OPEN ACCESS
Scholars International Journal of Chemistry and Material Sciences
Abbreviated Key Title: Sch Int J Chem Mater Sci
ISSN 2616-8669 (Print) | ISSN 2617-6556 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: http://saudijournals.com

Original Research Article

Coupling Strength and Synergy: Exploring the Mechanical Properties of Epoxy Hybrid Composites with S-Glass and Basalt Fibers

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DOI: 10.36348/sijcms.2024.v07i05.001 | **Received:** 17.04.2024 | **Accepted:** 25.05.2024 | **Published:** 29.05.2024

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Abstract

This research investigation centers on assessing the mechanical properties of hybrid composites formed by integrating composite fibers in woven mat form into a matrix element, employing diverse stacking sequences of symmetrical laminates. Specifically, the objective of this research is to experimentally evaluate the mechanical characteristics, including density, hardness, impact resistance, flexural strength, tensile strength, and interlaminar shear strength (ILSS) of S-glass and Basalt fiber epoxy hybrid composites, followed the procedures outlined as per ASTM standards. The laminates were manufactured using a combination of hand lay-up and compression molding techniques, employing four distinct stacking sequences. The mechanical characteristics of these hybrid composites were subsequently compared to those of pure composite counterparts. The mechanical robustness of the resultant composites was systematically evaluated. Experimental findings revealed that the hybrid composite with a stacking sequence of 2/2 B-S-E-C exhibited the highest tensile strength and flexural strength, measuring 330.5 MPa and 367.53 MPa, respectively. Furthermore, this composite demonstrated elevated density and Shore hardness, registering a value of 90. However, it is noteworthy that the impact properties and ILSS of the pure B-E-C composite were superior, boasting a Charpy impact strength of 98.85 KJ/m2, Izod impact strength of 1225.80 J/m, and ILSS of 38.10 MPa. To gain insights into the fracture morphology of the hybrid composites during testing, Scanning Electron Microscope (SEM) analysis was conducted. SEM images revealed that the hybrid composite with a 2/2 B-S-E-C stacking sequence exhibited fiber/matrix and its interfacial interactions upon their failure, mainly focusing its fractured surface in comparison to other hybrid composite configurations. Overall, the results underscore a significant enhancement in mechanical properties when hybrid composites are configured optimally.

Keywords: S-Glass, Basalt, Epoxy, Hybrid, Mechanical Properties.

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1. INTRODUCTION

Composite materials hold immense significance in the contemporary materials landscape as they offer a unique synergy of properties not achievable by individual constituents. Their lightweight yet high-strength characteristics are pivotal in aerospace, automotive, and construction industries, aiding in fuel efficiency and structural integrity [1]. Additionally, composites contribute to sustainability by enabling longer-lasting structures and reduced maintenance. Moreover, they play a vital role in advancing technology through applications in electronics, sporting equipment, and medical devices. Overall, composites are pivotal in addressing multifaceted challenges and driving innovation across diverse sectors [2]. In the contemporary materials world, synthetic fibers hold immense significance in composites due to their exceptional strength-to-weight ratio and tailorable properties. These fibers enable the development of lightweight yet high-performance materials used in aerospace, automotive, and sporting equipment, contributing to fuel efficiency and enhanced performance [3]. Synthetic fibers are also pivotal in sustainable construction practices by reducing the environmental impact of structures. Their versatility extends to medical devices and protective gear, revolutionizing healthcare and safety standards. In essence, synthetic fibers are a driving force in modern materials innovation, addressing diverse needs across industries [4].

Hybrid composites have emerged as a vital contributor to the materials world. By combining diverse materials, such as natural fibers with synthetic counterparts or different synthetic fibers, they optimize properties like strength, weight, and durability [5]. This innovation is pivotal in aerospace and automotive industries, where lightweight yet robust materials are in high demand, leading to enhanced fuel efficiency and performance [6]. Hybrid composites also promote sustainability by reducing the need for resource-intensive materials [7]. Their versatile applications span from renewable energy to construction, making them a transformative force in materials science [8].

Newer materials is essential to align with the latest technological developments, address emerging challenges, and harness innovative solutions for diverse industries [9]. Incorporation of graphene fillers significantly enhances the mechanical properties of glass/epoxy composites, leading to improved strength, stiffness, and overall performance. [10]. Delamination significantly influences the bending and viscoelastic behavior of woven E-glass/epoxy composite materials, causing alterations in stiffness, damping, and overall mechanical performance [11]. Inclusion of Syzygium cumini particulates in E-glass fiber-reinforced epoxy composites leads to altered mechanical, thermal, and morphological properties, offering potential for novel composite applications [12]. Addition of basalt powder has a pronounced influence on the mechanical characteristics and dynamic mechanical thermal analysis of hybrid epoxy composites reinforced with glass fiber, resulting in improved stiffness and thermal stability [13].

Graphene oxide leads to enhanced tensile and flexural properties in carbon/glass hybrid fiber-reinforced polymer composites, exhibiting improved strength and stiffness compared to non-modified composites [14]. Flexural and interlaminar shear properties of carbon and glass fabric reinforced thermoset composites, resulting in improved material performance, including increased flexural strength and enhanced interlaminar shear strength [15]. Notable effect on the indentation resistance and residual performance of patch-repaired glass/epoxy laminates. Acoustic emission monitoring revealed improved damage tolerance and reduced damage propagation in hybridized patches, indicating enhanced structural integrity in repaired laminates [16].

Presence of carbon nanotubes improves the resistance of composites to degradation under hydrothermal conditions, enhancing their long-term durability and reducing moisture-induced damage [17]. Glass fiber-epoxy laminates shows their high strength, stiffness, and the ability to withstand deformation under different loading conditions [18]. Barium sulfate-filled glass fiber-reinforced polymer composites exhibit enhanced mechanical properties and erosion resistance [19]. Varying fiber orientations impact the composites' stiffness, strength, and failure mechanisms, aiding in the optimization of composite designs for specific applications [20].

Fiber orientation significantly influences the thermo-mechanical response of symmetric glass/epoxy composites, with variations in stiffness, strength, and thermal behavior observed across different orientations [21]. Improved strength, stiffness, and thermal resistance, making these composites promising materials for various engineering applications [22]. Incorporation of Poly (Styrene- Co -Acrylonitrile) into epoxy resin/glass fiber composites significantly enhances their mechanical properties, including strength, stiffness, and impact resistance, making them suitable for a wide range of structural applications [23]. Different fiber percentages and orientations result in variations in stiffness, strength, and other mechanical characteristics [24].

Improved morphological characteristics, enhanced mechanical properties, and increased Shielding against electromagnetic interference increased effectiveness, making these composites suitable for applications requiring both structural strength and electromagnetic shielding capabilities [25]. Different stacking sequences result in variations in strength, stiffness, and other characteristics, which can be tailored for potential engineering applications [26]. Improved strength, stiffness, and impact resistance, which make them suitable for a wide range of engineering applications [27]. Different fiber sequences result in variations in strength, stiffness, and other mechanical characteristics, enabling tailored material properties for specific claims [28]. ZnO and TiO_2 nanoparticles enhances the thermal stability and mechanical properties of composites [29]. Changes in the material's mechanical properties, demonstrating its sensitivity to different environmental and loading conditions [30].

Basalt/epoxy composites have the potential for use in impact-resistant scenarios necessitating the use of lightweight materials [31]. Incorporation of these resin systems leads to improved mechanical performance and enhanced resistance to acid corrosion in the resulting composites, making them suitable for applications in chemically challenging environments [32]. Anhydride resin systems significantly influence the mechanical properties and acid resistance of basalt fiber-reinforced composites. The incorporation of these resin systems leads to improved mechanical performance [33]. Hybridization enhances the composite's strength and stiffness, making it an auspicious material for a wide spectrum of engineering application [34].

Accumulation of silane coupling means improves the in-between adhesion between the basalt fibers and epoxy matrix, resulting in increased tensile strength, flexural strength, and impact resistance [35]. Improved interfacial interaction has a direct and positive

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impact on the mechanical properties of the composites. Increased tensile, flexural strength's, and impact resistance were observed, which are key attributes for a wide range of structural and load-bearing applications [36]. Practicality of utilizing basalt fiber-reinforced laminates as a feasible, cost-effective alternative to traditional carbon fiber composites, underlining the significance of tailored material selection based on specific application demands and economic considerations [37].

Impact of hybridizing aramid and basalt fibers in epoxy composites, shedding light on how the combination affects their tensile and bending properties. The findings underscore the potential for optimizing composite materials to meet specific mechanical requirements by strategically blending different fiber types [38]. Effects on the interlaminar shear strength and fracture toughness of epoxy-based composites. The findings emphasize the significance of surface treatment in enhancing the performance of these composite materials [39]. The potential enhancements in composite materials achieved through nanoparticle incorporation, contributing to the field of advanced materials engineering [40]. Feasibility of utilizing basalt fiber composites in the transportation industry, addressing key performance considerations for materials used in this sector [41].

Tensile behavior of basalt fiber composites provides valuable insights into the better mechanical characteristics of these composites [42]. Distinct advantages of both glass and basalt reinforcements. Glass fabric-reinforced composites demonstrated notable mechanical strength, while basalt fabric-reinforced composites exhibited promising abrasive wear resistance [43]. Enhancement of mechanical properties achieved through the incorporation of basalt fibers in furan/epoxy composites. This improvement in tensile strength, flexural strength, and impact resistance makes these composites attractive for various structural applications [44].

Improvements in mechanical properties, such as tensile strength and flexural strength, due to the incorporation of nanoclay particles. This enhancement is particularly promising for applications requiring high structural integrity and load-bearing capabilities [45]. Glass and basalt fiber reinforcements impact the mechanical and abrasive wear behavior of epoxy composites [46]. Favorable attributes of BFRP, including its high tensile strength and modulus, making it a promising candidate for applications requiring structural integrity and load-bearing capabilities [47]. The role of effective dispersion and bonding between nanoparticles and the composite matrix, resulting in enhanced tensile strength, flexural strength, and impact resistance [48].

Enhanced mechanical characteristics, encompassing tensile and flexural strength and impact resistance, making basalt-fiber-reinforced composites [49]. Basalt fibers exhibit mechanical properties, including tensile strength and modulus, that are comparable to or superior to those of E-glass fibers [50]. Basalt fibers within the composite matrix significantly influences its mechanical characteristics. By manipulating the fiber alignment, it's possible to optimize tensile strength, flexural strength, and other properties to meet specific engineering requirements [51]. Dimensionally different nanoparticles can be strategically used to reinforce epoxy/basalt fiber composites, opening up possibilities for the development of high-performance materials. Nanoparticle types and concentrations to achieve the desired performance improvements while avoiding potential drawbacks, such as increased brittleness or processing challenges [52].

Surface treatments have the potential to notably enhance the interfacial adhesion between basalt fibers and the epoxy matrix, resulting in substantial advancements in mechanical performance [53]. Woven basalt and glass epoxy composites exhibit unique mechanical behaviors when subjected to high strain rates, with variations in energy absorption and deformation characteristics. These differences are crucial to consider in applications where rapid loading or impact resistance [54]. Modifying the interface between the fibers and the PP matrix, it is possible to achieve significant improvements in tensile strength, flexural strength, and impact resistance [55].

Hybridizing basalt fibers with glass in these composites has a notable impact on their impact behavior at low velocities. The hybridization results in improved impact resistance, offering greater resilience and durability in applications where low-velocity impact events are likely to occur [56]. Addition of basalt powder leads to notable improvements in tensile strength, flexural strength, and impact resistance and mechanically robust materials capable of withstanding dynamic thermal conditions [57]. Improving the adhesion between wood and both E-glass and basalt fibers. This improved bonding results in enhanced internal reinforcement, leading to increased mechanical properties such as tensile strength and flexural strength [59]. Combining flax, basalt, and E-glass fibers in epoxy composites leads to significant enhancements in mechanical properties [60].

Kevlar and basalt fibers in thermoplastic composites, both within and between layers, significantly influences their response to high strain rate compression [61]. Glass fabric-reinforced composites demonstrate robust mechanical strength [62]. Balance between mechanical strength and abrasive wear resistance when choosing between glass and basalt fiber-reinforced composites [63]. The incorporation of basalt fibers enhances the laminates' tensile and flexural strength of hybrid laminates [64]. Single-layer fabrics exhibit distinct characteristics, while multilayer configurations showcase enhanced tensile strength, making them suitable for applications requiring increased structural integrity [65]. Incorporation of basalt, carbon, and glass fibers in epoxy composites creates hybrid materials with impressive resistance to three-point bending fatigue [66].

Despite the extensive literature survey on various aspects of composite materials involving E-glass, basalt, and other reinforcements, there remains a notable research gap in understanding the synergistic effects of combining these reinforcements in composite materials. While individual studies have provided insights into the mechanical, thermal, and morphological properties of these composites when modified with different additives or reinforcements, there is limited research exploring the combined impact of multiple reinforcements, such as s-glass and basalt fibers, in a single composite matrix. Furthermore, there is a dearth of comprehensive investigations on the optimized fiber orientations, stacking sequences, and surface treatments for achieving superior mechanical properties tailored to specific engineering applications. Addressing this research gap is crucial to harness the full potential of composite materials and advance their applications in diverse fields, from aerospace to automotive and beyond.

Even if so much of work has been completed on different synthetic fibers and its composites, an effort has been finished in the present research work to introduce a new combination of matrix and synthetic fiber by means of reinforced S-glass & Basalt fiber with epoxy as matrix material. The aim of this study was to assess mechanical properties of reinforced basalt/s-glass fiber epoxy composites. The weight percentage of the basalt & s-glass fiber varied 0% to 55% wt in epoxy matrix of 45% wt. In this study, fibers weight is fixed to 55% and remaining 45% wt is epoxy matrix which is not fixed. Here, matrix is treated as total weight of the composite. The mechanical abilities were evaluated by conducting density, tensile test, impact test (Charpy & Izod method), hardness test (Shore D) ILSS test and flexural test (three-point bending test).

2. MATERIALS AND METHODS

2.1. Material Selection and Specimen Preparation

In the present study, S-glass fiber (satin type of 195 gsm) and basalt fiber (plain weave type of 220 gsm) are used as reinforcements. Epoxy is used as a matrix with the grade of Lapox L-12 with hardener of K-6. The matrix solution are prepared in 100.10 gms as per manufacturer information. The laminates were fabricated by hand layup and compression molding methods. The samples were machined according to ASTM standards are shown in figure 4.

In four different material configuration the composite materials were manufactured are shown in the figure 1. The type A (S-E-C), type B (B-E-C), type C (1/1 S/B-E-C) and type D (2/2 B/S-E-C). Table 1 represents the material preparation details.

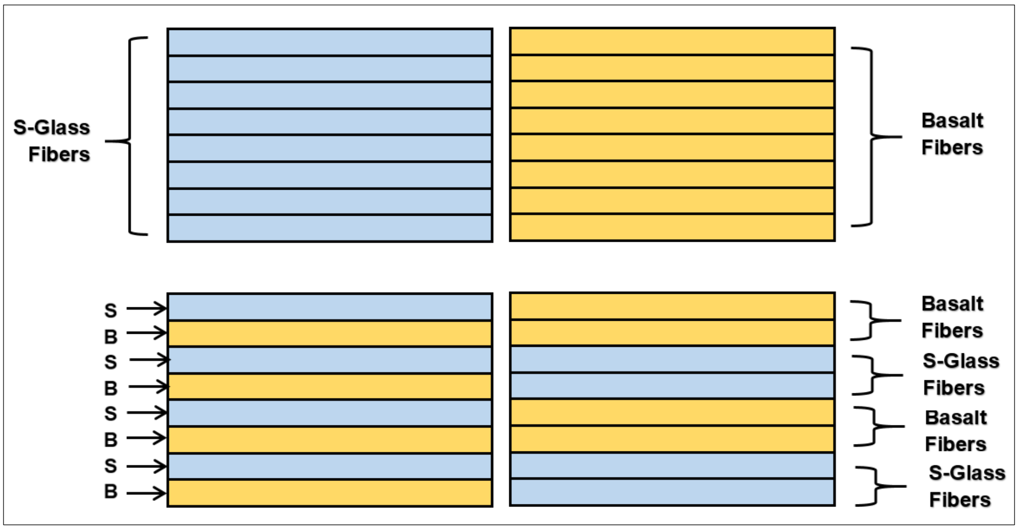

Fig. 1: Composite Material Configuration

Table 1: Material Preparation Details

Sl. No.	Material Code	Sample Code	Basalt Fiber (wt.%)	S-glass Fiber (wt.%)	Matrix (wt.%)
1	S-C-E	S1	0%	55%	45%
2	B-E-C	S2	55%	0%	45%
3	1/1 S-B-E-C	S3	22.5%	22.5%	45%
4	2/2 B-S-E-C	S4	22.5%	22.5%	45%

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2.2. Mechanical Testing

Testing of samples were done according ASTM standards. Table 2 gives the some highlights of testing conditions followed for mechanical assessments of the composite materials prepared. Hardness, Tensile, ILSS, Flexural, Impact, Density properties were evaluated of the fabricated samples [76].

Flexural, ILSS & Tensile specimens were test using computerized universal testing machine (C-UTM) and others tests were also done using standard testing equipment's/testers as shown in figure 2 & 3. The structural changes of the composite were examined by SEM. The fracture surfaces of the specimens underwent examination at varying magnification levels and were digitally imaged using a scanning electron microscope. The fracture surfaces of the composites were obtained from the tensile strength samples. Before going to tests, all samples were gold sputtered to avoid electrical charging and made them conductive.

Table 2: Testing Conditions & Equipment Details

Sl. No.	Test	Span Length (mm)	Cross Loading Rate (mts/min)	Testing Equipment	Ref
1	Density	NA	NA	Densometer	[67]
2	Hardness	NA	NA	Shore D Hardness Tester	[72]
3	Charpy Impact	NA	NA	Impact Tester	[73]
4	Izod Impact	NA	NA	Impact Tester	[71]
5	Tensile	57	5	C-UTM	[68]
6	Flexural	60	10	C-UTM	[69]
7	ILSS	30	5	C-UTM	[70]

Fig. 2: C-UTM & Impact Tester

Fig. 3: Densometer & Shore D Hardness Tester

Fig. 4: Specimens for Mechanical Testing according to ASTM Standards

3. RESULTS AND DISCUSSION

3.1 Density of Composites Materials

The results are tabulated in the Table 3. Composites of different fiber combination and its hybrid are studied. The variation of the density value of the composites is shown in figure 5 for hybrid composites, it was noticed that the stacking sequence and the relative fiber content have a visible effect on the density of the material. As the density of basalt fiber is higher in combination with silica glass fiber showed the high-density value of 1.58 for 2/2 B-S-E-C combination hybrid.

Table 3: Density of the Composite

Sl. No.	Material Code	Sample Code	Density
1	S-C-E	S1	1.25
2	B-E-C	S2	1.55
3	1/1 S-B-E-C	S3	1.56
4	2/2 B-S-E-C	S4	1.58

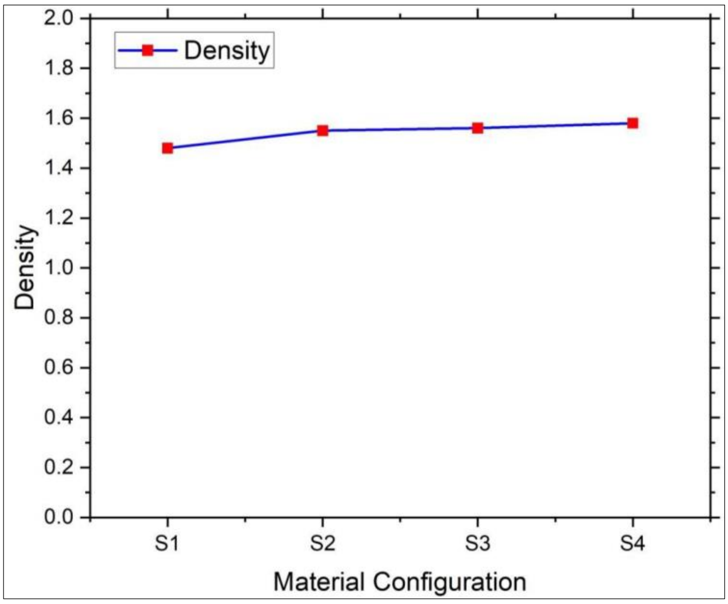

Fig. 5: Comparison - Density of the Composites

3.2 Mechanical Properties of Composites

3.2.1 Hardness

Table 5 provides a comprehensive summary of the Shore D hardness measurements of epoxy-based composites. Notably, the hardness values of hybrid composites surpass those of their counterparts composed solely of either pure S-G (S-Glass) or BF (Basalt Fiber) epoxy constituents. Of particular significance is the observed substantial increase in the Shore D hardness values, exemplified by the 2/2 B-S-E-C hybrid composite, which achieved a remarkable hardness value of 90, as illustrated in Figure 6. This elevated hardness can be attributed to the incorporation of both basalt and S-Glass fibers, which collectively enhance the composite's resistance to brittleness and, consequently, augment its overall hardness. This finding underscores the substantial enhancement in the load-bearing capacity of S-Glass reinforced epoxy composites through hybridization. The physical properties of the fiber component are chiefly influenced by its underlying physical and chemical characteristics, encompassing factors such as fiber structure, fibril angle, and degree of polymerization. In the composite, the thermosetting epoxy matrix phase and the inherently brittle fiber phases (basalt and S-Glass) undergo compression-induced consolidation, leading to their close contact and mutual resistance. Consequently, this interface efficiently facilitates load transfer, culminating in the observed increase in hardness within the hybrid composite.

Table 5: Shore D Hardness of Composites

Sl. No.	Material Code	Sample Code	Shore D Hardness
1	S-C-E	S1	86
2	B-E-C	S2	85
3	1/1 S-B-E-C	S3	88
4	2/2 B-S-E-C	S4	90

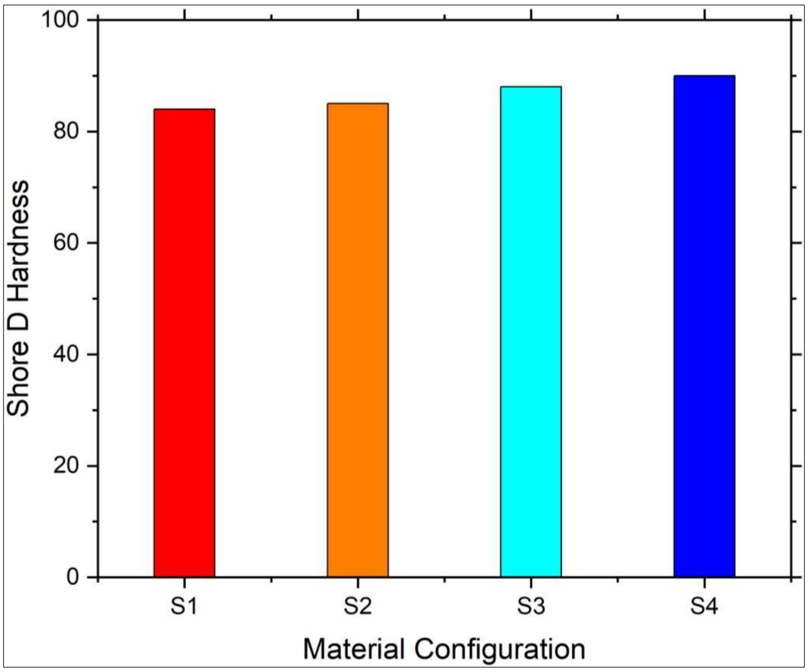

Fig. 6: Comparison – Shore D Hardness of the Composites

3.2.2 Impact Strength of Composites

Table 6 presents critical data pertaining to impact resistance, a pivotal material property whose assessment is instrumental in determining the viability of a material for specialized applications, predicated on its capacity to withstand accidental impacts. To evaluate impact strength, Charpy and Izod impact tests, in accordance with ASTM D 6110 and ASTM D256 standards, were conducted. The results reveal that the impact strength values of unfilled basalt fiber-reinforced epoxy composites surpass those of their counterparts filled with a striking 98.85 kJ/m^2 and 1228.8 J/m, as depicted in Figure 7. Notably, the impact strength of S-Glass fiber composites outperforms that of basalt fiber composites. This discrepancy can be attributed to the lower void content inherent in basalt fiber composites in comparison to S-Glass fiber composites. This reduced void content can be attributed to the superior interfacial bonding between the fiber and matrix, thereby significantly enhancing the composite's capacity to withstand impact loads. The heightened impact strength observed in basalt epoxy composites stems from the inherent chemical composition of basalt fibers within the epoxy matrix. The impact strength is further augmented in samples fabricated using 100% basalt fabric due to the superior bonding with the resin, surpassing that of S-

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Glass epoxy composites. It is worth noting that the impact strength of hybrid samples registered a marginal decrease, as the process of hybridization did not yield any discernible enhancement in the material system's impact properties.

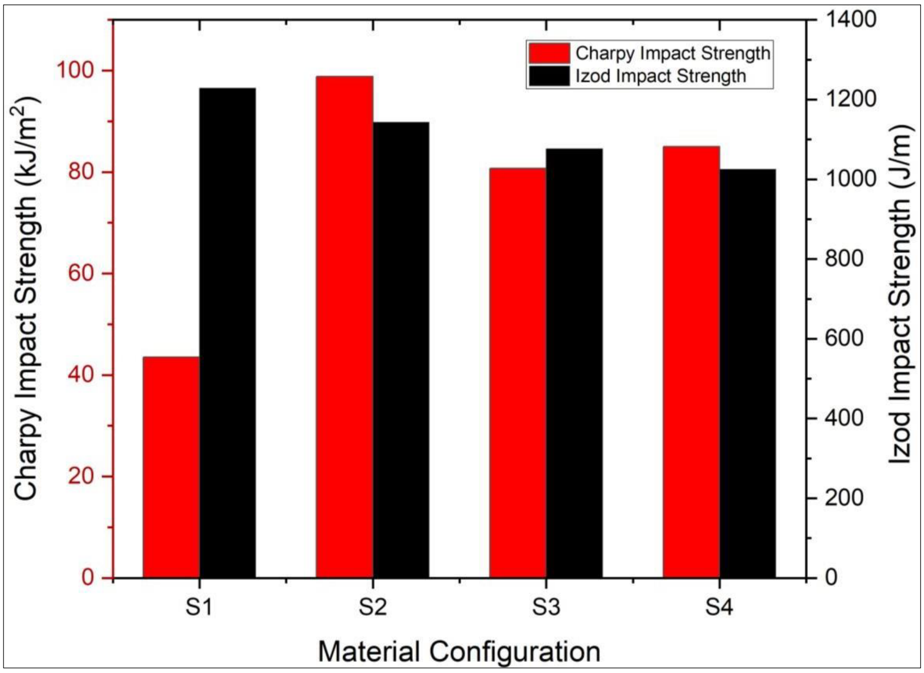

Fig. 7 Comparison – Impact Strength of the Composites

Table 6: Impact Strength of Composites

Sl. No.	Material Code	Sample Code	Charpy Impact Strength (KJ/m^2)	Izod Impact Strength (J/m)
1	S-C-E	S1	43.52	1142.81
2	B-E-C	S2	98.85	1225.80
3	1/1 S-B-E-C	S3	80.71	1076.40
4	2/2 B-S-E-C	S4	85.02	1025.01

3.2.3 Interlaminar Shear strength of Composites (ILSS)

The data presented in Table 7 demonstrates that the Interlaminar Shear Strength (ILSS) of the basalt fiber-reinforced epoxy composite stands at 38.10 MPa, surpassing that of other composite materials. Figure 8 corroborates this finding by illustrating that the ILSS value of the basalt epoxy composite exceeds that of the S-Glass epoxy composite by a substantial margin of 48.29%. This robust performance underscores the presence of a robust bond between the basalt fibers and epoxy resin. The enhanced interface between the fiber and matrix plays a pivotal role in securely anchoring the fibers, enabling them to withstand substantial compressive loads. Voids within composites pose a significant detriment to their load-bearing capacity due to stress concentration in their vicinity. The formation of pronounced voids at the epoxy-glass fabric interface results in a marked reduction in the interlaminar shear strength of S-Glass epoxy composites.

Table 6: ILSS of Composites

Sl. No.	Material Code	Sample Code	ILSS (MPa)
1	S-C-E	S1	19.70
2	B-E-C	S2	38.10
3	1/1 S-B-E-C	S3	26.90
4	2/2 B-S-E-C	S4	33.30

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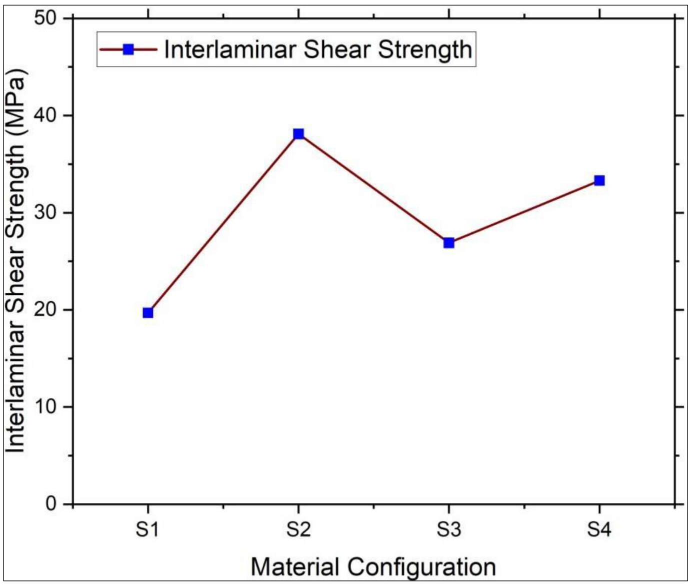

Fig. 8: Comparison – ILSS of the Composites

3.2.5 Tensile Properties of Composites

Table 7: Tensile Properties of Composites

Sl. No.	Material Code	Sample Code	UTS (MPa)	E (GPa)	Peak Load (N)	Maxi. Displacement (mm)
1	S-C-E	S1	294.8	11.36	8604.4	5.2
2	B-E-C	S2	284.6	17.27	6284	3.5
3	1/1 S-B-E-C	S3	298.7	11.29	10006.1	4.7
4	2/2 B-S-E-C	S4	330.5	10.03	10262.3	4.9

Table 7 enumerates the outcomes derived from experiments pertaining to the ultimate tensile strength, Young's modulus, peak load, and maximum displacement of composite materials reinforced with S-Glass fiber, basalt fiber, and their hybrid configurations, employing two distinct fiber loadings within the material system.

The outcomes reveal a significant reliance of tensile strength on the specific hybrid composition. Notably, the 2/2 B-S-E-C hybrid composite exhibits an ultimate tensile strength of 330.5 MPa and a Young's Modulus of 10.03 GPa, as illustrated in Figure 9. The introduction of basalt fiber into the hybrid composite in conjunction with glass fiber engenders an enhancement in tensile properties, attributable to basalt fiber's superior strain, strength, and modulus compared to glass fiber. In practical testing, this particular material configuration exhibits exceptional resistance to applied tensile loads, culminating in a peak load of 16,127.2 N and a maximum elongation of 6.4 mm leading to the point of peak load.

The hybrid composite demonstrates an ability to augment the maximum load in tensile tests compared to basalt/epoxy and glass/epoxy composites. Furthermore, the augmentation in tensile strength can be attributed to the effective layering design, particularly the balanced 2/2 B-S-E-C configuration, which establishes a synergy between the outer layer of the composite (comprising glass fiber mat) and the extended, continuous basalt fibers, which serve as a core and tendon for the composite structure. This proficient layering and structural arrangement within the composites effectively curtails the rapid propagation of micro-cracks towards the core by harnessing the reinforcing capability of individual glass fiber mats on the outer surface.

Moreover, an optimized matrix acts as a binder for the fibers, efficiently transferring loads to the fibers while bestowing rigidity and form upon the structure. This collective mechanism contributes significantly to the enhancement of the mechanical properties of the composites. Achieving a harmonious balance between basalt fiber and glass fiber is essential for imbuing the composite structure with both stiffness and toughness. In this context, the outer layer of glass fiber functions as a protective skin, thwarting the initiation of rapid micro or macro-cracking, while the core of the composites, primarily composed of basalt fiber, offers crucial reinforcement.

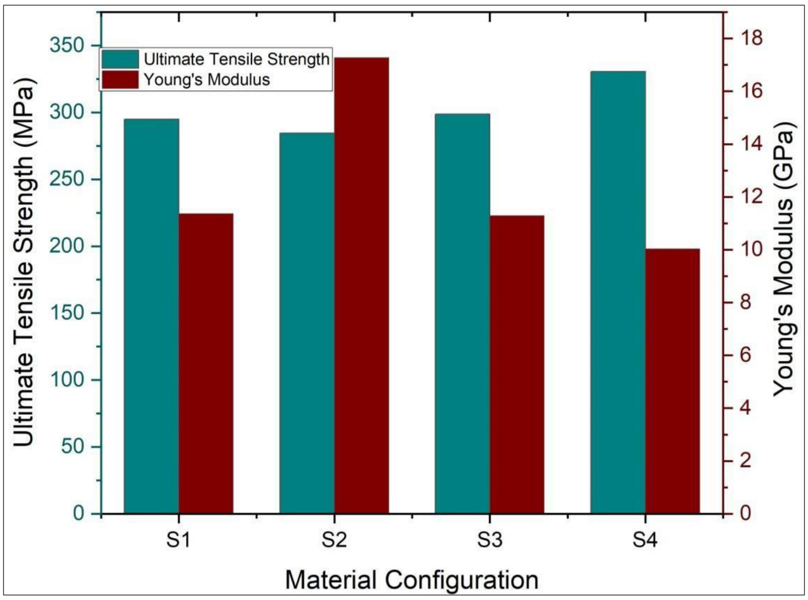

Fig. 8: Comparison – Tensile Properties of the Composites

3.2.6 Flexural Properties of Composites

Table 8: Flexural Properties of Composites

Sl. No.	Material Code	Sample Code	Maxi. Flexural Strength (MPa)	Flexural Modulus (GPa)
1	S-C-E	S1	225.50	9.30
2	B-E-C	S2	235.65	14.51
3	1/1 S-B-E-C	S3	278.74	18.86
4	2/2 B-S-E-C	S4	367.53	23.02

It is obvious from Table 8 that the strength and flexural modulus have the same trend. The asymmetric SBF hybrid composite underwent testing under 3 point bending loading. Hybridizing S4 composite with 2/2 B-S-E-C improves the flexural strength and modulus noted were 367.53 MPa and 23.02 GPa as in figure 9. Hybridizing S4 composite with S-glass & Basalt fiber (2/2 B-S-E-C) enhances the flexural strength and modulus by 38.64 and 59.65 %.

Considering the effect of the stacking sequence on the flexural strength and modulus, it was shown that placing Basalt fiber at the specimen skin and S- Glass fiber in the core i.e. SGBFs gives improved results. This is because the flexural strength and stiffness are controlled by the outer layers and stacking of the synthetic fibers in such a sequence.

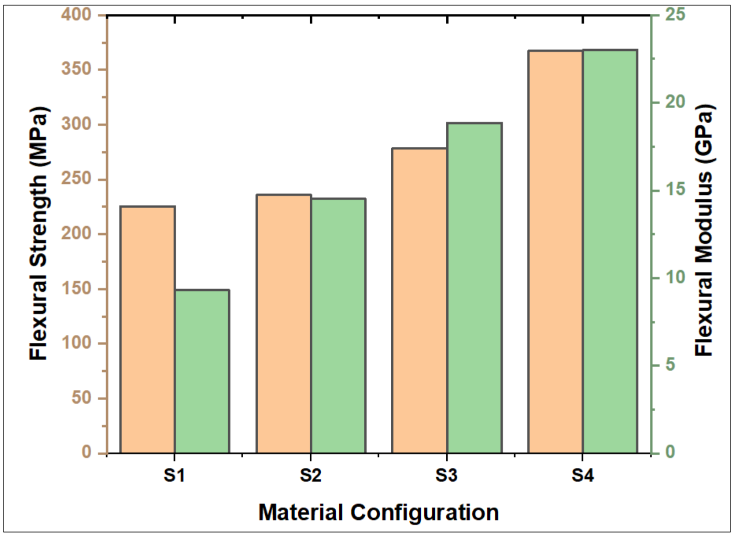

Fig. 9: Comparison – Flexural Properties of the Composites

4. SEM Analysis

Figure 10 presents the Scanning Electron Microscopy (SEM) imagery of a 2/2 S-Glass/Basalt fiber-reinforced epoxy composite subjected to tensile testing. The images provide distinct observations depending on the strain rate conditions applied. Under quasi-static strain rates, the imagery clearly exhibits instances of fiber pull-out, indicating the detachment of individual fibers from the epoxy matrix. Conversely, at high strain rates, the SEM images illustrate debonding occurrences, signifying the separation of fibers from the epoxy matrix.

Upon examining fractured shear samples of the basalt epoxy composites at various strain rates, it is evident that, in contrast to the glass epoxy composite, the basalt fibers exhibit a more widespread distribution with minimal traces of the epoxy matrix adhering to their surfaces. Additionally, signs of debonding are discernible within the remnants of the fractured epoxy matrix. Generally, the SEM analysis reveals a more robust fiber-matrix adhesion in the glass epoxy composites across diverse strain rate conditions. Furthermore, the SEM morphology analysis reveals a distinct profile characterized by a higher prevalence of fiber breakage and a reduced presence of voids in the glass fiber-reinforced composites. The outer surface of the glass fiber exhibits features such as fiber breakage, fiber pull-out, and micro-cracking, which contribute to the composite's structural response under tensile loading.

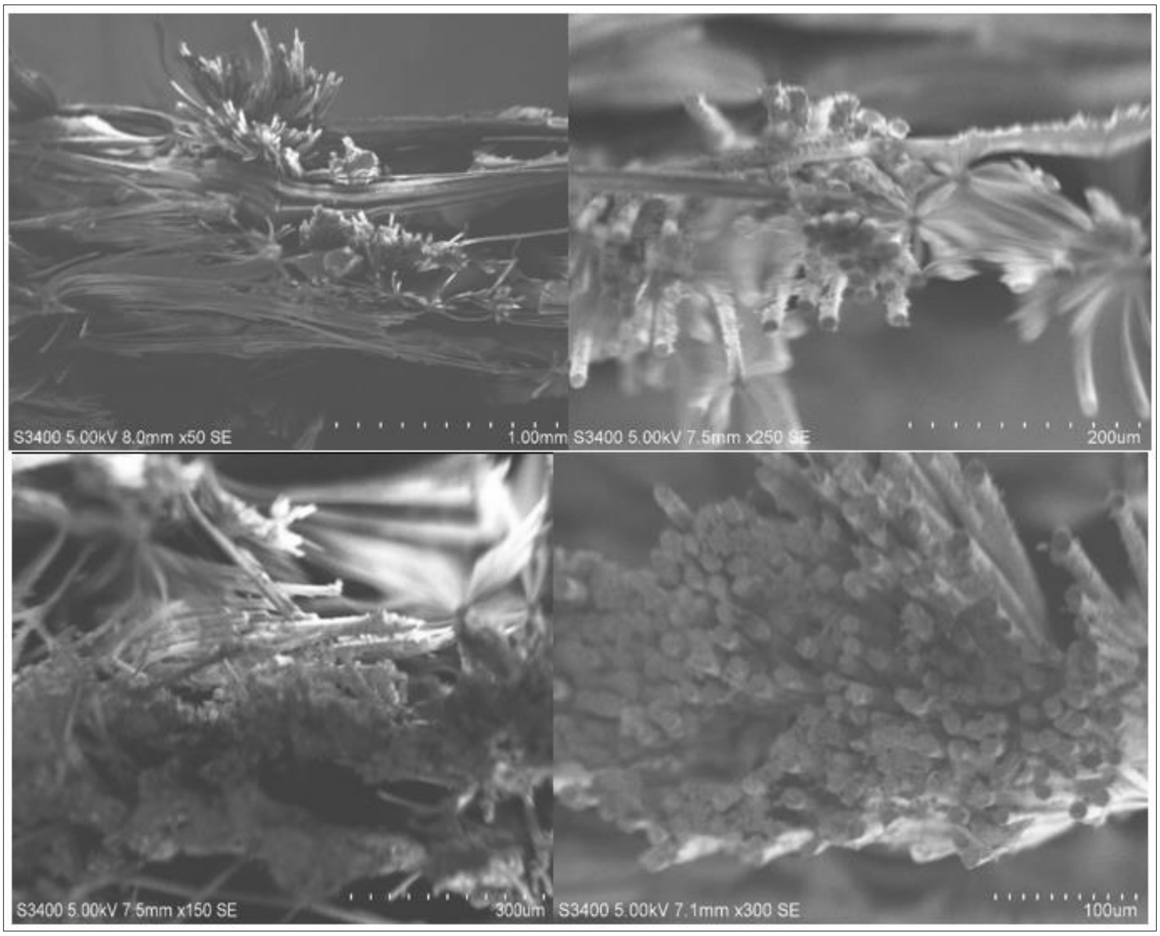

Fig. 10: SEM of Tensile Tested Sample (2/2 S-B-E C)

CONCLUSION

To summarize, this study has yielded valuable insights into the behavior of composites with different fiber combinations and hybridization. The study revealed that the density of hybrid composites is significantly influenced by the stacking sequence and relative fiber content, with the 2/2 B-S-E-C combination hybrid exhibiting a high-density value. Furthermore, the hardness of hybrid composites was found to be greater than that of pure fiber epoxy composites, indicating an enhancement in composite brittleness and hardness through hybridization. This improvement can be credited to the effective load transfer at the boundary between the thermosetting matrix phase and the brittle fiber phase. Impact strength findings indicated elevated values for basalt fiber-reinforced epoxy composites, and S-glass fiber composites exhibited superior impact strength due to better interfacial bonding. Additionally, the interlaminar shear strength (ILSS) of basalt epoxy composites was higher than that of S-glass epoxy composites, indicating strong bonding between basalt fiber and epoxy resin. Tensile strength and modulus were

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greatly affected by the hybrid combination, with the 2/2 B-S-E-C hybrid composite demonstrating impressive results. This improvement was attributed to the effective layering design and the core-tendon structure formed by basalt and glass fibers. Finally, flexural strength and modulus were enhanced by hybridization, with the stacking sequence of Basalt fiber at the specimen skin and S-Glass fiber in the core providing improved results. Scanning electron microscopy (SEM) analysis revealed important insights into fiber-matrix adhesion and fracture behavior at different strain rates. Overall, this research underscores the importance of fiber combination and hybridization in tailoring the mechanical features of composites for various applications, offering opportunities for improved performance and durability in engineering and structural materials.

Acknowledgement

I thank my guides for their guidance and support throughout the process of completing and publishing this research paper. Their expertise, mentorship, and unwavering commitment to my academic and research endeavors have been instrumental in bringing this work to fruition.

Conflict of Interest

We have no financial or interpersonal connections that may potentially bias or influence the content or findings presented in this research.

Funding: No funding was received from any agency to support the authors in publishing this paper.

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