this hybridization strategy result in a composite material that can withstand shear forces more efficiently.

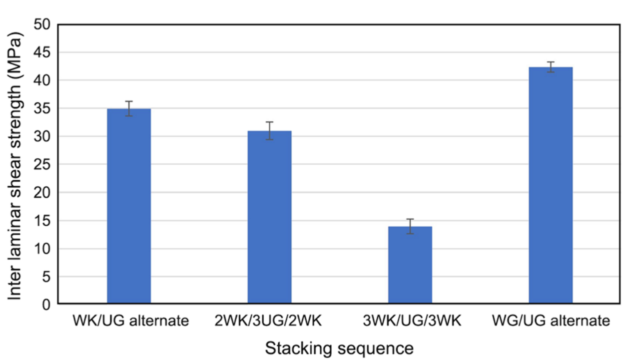


Fig. 9 ILSS properties

SEM analysis

Microstructural analysis of the tensile fractured specimens was studied. The specimen morphology and fibre-matrix interfacial adhesion were examined using scanning electron microscopy (SEM). Under tensile load, the most common failure modes for woven kenaf/unidirectional glass roving reinforced hybrid composites are matrix deformation, fibre breakage, microcracks, voids, and fibre pull-out. From WK/UG alternate samples (Fig. 10a), it is highlighted that the fracture in glass fibre rovings was relatively uniform and belonged to brittle failure [44]. The observation suggests that the glass fibres underwent a sudden and catastrophic breakage. However, kenaf fibres were seen disoriented while demonstrating a ductile fracture. Ductile fractures are characterized by plastic deformation and the ability of a material to undergo significant elongation before failure. The disoriented fracture pattern in kenaf fibres indicates that they underwent extensive deformation and stretching, contributing to the composite's ability to absorb energy before ultimate failure. This ductile behaviour can be attributed to the intrinsic properties of natural fibres like kenaf, which often exhibits good toughness and flexibility. The kenaf mats demonstrate a dense and tight fibre architecture, resulting in comparable tensile properties with conventional pure fibreglass composites. Besides, the chemically treated kenaf fibres demonstrate a rougher surface texture, ensuring good fibre-matrix adherence [45, 46]. The rougher surface provides more sites for mechanical interlocking and increases the surface area available for effective adhesion between the fibres and the matrix. This improved bonding is essential for ensuring the efficient transfer of loads between the reinforcing fibres and the matrix during mechanical stress, ultimately leading to enhanced mechanical properties and structural integrity of the composite material. According to Nayak et al. [47], chemical treatment eliminates undesirable substances in plant fibres, such as lignin and waxy materials. This process enhances fibre texture and quality, subsequently improving bonding between the fibre and matrix within treated composites.

The kenaf-matrix, kenaf-glass, and kenaf-kenaf interfacial adhesion are good in every hybrid variant. However, the experimental results show that the kenaf-glass interface in WK/UG alternate performs better than the kenaf-kenaf

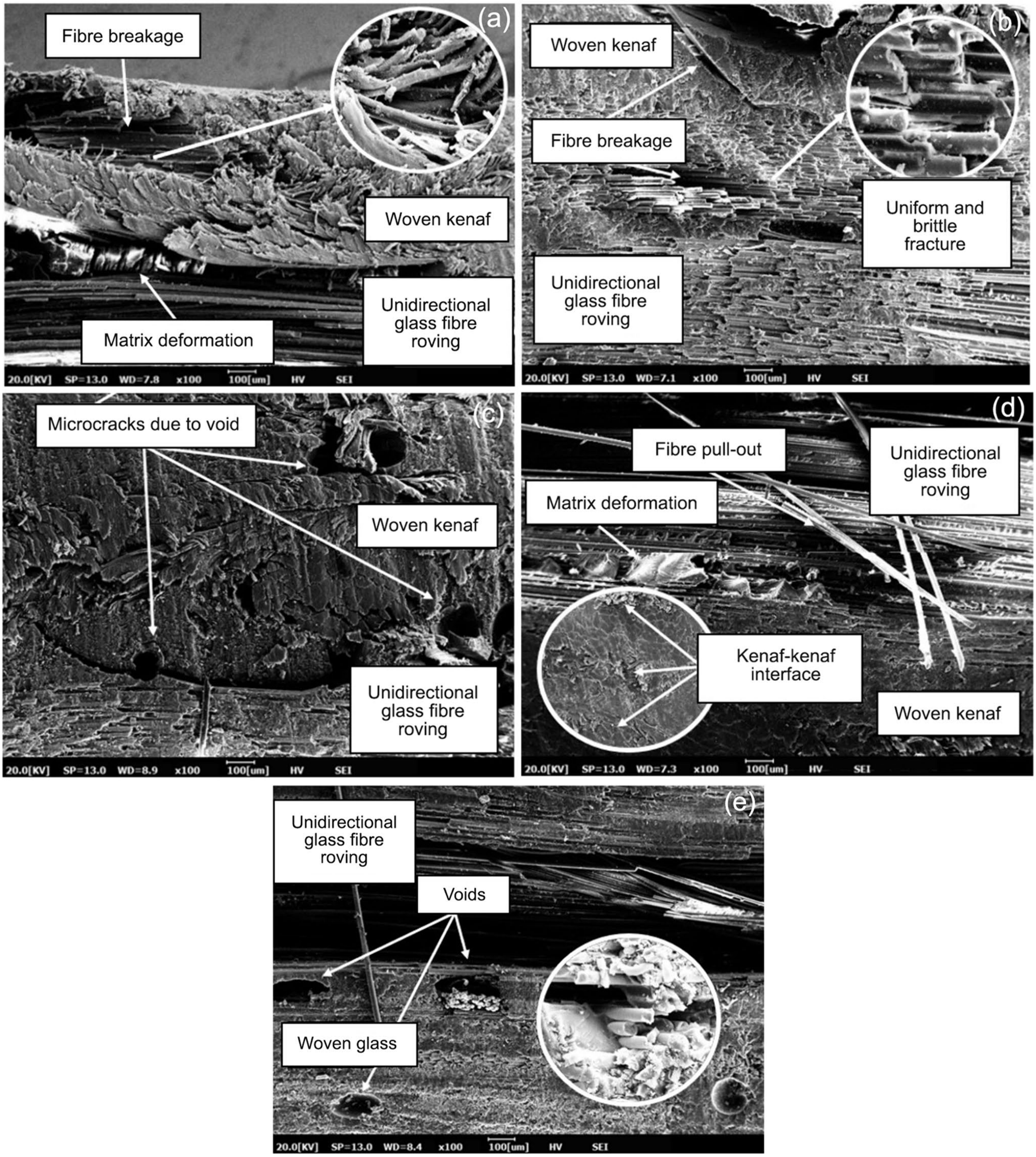


Fig. 10 **a**, **b** WK/UG alternate tensile fractured specimen, **c** 2WK/UG/2WK tensile fractured specimen, **d** 3WK/UG/3WK tensile fractured specimen, and **e** WG/UG alternate tensile fractured specimen

interface in 2WK/3UG/2WK, although the kenaf-to-glass ratio is controlled in both specimens. The observed limited debonding and fibre pull-outs in the kenaf/glass hybrid specimens indicate a robust and effective fibre-matrix interface. Limited debonding suggests that the bonding between the kenaf fibres and the matrix, as well as between the kenaf and glass fibres, is strong and resilient under the applied stress conditions. Fibre pull-outs, when controlled and limited, contribute to a controlled failure mode, preserving the integrity of the composite and preventing sudden and catastrophic failure. Due to the failure occurring within the fibre, such as fibre pull-outs, failure at the interface between the matrix and the fibre can be avoided [48]. By allowing fibres to pull out rather than undergo sudden fracture, the integrity of the fibre-matrix interface is preserved, preventing abrupt and catastrophic failure modes. Besides that, matrix deformation in the composites also indicated the strong bonding between the fibre and matrix. Matrix deformation signifies the ability of the matrix material to accommodate stress and strain, suggesting a cohesive interaction between the reinforcing fibres and the surrounding matrix. This deformability of the matrix under stress is crucial for distributing loads evenly and preventing localized stress concentrations that could lead to failure. Similar damage modes were observed by Cavalcanti et al. [49], where breakage of fibres and fewer voids present due to fibre pull-out indicated a good fibre-matrix adhesion. The reinforcement transfers stress uniformly throughout the matrix in the composites [50]. This uniform stress transfer contributes to the overall strength and durability of the composite material, highlighting the importance of a well-established and resilient fibre-matrix interface in enhancing the mechanical properties of the composite. Overall, the favourable interfacial adhesion observed in the kenaf/glass hybrid specimens, characterized by limited debonding and controlled fibre pull-outs, signifies a well-established and reliable fibre-matrix interface.

Conclusion

In conclusion, pure fibreglass specimens have recorded the highest mechanical properties in tensile, compressive, bending and ILSS tests. However, the kenaf glass hybrid composites have also proven their capabilities by showing good agreement with the conventional fibreglass samples. Satisfactory tensile results were obtained from WK/UG alternate samples and 2WK/3UG/2WK samples with a decrement of about 8.2% of tensile strength and 10.7% of tensile modulus compared to conventional fibreglass samples. Alternating sandwich WK/UG samples recorded higher compressive strength when compared to other hybrid specimens and recorded a slight decrease in strength value at 6.09% compared to pure fibreglass composites. However, the higher compressive modulus recorded by WK/UG alternate samples has reduced deformation in compressive loads. Highest modulus of rupture and modulus of elasticity were observed in hybrid alternate WK/UG samples than other hybrid laminates and recorded satisfactory bending properties with only a decrement of 4.13% in modulus of rupture and 1.9% in modulus of elasticity when compared to the control specimen. The ILSS of hybrid composites 2WK/3UG/2WK and alternate WK/UG showed good agreement with the pure fibreglass composites. SEM analysis revealed failure modes such as matrix deformation, fibre breakage, microcracks, voids, and fibre pull-outs in tensile fractured woven kenaf/unidirectional glass roving reinforced hybrid composites. The results show that alternate WK/UG can be a potential alternative to replace pure fibreglass composites in moderate load-bearing structural profiles in various industries such as aerospace, civil, marine, automotive, and sporting goods. For instance, bicycle frames, seat frames, ladders, stairs, gratings, flooring beams and mezzanine floors are some examples of moderate load-bearing structural applications in which kenaf-glass reinforced profiles can be potentially applied. Replacing glass mats with kenaf mats for structural composites can significantly reduce the cost, weight, and reliability of non-renewable petroleum-based materials. Further research on coatings of kenaf/glass composites is recommended to improve their shelf life and widen the application prospects in outdoor and marine environments due to hydrophilic nature of kenaf fibres and low thermal degradation.

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors state no conflict of interest.

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