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Fabrication and mechanical performance of bark cloth/glass fiber reinforced hybrid polymer composites for automotive applications

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Research Article

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Abstract

This study investigates the mechanical properties of hybrid composites reinforced with bark cloth (*Ficus natalensis*) and glass fiber in a polyester resin matrix. Composites were fabricated using the hand layup technique with varying fiber weight fractions (15%, 20%, and 25%) and hybrid ratios (3:1, 2:2, 1:3). The influence of hybrid ratio and stacking sequence on flexural, tensile, compressive, and impact strengths was evaluated. Results indicated that composites with higher glass fiber content exhibited superior mechanical performance, with optimal flexural (140.94 MPa), tensile (43.24 MPa), compressive (26.47 MPa), and impact strengths (32.44 kJ/m²) at a 1:3 hybrid ratio. Hybridization improved the mechanical properties of the composites, particularly flexural strength, which was significantly affected by stacking sequence. These findings suggest that bark cloth/glass fiber hybrid composites have potential for applications in automotive and structural industries.

Introduction

Bark cloth is a unique, non-woven fibrous textile produced from the bark of various tree species, with *Ficus natalensis* being the primary species used in Uganda. Locally known as "mutuba," this tree grows naturally in Uganda's tropical climate and requires minimal care, as it thrives without the need for fertilizers. *Ficus natalensis*, along with other species such as *Antiaris toxicaria* and *Ficus brachypoda*, is particularly valued for its renewable nature. The bark of the tree can be harvested annually without felling the tree, making it a sustainable resource[1,2]. A single tree can continue to produce bark cloth for over 30 years, with the bark regenerating after each harvest[3].

The production of bark cloth involves stripping the bark from the tree, which is then processed through steaming and beating with carved wooden hammers. This traditional method, passed down through generations, stretches the fibers and creates the distinctive terracotta-colored cloth. The cloth holds cultural significance in Uganda, being used for royal garments, religious ceremonies, and funerals[4]. The importance of bark cloth to Ugandan culture led UNESCO to recognize it as a "Masterpiece of the Intangible Cultural Heritage of Humanity," emphasizing the need to protect the knowledge and traditions surrounding its production[2].

In addition to its cultural value, bark cloth has gained attention for its potential as a reinforcement material in composite applications. Studies have shown that bark cloth consists of cellulosic microfibers aligned at 45° angles, providing moderate tensile properties. Scanning Electron Microscopy (SEM) analysis revealed that the fibers are oval-shaped and bonded by lignin and hemicelluloses, with diameters ranging between 10 and 20 μm[5]. The strength of bark cloth was measured at 101.7 N longitudinally and 23.5 N transversely, with a fabric thickness of approximately 1.084 mm[5]. These properties, along with its thermal stability below 200°C, suggest that bark cloth can be used for composite reinforcement, particularly in applications where lightweight and biodegradable materials are desirable[6–10].

Despite its potential due to its sustainability, low density, and cost-effectiveness, the key challenges in using bark cloth and other natural fibers for structural applications, particularly in the automotive industry, is their durability. Natural fibers have a high affinity for moisture due to their hydrophilic nature, which can lead to water absorption and subsequently reduced mechanical performance over time. For example, prolonged exposure to moisture can cause swelling, fiber debonding, and degradation of fiber-matrix adhesion, leading to a significant reduction in properties such as tensile and flexural strength. In addition, they generally exhibit lower mechanical properties than synthetic fibers, such as glass and carbon fiber, which limits their use in high-performance applications[11–14]. To address these limitations, researchers have explored hybrid composites that combine natural fibers with synthetic fibers. Hybrid composites leverage the sustainability of natural fibers while benefiting from the mechanical strength of synthetic fibers. This combination offers improved mechanical performance, including tensile, flexural, and impact strengths[14,15].

Recent studies have shown that treatments or hybridization with synthetic fibers, such as glass, can mitigate these effects by reducing moisture absorption and improving long-term stability[16–19,19–25]. For example, Santhanam et al.[26] reported significant improvements in tensile and flexural strength when glass fibers were added to banana fiber/polyester composites. Similarly, Selver et al.[27] demonstrated that hybrid composites made from jute and glass fibers showed enhanced mechanical properties compared to pure natural fiber composites. Sanjay et al.[28] reviewed the mechanical properties of natural fiber polymer composites, emphasizing that water absorption is a major factor affecting their long-term durability. The review suggests that hybridizing natural fibers with synthetic fibers or applying surface treatments can significantly mitigate these durability issues, improving the composites' resistance to environmental degradation. Another important aspect of improving natural fiber composites is enhancing their mechanical and moisture-resistant properties by hybridization. Sanjay et al.[29] discussed how hybridizing lignocellulosic fibers with synthetic fibers, such as glass, leads to composites that demonstrate improved mechanical properties and better resistance to moisture and environmental stresses. The incorporation of synthetic fibers into natural fiber composites not only improves their structural performance but also increases their applicability in sectors such as automotive and construction, where environmental resistance is critical[30,31]. Our study builds upon these findings by investigating the mechanical performance of hybrid composites made from bark cloth and E-glass fibers, with an emphasis on their potential for automotive applications.

The hybridization of natural fibers with E-glass fibers offers several significant advantages in composite materials, particularly for applications requiring high performance and sustainability[32,33]. Natural fibers, such as coconut leaf sheath, jute, and sisal, are lightweight and biodegradable, contributing to both weight reduction and environmental sustainability. However, their mechanical properties are often lower compared to synthetic fibers like E-glass. Studies by Bharath et al.[34] and Arpitha et al.[35] show that the combination of these natural fibers with E-glass fibers significantly enhances tensile and flexural strength, making the resulting hybrid composites suitable for structural and automotive applications. The hybridization also provides cost benefits, as natural fibers are more affordable than synthetic materials. Moreover, the addition of E-glass fibers improves the durability and resistance to moisture of the composites, addressing the common limitation of natural fibers in harsh environmental conditions. This balance of enhanced mechanical performance, cost-effectiveness, and sustainability makes hybrid composites highly attractive for a variety of industrial uses.

The automotive industry, in particular, has shown great interest in hybrid composites due to their potential to reduce vehicle weight while maintaining strength and durability. The use of natural fibers in automotive components can reduce both material costs and environmental impact[11,12]. For example[36], highlighted the role of natural fiber composites in the production of non-structural parts, while a number of studies have emphasized their potential to replace traditional materials such as aluminum and glass fibers in specific applications[37–39]. Hybrid composites, with their tailored mechanical properties, offer the versatility needed for a wide range of applications in automotive, construction, and other industries[26,27,40].

The mechanical properties of hybrid composites depend on several factors, including fiber weight fraction, hybrid ratio (the proportion of natural to synthetic fibers), and stacking sequence (the arrangement of fibers within the composite)[41,42]. Studies have shown that increasing the glass fiber content improves the mechanical properties of hybrid composites[43–45]. These studies reported that the tensile and flexural strength of hybrid composites increased with higher glass fiber content, while excessive natural fiber content led to poor fiber-matrix adhesion[46,47] Additionally, the stacking sequence of fibers plays a critical role in determining the composite's mechanical properties[48–51]. For example, Sanjay et al.[40] found that placing glass fibers in the outer layers of hybrid composites significantly improved flexural strength compared to composites with natural fibers on the surface.

Research has demonstrated the effectiveness of hybridization in improving the mechanical properties of composites. For instance, Santhanam et al.[26] found that hybrid composites with glass and natural fibers exhibit superior flexural and tensile properties. Other studies have confirmed the benefits of hybridization, including Dalbehera et al.[52] who observed improved impact strength and stiffness in jute/glass hybrid composites. Moreover, Altaee et al.[53] reported that hybrid composites with glass fibers in the outer layers and natural fibers in the core can offer optimal mechanical performance for specific applications, such as load-bearing and structural components.

Despite extensive research on hybrid composites using fibers such as jute, flax, and sisal, studies on bark cloth hybrid composites are still limited. However, recent research has shown that bark fibers from other plants, such as *Ficus carica* and *Prosopis juliflora*, possess desirable properties for composite reinforcement, including high cellulose content and thermal stability[9,10]. These findings suggest that bark cloth has the potential to be an effective reinforcement material when hybridized with synthetic fibers.

This study aims to fill the research gap by investigating the mechanical properties of bark cloth (*Ficus natalensis*) and glass fiber hybrid composites. Specifically, it focuses on the effects of fiber weight fraction, hybrid ratio, and stacking sequence on flexural, tensile, compressive, and impact strengths. The study seeks to optimize these parameters to enhance the performance of bark cloth-based hybrid composites, making them suitable for use in automotive, construction, and other industrial applications where sustainability and strength are key requirements.

Materials and Method

Materials

The materials used in this study include bark cloth, harvested from *Ficus natalensis* trees in Mukoko village, Masaka district, Uganda, and commercially available glass fabric (Fig. 1). Unsaturated polyester resin, with a density of 1.12 g/cm³, was used as the matrix, combined with methyl ethyl ketone peroxide (MEKP) catalyst in a ratio of 100:1 by weight. The glass fiber mat and resin were procured from Narkhi Enterprises Limited in Nairobi, Kenya. The characteristics of glass fiber and the unsaturated polyester resin is presented in Table 1.

Table 1
Characteristics of glass fibers and unsaturated polyester resin

Properties	Glass fibers	Polyester resin
Appearance	-	Opaque
Viscosity	-	4–5
Water absorption (%) (7 day value)	-	0.4
Heat distortion temperature (∘C)	-	63.1
Elongation at break (%)	3.1–4.8	2.9
Bending Strength (kgf/mm^2)	-	8.1
Bending Modulus (kgf/mm^2)	-	523.3
Tensile Strength (kgf/mm^2)	203.94–356.90	2.8
Impact Strength (kgf-cm/cm)	-	3.6
Density (g/cm3)	2.5–2.7	1.12
Toughness (MJ/m^3)	40–50	-
Tensile modulus (GPa)	70–76	-
Fiber diameter (µm)	11–12	-
Moisture Content (%)	0.15	-

Bark Cloth and Glass fabric Characterization

The characterization of bark cloth and glass fiber mat (also known as non-woven glass fabric) was conducted to determine their thickness, areal density, and tensile strength (Table 2). The thickness was measured using a digital thickness gauge under a pressure of 1 kPa, with the average thickness of five specimens recorded. Areal density was determined by cutting samples into 0.1 x 0.1 m squares and weighing them with an electronic balance, following ASTM D6242-98. Tensile strength was tested in both the longitudinal and transverse directions according to ASTM D5035-95 (Strip Method), using a Universal Testing Machine. The glass fiber mat’s areal density and fiber length were also characterized, with fiber length measured based on ISO 6989:1981 standards.

Table 2
Properties of bark cloth and non-woven glass fabric

Properties	Bark	Glass
Fabric type	Non-woven	Non-woven
Composition	100% bark	100% E-glass
Fabric thickness (mm)	1.45	-
Areal density (gsm)	385.80	394.00
Longitudinal tensile strength (MPa)	6.30	-
Transverse tensile strength (MPa)	0.26	-
Fibre length (mm)	-	45.68

Composite Fabrication

The composites were fabricated using the hand layup technique in a steel mold measuring 300 mm x 300 mm x 20 mm, with a polished lid. Bark cloth and glass fiber mats were cut according to the mold dimensions as depicted in Fig. 2. The polyester resin, catalyzed with methyl ethyl ketone peroxide (MEKP), was used as the matrix material. The fabrication process involved laying the first reinforcement layer into the mold, followed by resin application and consolidation with a roller to eliminate air voids. Subsequent layers were applied to achieve the desired hybrid structure, varying the stacking sequence and fiber weight fractions. Four layers of reinforcement were used.

A consolidation pressure of 3.57 kN/m² was applied, and the composites were cured at room temperature for 7 hours before demolding. In this study, various composite samples were prepared by varying two key factors: fiber weight fraction and the hybrid ratio of bark cloth to glass fiber. The experiments were designed to assess how these variations affect the mechanical properties of the hybrid composites. The fiber weight fraction was set at 15%, 20%, and 25%, while the hybrid ratio of bark cloth to glass fiber ranged from 3:1, 2:2, 1:3. Two control composites with bark cloth to glass fiber ratio of 4:0 and 0:4 respectively, were also fabricated. Ten types of composite samples were produced, as outlined in **Table 3**. These samples were fabricated by adjusting both the fiber weight fraction and the reinforcement stacking sequence. The samples included controls with either 100% bark cloth or 100% glass fiber. The hybrid composites consisted of varying combinations of bark cloth and glass fiber, arranged in different stacking sequences. By varying the fiber weight fraction and hybrid ratio, a comprehensive analysis of how these factors influence the mechanical behavior of bark cloth/glass fiber hybrid composites was achieved.

Table 1
Experimental design for producing the different composite sample types

Composite sample types	Fibre weight fraction (%)	Weight of fibres (g)	Resin weight (g)	Catalyst weight (g)	Composite designation	Reinforcement stacking sequence
1	15	92.7	520.1	5.2	3B1	B-B-G-B
2	25	107.8	320.2	3.2	3B2	B-B-G-B
3	15	134.6	755.1	7.6	3G1	G-G-B-G
4	25	138.0	409.9	4.1	3G2	G-G-B-G
5	20	88.2	349.3	3.5	B	B-B-B-B
6	20	159.2	630.5	6.3	G	G-G-G-G
7	20	104.0	411.9	4.1	BG1	B-G-B-G
8	20	109.0	431.7	4.3	BG2	B-G-G-B
9	20	113.1	447.9	4.5	BG3	G-B-B-G
10	20	132.5	524.8	5.2	BG4	B-B-G-G

Mechanical Testing

Composite samples were prepared and cut in accordance with ASTM and ISO standards to ensure uniformity across all tests. Prior to testing, the specimens were conditioned in the laboratory for 48 hours at a temperature of 23 ± 2°C and relative humidity of 65%, which ensured that the mechanical properties were assessed under controlled conditions. This helped to minimize the effects of moisture and temperature variations on the results.

The flexural strength of the composites was determined following ASTM D790. The test was conducted using a computer-controlled Testomeric machine (Model M/C S/No: 500-10171) with a 24.5 kN capacity, operating at a crosshead speed of 10 mm/min. The span length was calculated as 16 times the specimen thickness, and the specimen width was one-quarter of the span length, with an additional 25 mm overhanging allowance on both ends. The test involved applying a load at the center of the specimen until failure occurred, with five specimens tested for each composite type. Flexural strength is a crucial property for determining a material's resistance to bending, particularly in applications such as automotive and structural components.

Tensile strength tests were conducted in accordance with ASTM D3039, using a Universal Testing Machine (Model UT-10; S/No: 2015/12) with a 100 kN capacity at a crosshead speed of 5 mm/min. The specimens had dimensions of 300 mm in length, 25 mm in width, and a gauge length of 200 mm. Tensile strength is important for assessing the material's resistance to tension and stretching forces, which is relevant for applications where the composites will undergo pulling or stretching stresses.

Compressive strength tests were performed following ASTM D3410M, also using the Universal Testing Machine (Model UT-10; S/No: 2015/12) with a 100 kN capacity at a crosshead speed of 5 mm/min. Specimens were prepared with a length of 40 mm, a width of 25 mm, and a gauge length of 40 mm. This test measures the composite's ability to withstand compressive forces and eliminates the possibility of buckling, which is critical for evaluating the performance of the composites in load-bearing applications.

Impact strength was measured using an impact tester (Model HLE; S/No: 2015/15) according to ISO 179-1:2000 standards. The impact test was conducted with a 15 J hammer, and the specimens had a length of 60 mm, a width of 10 mm, and a span length of 40 mm. All the specimens were un-notched to evaluate their natural resistance to impact. Impact strength is an essential measure of a material's ability to absorb energy and resist sudden forces, which is especially important for safety-critical applications such as in the automotive industry.

For all mechanical tests, five specimens were tested for each composite type, and the average values were reported. These mechanical tests are vital for understanding the overall performance of the hybrid composites and determining their potential for use in various engineering applications.

Statistical Analysis

The experimental data obtained from the mechanical tests were statistically analyzed to determine the significance of the effects of fiber weight fraction and hybrid ratio on the mechanical properties of the composites. One-way Analysis of Variance (ANOVA) was used to assess the significance of differences in the flexural, tensile, compressive, and impact strengths of the various composite samples. The ANOVA was performed at a 95% confidence level, with a p-value of less than 0.05 considered statistically significant. The F-values and p-values were reported for each mechanical property to quantify the influence of the composite parameters. This statistical analysis provided a robust evaluation of the experimental results, identifying which factors had a significant effect on the performance of the bark cloth/glass fiber hybrid composites.

SEM Analysis

The Scanning Electron Microscopy (SEM) analysis was performed to investigate the surface morphology and cross-sectional structure of hybrid composites with various stacking sequences of bark cloth (B) and glass fibers (G). The samples were prepared with sequences G-G-B-G, B-G-B-G, and B-G-G-B. Small sections were cut from each composite for analysis. SEM images were taken using a VEGA3 TESCAN SEM at an accelerating voltage of 5.0 kV, with magnifications set at 250x for surface analysis and 2.00kx for cross-sectional analysis. The images provided insights into fiber pull-out, microvoids, and the fiber-matrix interaction, highlighting areas of poor resin impregnation and bonding. This methodology enabled a detailed assessment of the structural integrity and mechanical behavior of the composites.

Results and Discussion

The mechanical properties of the bark cloth and glass fabric hybrid composites were analyzed based on flexural, tensile, compressive, and impact strength tests. The effects of varying fiber weight fractions and hybrid ratios (bark cloth to glass fabric) on these properties were investigated to evaluate the performance of the composites. Composite thickness ranged from 4.0 mm to 5 mm. Figure 3 depicts the failed composites after undergoing the necessary named tests. As seen, most composites failed within acceptable levels.

Flexural Strength

The flexural strength of the bark cloth and glass fiber hybrid composites was significantly influenced by the hybrid ratio and fiber weight fractions of 15%, 20%, and 25%, as shown in Figs. 4. Composites with a higher proportion of glass fiber consistently exhibited superior flexural performance compared to those with a higher proportion of bark cloth. These results align with previous research, which also observed that synthetic fibers like glass provide enhanced mechanical reinforcement in hybrid composites. For instance, Hanifawati et al.[46] reported a notable improvement in tensile and flexural strength when glass fiber was added to a banana fiber/polyester matrix. Similarly, Bindal et al.[47] demonstrated that hybrid composites made from natural and synthetic fibers, such as jute/glass, exhibited improved flexural properties compared to pure natural fiber composites.

At 20% fiber weight fraction, composites showed better overall flexural performance than the 25% fiber weight fraction composites, but they were still slightly inferior to the 15% weight fraction composites, suggesting that 20% provides a balanced performance when fiber content and resin wetting are optimized. The observed poor performance at 25% fiber weight fraction is likely due to insufficient resin for fiber wetting, leading to poor fiber-matrix adhesion. Studies like Shahzad et al.[54] corroborate this observation, reporting that fiber agglomeration at higher content can lead to a decrease in mechanical properties due to inefficient load transfer between fibers. Additionally, Rachchh et al.[55] found that increasing the natural fiber content beyond optimal levels in glass/natural fiber composites leads to decreased tensile and flexural strength, further supporting our results. The ANOVA results (Table 4) for flexural strength indicated significant differences across hybrid ratios at all fiber weight fractions (15%, 20%, and 25%), with p-values lower than 0.05. The 20% fiber weight fraction composites showed improved performance compared to the 25% composites, likely due to better fiber distribution and resin penetration.

Table 4
Analysis of variance for effect of hybrid ratio on bark cloth and glass fabric reinforced polyester composites

Mechanical Property	Fiber weight fraction	Source of Variation	SS	df	MS	F-value	P-value
Flexural strength	15%	Between Groups	15335.84	1	15335.84	42.50619	0.000184
		Within Groups	2886.326	8	360.7908		
		Total	18222.17	9			
	20%	Between Groups	100503.2	5	20100.63	14.54638	1.34E-06
		Within Groups	33163.92	24	1381.83		
		Total	133667.1	29			
	25%	Between Groups	16341.81	1	16341.81	70.74337	3.04E-05
		Within Groups	1848.01	8	231.0012		
		Total	18189.82	9			
Tensile strength	15%	Between Groups	870.1158	1	870.1158	35.66891	0.000334
		Within Groups	195.1539	8	24.39424		
		Total	1065.27	9			
	20%	Between Groups	3329.748	5	665.9497	60.79107	7.7E-13
		Within Groups	262.9135	24	10.95473		
		Total	3592.662	29			
	25%	Between Groups	841.6228	1	841.6228	131.7509	3.01E-06
		Within Groups	51.10388	8	6.387985		
		Total	892.7266	9			

Mechanical Property	Fiber weight fraction	Source of Variation	SS	df	MS	F-value	P-value
Compressive strength	15%	Between Groups	60.12304	1	60.12304	0.496407	0.501076
		Within Groups	968.9316	8	121.1165		
		Total	1029.055	9			
	20%	Between Groups	3847.087	5	769.4174	10.87158	1.5E-05
		Within Groups	1698.559	24	70.77329		
		Total	5545.646	29			
	25%	Between Groups	290.8445	1	290.8445	45.23302	0.000149
		Within Groups	51.43932	8	6.429915		
		Total	342.2838	9			
Impact strength	15%	Between Groups	5.21284	1	5.21284	0.387706	0.55084
		Within Groups	107.5627	8	13.44534		
		Total	112.7756	9			
	20%	Between Groups	398.1756	5	79.63512	8.52665	9.43E-05
		Within Groups	224.1493	24	9.339555		
		Total	622.3249	29			
	25%	Between Groups	23.13441	1	23.13441	1.398344	0.270952
		Within Groups	132.3532	8	16.54415		
		Total	155.4876	9			

Tensile Strength

Tensile strength results mirrored the flexural strength trend, with higher glass fiber content improving the tensile strength of the hybrid composites (Fig. 4). This is consistent with findings from Misri et al.[56], who reported that the inclusion of glass fiber in sugar palm composites increased tensile strength by 59.20%. The highest tensile strength was observed at 15% fiber weight fraction, while the 20% fiber weight fraction composites performed better than those with 25%. The superior tensile performance at 15% can be attributed to better resin penetration and more uniform fiber distribution. Composites with a 1:3 hybrid ratio and glass fibers in higher proportion, such as composite BG3, exhibited the best tensile performance at 20% fiber weight fraction due to improved load transfer from the glass fibers.

Similar observations were made by Hemalatha et al.[57], who found that hybrid composites with higher synthetic fiber content, such as jute/glass composites, showed enhanced tensile performance due to better load transfer and fiber-matrix adhesion. In contrast, the 25% fiber weight fraction composites, such as 3B2 (B-B-G-B), exhibited reduced tensile strength, which could be attributed to insufficient resin and poor wetting of the fibers. According to Kumar et al.[58], higher natural fiber content increases matrix absorption, reducing resin availability for fiber wetting, which is a critical factor in tensile performance. The ANOVA results (Table 4) for tensile strength at all fiber weight fractions (15%, 20%, and 25%) showed statistically significant differences ($p < 0.05$), confirming that the hybrid ratio and fiber content played a crucial role in determining the tensile behavior of the composites.

Compressive Strength

The compressive strength tests revealed that hybrid composites with higher glass fiber content exhibited superior performance (Fig. 4), which aligns with the findings of Misri et al.[56], who reported that glass fibers provide superior resistance to compressive forces in hybrid composites. The 1:3 hybrid ratio composites showed the highest compressive strength at both 15% and 20% fiber weight fractions, with the latter providing a balanced performance. Composites with a 20% fiber weight fraction outperformed those with 25%, likely due to fewer agglomeration issues and better resin penetration. At 25% fiber weight fraction, composites suffered from reduced compressive strength due to inadequate resin distribution and fiber agglomeration, which hindered uniform load distribution.

The reduction in compressive strength at 25% fiber weight fraction can be attributed to fiber agglomeration and poor fiber-matrix adhesion, as observed in previous studies[54]. In glass/natural fiber hybrid composites, Rachchh et al. [55] reported that exceeding an optimal natural fiber content led to reduced compressive strength due to uneven fiber distribution and resin starvation.

The ANOVA results (Table 4) for compressive strength indicated significant differences at both 20% and 25% fiber weight fractions, with p-values below 0.05, confirming the importance of hybrid ratio and fiber content in determining compressive performance.

Impact Strength

The impact strength of the hybrid composites increased with the inclusion of glass fibers, consistent with findings from Kumar[59], who noted that good fiber-matrix adhesion improves impact resistance. At 20% fiber weight fraction, composite BG4 (B-B-G-G) exhibited the highest impact strength of 27.50

kJ/m², surpassing the performance of 25% composites. The presence of glass fibers in the outer layers facilitated effective load transfer during impact, allowing the composite to absorb and dissipate energy more efficiently.

Similar trends were reported by Mohanta et al.[60], where hybrid composites with synthetic fibers in the outer layers showed superior impact resistance compared to natural fiber composites. The impact performance of the 25% fiber weight fraction composites was lower due to fiber agglomeration and insufficient resin penetration, as noted by Shahzad et al.[54], and Rachchh et al.[55].

At 20% fiber weight fraction, hybrid composite BG4 (B-B-G-G) exhibited the highest impact strength of 27.50 kJ/m² (Fig. 5), outperforming the 25% composites but slightly underperforming compared to the 15% composites. The presence of glass fibers in the outer layers facilitated effective load transfer during impact, resulting in better energy absorption and distribution. This improvement in impact resistance is similar to the findings of Kumar[59], where good fiber-matrix adhesion improved impact strength.

The ANOVA results (Table 4) for impact strength at 20% fiber weight fraction revealed significant differences ($p < 0.05$), confirming that hybridization and fiber arrangement contributed to the improved impact resistance of the composites. The 20% composites performed better than the 25% composites due to better fiber-matrix bonding and fewer fiber agglomeration issues.

Effect of stacking sequence

The stacking sequence had a profound impact on the mechanical performance of the hybrid composites, particularly at 20% fiber weight fraction. As seen in Fig. 6, composites with glass fibers in the outer layers exhibited higher mechanical properties across flexural, tensile, and compressive strengths. The importance of the stacking sequence in enhancing the mechanical properties of natural fiber-based composites has been reported in previous studies[40,48]. In this study, composite BG3 (G-B-B-G) at 20% fiber weight fraction showed the best tensile strength, which can be attributed to the advantageous placement of glass fibers in the outer layers, improving load distribution. Similarly, composite BG4 (B-B-G-G) exhibited the highest impact strength (Fig. 7), benefiting from the glass fibers on the outer side, which facilitated effective load transfer during impact.

At 20% fiber weight fraction, the stacking sequence played a crucial role in optimizing the balance between the rigidity provided by glass fibers and the flexibility and sustainability of bark cloth. The 20% composites outperformed the 25% composites due to better fiber distribution and fewer agglomeration issues. When glass fibers were placed as the outer layers, as in BG3 and BG4, the composites showed significant improvements in mechanical performance compared to configurations where bark cloth was in the outer layers, such as B-G-G-B.

The results also showed that hybrid composites with alternating layers of bark cloth and glass fiber outperformed pure bark cloth composites in all mechanical properties. For instance, the flexural strength of hybrid composites increased by 137.98%, tensile strength by 81.59%, and compressive strength by

51.58% compared to pure bark cloth composites. These findings align with studies such as Santhanam et al.[26], which found that stacking sequence had a more substantial effect on flexural and impact strength than tensile strength.

The ANOVA results (Table 4) for the effect of stacking sequence on flexural, tensile, compressive, and impact strengths at 20% fiber weight fraction confirmed significant differences ($p < 0.05$). The F-ratio values were higher than the F-criteria values, indicating that the stacking sequence significantly affected the performance of the composites. The highest mechanical properties were consistently observed in composites with glass fibers in the outer layers, such as BG3 and BG4.

Surface Morphology and Cross-Section Analysis

The SEM analysis of the B-G-G-B hybrid composite highlights both surface and cross-sectional features that provide insights into the material's structure and performance. In the surface morphology at 250x magnification (Fig. 8a), roughness and fiber pull-out are visible, indicating regions of incomplete resin impregnation. These voids and surface irregularities suggest that the bonding between the matrix and fibers, especially in the bark cloth layers, may not be sufficient, which could lead to stress concentration points and reduced mechanical integrity.

In the cross-sectional view at 2.00kx magnification (Fig. 8b), the glass fiber layers are well integrated, showing a more uniform bond with the matrix. However, the bark cloth layers exhibit fiber pull-out and weaker bonding, with voids observed between the fibers and the matrix. This indicates potential flaws in the resin impregnation process, particularly in the natural fiber regions. These imperfections could act as points of failure under mechanical stress, compromising the overall durability of the composite[50].

For the B-G-B-G hybrid composite, the SEM analysis also reveals rough surface morphology (Fig. 8c), with significant fiber pull-out and voids, again suggesting incomplete resin impregnation. The bark cloth fibers show weaker bonding compared to the glass fibers. In the cross-section (Fig. 8d), glass fibers appear more consistently bonded to the matrix, while the bark cloth layers are less integrated, with visible fiber pull-out and voids that could reduce mechanical strength.

Finally, for the G-G-B-G hybrid composite, surface analysis shows a similar roughness, with some regions exhibiting fiber pull-out (Fig. 8e). In the cross-section (Fig. 8f), the glass fibers are well embedded, but the bark cloth layers show weaker bonding and void formation, indicating potential weaknesses in fiber-matrix adhesion. These defects highlight the need for improved resin infiltration and fiber alignment to enhance the composite's overall structural integrity and mechanical performance.

Conclusion

This study demonstrated that hybridizing bark cloth with glass fibers significantly enhances the mechanical properties of polyester composites, particularly in terms of flexural, tensile, compressive, and impact strengths. Composites with higher glass fiber content exhibited superior performance, especially when glass fibers were positioned on the outer layers. The 15% and 20% fiber weight fractions produced better mechanical properties due to improved resin wetting and reduced fiber agglomeration, while the 25% fiber weight fraction composites showed weaker performance due to insufficient resin and fiber clumping. The stacking sequence also played a critical role, with alternating layers of bark cloth and glass fibers showing enhanced load distribution and energy absorption. The 1:3 hybrid ratio (glass to bark cloth) and 20% fiber weight fraction provided an optimal balance between material efficiency and mechanical performance. Statistical analysis confirmed that the hybrid ratio, fiber weight fraction, and stacking sequence significantly influenced the composites' mechanical properties. The SEM analysis revealed that incomplete resin impregnation and the presence of microvoids, particularly in the bark cloth layers, contributed to fiber pull-out and weaker fiber-matrix bonding, highlighting the need for optimized resin infiltration and fiber alignment to improve the composite's mechanical performance and durability

Further, it is recommended to explore different natural fibers and hybrid ratios to further optimize performance, investigate resin formulations or surface treatments to improve fiber-matrix adhesion, especially at higher fiber content, and evaluate the composites' long-term durability and environmental resistance in real-world applications. These improvements could expand the use of hybrid composites in various structural and load-bearing applications, promoting sustainability without compromising performance.

Declarations

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding publication of this paper.

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Data Availability

Data available within the manuscript.

Author Contribution Statement

Frances Alibet: conceptualization, methodology, investigation, formal analysis, data curation, writing—original draft, and writing—review and editing. **Paul Wambua:** resources, writing—review and editing, supervision, and funding acquisition. **David Njuguna Githinji:** resources, validation, writing—review and editing, supervision, and funding acquisition. **Samson Rwahwire:** resources, validation, writing—review and editing, supervision, and funding acquisition. **Ocident Bongomin:** writing and editing the revised manuscript, methodology, visualization, writing—review and editing, validation, and formal analysis.

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Figures

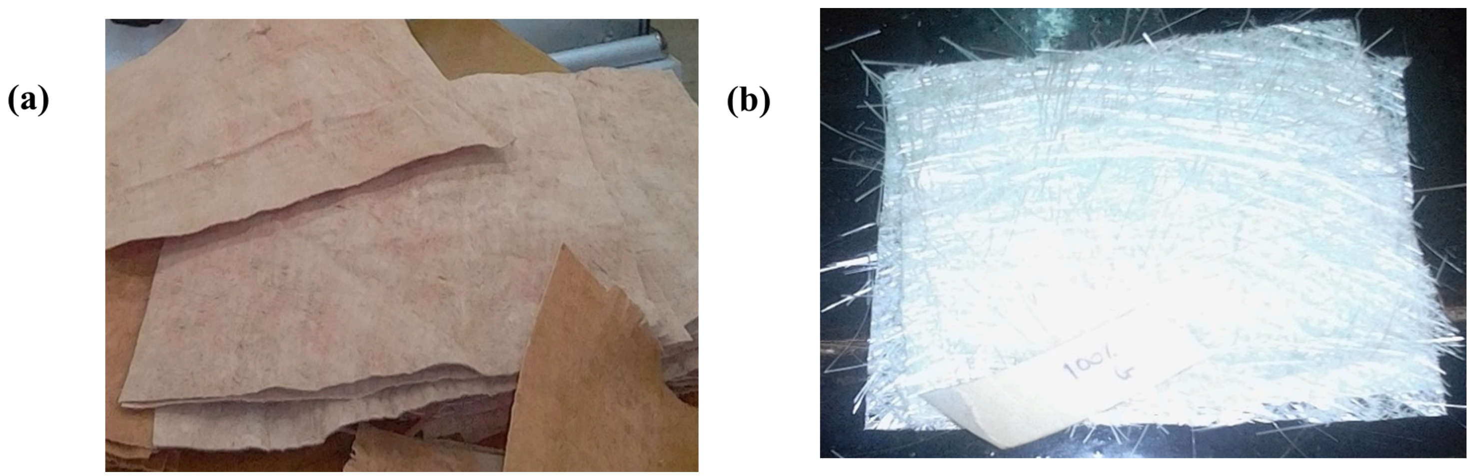

Figure 1

composite reinforcement materials (a) Bark cloth; (b) Glass fibre mat/fabric

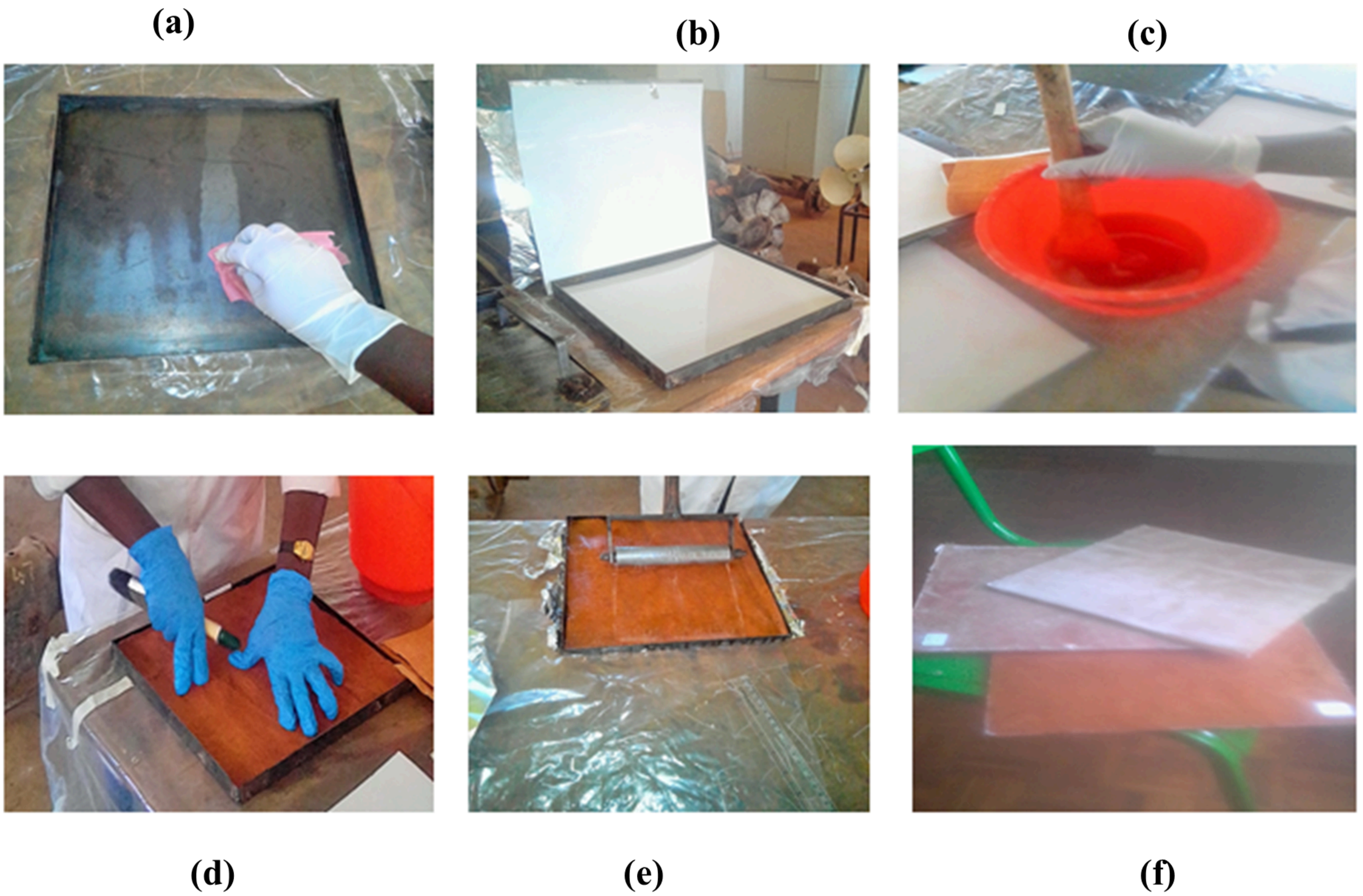

Figure 2

Composite fabrication (a) Cleaning mould; (b) Mould set up; (c) Mixing resin and catalyst; (d) Laying reinforcements and resin impregnation; (e) Bubble removal and squeezing out excess resin using a roller prior to drying; (f) Fabricated composites.

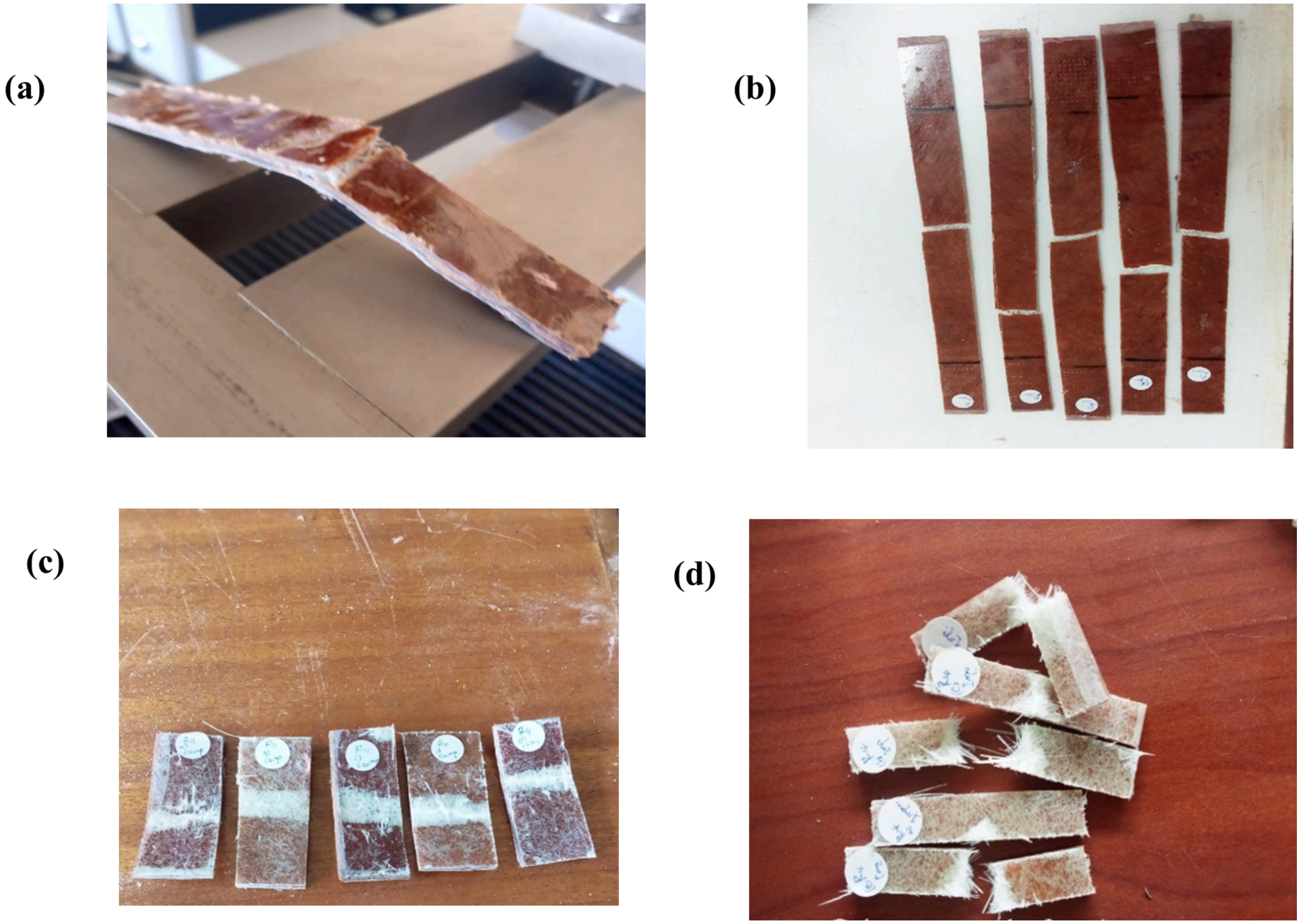

Figure 3

Failed composites after mechanical tests (a) After flexural test; (b) after tension test; (c) after compression test; (d) after impact test

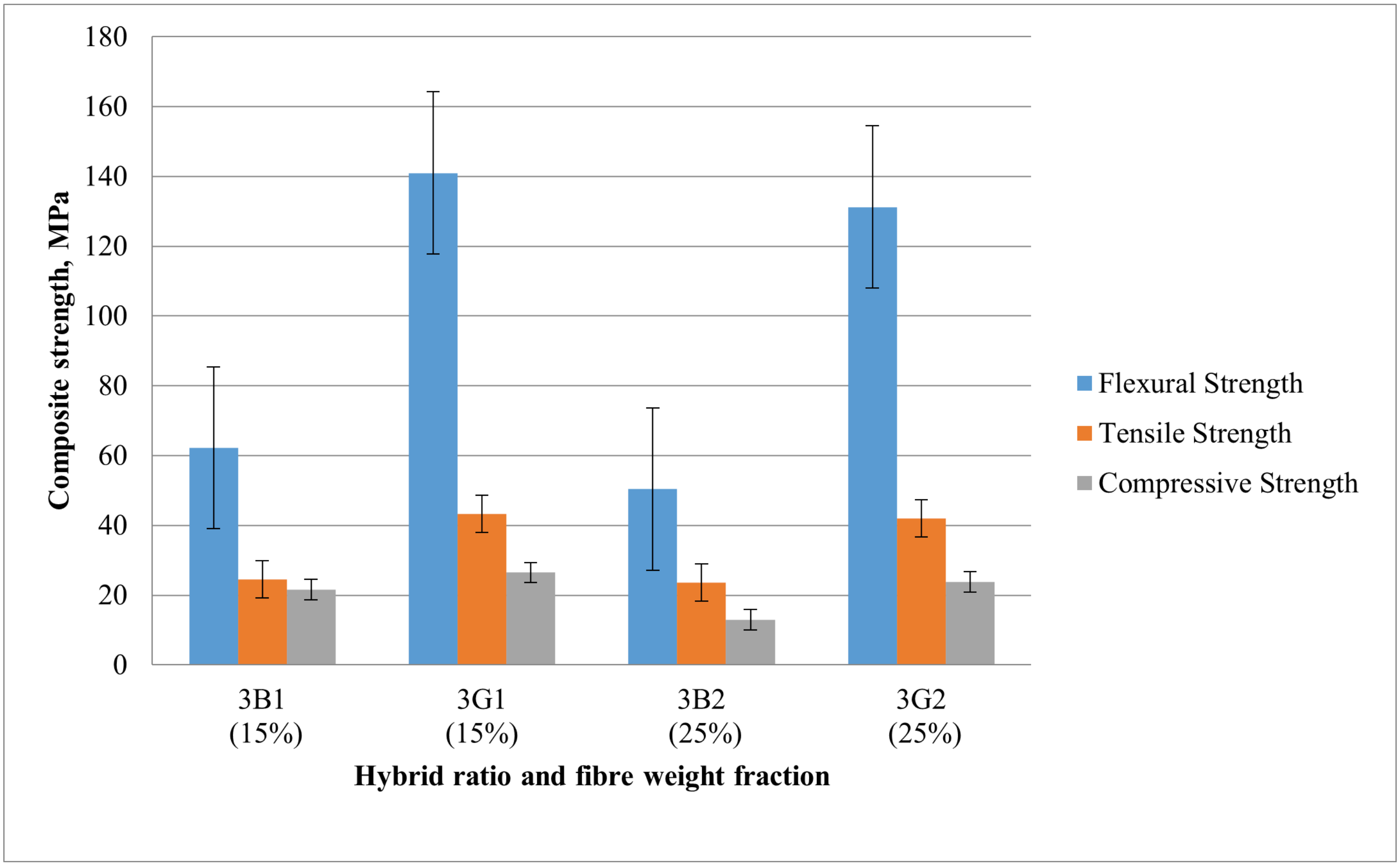

Figure 4

Flexural, tensile, and compressive strengths as a function of hybrid ratio at 15% and 25% fibre weight fraction

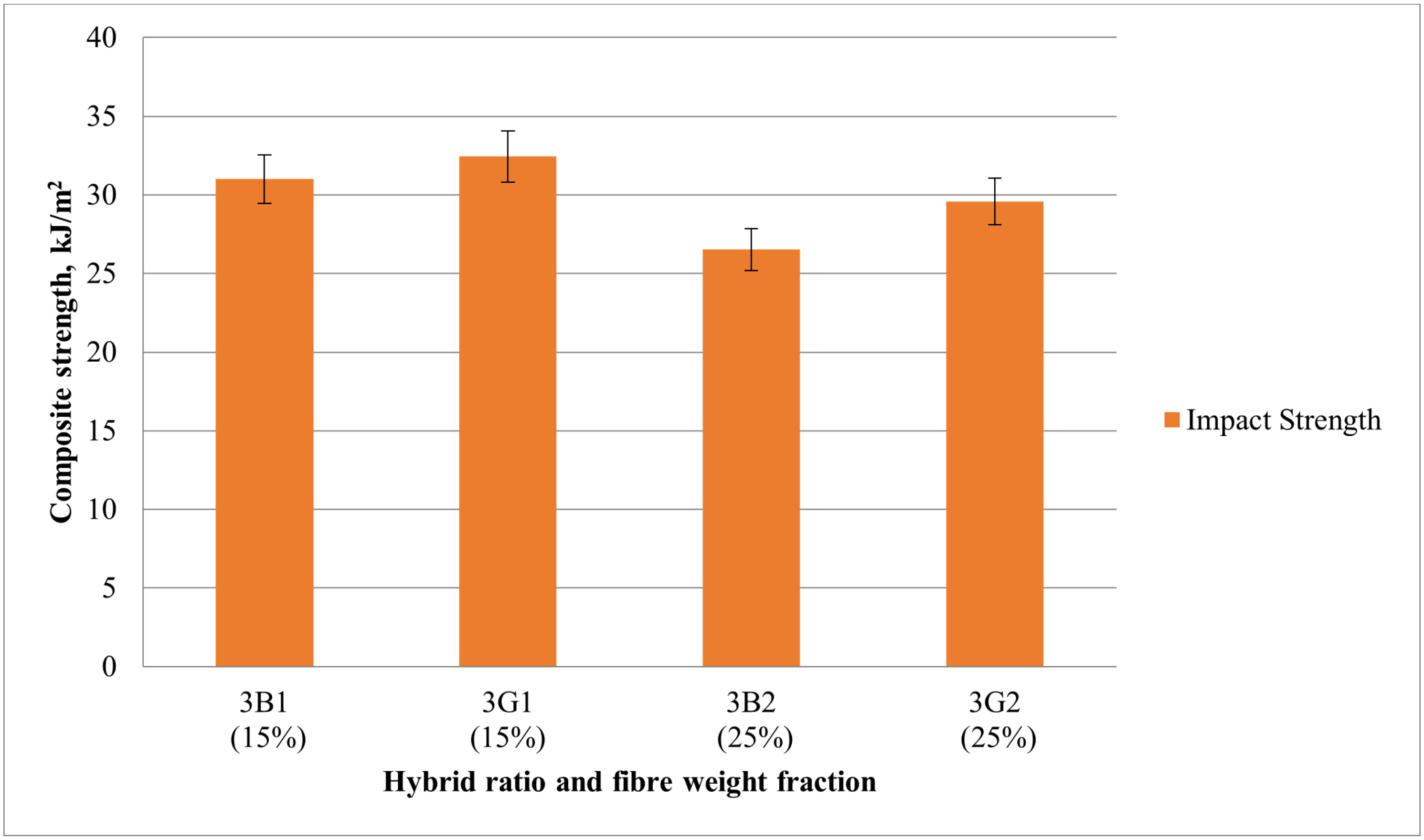

Figure 5

Impact strength as a function of hybrid ratio at 15% and 25% fibre weight fraction

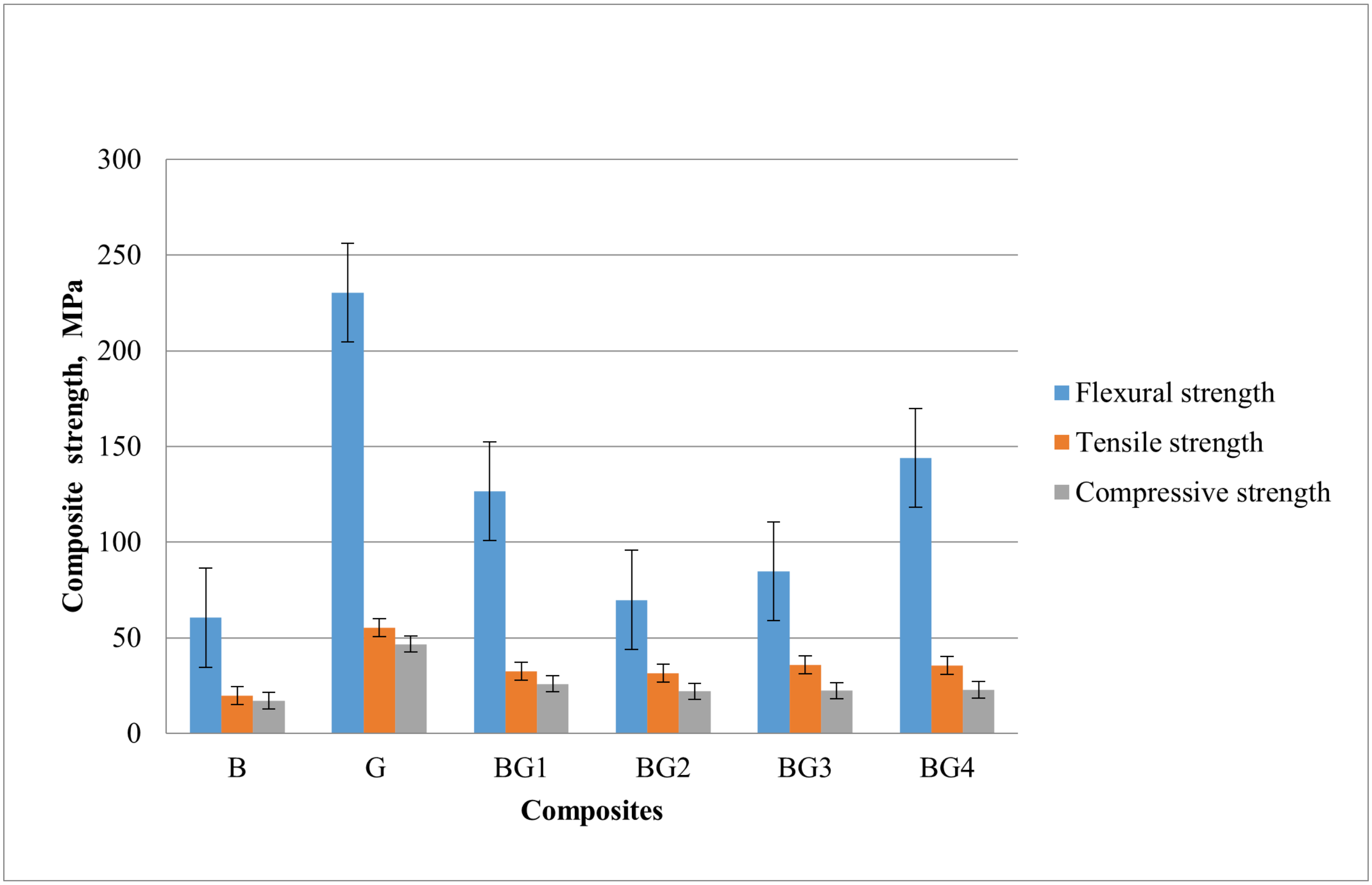

Figure 6

Flexural, tensile, and compressive strengths as a function of varying reinforcement stacking sequence

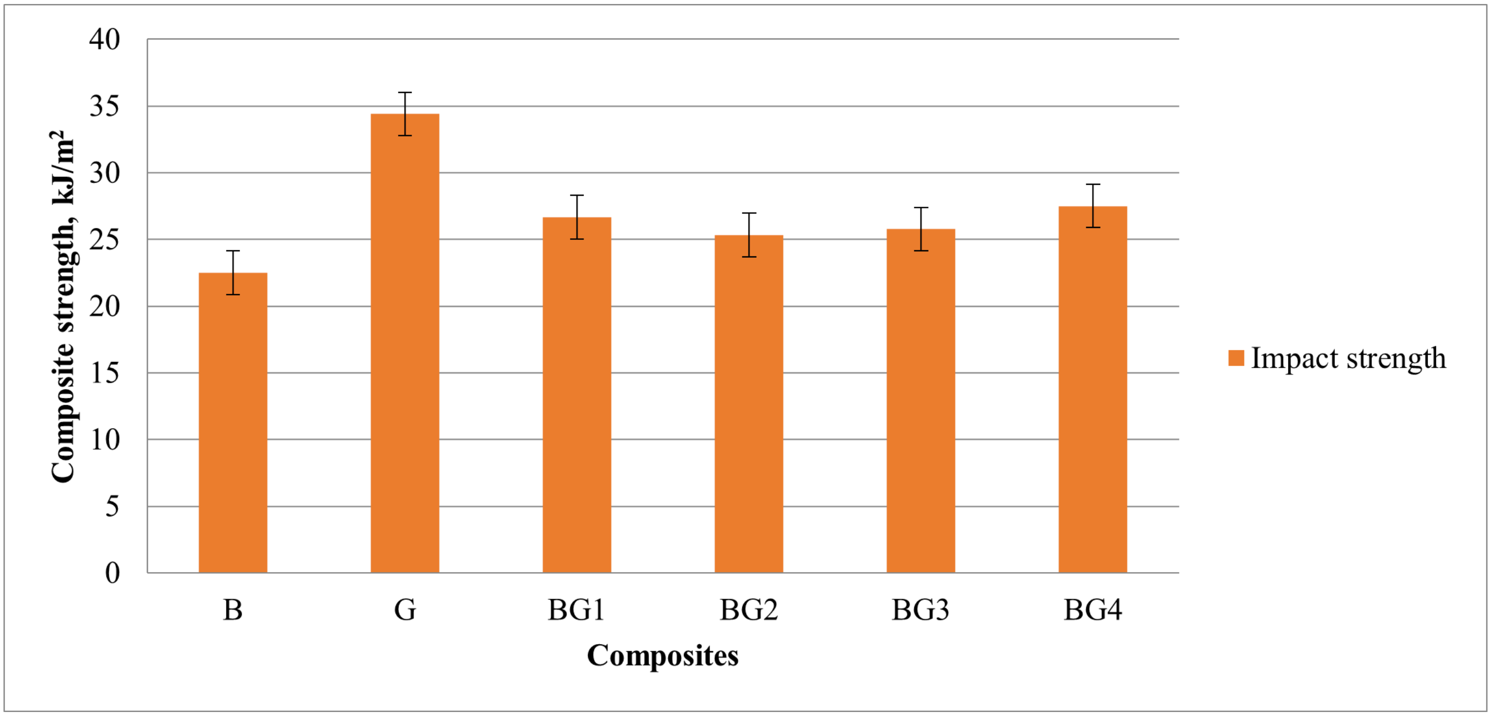

Figure 7

Impact strength of composites as a function of varying stacking reinforcement stacking sequence

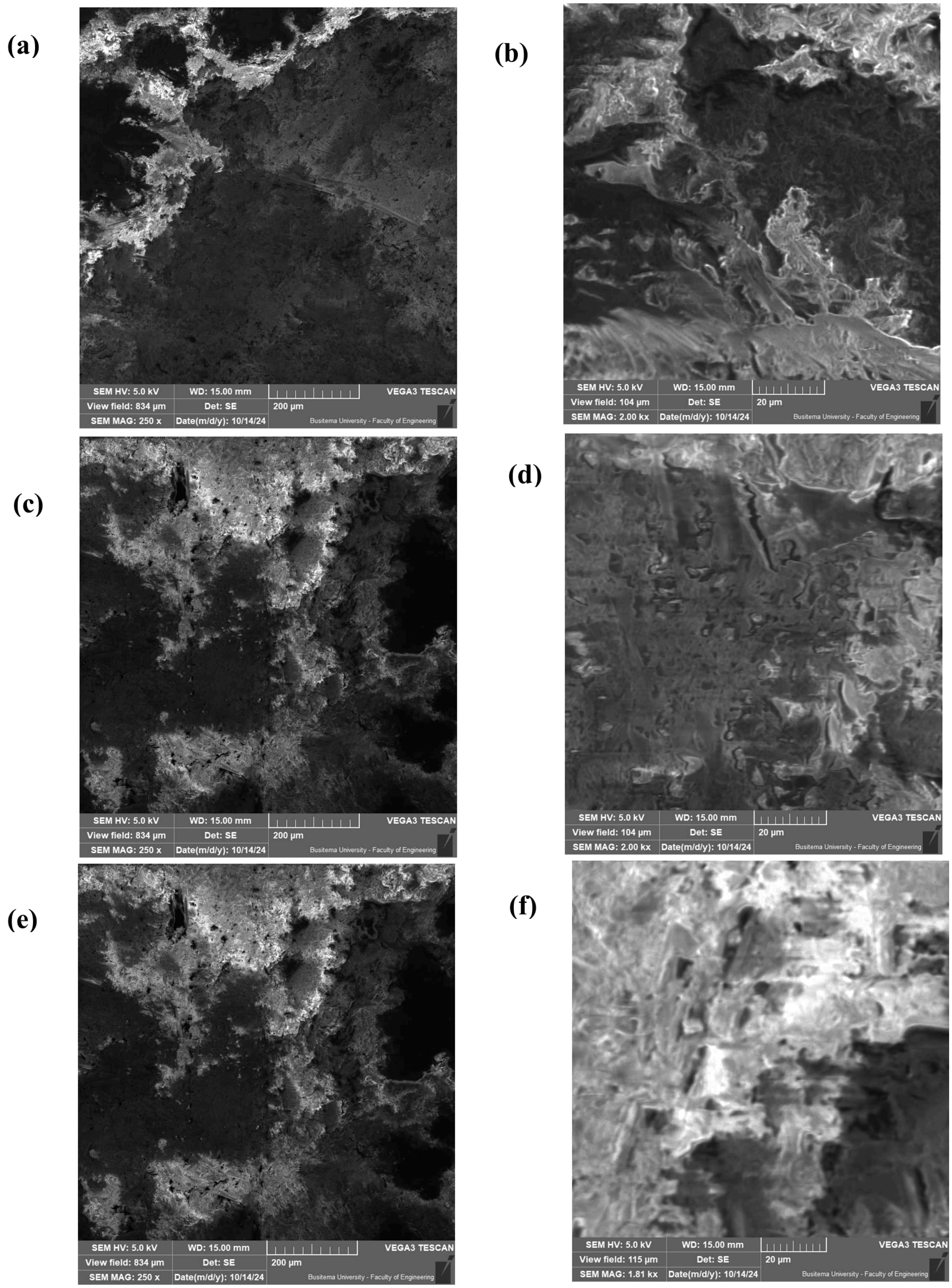

Figure 8

Surface morphology and cross-section SEM analysis of hybrid composite; (a, b) B-G-G-B hybrid; (c, d) B-G-B-G hybrid; (e, f) G-G-B-G hybrid.