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Performance Evaluation of Kevlar-Sisal-S-Glass Hybrid Composites with Ceramic Fillers for Structural Applications

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Abstract

This study examines the mechanical properties of hybrid composite laminates reinforced with Kevlar, sisal, and S-glass fibers, and incorporating ceramic fillers—silicon carbide (SiC) and aluminum oxide (Al_2O_3)—within an epoxy matrix. The hand lay-up method was utilized to produce the laminates, ensuring a uniform fiber stacking sequence and including 10% filler material. Two composite variations were synthesized: one incorporating SiC and the other Al_2O_3, and both underwent tensile, flexural, hardness, and inter- laminar shear strength (ILSS) assessments. The SiC-filled laminate exhibited greater tensile strength (93.4 MPa) than the Al_2O_3-filled variant (92.8 MPa). The flexural strength results preferred the SiC composite (37.5 kJ/m² compared to 32.9 kJ/m²), and hardness values exhibited a significant increase with SiC (65.33 HV) over Al_2O_3 (57 HV). The inter-laminar shear strength of the SiC laminate (212.0 MPa) was somewhat superior to that of the Al_2O_3 variant (211.6 MPa), suggesting enhanced bonding and delamination resistance. Analytical modeling via stiffness matrix computation and finite element simulation with ANSYS validated the experimental trends, corroborating the mechanical superiority of the SiC composite. The results confirm that the Kevlar/Sisal/S-glass hybrid composite with SiC filler provides the optimal combination of strength, durability, and stiffness. The optimum composite, characterized by its balanced mechanical properties, low weight, and resistance to mechanical stresses, is ideally suited for automotive structural components, especially car bumpers, where impact resistance and structural integrity are paramount. Nonetheless, owing to apprehensions over water absorption, these composites are not advisable for underwater applications.

Keywords: Cryogenic treatment, mild steel, mechanical properties, tribological behavior, wear resistance, machinability

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INTRODUCTION

Composite materials refer to materials that are formed by the combination of two or more distinct materials, which are supposed to have superior mechanical properties compared to the individual constituents. Composites that are usually made of a matrix and a reinforcement are superb in terms of strength -to- weight ratios, corrosion, and design flexibility and cannot be ignored in aerospace, car-building, and military industry. The paper is based on a hybrid composite laminate that is made of Kevlar, S-glass, and sisal fibers, where the epoxy resin is the matrix. Silicon Carbide (SiC) and Aluminum Oxide (Al_2O_3) filler materials were added to enhance the mechanical performance. The laminates were created using the hand lay-up process and tested based on tensile strength, flexural strength, hardness, and delamination performance. The objective is to find the effects of SiC and Al_2O_3 fillers on the mechanical properties of the composite. Simulations, experiments, and analytical computations using ANSYS software were done to support the findings. Hybrid composites are increasingly preferred over single-fiber composites in advanced structural applications due to their ability to combine the advantages of multiple reinforcement types within a single matrix system. Unlike single-fiber composites, which are limited by the inherent properties of one reinforcement, hybrid composites enable synergistic interaction between different fibers, resulting in improved mechanical performance and design flexibility. In particular, the combination of high-strength synthetic fibers such as Kevlar and S-glass with natural fibers like sisal provides a balanced response in terms of tensile strength, stiffness, impact resistance, weight reduction, and cost efficiency. The findings reveal that SiC-filled composites have superior performance and they are therefore suitable in structural applications like automobile parts. The study optimizes the production of the hybrid composites in lightweight and high-strength engineering practices. [1].The experiment indicates that the thermal conductivity and stability of Kevlar/epoxy composite is improved with surface-modified nano- Al_2O_3. This will be useful in our EV safety studies, as it proposes better heat-resistant and lightweight material to protect the battery and manage the thermo-regulation process [2]. The carbon-Kevlar composite laminates are also better in fracture toughness, damage tolerance, and impact energy absorption. The properties make them fit well in high-performance and safety critical applications. In hybrids they can increase the crash protection, structural integrity and safety of the passengers [3]. 3D-printed hybrid fiber composites degrade during hygrothermal aging, and continuous carbon/Kevlar fibers increase durability. This is in line with our EV safety study as it informs our material choice and long term performance forecasting. [4]. The short Kevlar fibers are used to increase tensile strength and failure resistance of adhesively bonded joints by increasing load transfer. This helps us in the study of EV safety by assisting in strengthening and building tougher joints to the car structures made of composites [5]. Friction performance of abaca fiber-based brake composites was similar to Kevlar, including eco-friendliness and cost-effectiveness. This can be applied to our EV study because it provides a sustainable solution to the braking system without reducing safety [6].The deposition of graphene, SiC, and Al_2O_3 nanoparticles on Kevlar fiber-reinforced epoxy composites resulted in mechanical strength and thermal stability improvements. This will help us in our EV safety studies as it underlines superior nanomaterial approaches of enhancing composite performance during extreme conditions. [7]. High GSM laminates of Glass-Carbon-Kevlar fiber-reinforced hybrid polymer composite exhibited good thermal stability and mechanical strength. This is in line with our EV safety work by providing strong composite answers to vehicle components with a high thermal and mechanic demand [8]. Mechanical properties and sustainability of Kevlar fiber-polypropylene composites were enhanced by additions of cotton stalk and granite particles. This reinforces our EV safety project by proposing environmentally friendly reinforcements to lightweight and robust car parts. [9]. Multi-scale modelling indicated that the moisture diffusion of carbon/Kevlar laminates during hygrothermal aging affected the integrity of these laminates in the long term. This is in line with our research on EV safety in that it helps to predict the behavior of materials under humid and high temperature working conditions. [10]. Dynamic mechanical analysis revealed that the fiber orientation has a great influence on the stiffness and damping of 3D-printed Kevlar-nylon composites. This helps our EV safety research by informing about our best fiber alignment to enhance vibration resistance and structural performance [11]. The hydration resistance was enhanced using chemical treatment.

Mechanical strength of basalt/Kevlar fiber-epoxy hybrid composites. This helps us to conduct safety studies on how to increase composite strength and stability when subjected to moisture in the real world. [12]. Glass/Kevlar fiber-reinforced phenolic composites with a hybrid structure were found to be more thermal stable and less flammable. This is conducive to our safety research in that providing the fire-

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resistant composite solutions to high-temperature and critical uses [13]. The shape of impactor nose and the arrangement of arranging fibers largely influence the low-velocity impact resistance of Kevlar/basalt fiber-epoxy composite. This is connected to your research in safety by informing the best composite design to enhance impact safety in structural lightings. [14]. The functionalities of depositing SiC, TiO 2, Al_2O_3, and graphene nanoparticles on Kevlar fiber mats led to interfacial adhesion and mechanical performance. This is in connection with the study as it enhances bonding and dependability of fiber reinforced composites under tough environments. [15]. Glass fibers improve the mechanical strength, durability and microstructure of concrete through it containment of cracks and optimization of pore structure. These results are important in supporting our study since they indicate that fiber reinforcement is an effective tool in enhancing concrete performance and sustainability [16]. Recycling procedures of carbon/glass fiber wastes of wind turbine blades focus on sustainable recovery. This helps to validate our study by emphasizing on the reuse of fiber composites in construction practice in an environmentally friendly manner [17]. Different processes of producing carbon/glass fiber- reinforced composites are covered, and their impact on mechanical and thermal characteristics is demonstrated. This relates to our study since it shows the effect of production methods on composite performance in the construction industry [18]. Structural Composites Glass fiber-reinforced polymer composites are stronger, stiffer and more resistant to corrosion.

This is relevant to our study as it confirms the appropriateness of glass fiber in improving the natural fiber composite material in terms of mechanical properties particularly tensile and flexural strength. [19].Glass fiber hybridized natural fiber composites exhibited improved mechanical properties particularly tensile and flexural strength. This is in line with our study as it points out to the advantages of using hybrid fiber reinforcement when used to enhance the performance of a composite to be used in construction. [20]. Waste paper reinforced glass fiber reinforced concrete under deformation exhibited enhanced load bearing and also enhanced energy absorption. This makes this research viable since it shows that fiber and waste materials improve structural performance in sustainable construction [21]. The research established that glass fibre composites are stronger in mechanical properties than banana fibre composites using the Taguchi method. This conforms to our study since it points to the effectiveness of glass fibers in complementing composite materials to be used in construction works [22]. Prolonged bending, water immersion and fiber hybridization influence the mechanical performance of carbon/glass fiber composite, and hybrid modes enhance durability. This assists our study by demonstrating the effects of environmental condition and fiber mixtures on composite behaviour in construction [23]. The mechanical properties of the carbon/glass fiber composite rods greatly depend on the type of fiber hybridization and some combinations of the hybridization increase the stiffness and strength. This substantiates our study by showing that hybrid fiber approaches will offer the best composite performance in structural applications [24]. Polymer and glass fibers enhance the strength, toughness, and crack resistance of concrete but they have issues such as workability and long term durability. This is relevant to our study as it explains the advantages and disadvantages of the application of glass fibers in fiber-reinforced concrete in the construction process [25]. Continuous carbon/glass fiber composite Hybrid layout and additive manufacturing technology provides a considerable improvement in mechanical properties such as strength and stiffness. This substantiates our study because it demonstrates that the arrangement of fiber and highly developed fabrication techniques enhance performance of composite in construction [26]. Glass fiber composites have fatigue performance that increases with a high fiber volume fraction to an optimum level, then it may decline. This follows our study given that fiber content is very important in improving the construction structural features since it increases the durability of the composite. [27]. Glass fiber hybridization and radiation treatment play a major role in increasing the mechanical and durability characteristics of the jute/glass hybrid composites. This is in line with our study since it shows that there are practical ways of enhancing the performance of sustainable fiber-reinforced materials as construction materials [28]. Glass and polypropylene fiber reinforcement enhance the mechanical characteristics and microstructure of concrete making it better in terms of crack resistance and toughness. This concurs with our study as it shows the synergistic interactions of fiber blends to enhance the performance of concrete to be used in construction [29]. The mechanical strength and freeze- thaw properties of lime-nanoclay stabilized marl clayey soil reinforced through glass fiber improved the soil structure and resistance. This is relevant to our study as it proves the efficiency of glass fibers to enhance material stability and performance. [30]. Ji et al. demonstrated that starch- sisal fiber composites with fillers have higher strength, water resistance, thermal stability and biodegradation. This aligns with the electric vehicle goals of the lightweight, environmentally sustainable materials with better performance in both thermal and mechanical conditions. [31]. Additionally, De Castro et al. found out that biopolymer composites in the form of sisal fiber are admirable in terms of mechanical strength and environmental friendliness. This makes research of electric vehicles easier by promoting sustainable materials that will guarantee reliable structural integrity [32]. Santos et al. found out that sodium carbonate and bicarbonate treatment improved adhesion and mechanical qualities of the sisal fibre composites. Such enables the electric vehicle materials to progress by enhancing the life of the sustainable fiber-reinforced materials. [33]. Kumar et al. found that the treated sisal fibers increased the physical, mechanical, and microstructure of the glass fiber-reinforced hybrid composites. This simplifies the process of conducting electric vehicle research by illustrating the effect of fiber treatment on the strength and durability of sustainable composite materials [34]. Zhuang and Zhao found that addition of expanded polystyrene and sisal fiber increased dynamic stability and microstructure of lightweight soil. This would ease the research on electric vehicles with the focus placed on sisal.

US patent application on enhancing vibration resistance and structural integrity of lightweight materials [35]. Bhagat and Ghosh revealed that the length of the fiber makes significant contribution to the mechanical and rheological properties of polypropylene/sisal composites. This helps in the development of electric vehicles through the development of more fiber-reinforced materials that would enhance strength and efficiency in their processing [36]. Prakash et al. found that sisal fiber and coconut shell waste strengthened lightweight concrete in terms of sustainability. This aligns with the goals of electric cars by promoting strong, eco-friendly materials when making cars [37]. Ferede et al. demonstrated that recycled PET composites with the addition of sisal fiber and sawdust have better mechanical strength and sustainability. This enables electric vehicle research through powerful, re-cyclable, and sustainable lightweight parts materials [38]. Rajaram et al. have found out that abaca/sisal fiber-reinforced epoxy composites have better mechanical properties and hybrid strength benefits. This makes the development of electric vehicles easier since flexible, bio-based materials are promoted towards sustainable structural applications [39]. Bhagat and Ghosh came up with the fact that the near-critical length of sisal fibers improves the mechanical performance of the PP/sisal composite and helps to predict the properties. This can be used to conduct research on electric vehicles by enhancing the development of powerful, light and eco-wanton materials [40]. Kushwaha et al. discovered that polyester/boron nitrate/sisal fibre hybrids have superior thermal conductivity and mechanical strength to apply in microelectronics. This assists the study of EV because it allows the use of thermally stable light-weight materials applicable in electronic and structural components [41].

Kevlar is widely employed in high-performance applications because it is a para-aramid fiber with rigid and highly oriented aromatic polyamide chains. Strong intermolecular hydrogen bonding and chain alignment provide Kevlar with high tensile strength, high specific modulus, low density, excellent energy absorption, and good resistance to impact and damage propagation. In addition, its thermal stability, chemical resistance, dimensional stability, and low electrical conductivity make it suitable for lightweight components operating under demanding mechanical and environmental conditions. In the present hybrid laminate, Kevlar contributes tensile strength, toughness, and impact-energy absorption, whereas S-glass provides high elastic modulus, tensile strength, flexural rigidity, thermal stability, and resistance to fatigue and environmental degradation. Compared with conventional E-glass, S-glass exhibits superior strength and stiffness, making it particularly suitable for structural components subjected to tensile, bending, vibration, and repeated loading conditions The originality of this research is to show the potential of hybrid fiber structures together with filler to offer high performance, lightweight and cost-efficient composites that can be used in strenuous structural applications

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particularly in the car industry. This research has made a great contribution to the development of sustainable composite materials through the combination of both natural and synthetic reinforcement technologies to enhance the mechanical properties.

MATERIALS AND METHODS

This project involved the fabrication of hybrid composite laminates utilising a combination of synthetic and natural fibers - Kevlar, S- glass, and sisal—coupled with epoxy resin as the matrix and ceramic fillers including Silicon Carbide (SiC) and Aluminium Oxide (Al_2O_3). The selected materials have exceptional mechanical features, including a high strength-to-weight ratio, thermal resistance, and environmental sustainability, rendering them appropriate for structural applications. The sisal fibres were first washed, purified, and severed into 300 mm long strands. They were completely desiccated to eradicate moisture, hence enhancing adhesion to the matrix. Kevlar and S-glass fibres were utilised in woven mat configuration, each section measuring 300 mm x 300 mm. Figure 1 depicts the images of Kelvar b) Glass Fibre c) Sisal fibre d) Epoxy resins

EXPERIMENTAL METHOD

This study utilised epoxy resin Araldite LY-556 as the matrix material, combined with hardener HY-917 in a weight ratio of 100:10. This combination offers superior mechanical qualities and chemical resistance, guaranteeing reliable performance under ambient temperature curing conditions. Two sets of hybrid laminates were fabricated via the hand lay-up method, one incorporating Silicon Carbide (SiC) filler and the other incorporating Aluminium Oxide (Al_2O_3) filler, both integrated into the epoxy resin at a concentration of 10% by weight.The reinforcements comprised Kevlar fabric, S-glass fibre, and sisal fibres, which were fabricated into 300 mm × 300 mm sheets. The sisal fibres were first cleaned, dried, and subsequently cut into lengths of 300 mm. The adopted stacking sequence consisted of Kevlar, S-glass, Sisal (0° orientation), Sisal (90° orientation), S-glass, and Kevlar. Each layer was separately infused with the resin-filler combination throughout the lay-up procedure to guarantee consistent wetting and adhesion.

Figure 1. (a) Kelvar; (b) Glass fibre; (c) Sisal fibre; (d) Epoxy resins.

Figure 2. The experimental setup for the following tests: (a) Tensile, (b) Delamination, and (c) Flexural

The layers were meticulously matched and compacted by hand with rollers to eliminate trapped air and improve resin infiltration.Upon the completion of the lay-up, substantial flat plates and weights were employed on the laminates to exert pressure and guarantee a polished surface. The arrangement was allowed to remain undisturbed for 30 hours to facilitate adequate curing at ambient temperature. Upon curing, the composite plates were cut to eliminate uneven edges and yield uniform square samples.Two varieties of laminates were fabricated for experimental assessment—one augmented with SiC and the other with Al_2O_3. The samples underwent mechanical tests, including tensile testing, flexural testing, Vickers hardness testing, and inter-laminar shear strength testing, to evaluate the impact of ceramic fillers on the composite's structural performance.

MECHANICAL TESTING

The mechanical tests performed as a part of the hybrid composite laminates were the tensile, flexural, hardness, and delamination tests. The experimented tests were conducted on flat-composite specimens of specific dimensions: 40 mm of gauge length, 10 mm of width and around 3.5 mm of thickness. Tensile test was carried out according to the ASTM D638-03 standard with the help of universal testing device to determine the properties of the composite under the impact of the axial load in terms of strength and elongation. The three-point bending method was used to test the flexural parameters in line with ASTM D790-03 to determine the bending strength and the modulus. A diamond indenter under a controlled applied load was used to determine the Vickers hardness test, and the obtained results were registered in accordance with the recommended standards of hardness testing. Interlaminar shear strength, which is a delamination resistance, was measured by the visual and mechanical analysis in line with the composite test requirements. Figure 2 shows the Experimental Setup for the Following Tests: (a) Tensile, (b) Delamination, and (c) Flexural.

RESULTS AND DISCUSSION

Tensile Test

Three composite specimens, reinforced with Kevlar-Sisal-S-Glass hybrid fibers and embedded with ceramic particles (SiC and Al_2O_3), underwent tensile testing according the ASTM D638-03 standard. The tensile test was conducted with a computerized universal testing machine with a servo-hydraulic system, facilitating accurate regulation of load and strain rate. The specimens exhibited a conventional dumbbell morphology, featuring distinct shoulders and a diminished cross-section in the gauge area to facilitate homogeneous deformation. The gauge length of each specimen measured 40 mm, with a width of 10 mm and a thickness of roughly 3.5 mm. The shoulders were engineered to conform to serrated grips for enhanced mounting convenience and improved alignment. A uniaxial load was applied axially at a steady pace until the specimen failed throughout the test. Load cells and strain gauges were employed to quantify the applied force and resultant elongation, respectively, with the data recorded and evaluated by a computerized data acquisition system.The major objective of the tensile test was to assess the composite laminate's performance under tension, ascertain its maximum tensile strength, and analyze its failure mode. This information is essential for evaluating the composite's capacity to withstand structural loads in practical applications. The test outcomes for the laminates infused with Silicon Carbide (SiC) exhibited a peak tensile strength of 93.4 MPa, whilst those augmented with Aluminium Oxide (Al_2O_3) attained 92.8 MPa. These findings demonstrate that both fillers had similar tensile performance, with SiC presenting a marginally superior improvement. The strain behavior demonstrated the ductility features of the laminates, with average strain values ranging from 3.4% to 4%, signifying the material's capacity for extension prior to fracture.

The tensile load-displacement graphs demonstrated uniform mechanical behavior among all three tested samples for both filler types. Minor differences were noted, which are characteristic of fiber-reinforced composites owing to inhomogeneity non fiber distribution or filler dispersion. Nevertheless, the findings validated that the hybrid composite laminates exhibit commendable tensile properties, rendering them appropriate for structural applications necessitating strength, stiffness, and mild ductility. The observed tensile fractures in the gauge section confirmed that failure transpired in the designated area, hence enhancing the credibility of the test findings. The tensile test revealed the material's capacity to withstand axial loads efficiently, exhibiting tensile strengths comparable to or surpassing those of typical engineering materials such as PVC or certain wood grades, thereby highlighting the composite's applicability in industrial sectors including construction, transportation, and defense. Figure 3 depicts the tensile strength of various samples.

Flexural Test

Three composite specimens which were made using Kevlar-Sisal-S-Glass fibers and with the addition of ceramic particles (SiC and Al_2O_3) were tested regarding flexural strength in accordance to ASTM D3878. The flexural test or bending test was conducted using a universal testing machine which had a three-point bending test. The purpose of this test was to determine the resistance the material has to bending loads as well as to determine the top most stress that the exterior of the material can endure before failure. Measures of each specimen were approximately 100mm in length, 10mm in width, and 3.5mm in thickness. In the experiment, the load was applied at the center by continually adding it to the specimen at both ends. The design ensured that the bending moment was highest at the middle and caused fracture development and failure in the region of the highest stress. The flexural strength formula is $FS = (3lP)/(2bd^2)$ where the l is the span length, P is the weight applied, b is the width of the specimen and d is the thickness.

The key goal of the test was to determine the ability of the composite to withstand bending forces, which form the key requirement in such applications as beams, panels, and automotive parts where flexural loads dominate. The results showed that flexural strength of the laminate filled with Silicon Carbide (SiC) was 37.5 kJ/m^2 and that of laminate filled with Aluminium Oxide (Al_2O_3) recorded a lower flexural strength of 32.9 kJ/m^2. These values show the effectiveness of ceramic fillers to increase the stiffness and strength of the hybrid composite under bending loads. The existence of flexural cracks on the lower tension surface was observed to be a result of visual inspection, which supported the fact that the failure occurred in the high-stress area. All three samples of the type in question showed a uniform mechanical response to flexural loading, which is encouraging in terms of production and the material design despite slightly different performances. The outcomes are important in supporting the usage of the material in structural elements that undergo bending forces. The flexural test provides data into the ability of the composite to resist deformation when under compressive load and helps to predict the behavior of the composite in actual situations when tension and compression act simultaneously.

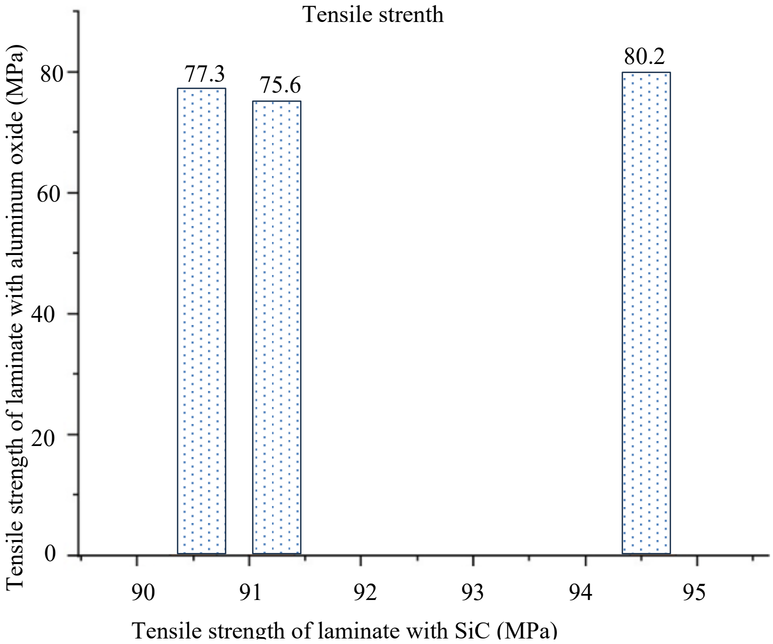

Figure 3. Tensile strength of various samples.

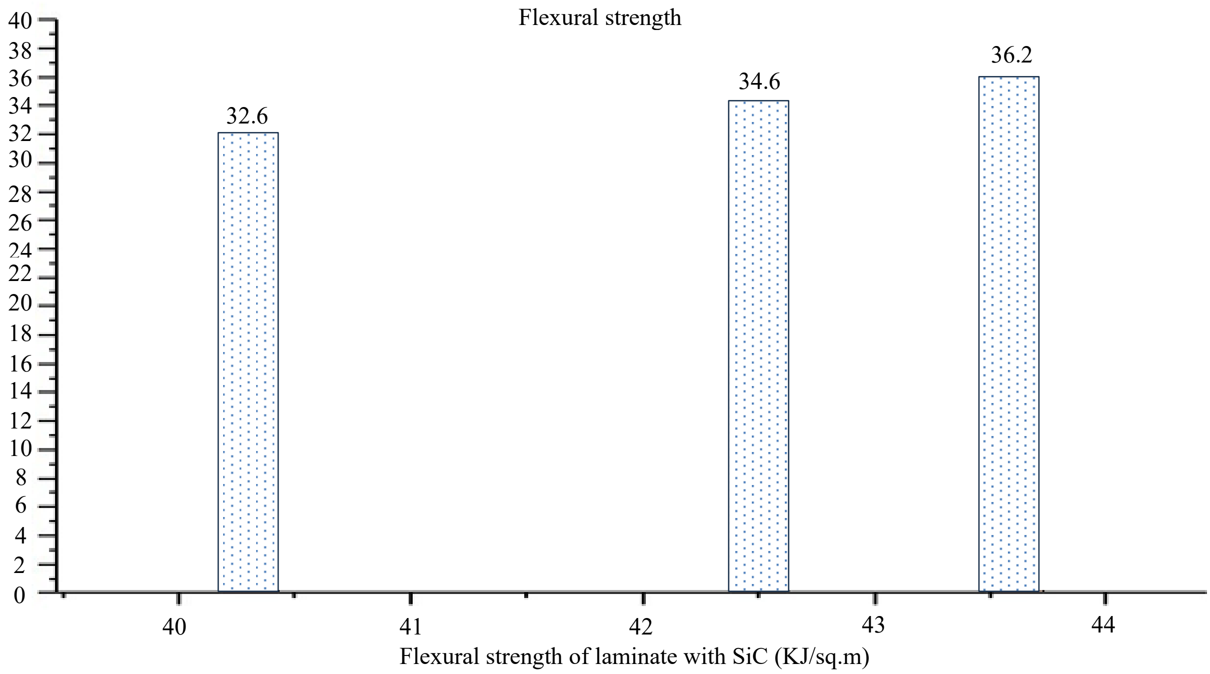

Figure 4. Flexural test for the samples.

These flexural properties that are achieved imply that such hybrid laminates, especially those involving SiC fillers, are suitable in the structural applications that demand high strengths and stiffness under flexural loads. Figure 4 shows the flexural strength of various samples.

Delamination Test

Three hybrid composite specimens composed of Kevlar, sisal, and S-glass, integrated with ceramic fillers, underwent delamination testing to assess their interlaminar shear strength (ILSS), an essential metric indicative of the bonding integrity between layers. The assessment utilized defined interlaminar shear testing protocols, often based on ASTM D2344, to evaluate the material's resistance to delamination under transverse pressure. The specimens were rectangular, measuring approximately 40 mm in length, 10 mm in width, and 3.5 mm in thickness. Testing was conducted with a universal testing equipment fitted with a short-span three-point bending fixture specifically developed for delamination assessment. A regulated load was exerted perpendicular to the laminate plane until delamination or interlayer failure ensued. Sensors and load cells attached to the machine accurately quantified the applied load and the resultant displacement, facilitating the determination of shear strength by the peak load reached before interfacial failure.The major aim of the delamination test was to assess the composite's capacity to preserve structural integrity under transverse and interfacial stress conditions, which are particularly vital in multilayer laminates subjected to bending, impact, or vibration during operation. The interlaminar shear strength (ILSS) of the composite laminate infused with Silicon Carbide (SiC) was measured at 212.0 MPa, whereas the laminate infused with Aluminium Oxide (Al_2O_3) exhibited a comparable value of 211.6 MPa. The elevated shear strength values underscore the remarkable adhesion between fiber layers and the matrix, signifying robust bonding and a diminished likelihood of fiber pull-out or interfacial debonding. The specimens displayed characteristic delamination features, including matrix cracking and fiber-matrix interface failure, especially in areas exposed to maximal shear stress. Notwithstanding slight variations in recorded values, all examined specimens demonstrated exceptional consistency in mechanical performance regarding delamination resistance, underscoring the dependability of the hybrid reinforcement and filler system. The phenomenon of delamination was meticulously examined to ascertain failure factors such as inadequate fiber-matrix adhesion or high localized stresses. In actual applications, robust ILSS guarantees that composite materials can withstand delamination-related deterioration when exposed to cyclic loads, vibration, or impact, prevalent in aerospace, automotive, and structural engineering contexts. The delamination test findings confirm the efficacy of SiC and Al_2O_3 fillers in preserving structural integrity and offer compelling proof of the material's appropriateness for advanced composite applications. Figure 5 shows the interlaminar shear strength of various samples.

Vickers Hardness Test

The Vickers hardness test was used to verify the resistance of these three hybrid composite specimens, which include Kevlar, Sisal, and S-Glass fibers combined with ceramic fillers (SiC and Al_2O_3) to the deformation of their surfaces. The test has been performed in accordance with the standard practice of Vickers in a precision Vickers hardness testing instrument, which uses a diamond indenter, having a square based pyramidal shape with an included angle of 136° between two opposing faces. The examination was done by adding a steady load-usually 10 kgf (kilogram-force)-on the indenter onto the polished surface of the composite samples over a period of 10-15 seconds. After removal of the load, the two diagonals of the resulting indent were measured using a microscope and their average was determined. The Vickers Hardness Number (VHN) was calculated using the known load plus the measured area of the indentation, as shown in the following formula: $HV = 1.854 \times F/d^2$ multiplied x F where F is the applied force in kgf and d is the average diagonal length in mm. The method produces very precise results that are suitable in evaluating soft and hard materials.

The overall goal of this test was to measure the hardness of the surface of the composite material, which also implies its ability not to experience localized plastic deformation, scratching, and wear. These properties are particularly essential in those applications where there is abrasiveness or mechanical contact. The laminate impregnated with Silicon Carbide (SiC) had a Vickers hardness of 65.33 HV, and that of the laminate impregnated with Aluminium Oxide (Al_2O_3) had a slightly lower value of 57 HV. The difference in hardness can be explained by the fact that the intrinsic hardness of the particles of SiC is higher and there is an increased contact between these particles and the remaining matrix, thereby, contributing to greater transference of loads and microstructural rigidity. Although there is a measurable difference in hardness between the two filler solutions, the two measurements are both sufficient in terms of hardness to be used in light structural applications. The fact that the values of hardness in the three samples of each type are consistent confirms that the ceramic fillers are well distributed within the matrix and the manufacturing process is reproducible. The results demonstrate that hybrid composites especially those with SiC reinforcements have better surface durability and are better suited to conditions related to friction, surface contact, or small abrasive pressures. The hardness test is performed on the Vickers and the outcome proves that the composite material is reliable in surface performance and this proves the findings of the tensile, flexural, and delamination tests, which in turn, justifies the overall structural integrity of the material. Figure 6 depicts the hardness of the samples.

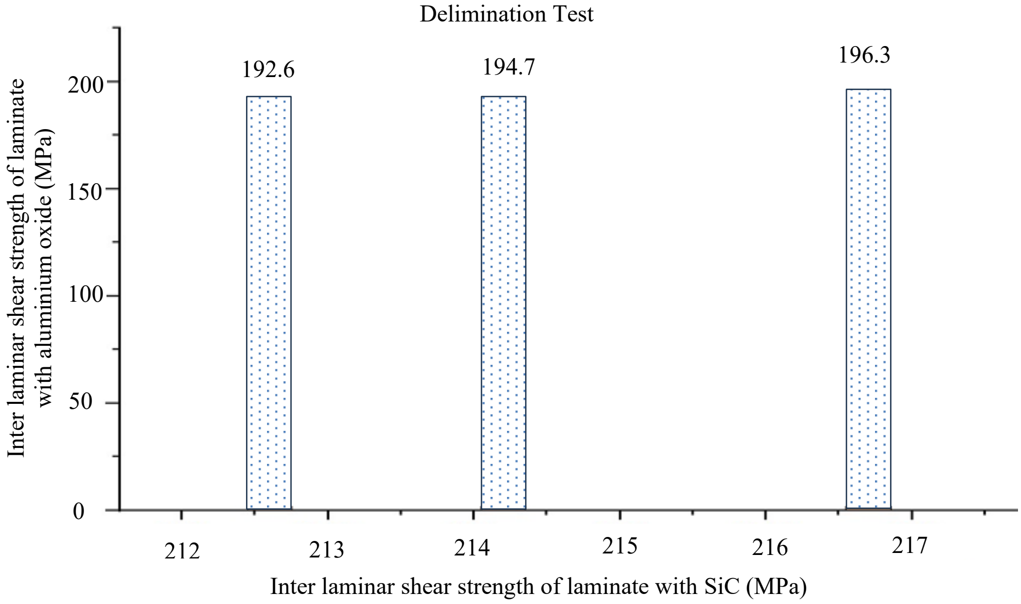

Figure 5. Delamination test for the samples.

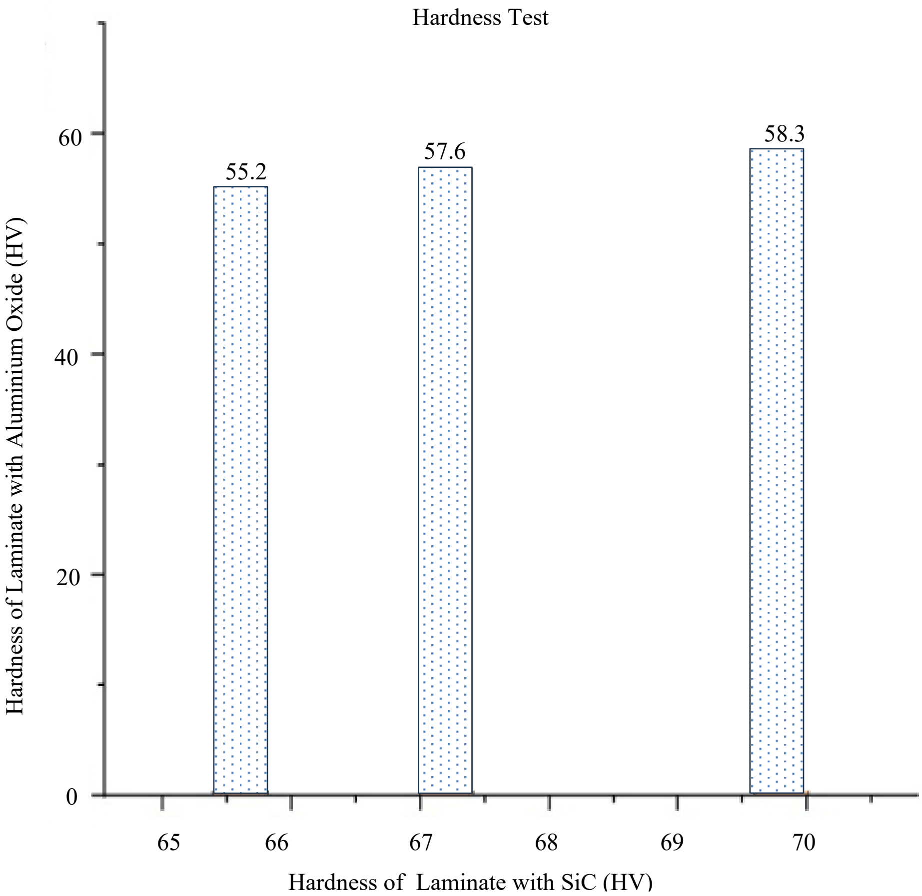

Figure 6. Hardness test for the samples.

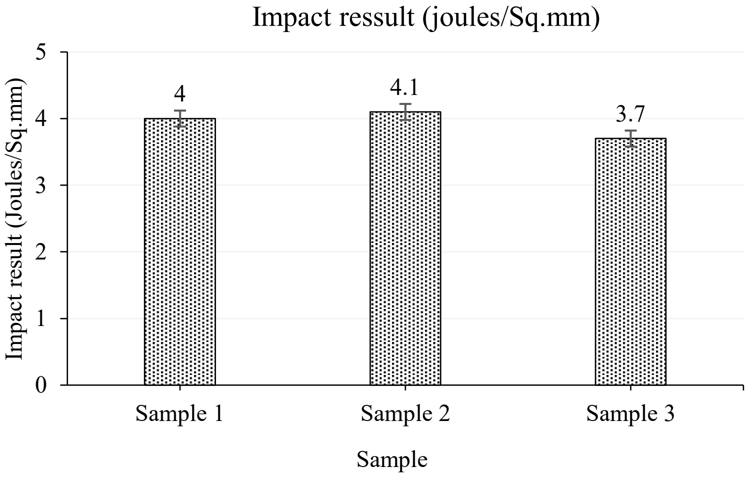

Figure 7. Impact test for the samples.

Impact Test

Impact tests are used to determine the energy that the material needs to become fractured, meaning the toughness and yield strength is connected with but not directly stated by a formula. The rate of strain influences the fracture behavior and the ductile-brittle transition temperature (DBTT) is a temperature range in which fracture energy alters. DBTT is empirical by fracture surface analysis or analysis of absorbed energy. Material behavior can be observed on fracture surfaces, flat fractures being the evidence of brittle material, and jagged edges the evidence of ductile material. Figure 7 shows the impact strength of various samples.

A test of the toughness of the composite samples was performed by the impact test, which was performed according to ASTM D256-05 and ISO 179 standards and was carried out using the Charpy method. Sample 1 had an impact strength of 4.0 J/mm^2, and Sample 2 had an impact strength of 4.1 J/mm^2. Sample 3 had an impact strength value of 3.7 J/mm^2. The mean impact strength of all the samples was 3.9 J/mm^2 which shows uniformity in the performance of the specimens being tested. These findings illustrate that the composites absorb energy when hit showing that they are tough and can withstand fracture. The consistency in the effects of impacts indicates the material to be applicable in the application of medium impact resistance, which meets the aim of manufacturing sustainable reinforced composites. The values validate the idea that the composite material is effective to cope with the sudden loads, thus it can be used as a viable alternative in lightweight, structural component but durable in the automotive and construction fields.

Comparative Study

The comparison of two hybrid laminates prepared with the same sequence of stacking alternatives of Kevlar, S-glass, and sisal fibers i.e. Kevlar/S-glass/Sisal/S-glass/Kevlar and reinforced with 10wt% silicon carbide (SiC) and aluminum oxide (Al_2O_3) fillers, respectively, indicates that there is a great difference in mechanical performance, especially in flexural strength, surface hardness and delamination resistance. It has been reported in tensile strength studies that both the laminates have near identical capacity to bear loads, although the SiC-filled hybrid has a slightly better tensile strength of about 93.4 MPa than the Al_2O_3 -filled composite, which is about 92.8 Mpa. Although the difference is minimal, it implies that SiC enables a more effective stress transfer process due to the edges that are sharper and the increased strength, which leads to the improved mechanical interlocking with the epoxy matrix compared to the Al_2O_3 particles that are smoother and weaker. Flexural testing highlights the increased flexural strength of the SiC hybrid which has a flexural energy absorption capacity of about 37.5 KJ/m^2, compared to the Al_2O_3 filled composite with a lower strength of about 32.9 KJ/m^2 thus presenting a clear superiority of the SiC in flexural loads. This is improved by the fact that with the use of SiC particles, the fracture deflection performance has been improved and facilitates the crack branching and dissipation of energy hence delaying the brittle failure under three-point bending conditions.

These results of surface hardness also confirm the benefits of SiC reinforcement, as Vickers hardness increases when using Al_2O_3 laminate (57 HV) to 65.33 HV using the hybrid of SiC, an increase that indicates improved indentation and wear resistance and localized matrix deformation in SiC. The interlaminar shear strength (ILSS), which is a measure of the ability of laminate to resist delamination between layers due to out-of-plane shear stresses, has similar values in both samples with the SiC- filled laminate having about 212 Mpa and the Al_2O_3 - filled composite having about 211.6 Mpa. Despite the fact that the bulk ILSS values are almost the same, fracture surface analysis of delamination tests reveals that SiC-filled laminates have a smaller crack propagation region and reduced fiber pull-out compared to Al_2O_3 filled laminates, which have a greater interfacial separation. This demonstrates that the microstructure bonding is increased by more than just shear resistance enhancement; augments the anchoring qualities between the resin and fiber reinforcement by providing a more coarse morphology to the SiC. The experimental results are supported by finite element simulations using ANSYS which can prove that there are reduced localized deformations and slightly reduced stress concentrations in the SiC-filled laminates in the same loading conditions, confirming their improved stiffness and structural integrity. Small differences between analytical predictions and experimental measurements can be likely explained by idealistic assumptions of boundaries, non-homogenous dispersal of particles in a simulation, and non-existence of process-based voids and micro-defects in theory. Combination of experimental, analytical, and numerical findings supports the fact that the two laminates are effective load-bearing materials but the SiC-reinforced hybrid is always superior to the Al_2O_3 version in flexural toughness, surface stability, crack arresting capacity and general energy absorption behavior.

In short, the best choice of the reinforcement system is the SiC filled Kevlar/S-glass/sisal composite laminate, which provides the best combination of tensile strength, flexural stiffness, interfacial bonding and wear resistance to suit lightweight structural components, automotive body parts, impact-resistant enclosures and applications that require better wear resistance and surface strength. Conversely, even though the hybrid with Al 2 o 3 is a viable alternative that has slightly lower tensile and shear strengths, its poor flexural strengths, and hardness means that it can be used in moderate load-bearing applications, where cost-effectiveness is important rather than optimum crack resistance and bending strength. The results clearly show that addition of SiC as a filler leads to a balanced composite system, which has better structural integrity coupled with better mechanical synergy of the hybrid fibers, therefore validating its consideration of being an outstanding reinforcement option in the development of advanced composite laminate engineering.

CONCLUSION

In conclusion, the thorough mechanical assessment of hybrid Kevlar/S-glass/sisal laminates reinforced with 10 wt% silicon carbide (SiC) and aluminum oxide (Al_2O_3) fillers has revealed that, although both composites retain structural integrity under tensile stress, the SiC-filled hybrid laminate consistently demonstrates enhanced performance in essential engineering metrics, including flexural strength, surface hardness, and delamination resistance. The slight enhancement in tensile strength of the SiC-based composite indicates improved stress transfer resulting from superior interfacial bonding, as seen by less crack onset and slower damage progression under bending loads. The elevated Vickers hardness values further validate the capacity of SiC reinforcement to enhance surface durability and indentation resistance, demonstrating its appropriateness for components exposed to abrasive or contact stresses. Although the ILSS values in quantitative assessments are nearly equal, qualitative delamination analysis indicates significantly smaller failure zones and diminished fiber pull-out in the SiC-filled hybrid, underscoring its improved resistance to interlaminar failure due to greater filler–matrix interlocking. Finite element models corroborate experimental results by demonstrating improved stress distribution and less localized deformation in the SiC-filled laminate under equivalent loading circumstances, hence affirming enhanced structural stability. Consequently, the SiC-reinforced hybrid laminate offers an enhanced equilibrium of stiffness, toughness, wear resistance, and delamination management, rendering it a superior option for advanced lightweight structural applications, including automotive body panels, aerospace secondary structures, ballistic shielding layers, and protective enclosures necessitating enhanced mechanical integrity and energy absorption capacity. In contrast, although the Al_2O_3-filled laminate retains mechanical viability, its diminished flexural resilience and hardness suggest it is better suited for moderately loaded, budget-sensitive applications where exceptional mechanical performance is not essential. Future endeavors may encompass the optimization of filler dispersion methodologies, investigation of hybrid nano–micro filler combinations, cyclic loading evaluations, impact resistance analyses, and assessments of environmental durability under thermal, moisture, and UV aging conditions to further augment the industrial applicability and performance predictability of these hybrid composite systems.

Declaration of Interest

The authors(s) have disclosed no conflicts of interest.

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Data Availability Statement

This study does not develop nor examines any new data

Ethics Statement

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