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Research Article

Mechanical Characterization of Glass-Basalt Hybrid Composites with Different Fiber Weight Fraction

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ABSTRACT

In recent years, many attempts have been made to make a composite either fully or partially from natural fiber as a part of sustainable development, which has superior strength compared to other natural fibers like flax, sisal, bamboo, and banana leaves. Basalt fiber is one of the naturally available mineral fibers that can overcome the issue of the low mechanical strength of natural fibers. The objective of this research is to determine the effect of hybridization on glass fiber composites with different weight fractions of basalt fiber. Composite laminates were made using the hand lay-up method from plain bidirectional glass fiber and plain bidirectional basalt fiber with epoxy as the thermosetting matrix material. Basalt fiber weight fraction varied to 0%, 26%, 54%, 84%, and 100% during the development of different laminates, and their density and mechanical characterizations were investigated using ASTM standards. A density test was carried out to evaluate the specific strength of different laminates. To evaluate the effects of different fiber weight fractions on the mechanical characteristics of the composite, tensile, flexural, and impact tests were carried out. It was observed that, compared to non-hybrid composites, hybrid composites showed superior properties in flexural, tensile, and impact tests. The results presented in this study show that in hybrid composites, different fiber weight fractions play a crucial role in the properties of the hybrid composite. one-way analysis of variance (ANOVA) was performed to see if there were any statistically significant differences between the measured mechanical properties. As one of the major benefits of composites is their high ratio of strength to weight, a comparison of specific properties is carried out, and the positive effect of hybridization was observed.

1. Introduction

Composites constructed from polymer matrix are widely employed across multiple industries such as aerospace, automobiles, renewable energy systems, marine vehicles, sports vehicles, biomedical devices, construction industry, space vehicles, and many other systems because of their great specific strength and stiffness in comparison to metal [1,2].

A hybrid composite is developed when two or more fibers have been combined with the same matrix. Significant research and development have been done into the creation and characterization of glass, Kevlar, and carbon fiber hybrid composites. Carbon fiber has the highest tensile and compressive strengths, as well as the highest ratio of strength to weight, but it has a low impact strength and can break abruptly. Glass fiber is cheaper, easily available, less chemical and moisture-resistant, and has less strength compared to Kevlar fiber and carbon fiber. Kevlar has high toughness and impact resistance but low compressive strength, poor UV resistance, and is costly. Kevlar and carbon fiber are more expensive than glass fiber [3,4].

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To develop a useful composite material, two or more materials need to be combined at the macroscopic level. One of the well-known materials, glass fiber has a wide range of uses, including the construction of automotive bodies, electrical and thermal insulation, and other sports equipment. However, it cannot be used for situations seeking great strength, which can be achieved by employing expensive resources with high strength, like carbon and Kevlar fiber. It makes sense to use different fibers with glass fibers to produce a hybrid composite that will provide the needed strength for the required application and ensure the low cost of using fiber-reinforced materials in various applications.

Basalt fibers have superior characteristics and comparable pricing to fibers composed of glass, carbon, and other materials. Basalt fibers fall between carbon fiber and glass fiber in terms of performance. Compared to E-glass fiber basalt fiber have greater tensile strength, larger breaking strain than carbon fibers, and superior resistance to fire, impact load, and chemical assault with less harmful emissions [5].

Each of the components of the glass fiber, which generally consists of 50% silica sand, oxide of aluminum, boron, and a variety of other minerals, must be fed separately into a metering system before going into the furnace. Basalt fibers, in contrast, are devoid of secondary elements. It just takes one feed line to transfer crushed basalt rock into the melting furnace [6].

The rapid cooling of lava at a planet's surface results in the formation of basalt, a type of igneous rock It makes up the majority of the Earth's crustal rocks. Glass fibers and basalt are made in the same way. Crushed basalt rock serves as the sole raw material required to create fiber. At a temperature of about 1500° C, volcanic basalt rock is melted to create a continuous fiber [7].

Basalt fiber reinforced composites provide exceptional weather resistance for outdoor use due to their UV resistance, higher acid resistance, somewhat superior alkaline resistance, and very little water absorption of the fibers. The potential of basalt fibers as an alternative to conventional glass fibers in the production of composite parts with excellent mechanical characteristics [8].

Basalt fiber finds applications in various industries, including automobiles, civil construction, power plant engineering, and electric power-oriented applications. Its mechanical properties enable longer blades with equal fiber content, increasing energy output compared to conventional E-glass. Basalt's outstanding corrosion and mechanical properties make it suitable for various athletic goods, such as tennis rackets, hockey sticks, arrows, skiing equipment, and snowboards [8].

M. Aniber Benin [9] used polypropylene (thermoplastic) and polyester polymer (thermosetting), reinforced with glass fibers, to create the composite specimens. Through the comparison of the compositional effects and tensile properties of the polypropylene and polyester polymers, it was discovered that polyester resin and glass fiber, when combined with the features of glass fiber, provide superior performance to polypropylene.

In a comparison of polyester and epoxy's mechanical and thermal characteristics, it was discovered that the only jute fiber-based composites' mechanical properties, for both the polyester and epoxy resins utilized, were enhanced by the hybridization procedure (jute and curava, jute and sisal). In comparison to polyester-based composites, the epoxy matrix-based composites demonstrated superior tensile strength and thermal stability [10].

The mechanical properties of the hybrid composite made from carbon fiber and basalt fiber were examined by Guangyong Sun et al. [11] utilizing experimental, analytical, and computational techniques. Seven symmetric composite laminates were produced using the vacuum-assisted resin transfer molding (VARTM) technique with varied hybridization ratios and stacking arrangement, and they were tested under tensile and bending loads, respectively. The results of the tests demonstrated that the stacking patterns significantly affected the material's strength and flexural modulus, but not as much its tensile modulus. The use of scanning electron microscopy (SEM) revealed that basalt fiber layers enhance failure resistance by preventing crack propagation.

Abd El-Baky [12] used flax, basalt, and E-glass fiber reinforcement to study the mechanical characteristics of epoxy composites. Using a vacuum bagging procedure, hybrid composite laminates were made. On the tensile, flexural, and impact characteristics, the effects of the relative quantities of the fibers and the sequence in which they were stacked were examined. Results showed that the hybrid composites produced had enhanced tensile, flexural, and impact characteristics when compared to flax/epoxy composites. The hybridization leads to decreased weight and cost when compared to glass and basalt fiber-reinforced composites with equivalent strength.

Nagaraja et al. [13] examined how different stacking configurations influenced the tensile and flexural characteristics of a carbon and glass hybrid composite. The vacuum infusion technique was used to create two distinct sets of laminate. They found that the composite with carbon fabric on the outside had greater tensile and flexural strength and modulus, whereas the composite with glass fabric on the exterior had somewhat poorer tensile and flexural properties.

By altering the volume percentage and layering order of various reinforcements, hybrid composites can have their mechanical characteristics customized. The influence of the sequence of layers of carbon and glass fiber in a hybrid laminated composite on its tensile attributes has been the topic of several studies. As an example, it was mentioned that combination composites that use carbon fabric layers inside and glass fabric layers exterior exhibit greater compressive strength than those that use carbon fabric layers inside and glass fabric layers exterior [14–16].

S.M. Sapuan et al. [17] examined the effect of longitudinal basalt fiber and woven glass fiber hybridization. They have kept the total fiber fraction at 30% and varied the glass/basalt fraction from 7% to 30%. It was observed that there is an improvement in tensile and flexural strength when compared to basalt and glass fiber alone.

David Plappert et al. [18] investigated the mechanical characteristics, such as tensile, shear, and compressive strength, of composites made from unidirectional basalt fiber and epoxy. It was observed that unidirectional basalt has superior properties compared to E-glass fiber but not as good as S-glass or carbon fiber. Additionally, basalt fiber has a lower shear strength than E-glass fiber.

Comparing hand layup and compression molding to vacuum-assisted resin infusion and vacuum bagging, higher mechanical characteristics may be shown in composites formed from glass and basalt fabric with epoxy resin in hand layup followed by compression. Compared to glass epoxy composite, basalt epoxy composite offers greater impact and tensile strength [19].

Alex O. Bonsu et al. [20] in their study investigated failure mechanisms in plain glass and basalt fiber-reinforced composites, including hybrid configurations, under artificial seawater conditions. Several hybrid laminates with varying sequences exhibit superior mechanical properties and aging resistance compared to plain laminates. SEM analysis reveals that different hybrid configurations prevent crack propagation to varying extents, altering the overall damage morphology.

Mohamed A. Attia et al. [21] in their study, explored the mechanical properties of epoxy composite laminates reinforced with hybrid flax-basalt-glass woven fabrics. Results show that hybridizing flax with basalt and/or glass enhances tensile, flexural, shear, and bearing properties while controlling impact strength. Different combinations excel in specific aspects, making these hybrids suitable for lightweight load-bearing structures.

Gang Wu et al. [22] addressed the performance issue of single fiber-reinforced plastic (FRP) bars by creating basalt-glass fiber hybrid FRP composite bars. They analyzed failure mechanisms via the finite element method, assessed mechanical properties under different fiber volume ratios experimentally, and finally calculated the optimum glass-basalt fiber ratio for improved performance of composite bars.

Taghipoor et al. [23] used polypropylene-based bio-composites reinforced with kenaf fibers, basalt fibers, and nanographene in their study and investigated the improvement in tensile strength and reduction in weight using the surface methodology and the multi-objective optimize method. The optimized compositions demonstrated improved mechanical properties and reduced sample weight, which could have practical applications in industries requiring lightweight and strong materials.

Niyaraki et al. [24] have examined, polypropylene and ethylene-propylene-monomer (EPDM) based nanocomposites reinforced with graphene, nano clay, and glass fibers. Using response surface methodology and varying component weight percentages, they found that lower graphene nanosheet and nano clay weights improved mechanical properties. Glass fibers enhanced impact strength and tensile modulus, but their impact on tensile strength varied. The inclusion of EPDM significantly improved impact strength but negatively affected tensile behavior

Alireza Albooyeh et al. [25], examined the effect of silica aerogel and hydroxyapatite nanoparticles on the mechanical properties and density of epoxy using response surface methodology (RSM). The study revealed that combining hydroxyapatite and silica aerogel nanoparticles in epoxy improves its mechanical properties, with specific compositions leading to enhanced tensile and impact performance while reducing density.

Taghipoor et al. [26] studied optimized polypropylene-based nanocomposites with varying graphene nanosheets, basalt fiber, and polypropylene-grafted maleic anhydride (PP-g-MA) content using response surface methodology. It was observed that 1% graphene nanosheets and 15% basalt enhanced tensile, flexural, and impact strength, and the addition of PP-g-MA improved adhesion, dispersion, tensile strength, and modulus.

It is evident from the literature that different researchers have attempted different iterations for glass and basalt fiber. The effect of basalt weight fraction and specific strength comparison is still debatable. The goal of this research is to examine the effect of different weight fractions of basalt fibers on glass/basalt hybrid composite by evaluating their mechanical characteristics and investigating their specific strengths to find enhancements in strength in comparison to density.

2. Materials and Methods

This section discussed, the materials used, fabrication techniques used, and different characterization methods used to identify different properties of composite laminates.

2.1. Materials

Different composite laminates were prepared using plain bidirectional 400 gsm (g/m^2) woven E-glass fabric and 380 gsm woven basalt fabric as a fiber, as shown in Fig. 1. Thermostat bisphenol-based epoxy resin was employed as a matrix in this research work. The configuration of laminates used in this study is shown in Table 1.

Fig. 1. (a) Glass fiber (b) Basalt fiber

Table 1. Laminate Stacking Sequence

Designation of Laminate	Stacking order	Laminate Thickness (mm)
Laminate-A	**G\G\G\G\G\G\G**	3.07
Laminate-B	**B\G\G\G\G\G\B**	2.95
Laminate-C	**B\G\B\G\B\G\B**	2.86
Laminate-D	**B\B\B\G\B\B\B**	2.79
Laminate-E	**B\B\B\B\B\B\B**	2.75

G = Glass fiber, B= Basalt fiber

As the thickness of a glass fabric layer was 0.40mm and a basalt fabric layer was 0.38 mm, the overall thickness of the laminate was reduced as the basalt fiber layer increased.

2.2. Laminate Fabrication

Both glass fiber and basalt fiber were cut into 310 mm x 310 mm size for each layer. With the Hand layup technique as shown in Fig. 2, a total of five laminates were fabricated. Epoxy and hardener were combined in a 2:1 ratio of weight and stirred for a few minutes to remove air bubbles from the resin. Resin is applied to the fabric using a brush, and a bubble paddle roller is used to remove any trapped air between different layers of fabric during fabrication. The pot life of the resin is 30 to 40 minutes, which is enough to make a laminated plate of seven layers. After preparing the required configuration, an additional weight of 120 Newtons was applied to remove access resin from the fabricated plate. The fabricated plate is allowed to cure for 24 hours before being removed from the mold.

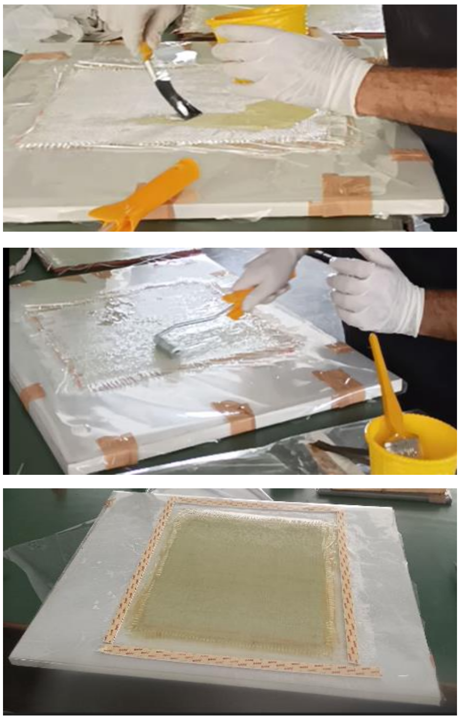


Fig. 2. Hand Lay-up Process

2.3. Testing

Tensile, flexural, and impact tests were carried out in compliance with ASTM standards to investigate the effects of various weight fractions of basalt fiber on the mechanical properties of glass fiber. To know the weight fraction of fibers an ignition loss test and to evaluate specific strength, a density test was also performed as per ASTM standard methods. From the fabricated laminates using water-jet cutting technology, specimens are cut as per the dimensions shown in fig. 3.

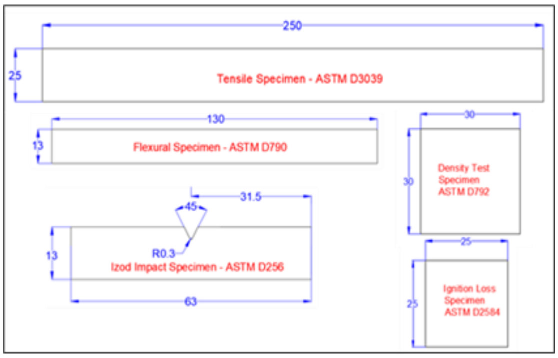


Fig. 3. Dimension of specimens used in this study

2.3.1. Weight Fraction and Density

An ignition loss test was carried out as per ASTM D2584 on 25mm x 25mm specimens to find out the fiber and resin weight fractions in the cured composite using a muffle furnace. Samples were heated to a temperature of 575°C for two and a half hours in a muffle furnace. After that, the samples were allowed to cool at room temperature for an hour before weight measurement. To find out the weight fraction of ignition loss, the following equation is used:

$$\%\,\Delta w = \left[\frac{(w_1 - w_2)}{w_1}\right] * 100 \qquad (1)$$

Δw = weight loss in ignition

w_1 = specimen weight before heating,

w_2 = specimen weight of the after heating

After measuring the weight of the matrix lost in ignition, aggregate and individual fiber weight fractions were measured and presented here.

As per ASTM D792, a density test was performed on a 30mm x 30mm specimen using a CONTECH density balance unit with 0.01mg accuracy. The specimen's weight was determined in both air and water, and its density was calculated using the given equation:

$$Specific\ Gravity = \frac{a}{[a - b]} \qquad (2)$$

$$\text{Density} = \text{Specific gravity} * \text{water Density} \qquad (3)$$

a = mass of sample in air,

b = mass of sample in water,

2.3.2. Mechanical Testing

Tensile tests on a 100 kN Dak UTM were performed, as seen in Fig. 3. Tensile tests were conducted as per ASTM D3039 with a feed rate of 2.0 mm/min on specimens measuring 250mm x 25mm x 't' mm (length x breadth x thickness). The gauge length was considered to be 50mm. Tensile strength and strain are calculated using the equation below.

$$\text{Tensile strength} = \frac{F_{max}}{A} \qquad (4)$$

F_{max} = maximum tensile load before failure,

A = initial cross-section area

$$\%\ Tensile\ Strain = \frac{\text{change in a gauge length}}{\text{original gauge length}} \text{ x } 100 \qquad (5)$$

The flexural tests were conducted on a 100 kN Dak UTM as shown in Fig. 3. Flexural testing was performed as per ASTM D790, where a test of three-point bending with a central point load was carried out on a simply supported beam with a feed rate of 1.3 mm/min on a specimen measuring 130mm x 13mm x 't' mm (length x breadth x thickness). A 16:1 support span-to-thickness ratio was considered for all the samples. Flexural strength and strain are computed as per the formula given below.

$$\text{Flexural strength} = \frac{3LF_{max}}{2bd^2} \qquad (6)$$

$$\%\ \text{Flexural srain} = \frac{6Dd}{L^2} \text{ x } 100 \qquad (7)$$

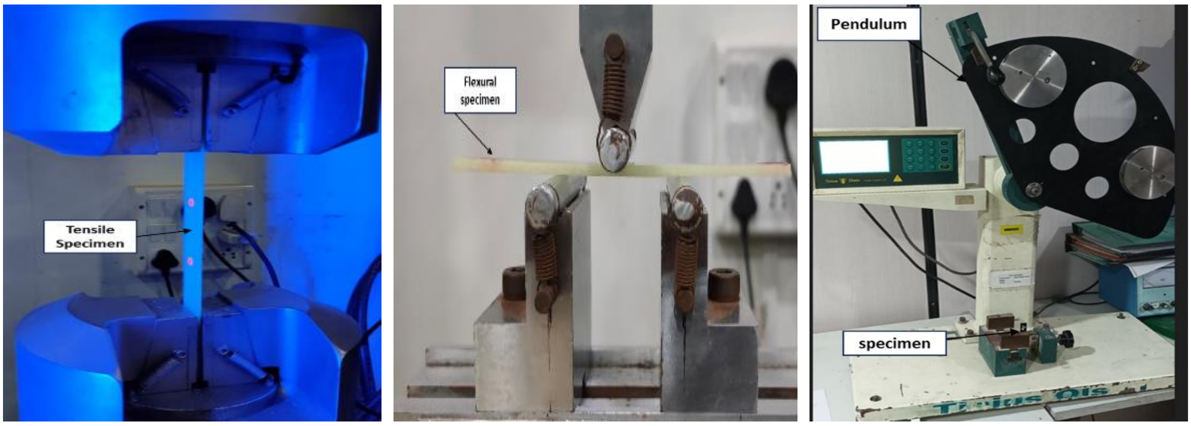
F_{max} = Maximum flexural load before failure,

L= support span,

b= specimen breadth, d = specimen thickness

D = deflection at F_{max} to the center of the beam,

The impact test was conducted using a standard falling-weight Izod impact Tinius Olsen 25 J device with specimen support, as illustrated in Fig. 3. The impact test was used to calculate the energy needed to break down the specimen. Impact testing was carried out using ASTM D256 on each sample which has dimensions of 63 mm x 13mm x 't' mm (length x breadth x thickness) with a notch of a 0.3mm radius at the center. A pendulum swung around each specimen as it was held in a suspended, vertical position. The impact energy was measured using a dial gauge that was affixed to the machine.



(a) Tensile Test in UTM (b) Flexural Test in UTM (c) Impact Testing Machine

Fig. 3. (a) Tensile set up (b) Flexural set up (c) Impact set up

Impact strength (IS) can be obtained as

$$\text{Impact Strength} = \frac{E}{bh} \tag{8}$$

E = energy used to break the sample,

b =sample width,

h = sample thickness

2.3.3. Statistical Analysis

Using an F-test in the form of a one-way (or one factor) analysis of variance (ANOVA) at a 5% level of significance (95% confidence level), the tensile, flexural, and impact strengths, as well as the tensile and flexural strain, were each individually analyzed to ascertain if the different weight fractions of fibers had a statistical effect on the mechanical properties of composite laminates in mechanical testing. If the value of $F_{critical}$ is less than F-value, the findings indicate that there are substantial variations in means across the composite laminates (Rejection of the null hypothesis). The other term that can be used to determine statistical significance is the p-value. The p-value, considering the null hypothesis is true, is the probability that the findings are as extreme as the sample data. To determine if the null hypothesis may be rejected, the p-value and alpha-value are compared. The data are considered significant if the p-value is less than the alpha value (0.05).

3. Results and Discussion

Fiber fraction was evaluated using the matrix digestion method, and density was evaluated using a method based on Archimedes' principle. Different mechanical properties of different laminates were assessed using tensile, flexural, and impact tests. The data in this section consists of the average results from five tests, one for each load case. Vertical bars show the standard deviations.

3.1. Fiber Weight Fraction

The overall fiber fraction achieved for all the different composite laminates is 58%±3%. As all the laminates were fabricated by hand layup method where fabrication was done manually; it has been challenging to maintain uniform matrix distribution and roller pressure during the fabrication of laminates, and small variations in overall fiber fraction were observed in all the laminates as shown in Table 2. Overall, hybrid composites show a slightly higher fiber fraction than non-hybrid composites. This may be because using basalt fiber along with glass fiber layers produces a better interfacial bond and a higher fiber fraction. The fiber fraction for the composites was found to rise as the basalt fibers' relative amounts increased because basalt has better adhesion properties [27]. Since, in the present case, both glass and basalt fibers are plain bidirectional due to similar weaving, resin that is draining from the basalt fabric will penetrate through the glass fabric easily and hence not accumulate at the interface. This leads to an overall reduction in the resin content, and so the hybrid composite matrix content is reduced compared to plain laminates.

Table 2. Fiber fraction for different laminates

Laminate Code	Glass fiber weight fraction (%)	Basalt fiber weight fraction (%)	Aggregate fiber fraction (%) in laminate
A	100	0	55
B	74	26	58
C	46	54	61
D	16	84	60
E	0	100	56

3.2. Density

From Table 3 and Figure 4 as the fiber fraction increases, the density of the composite increases because of the increase in the weight fraction of higher-density fiber material (G – 2.6 g/cc, B – 2.7 g/cc) compared to matrix material (resin – 1.31 g/cc). Similar trends were observed in research work [28]. An increase in basalt fiber fraction results in an increase in overall density for all the hybrid laminates. Maximum density was observed with alternate layers, and the overall fiber fraction was also the highest. In a non-hybrid configuration, laminate-A with only glass fiber shows higher density in comparison to laminate-E with only basalt fiber, as glass fiber is 400 gsm and basalt fiber is 380 gsm used in this study, and lower gsm means the material is thinner with low aerial density and less fiber per unit area. Thus, a high-density value of glass fiber laminate was seen due to the dense packing of a large amount of fiber into the specified composite volume [28].

Table 3. Density

Laminate Code	Density (gram/cm^3)
A	1.5986
B	1.6206
C	1.6795
D	1.6390
E	1.5682

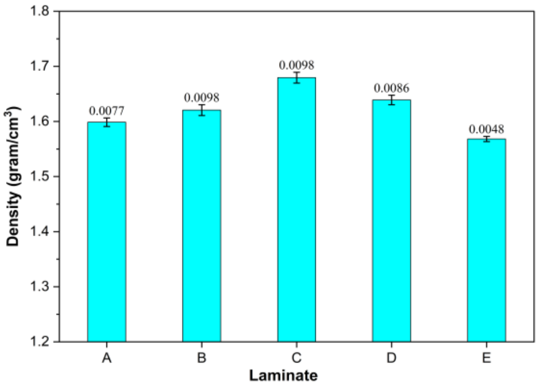


Fig. 4. Density of different Laminates

3.3. Tensile Test Results

The tensile stress-strain curves of different laminates are shown in Fig. 5 and Fig. *6*. The highest dispersion was observed among the five samples of laminate-A, as represented in Fig. 5 . As shown in Figure 7, all the specimens fail in a brittle manner, which can be seen with respect to the stress-strain graph as well. For all the laminates, the stress-strain graph was almost perfectly linear until sudden fiber failure occurred [17]. In addition to that, specimens generally failed in or near their gauge section for all laminates.

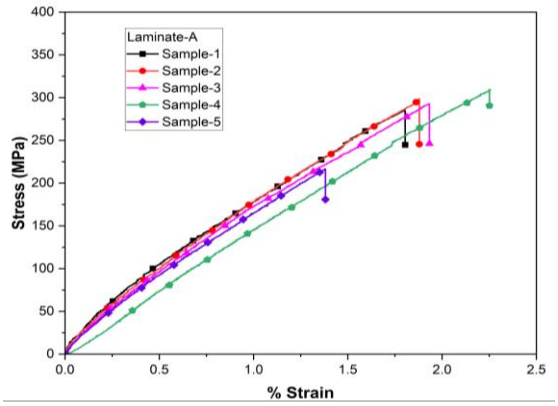


Fig. 5. Tensile stress-strain curves of all samples for laminate-A

Figure 8, shows a comparison of the tensile strengths of five different laminates used in the present study. In comparison to non-hybrid laminates-A (G-100%) and E (B-100%), basalt fiber laminate shows a higher tensile strength of 328.80 MPa compared to only glass fiber laminate-A, with a value of 280.44 MPa. Hybrid laminates B (B-26%), C (B-54%), and E (B-84%) show tensile strengths of 337.25 MPa, 310.91 MPa, and 332.48 MPa, respectively. All hybrid laminates show higher tensile strength than non-hybrid laminates, and thus increasing the basalt fraction improves the tensile properties of hybrid laminates. A similar outcome was seen in the study of glass and basalt fiber with polyester resin [17].

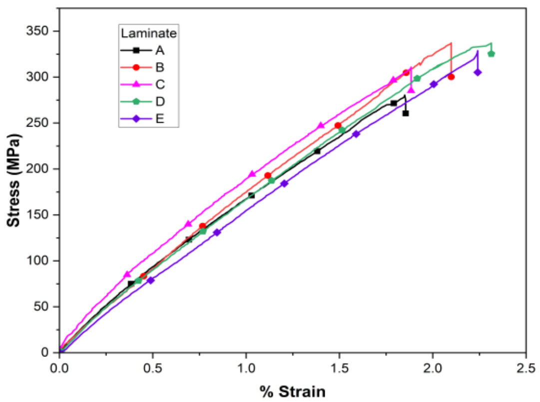


Fig. 6. Tensile stress-strain curve of all laminates

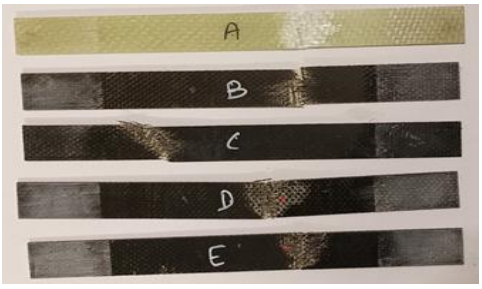


Fig. 7. Failed sample after Tensile test

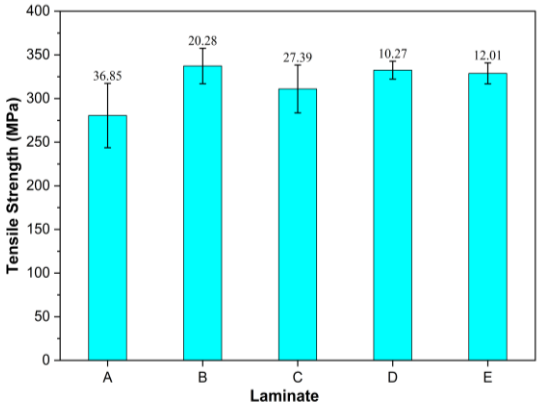


Fig. 8. Max. Tensile strength of different laminates

Due to basalt fiber reinforcement in the epoxy matrix, hybrid composites' tensile strength has increased. In a tensile test, loading is along the fiber direction, so the fiber fails. In hybrid laminates, higher tensile strength was observed when a basalt fiber layer was employed only as the outer layer. The composites' increased tensile strength can be attributed to a balanced layering design between the inner glass fiber and outer basalt layers. This prevents microcrack propagation and optimizes the matrix, providing stiffness and form, ultimately improving the composites' mechanical characteristics [29]. When basalt and glass are used as alternate layers in laminate, the hybrid composite laminate shows lower tensile strength. The lack of matrix in laminate could be attributed to such results, and similar results were presented by Mini et al. [30].

From Figure 9, it was observed that elongation at failure is highest for only basalt fiber laminates in comparison to only glass fiber laminates. The strain at failure for non-hybrid laminates-A (G-100%) and laminate-E (B-100%) is 1.85% and 2.26%, respectively. The strain values for hybrid laminates corresponding to laminates-B (B-26%), laminate-C (B-54%), and laminate-E (B-84%) are 2.09%, 1.88%, and 2.24%, respectively.

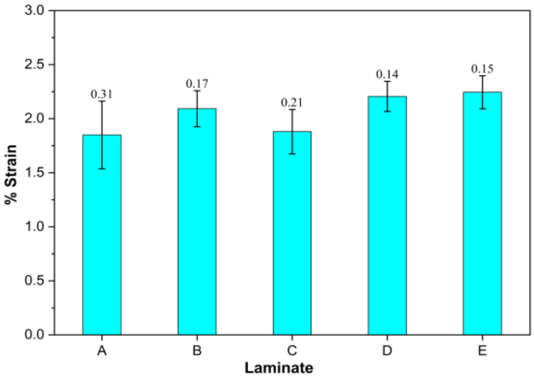


Fig. 9. Strain (%) at Max. Tensile Strength

Thus, the inclusion of basalt fiber can improve the elongation before failure in hybrid composites; The reason for this can be attributed to the fact that fibers with low elongation break first and generate fractures. However, as the adjoining high-elongation fibers support the low-elongation fibers, it allows the stronger low-elongation fibers to reach their breaking strain. However, in laminate-C with 54% basalt fiber and an alternate fiber layer of basalt and glass in sequence, the elongation of hybrid composites before failure is reduced. When basalt and glass fiber reinforcement are present as an alternate layer and approximately in equal proportions, they behave as independent systems with significant delamination and premature failure, which result in low elongation before failure [31].

3.4. Flexural Test Results

The stress-strain curves of different laminates tested under a 3-point bending load are shown in Fig. 10 and Fig. 11. Failed samples of each laminate are shown in Fig. 12. The highest depression was observed among the five samples of laminate-E as represented in Fig. 10. Elastic as well as Plastic deformation is observed for all the laminates in the flexural stress-strain diagram Fig. 11. Where hybrid laminate-C (B-54%) with an alternate layer of glass and basalt exhibits the highest plastic deformation compared to all other hybrid and non-hybrid laminates. In the linear portion of these curves, a similar trend was observed, but once failure occurred, a deviation in trend was noticed.

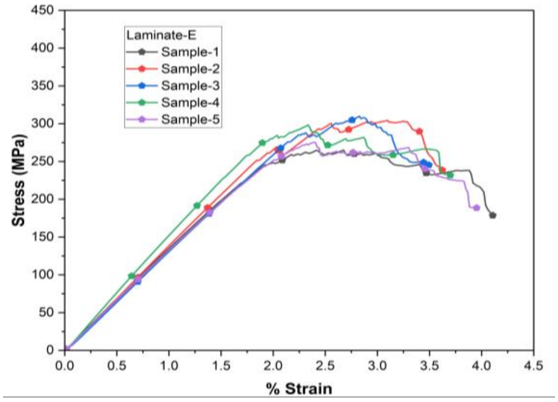


Fig. 10. Flexural stress-strain curve for all samples of laminate-E

Figure 13 shows a comparison of the flexural strengths of five different laminates used in the present study. Non-hybrid laminate-A (G-100%) has a flexural strength of 339.44 MPa, and laminate-E (B-100%) has a flexural strength of 294.18 MPa. Hybrid laminates-B (B-26%), laminate-C (B-54%) and laminate-E (B-84%) show flexural strengths of 343.74 MPa, 383.42 MPa and 350.05 MPa respectively.

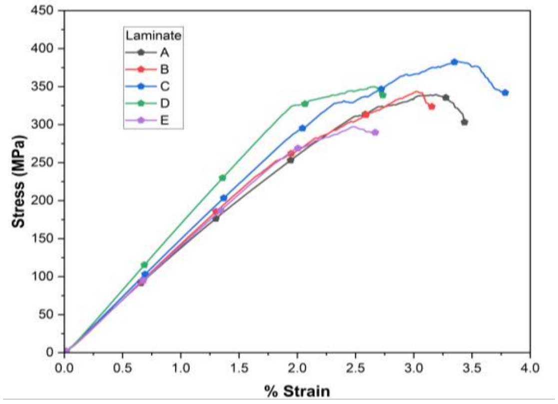


Fig. 11. Flexural stress-strain curves of all laminates

Increasing the basalt layer will improve the stiffness of hybrid structures [32] all hybrid laminates show higher flexural strength compared to non-hybrid glass fiber and basalt fiber laminates. Because of the better adhesion property of basalt fiber and the good interfacial bond achieved between glass and basalt fiber higher flexural strength was observed for hybrid laminates. Thus, an increase in basalt fiber enhances flexural behavior.

Fig. 12. Failed samples after Flexural test

The highest flexural strength is observed in hybrid laminate-C (B-54%) where layers were arranged in alternate layers, compared to hybrid laminate-B and laminate-D where basalt layers are on the outer side. This was due to the effective transfer of loads between fibers and the inherent properties of basalt fiber at the inner level [18]. However, non-hybrid laminate-A (G-100%) shows higher flexural strength than non-hybrid laminate-E (B-100%). As the overall thickness of laminate-E is the smallest among all laminates, this will lead to a decrease in its flexural strength. Thinner materials have less cross-sectional area to resist bending forces, making them more susceptible to failure when subjected to bending load.

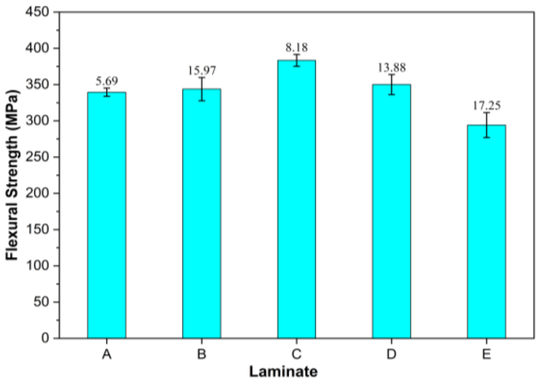


Fig. 13. Max. Flexural strength of different laminates

From Figure 14, it is observed that in non-hybrid composites the elongation at break is 3.19% for glass fiber laminate-A(G-100%), which is higher in comparison to the 2.94% strain value of only basalt fiber laminate-E (B-100%). Hybrid laminates-B (B-26%), laminate-C (B-54%), and laminate-D (B-84%) show an elongation at break of 3.03%, 3.36%, and 2.66%, respectively. As basalt fiber has less elongation under flexural load, enhancing the fraction of basalt fiber in fiberglass composite laminates also decreases elongation at break. Due to the composites' high stiffness, a decrease in flexibility was evident by a decrease in elongation at break [17]. However, when basalt and glass fiber are used as alternate layers, the highest elongations were observed before failure, as dissimilar basalt and glass fiber have better interfaces and have good adhesion or interlocking mechanisms, which can prevent premature delamination or fiber pull-out, contributing to the overall elongation of the composite during bending.

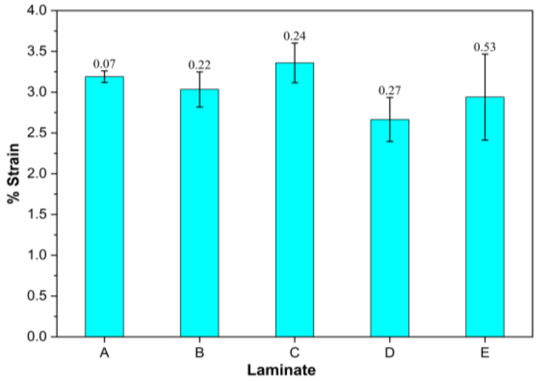


Fig. 14. Strain (%) at Max. Flexural strength

3.5. Impact Strength

The Izod impact test was used to determine the amount of energy needed to break the specimens. From Figure 15, it is observed that all the specimens failed at the notch region.

Fig. 15. Failed samples after Impact test

Figure 16 shows the impact energy absorbed by all the laminates before they were broken. It was observed that non-hybrid basalt fiber laminate-E (B-100%) shows a higher impact strength of 76.76 kJ/m^2 than the impact strength of 70.81 kJ/m^2 of only glass fiber laminate. Hybrid laminates-B (B-26%), laminate-C (B-54%), and laminate-D (B-84%) show impact strengths of 81.12 kJ/m^2, 80.05 kJ/m^2 and 78.80 kJ/m^2 respectively. It was observed that, compared to non-hybrid laminates, hybrid laminates have higher impact strength. A similar trend was observed by Ramesh et al. in their research work for hybrid composites [33]. The highest impact strength is observed for hybrid composites with 26% basalt. Other hybrid configurations show impact strength almost near to this value.

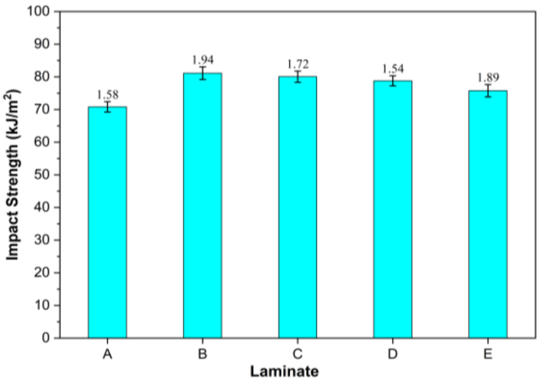


Fig. 16. Impact strength of different laminates

3.6. Results of Statistical Analysis

Utilizing one-way analysis of variance (ANOVA), statistical analysis was carried out for tensile, flexural, and impact test results, and the same is presented in Table 4.

In all ANOVA tests, the p-value was less than 0.05, which discards the null hypothesis and indicates a significant difference in the mean value of the strength and strain of the composites. ANOVA revealed that the weight fraction of basalt in glass/basalt hybrid composites had a statistically significant influence on the means of the tensile, flexural, and impact strengths, as well as the tensile strain and flexural strain.

3.7. Specific Strength

An important material characteristic known as specific strength measures a material's strength in relation to its density. For a variety of engineering and design applications in aerospace, automotive, and energy efficiency, specific strength is essential where it is required to make lightweight and high-strength structures. Here, the specific attributes were supplied for each laminate due to the variation in fiber density and to make comparisons more useful. Specific strength was calculated using the below relationship.

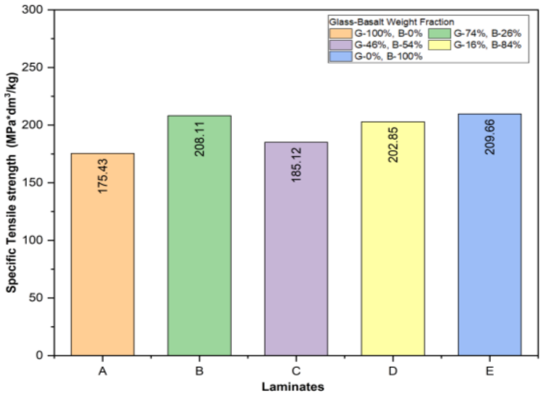
$$\text{Specific Strength} = \frac{\text{Strength of Material}}{\text{Density of material}} \tag{9}$$

From the specific strength comparison shown in Fig. 17, it was observed that the specific tensile as well as impact strengths of only basalt fiber laminate-E (B-100%) were higher than those of only glass fiber laminate-A (G-100%), while specific flexural strength of laminate-E is lower. All the hybrid laminates show higher specific tensile and impact strengths compared to glass fiber. The laminate-B (B-26%) shows 18% higher specific tensile strength and 13% higher specific impact strength compared to only glass fiber laminate-A. The laminate-C (B-54%) shows the highest specific flexural strength and it is 7.5 % higher than only glass fiber laminate-A. The specific flexural strength of hybrid laminates is not significantly different from the specific flexural strength of glass fiber, and they are on the higher side compared to the flexural strength of only basalt fiber laminate. Even in this case, all the already discussed trends were confirmed, so they do not require further discussion.

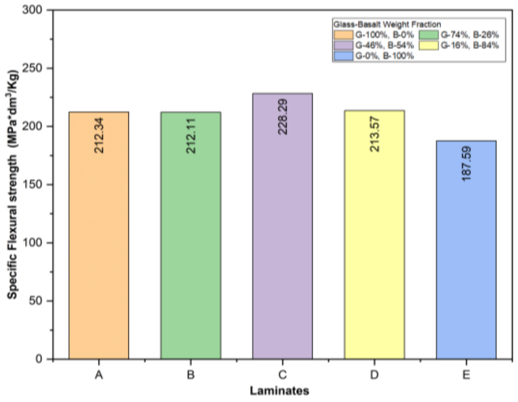
Table 4. ANOVA results for Mechanical characteristics on hybrid laminates based on different fiber weight fraction

Source of Variation	***SS***	***df***	***MS***	***F***	***p-value***
Tensile Strength (MPa)					
BG	10787.3256	4	2696.8314	4.8681	0.00661
WG	11079.6690	20	553.9834		
Tensile Strain at failure (%)					
BG	0.410627	4	0.102657	3.1564	0.0365
WG	0.65046	20	0.032523		
Flexural Strength (MPa)					
BG	20383.66	4	5095.915	23.9030	0.0000
WG	4263.837	20	213.191		
Flexural strain at failure (%)					
BG	1.375965	4	0.343991	3.5902	0.0231
WG	1.916303	20	0.095815		
Impact Strength (kJ.m^{-2})					
BG	344.2929	4	86.07322	26.6689	0.0000
WG	64.5496	20	3.22748		

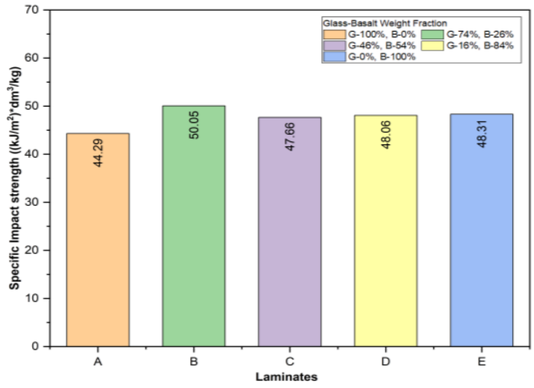
BG-between groups; WG-within groups; SS-sum of squares; df-degree of freedom; MS-mean square



(a) Specific Tensile Strength



(b) Specific Flexural Strength



(c) Specific Impact Strength

Fig. 17. Specific Strength of different laminates

4. Conclusions

The mechanical characterization of a glass-basalt hybrid composite with varying fractions of basalt fiber was investigated here. The density of the hybrid composite with the addition of basalt fiber was slightly increased within the range of 2% to 5%. In comparison to only glass fiber laminate (G-100%), basalt fiber laminate (B-100%) shows 17% higher tensile strength, 7% higher impact energy, and 15% lower flexural strength. With glass-basalt hybridization, tensile strength was increased by 20%, flexural strength was increased by 12%, and impact strength was increased by 14% compared to only glass fiber laminate. Also, it was possible to achieve higher elongation at failure in glass fiber with hybridization in tensile as well as flexural loading. The maximum tensile and impact strengths were observed in a hybrid laminate with 26% basalt fiber. Whereas maximum flexural strength is observed in a hybrid laminate with 54% basalt fiber. ANOVA statistical assessment noted significant differences in the average values of the composite's mechanical strengths. Finally, in a specific strength comparison, it was observed that hybrid configuration results in better specific tensile and impact strength and comparative specific flexural strength. Considering basalt fiber has superior properties compared to glass fiber and better adhesion with matrix, research was conducted here to create a hybrid composite with glass and basalt fiber which has high strength as well as light weight may identify possible applications where specific mechanical characteristics are essential for a suitable product design.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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