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Enhancing Mechanical Performance in Reinforced Hybrid Composites using Silicon Carbide and Aluminium Oxide Fillers

G. Ashwin Prabhu[1,*], G.M. Lionus Leo[2], Arun M.[3], Karthick Rasu[4], K. Gnanasekaran[5], Ramesh Krishnan[6], Varun K.S.[7], M. Veerakumaran[8]

Abstract

Hybrid composites are becoming useful because they have better qualities than regular composites. This study examines the conventional properties of composites that utilise SiC and Al_2O_3 as filler components. Kevlar, S-glass, and sisal fibers at 90° and 0°, followed by additional layers of S-glass and Kevlar. To make sure that the material qualities were the same throughout, the resin and fibre layers were arranged in an alternating pattern. Mechanical testing showed that important performance parameters have improved a lot. The tensile strengths of laminates using SiC and Al_2O_3 were 93.4 MPa and 92.8 MPa, respectively. The flexural strength values were 37.5 kJ/m² for SiC and 32.9 kJ/m² for Al_2O_3. Hardness tests showed considerable improvements, with SiC-reinforced composites getting 65.33 HV and Al_2O_3 - reinforced composites getting 57 HV. The interlaminar shear strength for SiC was a little greater, at 212.0 MPa, than for Al_2O_3, which was 211.6 MPa. These results show that SiC and Al_2O_3 fillers could be useful in hybrid composites because they provide a good mix of strength, thermal stability, and wear resistance. The findings suggest that these materials are suitable for customization in demanding engineering applications, enhancing mechanical reliability and durability. Future research will focus on improving filler formulations and examining their effects on qualities like fatigue resistance and impact strength.

*Author for Correspondence
G. Ashwin Prabhu

[1,3,5]Assistant Professor, Department of Mechanical Engineering, St. Joseph's College of Engineering, Old Mahabalipuram Road, Chennai, Tamil Nadu, India
[2]Associate Professor, Department of Mechanical Engineering, St. Joseph's College of Engineering, Old Mahabalipuram Road, Chennai, Tamil Nadu, India
[4]Assistant Professor, Department of Mechanical Engineering, Velammal College of Engineering and Technology, Madurai, Tamil Nadu, India
[6]Assistant Professor, Department of Mechanical Engineering, St. Joseph's Institute of Technology, Old Mahabalipuram Road, Chennai, Tamil Nadu, India
[7,8]UG Student, Department of Mechanical Engineering, St. Joseph's College of Engineering, Old Mahabalipuram Road, Chennai, Tamil Nadu, India

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Keywords: Sisal fibre, kevlar, silicon carbide, aluminium oxide, fibre reinforced, hybrid composite, polymers, composites.

INTRODUCTION

The incorporation of natural fibres in high-strength concrete and polymer composites has garnered significant attention recently due to its sustainability, cost-effectiveness, and environmental benefits. The increasing need for sustainable and eco-friendly materials has prompted the investigation of fibre-reinforced hybrid composites with filler elements as potential substitutes for conventional synthetic materials across multiple industries. S-glass and sisal fibres have emerged as viable options owing to their renewability, biodegradability. Natural fibre-reinforced composites are increasingly recognised for their lightweight, mechanically efficient, and environmentally sustainable materials is paramount [1, 2]. The recent advancement of sophisticated hybrid composite materials has garnered significant attention because to their capacity to provide enhanced mechanical, tribological, and thermal properties compared to conventional single-reinforcement composites [3]. This work aims to investigate the integration of fiber-reinforced hybrid composites with filler materials. The laminates were manufactured utilising the hand lay-up method, a prevalent and economical way for creating fiber-reinforced composites [4]. The incorporation of filler materials has recently generated interest within the materials sector [5]. Neat polymer matrices generally exhibit inherent mechanical limitations, including low stiffness, limited hardness, poor wear resistance, and a tendency toward crack initiation and propagation under mechanical loading. These deficiencies restrict their applicability in structural and load-bearing components where enhanced strength, surface durability, and resistance to deformation are required. The incorporation of ceramic fillers such as silicon carbide (SiC) and aluminium oxide (Al_2O_3) is an effective strategy to overcome these limitations. Due to their high elastic modulus, intrinsic hardness, and thermal stability, ceramic fillers act as micro-load-bearing elements within the matrix, improving stress transfer efficiency, restricting matrix deformation, and delaying crack growth. As a result, the mechanical performance and durability of polymer-based hybrid composites are significantly enhanced. Hybrids that utilise ceramic particles as filters, have become appealing alternatives. These ceramic reinforcements are optimal for enhancing lightweight metal or polymer matrices [6–9]. The reinforcement efficiency of particulate fillers in polymer composites is highly dependent on filler size, morphology, and surface characteristics. Finer filler particles with uniform dispersion provide a larger interfacial area, facilitating efficient stress transfer from the polymer matrix to the rigid ceramic phase while simultaneously suppressing localized stress concentrations. Particle morphology also plays a crucial role; angular and irregular-shaped ceramic fillers promote mechanical interlocking with the matrix, thereby improving load transfer and resistance to crack initiation. Furthermore, surface characteristics such as surface chemistry and interfacial compatibility significantly influence composite performance [10]. Fillers exhibiting strong interfacial adhesion with the polymer matrix restrict particle debonding and crack propagation, leading to enhanced matrix-dominated properties including hardness, flexural strength, and interlaminar shear strength. Conversely, inadequate interfacial bonding may reduce reinforcement efficiency by acting as stress concentration sites. Tensile, hardness, interlaminar shear strength, and flexural tests were employed [11]. The integration of SiC and Al_2O_3 particles into a cohesive hybrid composite may yield synergistic advantages that beyond those obtainable by the use of individual filters independently [12–14]. SiC enhances wear resistance, diminishes friction, and elevates thermal stability, whilst Al_2O_3 increases hardness and load-bearing capacity. The hybrid approach provides a controlled amalgamation of properties, facilitating enhanced thermal stability and augmented wear resistance [17–22]. To enhance the microstructure and attain the requisite mechanical and functional qualities, comprehensive testing and thorough material characterisation are essential. Tensile analysis and wear analysis can clarify the links between material composition, manufacturing conditions, and final performance [23–26]. Micro- and nano-scale fillers contribute differently to the mechanical performance of polymer composites owing to their distinct size-dependent reinforcement mechanisms. Micro-scale fillers primarily function as rigid load-bearing constituents, enhancing strength and stiffness by facilitating stress transfer within the polymer matrix [27]. Their contribution is most pronounced in improving tensile and flexural properties; however, their relatively lower surface area limits interfacial interactions, which may reduce their effectiveness in enhancing toughness. In contrast, nano-scale fillers possess a high surface area-to-volume ratio, leading to strong interfacial bonding with the matrix and enabling effective crack-bridging, crack deflection, and crack-pinning mechanisms [28]. These nanoscale interactions significantly enhance energy dissipation during deformation, thereby improving fracture toughness and resistance to crack propagation, even at low filler contents.

The findings provide optimisation strategies that enable these hybrid composites to meet or exceed the stringent requirements of advanced technical applications [29, 30]. Previous studies have concentrated on various natural fibres, including flax, hemp, and jute; however, there has been no specific investigation into the synergy between s-glass and sisal fibre in the realm of artificially reinforced fibre development. The existing gap in the literature emphasises the originality of this study, which highlights the promise of these fibres as a sustainable, cost-effective, and high-performance substitute for natural reinforced materials. This study plays a crucial role in advancing sustainable options within material engineering and paves the way for further investigation and utilisation of s-glass and sisal fibre-reinforced hybrid composites.

MATERIALS AND METHODS

Kevlar facilitates strong intermolecular hydrogen bonding. This molecular structure offers remarkable tensile strength. Furthermore, its high thermal stability and durability against abrasion and impact improve its versatility in various applications. The unique properties of Kevlar have led to its widespread application in numerous fields. This serves as the essential framework for the composite system. Integrating reactive epoxide groups. The presence of these groups facilitates a chemical reaction in the resin upon mixing with a hardener. The hardener utilised in this investigation is HY-951, a catalyst essential for initiating. The unique characteristics of cured composite are largely determined by the ratio and type of hardener used, influencing properties like adhesion, hardness, and chemical resistance.

Glass and sisal fibres were chosen for use as a composite material. Sisal fibre was obtained from the Agave sisalana plant, which underwent chemical processes for extraction from the leaves. Sisal demonstrates exceptional tensile strength, establishing it as a favored option for applications that require durability. Glass fibre, noted for its thermal stability and strength-to-weight ratio, serves as the alternative composite material. Additionally, it provides significant tensile strength, elastic modulus, and density, which are advantageous characteristics for utilization as a composite material. The selected fibres were based on their ecological benefits and their potential application as sustainable reinforcements in composite materials. The fibers were collected in their unrefined form, subjected to purification, and subsequently processed before being incorporated into the composite matrix. Figure 1 illustrates the reinforcement materials: a) glass fibre b) sisal fibre.

The small particle characteristics enable consistent distribution in polymers, reduce defects, and ensure dependable performance. Silicon carbide improves wear in composite materials. Sisal, Kevlar, glass fibre, epoxy resin, aluminium oxide, and silicon carbide fillers results in a robust and long-lasting material. Figure 2 illustrates the filler materials: a) silicon carbide and b) aluminium oxide. This document comprises six figures and two tables in total. Figures 1–3 depict the reinforcement and filler materials alongside the laminate fabrication process. The experimental results are illustrated in Figures 4–6, encompassing tensile, delamination, and comparative mechanical performance data. Table 1 presents a comprehensive overview. Meanwhile, Table 2 details the properties of fillers [31].

Table 1. Properties of glass fibre, sisal fibre, kevlar and epoxy resin.

Properties	**S-Glass**	**Sisal Fibre**	**Kevlar**	**Epoxy**
Poisson's Ratio	0.13	0.36	0.36	0.31
Young's Modulus (GPa)	90	9.4	120	3
Shear Modulus	3.46	3.4	44.12	2.1
Density (g/cm^3)	2.69	1.57	2.44	2.1

Figure 1. Natural Fibres (a); Glass Fibre (b); Sisal Fibre (c) Kevlar.

Table 2. Properties of silicon carbide & aluminium oxide.

Properties	**SiC**	**Al_2O_3**
Poison's Ratio	1.14	0.21
Young's Modulus (GPa)	115	470
Shear Modulus (Pa)	50.44	206.6
Density (g/cm^3)	3.2	3.95

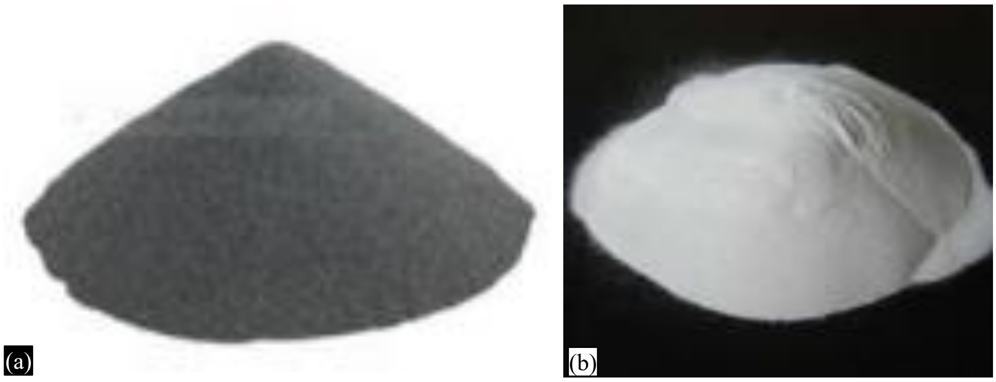

Figure 2. Filler Materials (a); Silicon Carbide (b); Aluminium Oxide.

EXPERIMENTAL METHODS

Composite laminates were developed using s-glass and sisal fibers. The Kevlar and S-glass fiber cloths were cut into 300 mm squares, consisting of two layers of each type. The sisal fiber, originally measuring 90 cm, underwent a cleaning and desiccation process before being cut into 300 mm strands. The epoxy, hardener, and filler components were combined in a ratio of 100:10:10. The composite laminate consists of several layers, alternating between glass fibre and sisal fibre layers until the target thickness is reached. A mat with a large surface area is placed on the floor. Following this, a matrix layer is meticulously applied over the wax, ensuring a precise orientation. Subsequently, layers of s-glass and sisal are arranged alternately, with matrix applied in between. The stacking sequence of the laminates is as follows: Kevlar, s-glass, sisal (0º), sisal (90º), s-glass, Kevlar. Two laminates were developed employing the same stacking sequences, utilizing distinct filler materials; Silicon carbide was incorporated in one laminate while aluminium oxide was utilized in the other. The hardener was applied prior to fabrication, and layers were coated with epoxy resin. The only difference between the two laminates lies in the filler material utilized alongside the epoxy. One laminate consists of Al_2O_3, while the other is composed of SiC. A total of ten percent of these filler materials is incorporated into the epoxy, with the hardener introduced immediately prior to the commencement of the plate preparation process. The materials are arranged in a vertical sequence, with epoxy meticulously applied to each individual layer. Once the epoxy is applied, substantial weights are positioned atop the laminates, ensuring that both the top and bottom surfaces remain flat for an even finish [32]. Once the weights are applied to the laminate, it remains undisturbed for a duration of thirty hours. Following this period, the edges of the plates are trimmed to form a precise square laminate. Figure 3 presents the sample plates acquired following the hand lay-up process.

EXPERIMENTAL RESULTS

Tensile Test

The tensile behavior of the fabricated hybrid laminates was investigated following ASTM D638 standards. Figure 4 presents the tensile stress–strain responses for two representative samples from each composite system. The observed stress–strain relationship demonstrated a nearly linear progression of stress in response to strain until reaching the yield point, after which a gradual failure ensued. Both systems exhibited significant load-bearing capacity, with the SiC reinforced laminate attaining a slightly superior tensile strength of 93.4 MPa in comparison to the Al_2O_3 filled laminate, which measured 92.8 MPa. The observed enhancement in the SiC system is linked. The inherent stiffness of the ceramic filler likely served as a micro-load-bearing component, postponing the initiation and propagation of cracks. In contrast, while Al_2O_3 exhibits exceptional intrinsic stiffness ($E = 470$ GPa), its comparatively greater density and less robust interface with the polymer could have diminished its performance in stress transfer during tensile loading.

Regarding deformation, both SiC and Al_2O_3 based laminates exhibited elongations between 2.5–3.0% strain, aligning with the brittle characteristics of fiber-dominated hybrid composites. The closely aligned stress-strain curves of Sample 1 and Sample 2 across both systems indicate a consistent fabrication process and a uniform distribution of fillers. In comparison to previous studies [15–17], incorporating particulate fillers into fiber-reinforced composites improves microstructural rigidity and diminishes localized stress concentrations. The slight variation in tensile strength noted here suggests that both SiC and Al_2O_3 serve mainly as secondary reinforcements, enhancing but not significantly changing the fiber-dominated load transfer mechanism.

The tensile test demonstrates that the addition of ceramic fillers enhances the laminate's resistance to uniaxial loading, while also ensuring consistency among the samples.

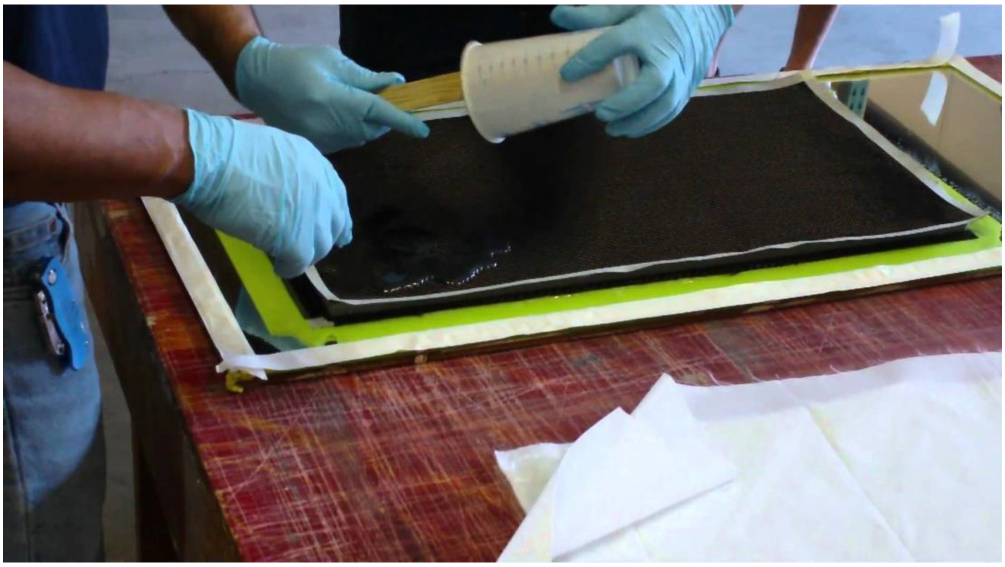

Figure 3. Hand lay-up process.

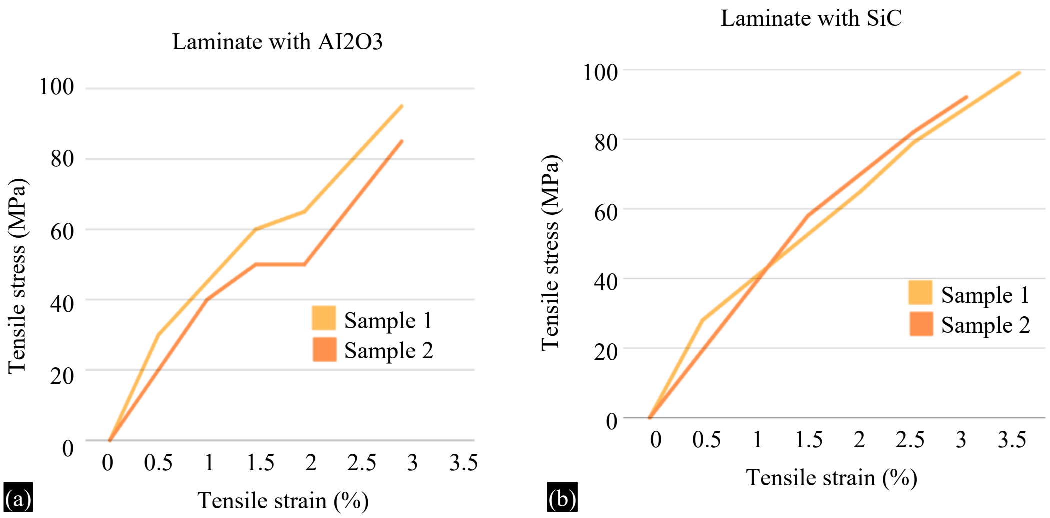

Figure 4. Tensile stress vs tensile strain graph of samples.

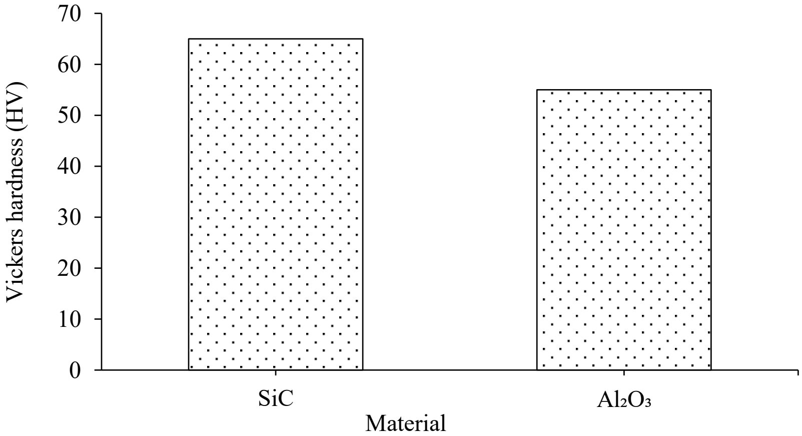

Figure 5. Comparison of vickers hardness for SiC and Al_2O_3

Vickers Hardness Test

The evaluation of Vickers hardness demonstrated that the laminate filled with SiC showed a significantly greater hardness value of 65.33 HV in contrast to the laminate filled with Al_2O_3, which measured 57 HV. The enhancement in hardness indicates a direct correlation of ceramic filler. The exceptional hardness of the SiC filled laminate is due to the inherent hardness of SiC particles (25 GPa) and their effective load transfer to the adjacent epoxy matrix. The small particle size and effective interfacial bonding with the polymer limit localized indentation, resulting in a surface that is stiffer and more resistant to abrasion. Furthermore, SiC serves as a barrier to the initiation of cracks during indentation by effectively redistributing stresses at the matrix–filler interface.

Conversely, although Al_2O_3 ($E = 470$ GPa) exhibits mechanical stiffness and thermal stability, its comparatively lower hardness in relation to SiC and less efficient bonding with the epoxy matrix led to a diminished hardness value. The Al_2O_3 filled laminate exhibited sufficient indentation resistance while emphasizing thermal stability rather than surface strength. The results align with previous research indicating that the inclusion of SiC fillers in polymer composites leads to increased hardness, as they effectively impede localized deformation and bolster wear resistance. This enables materials engineers to achieve an optimal balance between surface hardness, as seen in SiC filled composites, and thermal endurance, exemplified by Al_2O_3 filled composites.

From an application standpoint, the notably increased hardness of the SiC filled laminate renders it more appropriate for environments that are wear-intensive and prone to abrasion (e.g., protective panels, automotive brake components, aerospace surface structures). On the other hand, composites based on Al_2O_3 would offer greater benefits in high-temperature service conditions, where maintaining dimensional stability is more critical than resistance to indentation. The Vickers hardness test demonstrates that incorporating ceramic fillers improves surface performance, with SiC exhibiting exceptional hardness owing to its compatibility with the epoxy matrix and its naturally high resistance to indentation. Figure 5 illustrates the comparison of Vickers hardness between SiC and Al_2O_3.

Interlaminar Shear Stress Test

ILSS refers to the ability of a composite laminate to endure shear forces that operate parallel to the plane of its layers. This property is essential for preserving the durability. The SiC-filled laminate exhibits an interlaminar shear strength (ILSS) of 212.0 MPa, slightly surpassing the 211.6 MPa achieved by the Al_2O_3-filled laminate. This improvement arises from the enhanced dispersion of SiC particles [33].

SiC and Al_2O_3 fillers serve as micro-reinforcements, mitigating localized shear-induced deformation. As a result, the composite material demonstrates less vulnerability to interlaminar shear failure. The heightened ILSS values for SiC-based laminates are significant when compared to those of Al_2O_3 (211.6 MPa). Both SiC and Al_2O_3 inhibit fracture initiation and propagation, hence augmenting the laminate's resistance to delamination. Silicon carbide (SiC) efficiently inhibits crack propagation by connecting micro-cracks under shear pressure. This results in a superior ILSS value of 212.0 MPa for SiC laminates, compared to 211.6 MPa for Al_2O_3 filled laminates, indicating that SiC exhibits somewhat improved resistance to crack propagation and delamination. While Al_2O_3 (with a Young's modulus of 470 GPa) does not bond as strongly to the epoxy matrix as SiC, it significantly improves thermal stability.

The ILSS of Al_2O_3 filled laminates is slightly lower (211.6 MPa), although their superior thermal stability is beneficial for high-temperature applications, such as engine components. In conclusion, the integration of ceramic fillers like SiC and Al_2O_3 significantly enhances the interlaminar shear strength of hybrid composites. SiC exhibits slightly enhanced performance in ILSS (212.0 MPa) compared to Al_2O_3 (211.6 MPa), with both fillers improving shear resistance and overall laminate effectiveness. These findings highlight the imperative of tailoring filler selections according on the specific application, whether related to strength and crack resistance (SiC) or thermal stability (Al_2O_3). Figure 6 illustrates the comparison of interlaminar shear strength (ILSS) for silicon carbide (SiC) and aluminum oxide (Al_2O_3).

Flexural Test

The flexural behaviour of hybrid laminates was examined to evaluate their bending resistance. The three-point bending tests were conducted following established testing protocols, and the findings are encapsulated in Table. The SiC-filled laminate had a superior flexural strength of 37.5 kJ/m², in contrast to 32.9 kJ/m² for the Al_2O_3-filled laminate, illustrating the impact of filler type on load-bearing capacity under bending loads. The enhanced performance of SiC-filled laminates is due to the inherent stiffness and hardness of SiC particles, which serve as micro-reinforcements that improve stress transfer within the matrix [34]. The consistent distribution of SiC inside the epoxy likely inhibits crack formation under bending stresses and postpones catastrophic failure, hence enhancing total flexural strength. The enhanced interfacial connection between SiC particles and the polymer matrix facilitates more effective stress redistribution during bending.

In contrast, the Al_2O_3 filled laminates exhibited considerable bending strength but demonstrated a relatively lower flexural strength. The decrease may result from the comparatively inferior adhesion between the Al_2O_3 particles and the matrix, which can act as stress concentrators during flexural loading. Nonetheless, the Al_2O_3 filled laminates exhibit superior thermal stability, indicating that although they may not surpass SiC in pure mechanical bending, they may be advantageous in high-temperature settings where dimensional integrity is essential. Figure 6 presents a comparative histogram of all evaluated properties, distinctly demonstrating the SiC-based laminates exhibit superior performance in flexural and tensile strength, as well as hardness, whereas Al_2O_3-based laminates display slight superiority in interlaminar shear strength [35].

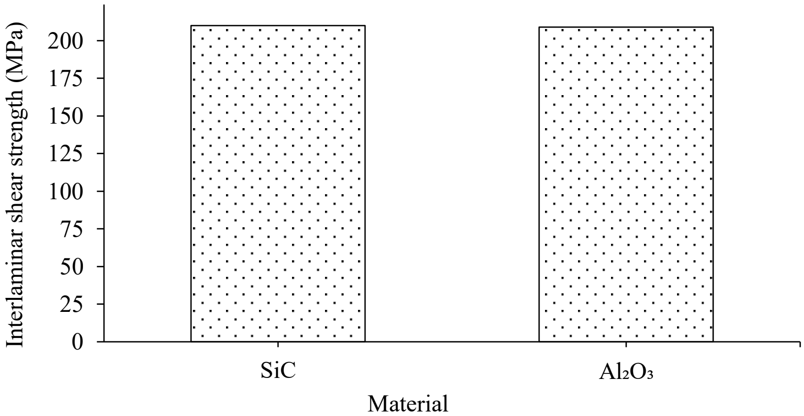

Figure 6. Comparison of ILSS for SiC and Al_2O_3.

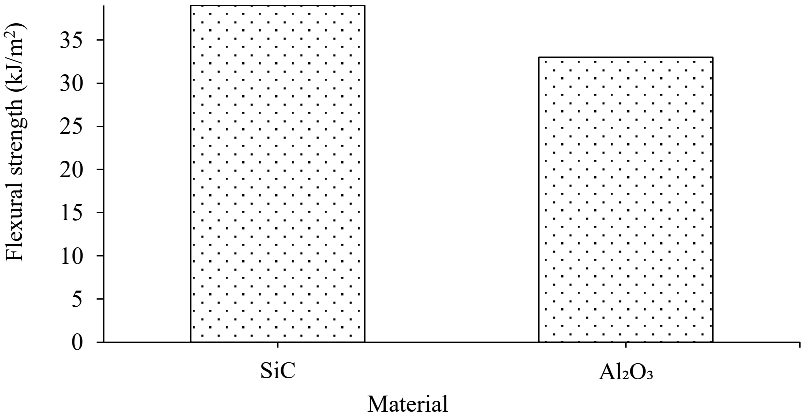

Figure 7. Comparison of flexural strength for SiC and Al_2O_3.

The results align with prior studies, indicating that SiC fillers owing to their substantial hardness and robust compatibility with epoxy matrices. The little compromise between interlaminar shear strength (greater in Al_2O_3) and flexural performance (superior in SiC) underscores the necessity of customising filler selection according to the specific application. From an application standpoint, the enhanced flexural resistance of SiC-filled laminates indicates its appropriateness for structural applications exposed to bending loads, such as aerospace panels, automotive components, and load-bearing protective structures. In contrast, Al_2O_3 filled composites may be better suitable for thermally demanding applications, where their enhanced thermal stability compensates for reduced bending performance. The flexural tests demonstrate that SiC has improved flexural strength relative to Al_2O_3, principally attributable to enhanced stress transfer and crack resistance. The aggregate outcomes from all assessments indicate that although both fillers improve mechanical performance, SiC is superior for applications necessitating high flexural rigidity and surface hardness, whereas Al_2O_3 is preferable when thermal stability and interlaminar integrity are critical. Figure 7 illustrates the comparison of flexural strength between SiC and Al_2O_3.

Comparative Study of Mechanical Tests

A comparative evaluation of all mechanical tests conducted on hybrid laminates containing silicon carbide (SiC) and aluminium oxide (Al_2O_3) highlights the distinctive yet complementary roles of these ceramic fillers in affecting composite performance. Both systems demonstrated substantial improvements in tensile strength, hardness, interlaminar shear, and flexural testing relative to unfilled laminates, hence confirming the effectiveness of ceramic particle reinforcement in fiber-epoxy hybrid composites. Under tensile loading, both laminates exhibited comparable strength, with the SiC-filled composite displaying a somewhat higher tensile strength of 93.4 MPa relative to the Al_2O_3-filled composite at 92.8 MPa. This indicates that while fibre architecture primarily affects tensile characteristics, SiC offers somewhat improved stress transmission due to its superior filler-matrix compatibility and crack-bridging capacity. The analogous values signify consistent production quality and uniform filler dispersion in both systems.

The hardness tests revealed a more significant distinction among the fillers. The SiC-filled laminate achieved a much higher Vickers hardness of 65.33 HV compared to the Al_2O_3 filled laminate, which recorded 57 HV. This gap is attributed to the inherently higher hardness of SiC particles and their ability to endure localised plastic deformation, making SiC-based composites more suitable for applications prone to wear and abrasion. The interlaminar shear strength (ILSS) measurements demonstrated that both fillers substantially enhanced delamination resistance. The SiC laminate exhibited an ILSS of 212.0 MPa, while the Al_2O_3 laminate showed a similar value of 211.6 MPa. Notwithstanding the slight variation, SiC demonstrated a negligible advantage in crack arrest and shear load transfer. Conversely, the analogous performance of Al_2O_3 demonstrates its effectiveness in maintaining interfacial integrity, particularly under thermally demanding conditions.

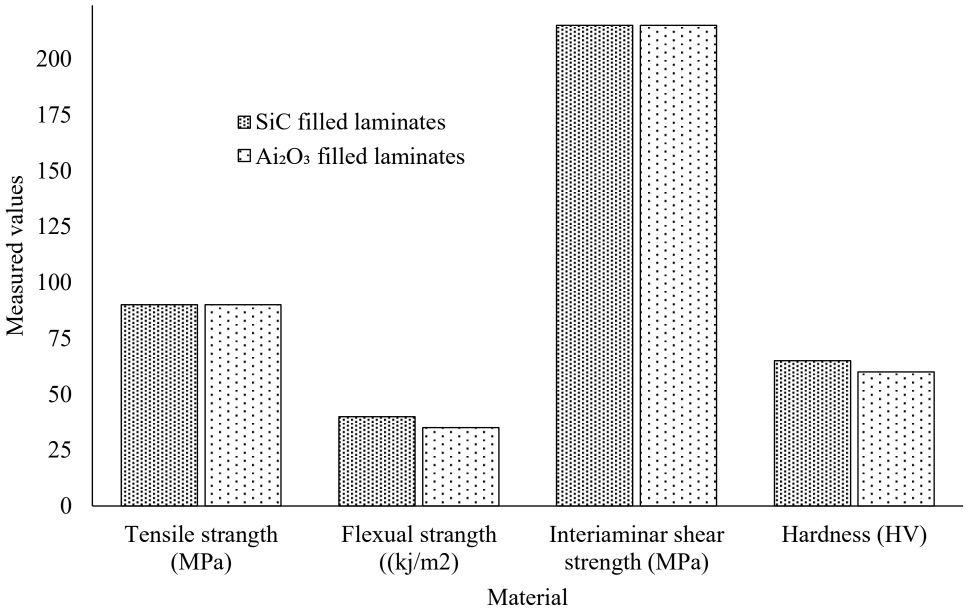

Figure 8. Comparison chart from the tests conducted.

Flexural testing further highlighted the superiority of SiC in load-bearing applications. The SiC-filled laminate demonstrated enhanced flexural strength (37.5 kJ/m^2) compared to the Al_2O_3-filled laminate (32.9 kJ/m^2). This enhancement correlates with the augmented stiffness and enhanced filler-matrix interaction of SiC, which delays the initiation and propagation of fractures during bending. Al_2O_3-filled laminates demonstrate somewhat reduced flexural strength while preserving advantages in thermal stability and dimensional integrity. The comparative research indicates that SiC-filled hybrid composites often surpass Al_2O_3-filled composites in tensile strength, hardness, and flexural strength, making them more appropriate for mechanically demanding and wear-intensive applications. These findings demonstrate that filler selection enables tailored composite design, allowing engineers to enhance mechanical performance and functional requirements based on specific application needs. Figure 8 illustrates the comparative chart of multiple conducted tests.

CONCLUSION

This work rigorously examined the mechanical properties of hybrid composite laminates reinforced with S-glass fibres. A variety of mechanical tests, including tensile strength, Vickers hardness, interlaminar shear strength (ILSS), flexural strength, and delamination resistance, were performed to evaluate the impact of these two ceramic fillers. The findings indicated that the SiC-filled laminates consistently surpassed the Al_2O_3-filled laminates in the majority of mechanical metrics. The tensile strength of SiC laminates was 93.4 MPa, somewhat above that of Al_2O_3 laminates at 92.8 MPa. The hardness of SiC laminates (65.33 HV) was markedly superior to that of Al_2O_3 laminates (57 HV), indicating the better intrinsic hardness and enhanced filler-matrix compatibility of SiC. Likewise, SiC-filled laminates exhibited greater flexural strength (37.5 kJ/m^2) than their Al_2O_3 counterparts (32.9 kJ/m^2), underscoring the improved resistance to bending stresses attributable to efficient stress transfer and crack resistance. The interlaminar shear strength (ILSS) of Al_2O_3 filled laminates (211.6 MPa) slightly surpassed that of SiC laminates (212.0 MPa vs. 211.6 MPa according to ASTM D2344 results), indicating that Al_2O_3 particles marginally enhance delamination resistance, presumably due to their thermal stability and effect on interfacial bonding. Overall, the findings confirm that fibre-reinforced hybrid laminates produced via wet hand lay-up can deliver mechanical performance comparable to traditional synthetic composites, while also supporting sustainability. These laminates, especially those filled with SiC, are promising candidates for automotive applications such as bonnets, roofs, visors, and bumpers. Future work should focus on evaluating the long-term durability under varying environmental conditions (moisture, temperature cycling, and chemical exposure) and incorporating microstructural analyses (e.g., SEM of fracture surfaces) to provide deeper insights into failure mechanisms. Such studies would further guide the optimization of hybrid composites as eco-friendly, high-performance alternatives in engineering applications.

Declaration of Interest

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

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The authors have no acknowledgements to declare.

Data Availability Statement

This study does not develop nor examines any new data

Ethics Statement

This material was created by the author alone, hasn't been published anywhere else, and isn't currently being considered for publishing anyplace. It fully and properly reflects the study and analysis of the author or authors.

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