Mechanical properties analysis of basalt, hemp, carbon, and glass fiber-reinforced hybrid composite by hand lay-up technique

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Abstract

Natural fiber reinforced composites are an emerging area in polymer science and future trend applications. These natural fibers are comes with low-cost fibers with superior mechanical properties, low density and high specific properties, biodegradable and non-abrasive nature. These may offer specific properties comparable to those of conventional fiber composites. By applying the fibers in a hybrid form to take the advantage of both natural and synthetic fibers in order to bring out the various attractive properties, which resulted in superior mechanical and tribological properties. Keeping this view, the present work has been under taken to develop a polymer matrix composite (epoxy resin) using Hemp, Basalt, Carbon and E-Glass fibers fabricated by using Hand lay-up technique. Mechanical properties such as tensile, flexural, impact strength and hardness of each composite will be investigated. In order to increase fibre/matrix compatibility and the properties of the natural fibers were treated with the chemical treatments like alkaline and silane treatments. This research aims to synthesize the epoxy hybrid composite by utilizing the hemp (H), basalt (B), carbon fiber (C) and chopped mate E-glass fiber (G) as layering via hand layup techniques. Using above these reinforcements' C1 H/B/G/C (hybrid), C2 B/G/H, C3 B/H/G, C4 G/H/C, C5 B/H/G five different combinations have been developed as per ASTM standards and mechanical testings' such as tensile, flexural, impact, and hardness is carried out. From the test results, it was found that the C1 H/B/G/C sample exhibits the maximum tensile strength and flexural strength of 365.61 MPa and 820.31 MPa at the ultimate loads of 28.664KN and 2.5KN and impact strength of 26J which was maximum compared with other samples C2 B/G/H, C3 B/H/G, C4 G/H/C, C5 B/H/G.

Keywords: Hybrid composite, epoxy, Hemp fiber, Basalt fiber, Carbon fiber, E-Glass fiber, Tensile strength, Flexural strength, Impact strength, Hardness

1. Introduction

In hybridization, a technique involves combining two or more distinct reinforcements into a single composite laminate to address the limitations of each reinforcement while leveraging their respective advantages. Sometimes it also refers to as implementation of fibers in the filler composites. It is not new to the researchers in fact, it has been in practice for centuries.

Both natural and synthetic fibers exhibit their own advantages and disadvantages concerning the polymer. By combining them in a hybrid form, it is possible to harness the benefits of both types of fibers, resulting in composite fibers with superior mechanical and tribological properties. Which is generally called as hybridization in composite this can lead to significant improvement in impact resistance and damage tolerance of natural composites.

The essential factors for achieving promising results in composite properties include fiber type, fiber size, percentage of fiber, polymer choice, processing techniques, and chemical treatment.

The Properties such as physical, mechanical, and thermal and superior performance get influenced in a positive manner because of the hybridization. [1] It can be described as an best approach towards synergy effect. The natural fiber reinforced composites have a lot of benefits with the superior properties like high specific strength and environmental concern. [1–3] The reinforcements can be classified into continuous fibers and discontinuous fillers. Continuous fibers provide high strength and stiffness where as discontinuous fibers like particulate or short fibers improve impact resistance, dimensional stability, and wear resistance. There are mainly two types of hybridization, 1. Interlaminate and 2. Intralaminate. When different fibres are deposited on different layers interlaminate is formed, whereas intralaminate which is obtained by arranging different fibres within a single layer. There are several ways to achieve hybridization like multi-layered composite, blending and intermingling. [2]

Hybridization in polymer composites yields several advantages, including enhanced mechanical properties, tailored characteristics customizable for specific applications, enabling a balance between strength and weight for resistance to specific atmospheric conditions. Moreover, it facilitates cost optimization by combining less expensive fibers with high-performance ones, thereby minimizing material costs while meeting desired requirements.[4]

Hybridization does not always work for every aspect of composite taken into consideration. It can be stated that enhancement of one property sometimes leads to reduction of another vice versa. [1]

Hemp, which is a plant fiber, is also finding its place in hybridization because of its influential properties. In hybrid composites, the arrangement of layers significantly influences the mechanical properties of the resulting composite. [1] The conclusion is that hybrid laminates featuring synthetic fibers on both sides achieve an optimal amalgamation, striking a favourable balance between properties and cost. Additionally, the hybridization of glass fibers with hemp fibers has been observed to enhance mechanical and physical properties while reducing the overall cost of composites.

[5] In this research article studies that the natural fibers contains lignin, cellulose, hemicellulose, wax, which responsible for the performance of the natural fibers. Hemicellulose is responsible for the biodegradation, moisture absorption, thermal degradation of the fiber as it shoes the least resistance. Lignin is thermally stable but it is responsible for the UV degradation. And also, by working with thermosets which have highly cross-linked three-dimensional which are highly solvent resistance, tough and creep resistance network structure. The properties of the fibers, the aspect ratio of the fibers, and the interaction at the fiber–matrix interface collectively dictate the characteristics of the composites. The interfacial adhesion between the fiber and the polymer is crucial for transmitting stress from the matrix to the fiber, thereby influencing the overall performance of the composite. Another important aspect is the thermal stability through pyrolysis process. Due to the hydrophilic nature of the natural fibers, they are very incompatible with the hydrophobic polymer and tendency to form aggregates and exhibits a poor resistance. For elimination these problems treatment of fibers with hydrophobic aliphatic and cyclic structures have been attempted. A strong interface, low stress concentration, fiber orientation is required for improving the tensile strength. Fiber concentration, fiber wetting in the matrix phase, and high fiber aspect ratio [6][7–11] determine tensile modulus. For determining the fracture properties aspect ratio is very important.

Tom Sunny and Kim L. Pickering [12] investigated that the alkali treatment of hemp fiber in which results shows that at 5 wt% NaOH and 2 wt% Na_2SO_3 solution at temp 120°C for 30 min can improved the tensile strength and young's modulus. It also improves the fiber separations of fiber bundles. [13][10] for reducing the drawbacks of the natural fibers surface treatments are very necessary for better performance with the matrix.

The present research deals with the effect of hybridization of hemp, basalt, carbon fiber and E-glass fiber was taken for studying the mechanical properties. The findings of this study can be effective in contributing towards optimization of hybrid laminates leading more efficient and cost-effective production for semi-structural applications. The present investigation deals with fabricating hybrid composite with fore types of reinforcing materials and five combinations. Furthermore, micro structure study has been conducted on fractured surfaces of tests samples.

2. Materials selection

The quality of a composite greatly relies on the selection of raw materials and the processing technique. In this experimental work, the base matrix chosen is epoxy resin LY-556, a low-density two-part synthetic resin polymer material with high mechanical and thermal properties. It exhibits chemical and corrosive resistance to alkalis and acids, along with strong adhesion properties. The hardener HY-951 functions as the curing agent (catalyst) and initiates the curing process of the adhesive is chosen (10.1). The ultimate characteristics and suitability of an epoxy coating for a specific environment are determined by the precise selection and combination of the epoxy and hardener components.

In this experimental work various filler materials were considered for their unique properties: Hemp fiber, chosen for its excellent strength at a low density of 1.3 - 1.5 g/cm^3; carbon fiber, recognized for its high strength but with poor damage tolerance; basalt fiber, more cost-effective than carbon fiber yet stronger than glass fiber; and chopped E-glass mat, known for its good electrical resistance, impact resistance, and toughness, were all included in the study. The properties were tabulated in **Table 1.**

2.1 Hemp fiber

Hemp, a species of Cannabis sativa, is a versatile, eco-friendly natural fiber known for its good tensile strength at low density, biodegradability, and cost-effectiveness as a substitute for synthetic fibers. These fibers are obtained from the stalks of the hemp plant, and it falls under the category of bast fibers, referring to the outer protective layer of the plant stem, which includes the phloem tissue. Due to its local availability, it is being evaluated as a viable natural plant fiber reinforcement for incorporation into the current research.

The mechanical characteristics of plant fibers are influenced by various factors beyond botanical classification. These factors encompass chemical composition, structure, harvesting timing, extraction techniques, treatment processes, and storage conditions.

Natural fibers, composed of lignin, cellulose, and hemicellulose, which influence adhesive bonding with polymer matrices and moisture absorption. Through the chemical treatments these can reacts with fibers surfaces and make it more suitable for applications, by removing the hydroxile groups from the fibers. Before any chemical treatment the raw fibers was cut into short form.

These treatments aim to improve the adhesion, wetting, and compatibility of the fibers with polymer matrices, leading to enhanced mechanical properties, reduced water sensitivity, and better overall performance of the resulting composite material. By optimizing the fiber-matrix interface through surface treatment, we can create composite materials with improved strength, durability, and other desirable properties

2.1 Basalt fiber

The basalt fiber as shown in the **Fig.1** are created by melting basalt rocks, which are of igneous origin, and then converting the molten material into various types of fibers. This process primarily consumes natural energy resources. It consists mainly of the basalt rock, which is rich in elements like iron, magnesium, and calcium. The melting process transforms the rock into a molten state, from which the fibers are drawn. It has gained recognition as a remarkable material due to its exceptional strength, durability, high modulus of elasticity, relatively light weight and versatility. They are highly resistance to chemical corrosions, UV rays and remains sterile which makes them suitable for the use in harsh environments, these exhibits excellent impact resistance and have a low thermal coefficient of expansion and also excellent acoustic insulation. Basalt fiber has many advantages, such as high strength, high temperature resistance, good chemical stability, low energy consumption, and environmental friendliness.

2.2 Glass fiber

The E-Glass fibers as shown in **Fig. 2** are the most widely used and least expensive as all fibers. Chopped E-glass fibers refer to short-length strands of E-glass that are cut to specific lengths for use in reinforcing composite materials. These fibers are typically added to a matrix material, such as a resin, to create a composite with improved mechanical properties. It is named "E-glass" because the "E" stands for "electrical," indicating its good electrical insulating properties. In general, E-glass named as calcium alumino-borosilicate glass with less than 1% alkali oxide, Na_2O. The chopped form allows for easy blending and distribution within the matrix during the manufacturing process. It enhances the strength, stiffness, and impact resistance of the resulting composite. This form of reinforcement is employed in a variety of applications, including automotive components, construction materials, and consumer goods, where the goal is to combine the benefits of E-glass with the convenience of handling short fibers during the production of composite structures.

Fig. 1. Basalt fiber

2.3 Carbon fiber

Carbon fiber is a lightweight and high-strength material composed of thin strands primarily consisting of carbon atoms. Renowned for its exceptional strength-to-weight ratio, carbon fiber exhibits remarkable stiffness and resistance to temperature. The plain weave is the simplest and most commonly used woven fabric as shown in the **Fig. 3.** With fibers typically derived from precursor materials like polyacrylonitrile or pitch, carbon fiber undergoes a meticulous process of heating and carbonization. The resulting material is corrosion-resistant, making it highly durable in various environments. Its low weight, coupled with impressive strength, renders carbon fiber an ideal choice for applications in aerospace, automotive, and sports equipment. The manufacturing process allows for versatile applications, contributing to its widespread use in industries where superior mechanical properties and reduced weight are paramount.

Fig. 2. Direct draw roving E-glass fiber

Fig. 3. Carbon fiber

Table 1

Properties of Epoxy LY556 and Hardener HY951

Properties	**Epoxy LY556**	**Hardener HY951**
Visual appearance	Medium viscosity, colourless clear liquid.	Brownish yellow colour liquid.
Viscosity at room temperature	9000–12000 MPa	500–1000 MPa
Density at room temperature	1.13–1.16gm/cc	0.946 gm/cc

2.4 Chemical treatment of fiber

The present two different processes are used to modify the surface properties of fiber.

1. Alkaline treatment

The Alkali treatment which is also known as mercerisation. It is primarily used to remove impurities, sizing agents, oil, wax, lignin, cellulose, hemicelluloses and other contaminants from the surface of fibers.

This results in fiber separation, surface roughness, enhances the chemical activity by exposure of hydroxyl groups on the fibre surfaces there by improving interfacial bonding between reinforcement and matrix (mechanical interlocking) and increasing thermal stability.

To evaluate the effect of the NaOH solution concentration, the hemp fibers were treated using 5 wt% NaOH and 2wt% NA_2SO_3 (sodium sulphate) solution in water. Each fiber was soaked in the alkaline solution for 60 min at 120ºC using a ratio between the volume solution. Afterwards, the alkalized fibers were washed with distilled water until all the NaOH solution was eliminated and maintaining the pH of the water level equal to 7. The washed fibers were then dried in an oven at 70 °C for 24 h.

The separation of fibers, resulting in the development of increased surface area and enhanced wetting area for the resin, is accompanied by consequential modifications in cell structure, fiber orientation, and crystallinity. This transformative effect is attributed to the alkaline treatment's ability to hydrolyze hydroxyl groups on cellulose chains, causing disruption of hydrogen bonds, ultimately leading to increased crystallinity and surface roughness.

2. Silane treatment

The silane treatment is a coupling agent (an organosilicon compound) is applied to the fiber surface that fills the micropores present in the natural fibers surface and in so doing strengthening interfacial adhesion. [13]

Natural fiber contains inactive hydroxyl group in its surface. After silane treatment, it is activated and the strong bond is formed between the matrix and fiber. The silane coupling agents contains both hydrophilic and hydrophobic compounds with a silicon atom bonded to different functional groups (a bifunctional groups) one group reacts with matrix and another one reacts with hydrophilic fiber which acts a bridge between them to improve interfacial adhesion. This process helps to reduces the absorption of water by decreasing the amount of hydroxyl group in the fiber surface and to control the hydrophilic characteristics of natural fiber and enriched its physical and mechanical behaviours. [9]

The already alkaline treated hemp fibers are kept in a bowl filled with pH=4 silane solution containing 1wt% of silane coupling agent and processed for 60min in ethanol and water. Finally, the fibers were dried at ambient temperature for 48 hrs.

3. Fabrication process

A simple and economical hand lay-up technique is assisted used for epoxy hybrid composite fabrication. This method also requires minimal infrastructure. First the pain woven fabrics were cut according to the proper size. A Thin plastic sheets (Perspex) are used for easy removal and good surface finish of the fabricated part. Before placing the mats Perspex sheet, a release agent (remover) like wax is applied on the mold and dried it for few minutes. Percentage of epoxy hardener in the specimen were calculated by weight fraction. Hardener used in the epoxy hardener mixture is 10:1 After calculations of varying fibre % and their alignment angle, hardener and epoxy resin were mixed thoroughly in suitable proportion and applied onto the thin sheet. After that according to the composite combination fibers were placed proceeding based upon the stacking sequence example like in the first sample the carbon fiber is placed after that by using the roller again the resin in applied on top of that fiber mat, then second layer basalt fiber is placed on top of that and applying the resin with the help of brush and the roller moved to the mat-polymer layer with a slight pressure to remove any air trapped and excess polymer. The process is repeated for each layer until the segments have been stacked. After the final sheet was mounted, the release fluid was poured onto the inner surface of the top mold plate, which remained on the lined layers. finally, the layers were compressed axially by applying a load on top of the mold to prevent any degradation during shrinkage and can be stabilized at room temperature for 48 h. It is to develop the required strength. Similarly, the fabrication procedure is the same for samples 2,3,4 and 5. Fabricated samples were cut as per ASTM standards as shown in the **Fig. 4**

Table 2

Layer arrangement and fiber volume fraction of hybrid composite

Sample Layup Code	Reinforcement Arrangement	Fabric Pattern	No. of layers			
			Hemp Fiber	**E-Glass Fiber**	**Basalt Fiber**	**Carbon Fiber**
[C/B/H/G] (**C1**)	CBHGGHBC	Plain weave	2	2	2	2
[C/B/G] (**C2**)	CBGCGBGBC	Plain weave	0	3	3	3
[C/B/H] (**C3**)	CHBCHBCHB	Plain weave	3	0	3	3
[C/G/H] (**C4**)	CGHHGCGHC	Plain weave	3	3	0	3
[B/H/G] (**C5**)	BHGHGBHGB	Plain weave	3	3	3	0

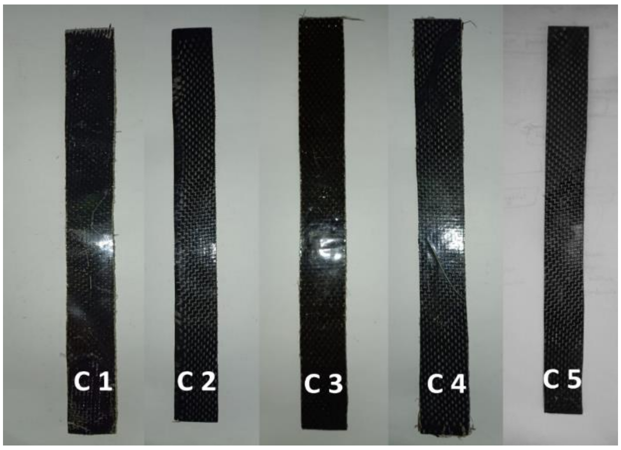

Fig. 4. Tensile Samples ASTM D3039

4. Testing

Mechanical properties such as Tensile strength, Flexural strength, are computed from the test conducted using universal testing machine (UTM) in **Fig.6** in accordance to ASTM standards for specimen preparation.

4.1 Tensile Test

The tensile strength of a material is assessed by its ability to endure applied loads until reaching the point of fracture or failure. In this investigation, the tensile strength was measured on the samples belong to five different combinations. Tensile test was performed in universal testing machine of make AE 50KN Computerised Universal Testing Machine shown in the **Fig.6** The test was carried out according to the standard testing procedure ASTM D3039. The test sample size is 250mm × 25mm × 3.2mm the testing speed was maintained as 5 mm/min for all the samples. Five samples were examined and the mean value was finalized for the discussions. The ASTM D3039 standard established the tensile test species showed in the **Fig.4** The type of material (polymer), gauge length of the specimens, thickness of the specimens, maximum load, crosshead speed (5mm/min) until the specimen was split, given as the input for UTM and the test was carried out. The UTM uses a digital data acquisition system; hence digital output can be obtained. Depending on the test carried out (tensile or bending) the fixture can be changed accordingly. The tensile stress is calculated using the relevant formula as per the recorded data.

4.2 Flexural test

The capacity of a material to withstand the load distribution is called flexural strength. The standard ASTM D790 or ISO 178 prepared the flexural test. The sample size is 150mm × 25mm × 4mm. The 3-point flexural test can be carried out on the same machine AE 50KN computerized universal testing machine as shown in the **Fig.6**

4.3 Impact test

The Charpy Impact Tester was used to asses the impact force of composite specimens according to the ASTM D256. The sample size is 64 × 13 × 8 mm. The test setup was showed in the **Fig.7** The experiments were replicated three times in each case, and the average values are used for the submission.

Fig. 5. Rockwell Hardness

Fig. 6. (AE 50KN) UTM & Flexural Test

1.1 Hardness test

Hardness is a characteristic of a material, not a fundamental physical property. It is defined as the resistance to indentation, and it is determined by measuring the permanent depth of the indentation. The assessment of hardness properties involved applying an indentation load perpendicular to both the fiber diameter and fiber length. The hardness testing machine is as shown in the **Fig.5**

Test Reference: ASTM D 785

Type of Hardness – HRB, HRC

Machine Model – RAS 150

Sample ID – Mechanical hardness testing machine

HRB Indenter: 1/16" tungsten carbide ball indenter

HRC indenter: Diamond cone indenter

Major load: 100kgf, 150kgf

Fig. 7. Impact testing machine

5. Results and discussion

5.1 Tensile properties

The tensile strength of the five different composite samples was tested in AE 50KN Universal Testing Machine. The **Fig.8** shown that the results of ultimate tensile strength of the developed composite samples. It has been noted in **Fig.8** that the UTS of the [H/B/G/C] hybrid sample one composite was found to be 365.61 MPa bearing at a peak load of 28KN. The ultimate tensile strength of the sample 2 and the sample 3 shows better performance results compare to the sample 4 and 5 of 348.317 MPa and 322.409 MPa at an ultimate load of 26.55KN and 24.74KN respectively. The decreased ultimate tensile strength of the composite sample 4 was due to the poor interfacial reactions between the matrix and the reinforcement. Compare to the sample 4 sample 5 significantly increases to the 21KN and tensile strength of 283.728MPa. The improved UTS of sample 5 composite is the reason for effective interfacial strength between the matrix and the filler material. The chemical treatment of fibers also a one of the reasons for these results. The ultimate tensile strength found optimum for hybrid composite.

5.2 Flexural properties

The flexural properties test results of five different samples were tested and presented in the **Fig.9.** The highest recorded flexural strength 820.31MPa the sample found to be hybrid combination H/B/G/C because the ability of better interaction of reinforcement fibers to the epoxy matrix. The sample B/G/C and G/H/C also shows the better results of 721.875 MPa and 656.25 MPa at ultimate loads of 2.2KN and 2.4KN. the flexural strength.

5.3 Impact test

The ability of a material to withstand or absorb the energy form an impact without undergoing significant damage or failure. The impact strength of the different combinations composite samples were tested and presented in the **Fig.10** The experimental Charpy impact test values shown that the H/B/G/C sample one reinforced hybrid composite test specimen having mor energy absorption. The greater the thickness of the laminate is proportional to the energy absorption. The increased impact toughness of the epoxy composite is the reason for the synthetic fiber ability to endure the maximum sudden high-impact load.

5.4 Hardness Test

The Hybrid reinforced fiber is tested by Hardness testing machine. The hardness test is carried out and the test results can be presented in the **Fig. 11** The five test samples are subjected to Hardness test using RAS 150 Shown in the **Fig.5** Rockwell hardness testing machine. Each sample was tested at different locations with the test specimen being subjected to a load of 100 kgf and 150kgf for a dwell time of 30 s for each location. It is observed that the hardness value of H/B/G/C fiber reinforced composite material is higher.

Test results

Table 3

Tensile Test results

Composite Combinations	**Load (KN)**	**Tensile Strength (MPa)**
[C/B/H/G] (**C1**)	28.664	365.61
[C/B/G] (**C2**)	26.55	348.317
[C/B/H] (**C3**)	24.74	322.409
[C/G/H] (**C4**)	17.663	227.601
[B/H/G] (**C5**)	21.764	283.728

Table 4

Flexural Test results

Composite Combinations	**Load (KN)**	**Flexural Strength (MPa)**
[C/B/H/G] (**C1**)	2.5	820.31
[C/B/G] (**C2**)	2.2	721.875
[C/B/H] (**C3**)	1.4	460.375
[C/G/H] (**C4**)	2.0	656.25
[B/H/G] (**C5**)	1.8	590.625

Table 5

Impact Test results

Composite Combinations	[C/B/H/G] (**C1**)	[C/B/G] (**C2**)	[C/B/H] (**C3**)	[C/G/H] (**C4**)	[B/H/G] (**C5**)
Impact (J)	26	24	20	18	22

Table

Hardness Test results

Composite Combination	[C/B/H/G] (**C1**)	[C/B/G] (**C2**)	[C/B/H] (**C3**)	[C/G/H] (**C4**)	[B/H/G] (**C5**)
HRC–150 (kgf)	87	70	68	53	59
HRB–100 (kgf)	106	91	87	64	70

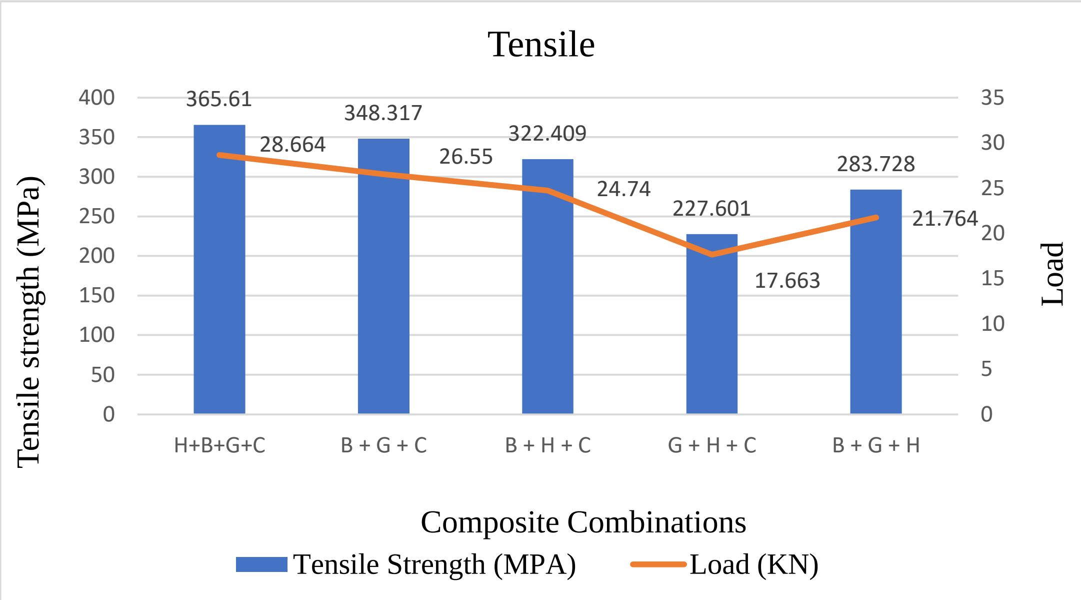

Fig. 8 Load vs Tensile Strength

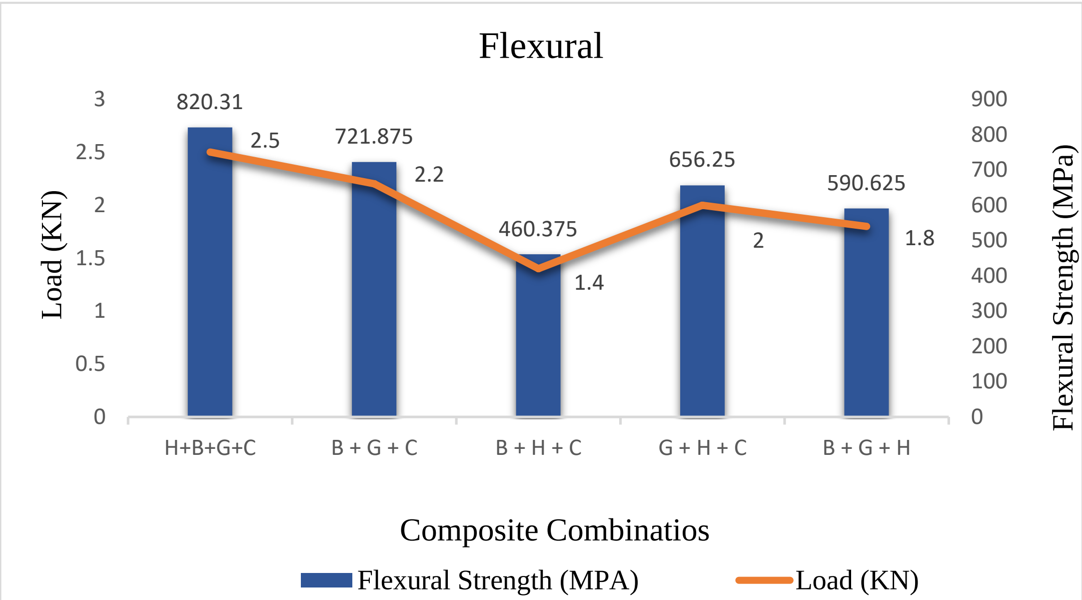

Fig. 9 Load vs Flexural Strength

6. Conclusion

The five different combinations of composites such as H/B/G/C (sample 1), C/B/G (sample 2), C/B/H (sample 3), C/G/H (sample 4), B/H/G (sample 5) were prepared by conventional hand layup technique. The specimens were subjected to tensile, flexural, impact and hardness test.

This work is focused to find the best composite among the five combinations. After all the tests has performed on the specimens the HEMP/BASALT/GLASS/CARBON fibre reinforcement combination a hybrid sample shows a best result in the tensile strength (365.61 MPa) impact strength (26 J), hardness test (106) and as well as flexural strength (820.31 MPa). The fiber stack sequence effects the properties and as we increase the fiber percentage the brittleness of the specimen also increases with it.

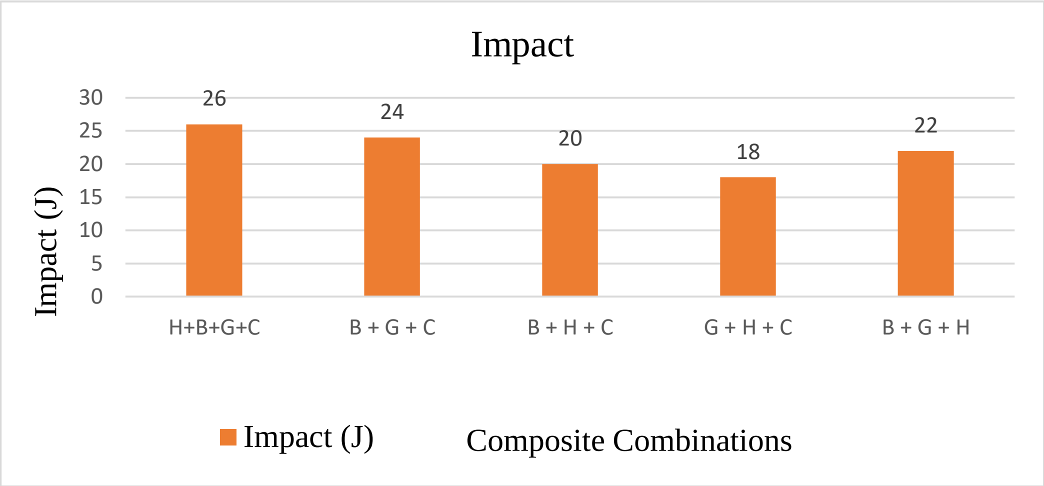

Fig. 10. Impact Test

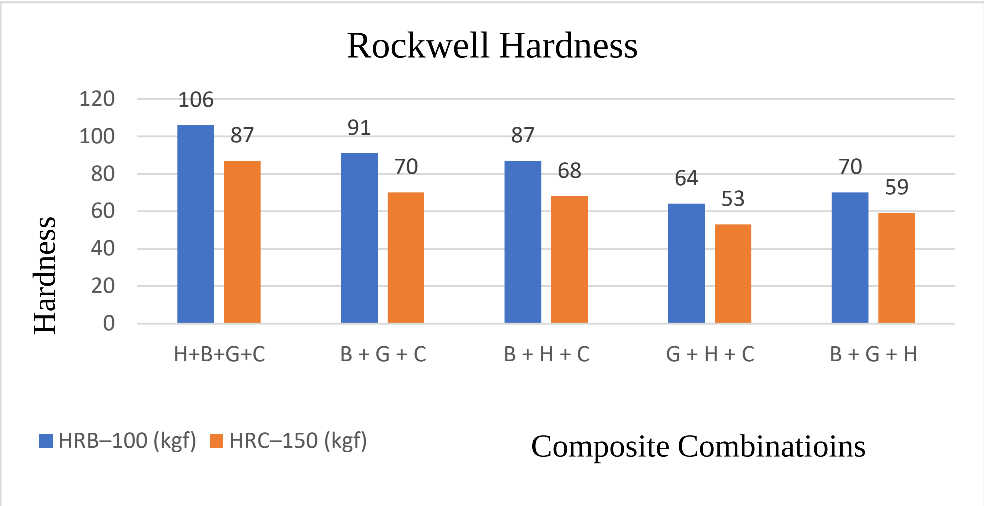

Fig. 11. Hardness Test

7. Future scope

It is known that fiber surface modification increases the bonding strength between fiber and the matrix. Therefore, fiber modification can be done to improve the strength. In addition to tribological testing mechanical tests should be carried out. Using Bio matrices rather than polymer matrices can make environmental concern.

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