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PERFORMANCE ANALYSIS OF HYBRID GLASS AND SISAL FIBRE REINFORCED EPOXY MATRIX COMPOSITE FOR AIRCRAFT STRUCTURES

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Highlights:

- GF30 sample has the highest flexural strength (138.1 MPa) and flexural modulus (3272.6 MPa)
- GF30 sample has the highest tensile strength (137.12 MPa) and modulus of elasticity (685.6 MPa)
- The hybrid composite GF30SF10 has the highest impact strength (0.18 J/mm²)

Abstract: Aerospace industries globally have considered fibre composites as substitutes for structural applications. There is gross challenge to analyse and evaluate the performance of different fibre composites and their manufacturing processes to determine the most effective, efficient and sustainable material for aircraft structures. Therefore, in order to reduce drag in flight, the material for the structure is an important factor to consider in designing aircrafts. In this study, woven E-glass fibre/natural sisal fibre hybrid composite was developed and their mechanical properties, such as flexural strength, tensile strength and impact strength were evaluated. The flexural test results showed that hybrid composite samples (GF30SF5 and GF30SF10), each with an equal amount of glass fibre (30 wt%), exhibited high flexural strength (108.9 MPa and 124.6 MPa) and flexural modulus (2863 MPa and 2667.6 MPa) compared to the SF15 (41.3 MPa and 1771.8 MPa). For the tensile properties, GF30SF5 had the higher tensile strength (118.76 MPa) and Young's modulus (565.5 MPa) compared to the SF15, while GF30SF10 had the best elongation at break (36%) among the composite samples. As for the impact properties, GF30SF10 had the highest impact energy (11.5 J) and maximum impact strength (0.18 J/mm^2) compared to the GF30 and the SF15 samples. Overall, hybridization enhances mechanical properties, with glass fibre showing superior flexural and tensile characteristics. These findings have implications for the development of stronger and more reliable hybrid composites, especially in aircraft structures like wing components. Hybridization is an important replacement for synthetic materials in aerospace application due to their biodegradability, cost-effectiveness and recyclability making them useful in various applications.

Keywords: Fibre Composites; Aircraft Structures; Hybridization; Mechanical Properties

1. Introduction

Fibre composites have been used for thousands of years. Ancient Egyptians and Mesopotamians used a mixture of clay and straw to make bricks for building walls, and straw was also used to reinforce pottery and boats. Carbon fibres, first patented in 1961, quickly found applications in the maritime and air traffic industries. However, the widespread industrial use of carbon fibre composites began in the 1990s, particularly in construction and transportation. In aerospace, fibre composites have been essential since the Wright Brothers' first flight in 1903 and more reason carbon fibre-reinforced polymers (CFRP) has been considered for the manufacture of various components and structures in the aircraft (Davies, 1996; Awode *et al.*, 2024). They are now used in both military and civil aircraft, as well as unmanned aerial vehicle (UAV), space launchers, and satellites (Soutis, 2005). The use of fibre composites is driven by their excellent mechanical properties, cost-effectiveness, lightweight nature, and environmental benefits (Atmakuri *et al.*, 2020). Recently, aerospace industries globally have considered fibre composites as substitutes for structural and engineering applications. Asyraf *et al.* (2022) explored the advancements in composites within the aircraft industry, highlighting their role, potential applications, and the progress in developing new composite materials and manufacturing techniques, focusing on opportunities, challenges, and future perspectives. Recent advancements in fibre technology and manufacturing have led to more sophisticated hybrid fibres that display enhanced mechanical properties through the addition of reinforcing agents like fillers, short fibres, or fabrics (Ramesh *et al.*, 2021). Analysing existing research on carbon and fibre glass, natural, nano, and hybrid fibres is crucial to understanding their current state. Therefore, the use of polymer matrix composites (PMC) like CFRP has been considered for the manufacture of various components and structures in the aircraft, from the fuselage to the wings and the engines mainly because of their light-weight properties (Awode *et al.*, 2024). Hybridization plays a major role as a substitute for synthetic materials in aerospace application due to their biodegradability, cost-effectiveness and recyclability making them useful in various applications.

Researchers have studied various hybrid composites, revealing significant improvements in mechanical properties like flexural and tensile strength. For example, Sapuan *et al.* (2020) found that adding basalt to glass-fibre-reinforced unsaturated polyester resin significantly increased the tensile strength to 269.85 MPa, a substantial improvement from the 8.14 MPa of neat unreinforced polyester. Nurazzi *et al.* (2018) demonstrated that hybridizing sugar palm yarn with glass fibres improved mechanical properties compared to single-fibre composites. Challenges such as fibre-matrix compatibility, moisture absorption, and interfacial bonding were employed to demonstrate and achieve the hybridization. Asim *et al.* (2018) showed that hybrid composites made from pineapple leaf and kenaf fibres with phenolic resin had better tensile strength (46.96 MPa), flexural strength (84.21 MPa), and impact strength (5.39 kJ/m^2) compared to composites made solely from pineapple leaf fibre/phenolic resin or kenaf fibre/phenolic resin. Hashmi *et al.* (2011) found that adding glass fibre to sisal-epoxy composites increased tensile strength from 32.5 MPa to 71.2 MPa, suggesting sisal paper could replace much of the glass fibre. Pappu *et al.* (2019) studied hybrid green composites made from sisal and hemp fibres with polyester made from lactic acid (PLA), finding improved tensile strength (46.25 MPa) and flexural strength (94.83 MPa). Madhuri & Rao (2014) fabricated hybrid composites reinforced with glass and sisal fibres in treated forms. The alkali treatment improved the mechanical properties (tensile strength, hardness, and compressive strengths) of sisal/glass hybrid composites. Thermal analysis showed increased decomposition and glass transition temperatures for the treated hybrid composites.

All studies highlight the potential of natural-synthetic fibre hybrid composites as environmentally friendly alternatives to fully synthetic composites. Collectively, the research emphasizes the importance of fibre content, fibre ratios, surface treatments, and hybridization in optimizing composite performance, providing valuable insights for developing high-performance, cost-effective, and sustainable composite materials. The competitive nature of the aviation industry ensures that any opportunity to reduce operating costs is explored wherever possible. Additionally, with advancements in this field, there is a need to analyse the performance of fibre composites to determine the most cost-effective, efficient, and sustainable material for aircraft structures. Therefore, this study aims to analyse the performance of glass/sisal/epoxy fibre composites by incorporating untreated natural sisal fibre with glass fibre in epoxy matrices to fabricate a hybrid composite. The flexural, tensile and impact properties of this hybrid composite were examined.

2. Materials and Methods

2.1. Fabrication of Glass/Sisal/Hybrid Composites

Raw samples of E-glass fibre were obtained from China free market via the courier service Ali Express. Untreated sisal fibre was sourced from the local market in Pantaker, Kaduna State, Nigeria. The epoxy resin (polyepoxide) and hardener were obtained from Port Harcourt, Rivers State, Nigeria. Other materials used during the fabrication process included a steel mold, release wax, measuring scale, hacksaw, hand gloves, face masks, and brushes, all of which were obtained from the Aircraft Engineering Department Laboratory at the Airforce Institute of Technology, Kaduna State. The flexural strength testing and tensile strength testing of the samples of fibres was done in the Strength of Materials Laboratory, Mechanical Engineering Department, Ahmadu Bello University (ABU) Zaria. Kaduna State, Nigeria. The impact test was done in the Metallurgical and Materials Engineering laboratory, ABU Zaria. The composites were fabricated using the hand-layup method in a steel mold measuring 200 mm × 200 mm × 6 mm (**Figure 1a, b, c, d and g**). The fibres and epoxy resin were fabricated into sandwich-structured composites and cured for 24 hours at room temperature. The epoxy resin and hardener were applied according to a weight ratio of 2:1. A total of five samples were made. **Table 1** shows the composition of the fibres and resin used in this process.

Figure 1. The equipment, machines, and processes for the experiment. (a) glass fibre, (b) sisal fibre, (c) epoxy resin and hardener, (d) hand-layup process of sample 2, (e) universal testing machine, (f) Charpy impact testing machine, (g) hand lay-up process of glass fibre 30wt% + sisal fibre 10wt%, and (h) tensile test specimen

Table 1. Fibre composition for fabrication of glass/sisal/epoxy hybrid fibre composites

Samples	**Sample Designation**	**Composition**	**Matrix (wt%)**	**Fibre (wt%)**	
			Epoxy	Glass Fibre (wt%)	Sisal Fibre (wt%)
1	Matrix	Epoxy resin + Hardener	100	0	0
2	Glass fibre/Sisal fibre (GF30SF5)	9 layers woven glass fibre + 12g sisal fibre	65	30	5
3	Glass fibre/Sisal	9 layers woven glass fibre + 24g sisal fibre	60	30	10

	fibre (GF30SF10)				
4	Glass fibre (GF30)	9 layers woven glass fibre	70	30	0
5	Sisal fibre (SF15)	36g sisal fibre	85	0	15

2.2. Fibre Testing

The fabricated fibre samples underwent flexural strength testing, tensile strength testing, and impact testing. A set of five test specimens were cut according to ASTM standards for each test. The specimens for the tensile test were cut according to the ASTM D-3039 standard. The machine used was the Hounsfield tensiometer Type W (S/N: W3179) with a beam deflection of 10 KN and a gauge length of 40 mm (**Figure 1e**). A graph sheet was used to record the results. The impact test was performed using the Charpy impact testing machine (serial number: CHARPY 412-07-15269C, model number: HD96QD) with an energy capacity of 15 J (**Figure 1f**). The specimens were cut in a rectangular form with dimensions of 80 mm × 13 mm × 5 mm. The measured specimen was struck with a swinging pendulum imparting a sudden load. This Charpy test was performed according to the ASTM D6110 standard. The energy absorbed by the specimen was carefully measured to provide a direct indication of its toughness. Additionally, at different measured thicknesses, the varying extensions were measured and recorded. The mechanical behaviour of each specimen subjected to bending forces was examined during the flexural strength test using the Universal Testing Machine (Enerpac - 100KN Capacity – Category Number: 261). Using a gauge length of 80 mm and 100 mm × 30 mm according to ASTM D7264 standard, the test allowed observation of the varying deflections for each applied load at different measured thicknesses for the specimen. The tests specimens after undergoing the flexural strength, tensile strength and impact testing are shown in **Figure 1h**.

3. Result and Discussion

3.1. Flexural Properties

Comparison of the flexural properties of hybrid samples to the synthetic and natural fibre samples is shown in **Figure 2** which shows relationship between modulus of rupture (MOR) and modulus of elasticity (MOE). The GF30 sample exhibited the highest flexural strength and flexural modulus. This indicates that it performed best under bending loads compared to the hybrid and natural fibre samples. It was found that hybrid composite samples (GF30SF5 and GF30SF10), each with an equal amount of glass fibre (30 wt%), had high flexural strength and flexural modulus compared to natural fibre sample (SF15). This indicates that the addition of glass fibre increases the flexural strength and flexural modulus. The presence of glass fibre improves the flexural strength of hybrid composites (Ramesh *et al.*, 2021). The glass hybrid laminates are superior to pure natural laminates, with properties that increase with the incorporation of the glass fibres; however, adding beyond a particular limit affects its strength-absorbing characteristics (Atmakuri *et al.*, 2020). The addition of more than three glass fibre layers increases the flexural strength and modulus of hybrid composites compared to only natural fibres (Faraj *et al.*, 2022). As seen in **Table 1**, the GF30SF5, GF30SF10 and GF30 samples have nine layers of woven glass fibres that enhance their flexural properties. The GF30SF5 sample, which has 5 wt% sisal, outperformed GF30SF10 sample, which has 10 wt% sisal fibres, with a 7.3% increase in its flexural modulus. When only sisal fibre is added without glass fibre, a reduction in strength can occur (Flynn *et al.*, 2016). This correlates with the low strength and modulus observed in sample 5 due to the incorporation of only sisal fibres.

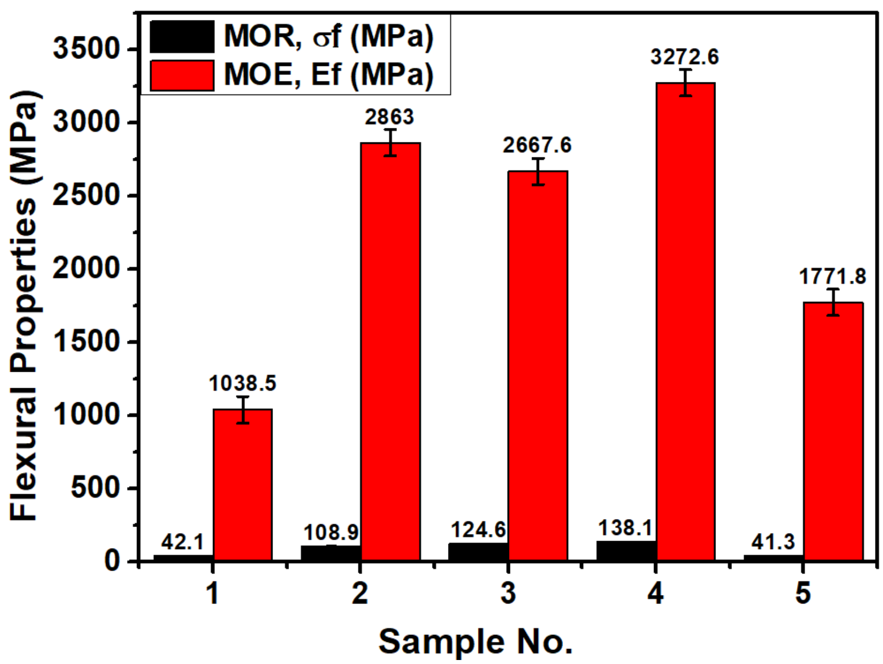

Figure 2. Flexural properties of glass/sisal/epoxy hybrid fibre composites

3.2. Tensile Properties

The comparison of tensile properties on ultimate tensile strength (UTS), elongation of break and Young's modulus (E) among hybrid, synthetic, and natural fibre samples is presented in **Figure 3**. The GF30 sample exhibits the highest tensile strength compared to the GF30SF5, GF30SF10 and SF15 samples. Although the GF30SF5 and GF30SF10 samples contain same weight percentage of glass fibre, GF30SF5 demonstrates superior tensile strength. Both GF30SF5 and GF30SF10 samples show higher tensile strength than the SF15 sample, indicating that the sisal fibre compositions in the hybrid samples contribute to their enhanced tensile strength. A 5 wt% addition of sisal fibre combined with 30 wt% glass fibres resulted in a positive hybrid effect, improving the tensile strength of GF30SF5 sample. Reducing the amount of sisal fibre in the hybrid composite can further increase tensile strength (Park *et al.*, 2020). A lower weight percentage of glass fibres combined with sisal fibre reinforcement yields composites with enhanced performance compared to 100% sisal fibre-reinforced composites (Mandal *et al.*, 2018). Sisal fibre can effectively transfer loads from the glass-fibre, thereby enhancing tensile strength (Mandal *et al.*, 2018). Increasing the number of glass-fibre layers further improves the tensile properties of composite laminates (Mandal *et al.*, 2018). This is evident in the GF30SF5, GF30SF10 and GF30 samples with nine layers of woven glass fibre, which demonstrate higher tensile strength compared to the SF15 sample. Interestingly, GF30SF10 sample exhibits the best elongation at break compared to GF30SF5, GF30 and SF15 samples. However, GF30SF10 sample has a lower Young's modulus than GF30SF5 and GF30, but higher than SF15 sample. Overall, the hybrid samples outperform the natural fibre sample in terms of tensile strength, elongation at break, and Young's modulus.

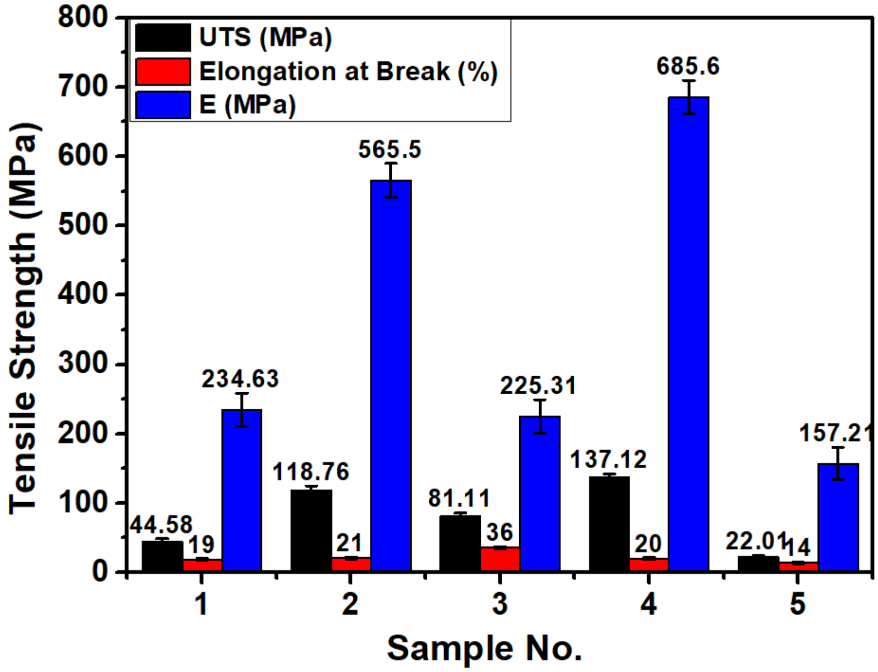

Figure 3. Tensile properties of glass/sisal/epoxy hybrid fibre composites

3.3. Impact Properties

The comparison of impact properties for hybrid, synthetic and natural fibre samples is presented in **Figure 4**. Fibres significantly influence the impact resistance of composites by interacting with crack formation in the matrix and acting as a medium for stress transfer (Mishra *et al.*, 2023). Hybrid samples exhibit the highest impact energy and impact strength compared to both synthetic and natural fibre samples. The GF30SF10 sample outperforms GF30SF5, showing a 9.8% increase in impact energy and 12.5% increase in impact strength. It also surpasses GF30 sample, with a 187.5% increase in impact energy and a 190.3% increase in impact strength. The inclusion of sisal fibre with glass fibre in hybrid samples results in greater impact energy absorption compared to synthetic and natural fibre samples. Additionally, an increase in the weight percentage of sisal fibre enhances impact strength and energy absorption. The impact energy of natural fibre laminates is lower compared to hybrid laminates that combine glass fibres. The presence of alternating layers of sisal and glass fibres in the hybrid laminates allows the glass fibres to absorb a significant amount of energy (Arthanarieswaran *et al.*, 2014).

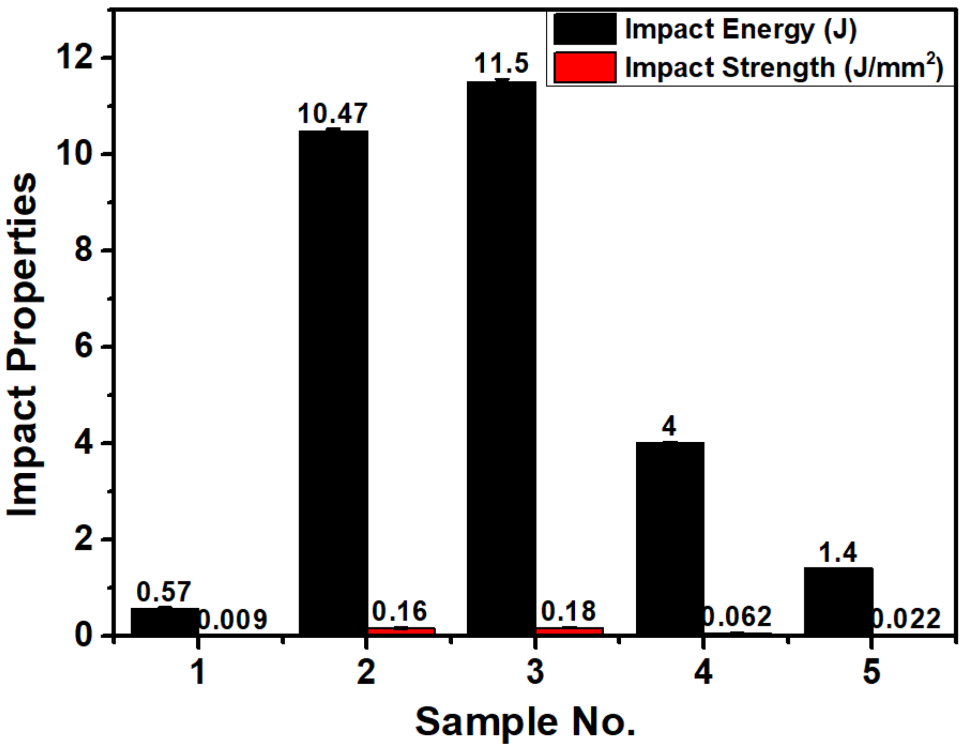

Figure 4. Impact properties of glass/sisal/epoxy hybrid fibre composites

3.4. Discussion

Hybrids are conceptually fabricated to have positive gains of all the constituent reinforcements. As glass fibres have low specific strength and specific modulus, some volume fraction of carbon fibres (having high specific strength and modulus) should be incorporated in glass fibre reinforce polymer (GFRP) composite to enhance the mechanical properties and result in a better composite compared to GFRP. Suresh (2020) investigated the influence of glass fibre hybridization on the mechanical properties of natural sisal fibre-reinforced composites. The study showed that the glass-sisal-glass (GSG) composite had the highest tensile strength (211.83 MPa), flexural strength (388.65 MPa), and impact strength (3.8 kJ/m^2). In contrast, **Figure 4** of this study indicates that hybrid composite samples (GF30SF5 and GF30SF10) exhibit the highest impact properties. However, GF30 sample demonstrates the highest flexural properties, ultimate tensile strength, and modulus of elasticity. The superior flexural modulus and strength of GF30 sample shows the inherent advantages of synthetic fibres in applications requiring high stiffness and load-bearing capacity. The 215.1% increase in flexural modulus and 84.7% increase in flexural strength compared to matrix and SF15 samples, respectively. This validates the effectiveness of E-glass fibres in enhancing structural integrity.

As increased is recorded in glass fibre content, the glass fibre tensile and flexural modulus of the composite showed a linear increase. However, the higher volume fraction of glass fibre than optimum content induced a drop of the reinforcing efficiency of fibres because of greater void content. Therefore, this reflects an optimal blend of natural and synthetic fibres to maximize tensile strength could provide more concrete design guidance for applications. Conversely, GF30SF5 and GF30SF10 hybrid composites show the highest elongation at break, illustrating the synergistic effects achieved through hybridization. This signifies a higher percentage elongation could mean a higher ductility of the material which makes it suitable for aerospace application and can undergo greater deformation before breaking. These findings align with previous research by Sapuan *et al.* (2020) and Asim *et al.* (2018), indicating that hybrid composites combining synthetic and natural fibres can achieve improved mechanical properties. Gupta *et al.* (2015) found through statistical analysis that adding glass fibres to sisal-reinforced composites increased its mechanical resistance. According to Kausar (2019), there was no significant improvement in the impact strength of sisal/glass hybrid composites when treated with NaOH and trimethoxy silane (a coupling agent). However, this study showed that the glass/sisal/epoxy hybrid composite achieved excellent impact properties, with an impact energy of 11.5 J and impact strength of 0.18 J/mm^2, without any treatments. The observations regarding tensile properties corroborate findings from Haider and Yasmeen (2018) that reported enhanced mechanical properties in hybrid composites. The ability to modify the mechanical properties through hybridization offers significant advantages in designing materials for specific aerospace applications, such as control surfaces and fuselage panels, where both flexibility and strength are essential.

This study reveals that hybridization of fibre composites plays an important role in the structural components of aircraft. Glass fibre, with its superior flexural properties, is suitable for load-bearing components or structures of the aircraft. The hybrid composites with an impact strength of 11.5 J are appropriate for areas with less load and structures involving impact loading, such as the empennage, wing flaps and cowlings. They can also be used as protective layers to mitigate bird strikes or impact loading. In contrast, pure sisal and glass fibre composites are better suited for areas that do not experience high bending or impact loads, such as interior parts of the aircraft, including baggage bins and seats. These materials can also be combined with traditional materials like polyester to enhance their properties. Utilizing lightweight materials will reduce fuel consumption, decrease carbon emissions, and improve overall aircraft performance, making it more environmentally friendly.

4. Conclusion

This study aims to investigate the performance of glass/sisal/epoxy hybrid fibre composites for aircraft structures. The following conclusions have been made:

- GF30 sample, comprising glass fibre and epoxy possessed the highest flexural strength of 138.1 MPa and flexural modulus of 3272.6 MPa than the other composite samples.
- GF30 sample possessed the highest tensile strength of 137.12 MPa and modulus of elasticity of 685.6 MPa than the other composite samples.
- The hybrid composite sample (GF30SF10) possessed the highest strength of 0.18 J/mm^2 and absorb more impact energy of 11.5 J than the other composite samples.
- Glass fibre exhibited high mechanical properties, thereby enhancing and improving the properties of the hybrid composites, which also showed excellent mechanical properties.

Future research could focus on optimizing the fibre ratios to further improve the overall performance of these hybrid composites for aircraft structures.

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Credit Author Statement

Conceptualization and methodology, Awode, E.I. and Kwarkas, N.P.; software and validation, Awode, E.I., Omiogbemi, I.M. and Kwakas, N.P.; investigation, Awode, E.I. and Omiogbemi, I.M.; data curation, Awode, E.I., Kwarkas, N.P. and Bamisaye, O.S.; writing—original draft preparation, Awode, E.I. and Kwarkas, N.P.; writing—review and editing, Awode, E.I. and Kwarkas, N.P.; visualization, Bamisaye, O.S.; supervision and project administration, Awode, E.I.

Conflicts of Interest

The authors declare no conflict of interest.

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