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A cost-effective approach for producing carbon composite by altering the fiber architecture and hybridization

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Abstract

Carbon composites have been used in high-performance applications like automotive, marine, civil engineering, and many more. But due to their high cost, researchers have focused their efforts on the development of sustainable carbon composites. In various applications, the material is loaded in a specific direction, and higher strength is needed in that direction. So, in the other direction, the material which provides the needed performance for the product with less cost can be substituted. This cost-effectiveness of composite is attained by the hybridization approach. For this study, carbon composite is considered, wherein the loading direction carbon yarn has been taken whereas it has been substituted with high density polyethylene (HDPE) flat yarn for cost reduction in other direction. Hand lay-up technique is used to prepare carbon-HDPE epoxy hybrid composites. Mechanical properties: tensile, flexural & impact, and physical properties like density and fiber volume fraction were studied. Assessment of performance and comparison of mechanical properties of composites with varying fiber architecture viz. plain, twill, and sateen, is done by taking stacking sequence as constant. A comparison has been established between these composites and metals like steel and aluminium by their specific strength. It is observed that it exhibits satisfactory specific strength in the direction of load. It displays high tensile stress, flexural strength, and impact strength. Comparison with carbon composites showed analogous values in the loading direction. Thus, cost-effective and functionally beneficial hybrid composite materials can be developed by incorporating the suitable hybridization, layering sequence, and architecture of the fabric.

Keywords: Carbon-Epoxy composite, Cost-effective, Fiber architecture, Fiber volume fraction, Hybridization approach, Mechanical properties

1. Introduction

Carbon composite materials are lightweight, high strength-to-weight ratio, corrosion resistance. They have good chemical resistance, excellent electrical conductivity, and thermal conductivity, high specific strengths compared to steel and aluminium [1-3]. Carbon composite raw material and its production is a costly issue [1]. Due to the scarcity of natural resources, the composite industry is placing a renewed emphasis on material efficiency, and composite manufacturers are increasingly adopting a sustainable approach to development. Different methods like increasing the life span of machinery and its components and product development by replacing products that consume more costly raw materials with new materials are adopted. Here, economic sustainability in terms of cost-effectiveness, performance orientation, and consumer benefit plays an important role. Hybrid laminates are those that include multiple fiber types. Hybrid composites can be categorized: as interply, intraply, intra-interply, etc. subjected to the geometric arrangement of the reinforcing material, and ply. [2-4]. Hybridization gives better control of the properties of composite by achieving an optimum balance between the properties of the material used. Innovations in composite manufacturing and designing help to achieve the goal of sustainability. Small modifications and reinventing the design help to reduce costs. Properly selecting alternative materials to manufacture the same product makes a great impact. In many high-demanding applications like vehicle manufacturing, properties such as strength, stiffness, and lightweight, etc. are important. In addition to this affordability is also an important issue [3,5-9].

The high-density polyethylene (HDPE) yarn is one of the affordable materials which have greater impact resistance, abrasion resistance, excellent chemical resistance, electrical resistance, and weatherproof properties. It's lightweight, has high-tenacity, long-lasting, and cost-effective [10-12]. Due to the usage of the combined effect of properties of various fibers, hybridization helps to improve performances in a particular direction [11,13-17]. It has been found that hybrid composite properties are affected by fiber volume fraction, fiber architecture, and stacking sequence [18-24]. In the recent work, a hybrid composite has been prepared, wherein HDPE flat yarn has been considered to substitute costly carbon in a direction, other than the direction where the axial load is applied. Here, carbon yarn is placed in the transverse direction and HDPE flat yarn is placed in the longitudinal direction. Three fabric samples of different weave structures such as plain, twill, and sateen were taken. Four fabric layers of the same weaves have been taken and placed in a unidirectional stacking sequence at [0,0,0,0] to prepare the composite. Thus, a step has been taken toward sustainable manufacturing by implementing sustainable product design by substituting cheaper HDPE with costly carbon.

The cost of producing composite materials per square meter using an epoxy matrix and either HDPE flat yarn or carbon yarn depends mainly on the costs of raw materials and manufacturing. Carbon yarn and epoxy resin are the primary raw materials used in making carbon-carbon composites, with carbon yarn costing 20 USD to 30 USD per kg and HDPE flat yarn being relatively cheaper at 1 USD to 5 USD per kg. Epoxy resin costs between 10 USD to 30 USD per kg and is used for both types of composites. The manufacturing cost per square meter is assumed to be the same for both composites since the hand lay-up technique was used for both. Based on the estimated costs, using HDPE flat yarn in composite materials with an epoxy matrix is more cost-effective than using carbon yarn. This is because HDPE flat yarn is cheaper and can provide added durability and resistance to environmental factors, increasing the lifespan of the material and reducing replacement costs. However, it's important to note that the cost-effectiveness of each material will depend on the specific application and intended use of the composite material.

2. Materials and methods

2.1 Materials

For the fabrication of woven reinforcement fabric, raw materials 12K carbon tow (1.81 g/cm^3) as weft and flat HDPE yarn (0.97 g/cm^3) as warp was used. The properties of the reinforcement yarn are depicted in Table 1. Three fabric samples with plain, twill, and sateen weave were manufactured on a CCI rigid rapier sample loom with the necessary modifications suggested by Agrawal [3,25].

Table 1 Properties of the reinforcement yarns.

Reinforcement yarn	Linear density (tex)	Density (g/cm^3)	Tensile strength (MPa)	Strain (%)	Modulus of elasticity (MPa)
12K carbon	817	1.81	1630	2.64	617.4
HDPE (flat yarn)	122	0.97	509	19.82	25.7

2.2 Methods

Three composite samples consisting of four-ply laminates, prepared by impregnating each fabric with the functionalized Epoxy resin grade Polysil 100EC have been prepared using the hand layup technique. Three different weaves plain, twill, and sateen with a thickness of about 2 mm and stacking sequence of [0,0,0,0] were considered for the preparation of composites. The composites were allowed to cure at room temperature for 2 hours. Figure 1 shows a schematic representation of the prepared composites.

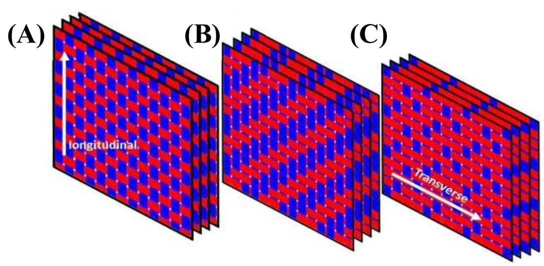

Figure 1 Schematic diagram of carbon -HDPE composite with orientation (0/0/0/0) with different weaves: (A) plain (B). twill (C). sateen [Blue-warp (HDPE) longitudinal direction; Red-weft (carbon) transverse direction].

2.3 Testing and evaluation

The composite samples were tested for physical and mechanical properties by using standard methods.

2.3.1 Physical properties

The density of the hybrid composite has been determined by the methods, as defined by Agrawal [3,26]. The fiber volume fraction has been calculated using a modified equation for woven composites developed by Agrawal [3].

2.3.2 Mechanical properties

Tensile properties were determined using an ASTM D 3039, Universal Testing Machine (UTM). Flexural strength has been measured using a three-point bending test on a universal mechanical testing machine. The flexural modulus has been computed. The impact pendulum tester XJUD-5.5 has been used for the izod impact test. Five specimens of each type of composite laminate were used for each test. The average values of test results are shown here.

3. Result and discussion

3.1 Physical properties

The physical properties of the composites are mentioned in Table 2. Density variation is observed when comparing samples A1, A2, and A3. A1 has the lowest density, 1.1358 g/cm^3, A3 has the highest density, 1.2571 g/cm^3, and A2 has a density, 1.2184 g/cm^3. A1, A2, and A3 are plain, twill, and sateen, implying that the fiber architecture affects the density. The plain weave structure is closely woven. Attributable to the intricate woven structure and lightweight fiber (Table 1), HDPE is considerable per unit area, and hence density is consequently lower. This implies that the weaving pattern influences the density of the composite. For comparison A0, a carbon-carbon composite sample is included [4].

Table 2 Physical properties of Carbon-HDPE epoxy composite.

Sample No.	Weave	Density (g/cm^3)	Fiber volume fraction V_f (%)
A0	Plain	1.3349	65.90
A1	Plain	1.1358	61.77
A2	Twill	1.2184	52.97
A3	Sateen	1.2571	48.00

V_f values vary significantly when samples A1, A2, and A3 are compared. A1 has the highest V_f of 62 percent, followed by A2 and A3, which have V_f values of 53 percent and 48 percent, respectively. Plain weave structures have more interlacement than twill and sateen. As a result, it has a denser structure than the others. The plain weave has the highest HDPE proportion while the sateen has the lowest. A1 has a greater V_f value due to its lighter fiber. Similarly, sateen has a relatively low V_f value than twill. In the composite, HDPE has a lower density than other hybrid fibers. That is, denser structures generate more volume. This explains the prominent V_f value in A1. This suggests that the fiber architecture has a significant effect on the fiber volume fraction of the composite. On comparing these values with plain weaved carbon- carbon sample at (0/0/0/0) orientation as prepared by Agrawal et al. [4]. The results indicate that the performance of the carbon-HDPE hybrid composite (61.77) is similar to that of the carbon-carbon sample (66.74).

3.2 Mechanical properties

3.2.1 Tensile properties

According to Table 3, the plain structure has the highest longitudinal tensile strength, approximately 45 MPa, when compared to other structures. Twill and sateen, on the other hand, have tensile strengths of 38 and 32 MPa, respectively, which are lesser than plain structure. This is because the fiber architecture is less dense than plain weave. When compared to other weave structures, the sateen weave structure had the highest tensile strength in the transverse direction, around 370 MPa. The tensile strength of plain weave and twill weaves, on the other hand, is 242 and 324 MPa, respectively.

Table 3 Tensile properties of Carbon-HDPE epoxy composite.

Sample code	Longitudinal			Transverse		
	Strain (%)	Stress (Mpa)	Modulus of Elasticity (GPa)	Strain (%)	Stress (Mpa)	Modulus of Elasticity (GPa)
A0	4.91	268.98	5.475	6.27	980.06	15.63
A1	15.03	45.60	0.303	6.57	242.40	3.691
A2	21.67	38.48	0.178	7.84	324.35	4.139
A3	19.17	32.08	0.167	8.51	369.75	4.345

This is owing to the fiber architecture and lack of interlacement in sateen. Carbon is in the loading direction in the transverse direction. Plain has the most yarn interlacement compared to twill, while sateen does have the least. In terms of numbers, carbon fiber has quadruple times interlacement in plain as compared to sateen. Twill, on the other hand, doubles. As a result, the plain weave will give carbon a lower performance than sateen in the transverse direction.

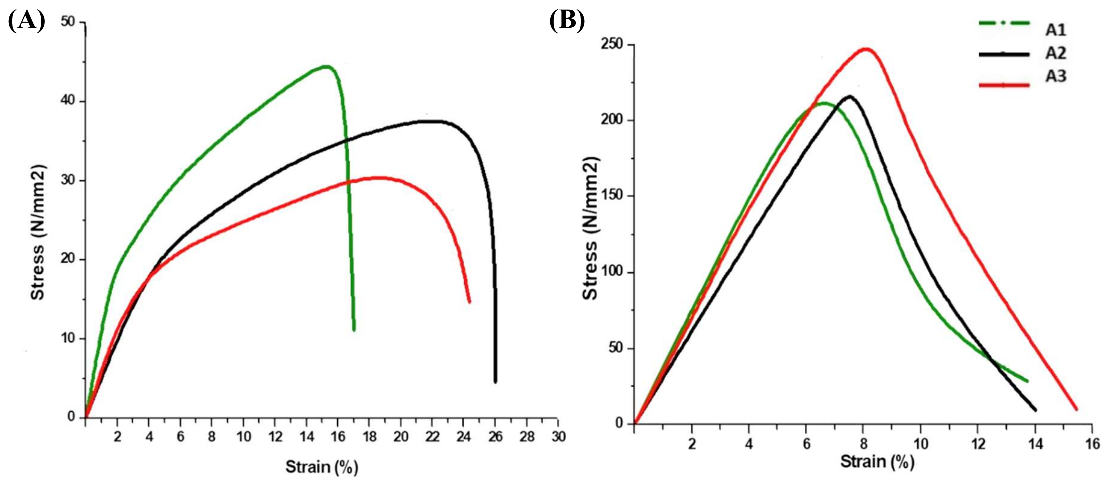

Figure 2 Effect of Plain, Twill, and Sateen weave on the tensile performance of composite in (A) longitudinal and (B) transverse directions.

Figure 2 (A) depicts the fracture behavior of all three samples in the longitudinal direction. Curves begin with a nonlinear increase in stress with increasing strain until a fracture occurs. Subsequently, due to the crack's initiation, there is a remarkable decrease in stress. Twill weave has more strain than plain weave at the same stress, while sateen has the most. Plain weave has the highest resistance to deformation. The modulus of elasticity is what determines deformation resistance. Figure 2 (B) depicts a similar study of transverse loading. In this figure, nature indicates that the fracture behavior of all fiber architecture is similar. The curve begins with a linear increase in strain with increasing stress until a fracture occurs. Stress is gradually decreasing. This pattern continued until it has been broken. In comparison, twill and sateen weaves have more strain than plain weaves under the same stress. However, at the yield point, sateen has the highest modulus of elasticity, while twill and plain have the lowest. This means that it will be less resistant to applied stress. Divergent behavior is observed in the longitudinal (Figure 2 (A)) and transverse (Figure 2 (B)) directions. The stress vs. strain curve in the transverse direction exhibits almost elastic behavior, whereas in the longitudinal direction it exhibits plastic behavior until the crack initiates. When the values of samples A1, A2, and A3 are compared with carbon composites [4,27,28] it has equivalent values in direction of load application. As depicted in Table 4, comparing values of specific strength of hybrid composite with steel and aluminium [29], it was found that values are comparable to these metals. On comparing A0 and A1, the level of bonding between the carbon fibers and matrices is greater than that of carbon-HDPE fiber. When there is a strong bond between the fibers and matrices, more stress can be transferred through the composite fibers. Conversely, a weak bond will result in less adhesion between the fibers and matrices. If the applied force on the composite exceeds the bonding force, it can cause the fibers to break and come out. This explains the difference in the results obtained. Some representative samples before and after tensile deformation have been depicted in Figure 3.

Table 4 Comparing specific strength of hybrid samples with metals.

Direction of load	A1	A2	A3	Steel (ASTM 228)	Steel (stainless)	Aluminium alloy (7075-T6)	Aluminium alloy (6061-T6)
Longitudinal	40.15	31.58	25.52	204-428	63.1	204	115
Transverse	213.42	266.21	294.13	204-428	63.1	204	115

Note: Specific strength = kN.m/kg

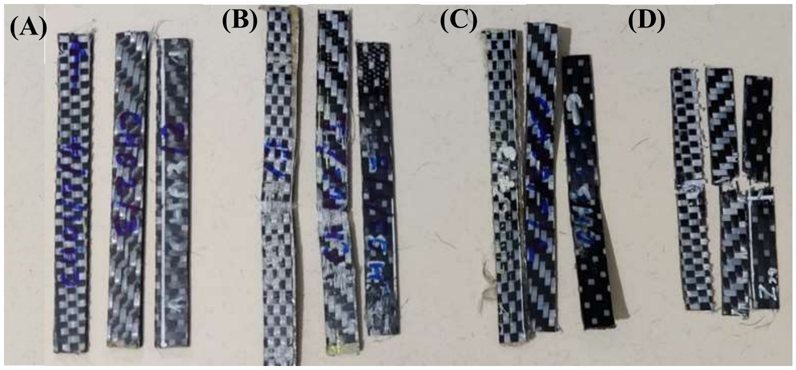

Figure 3 Representative samples for before and after deformation: (A) original samples, (B) after tensile deformation, (C) flexural deformation and (D) impact deformation.

3.2.2 Flexural properties

The flexural properties of the sample are depicted in Table 5. The correlation between load and displacement of A1, A2, and A3 is depicted in Figures 4 (A-B)

Table 5 Flexural properties of Carbon-HDPE epoxy composite.

Sample code	Longitudinal				Transverse			
	Load F kN	CHT mm	Flexural strength of MPa	Flexural Modulus GPa	load kN	CHT mm	Flexural strength of MPa	Flexural modulus GPa
A0	0.136	4	260.39	0.26	0.220	2.75	280.45	17.78
A1	0.028	12.9	52.03	0.05	0.164	3.75	394.08	25.76
A2	0.035	13	80.20	0.08	0.253	3	451.48	31.04
A3	0.026	9.4	51.26	0.05	0.206	3.75	457.86	28.11

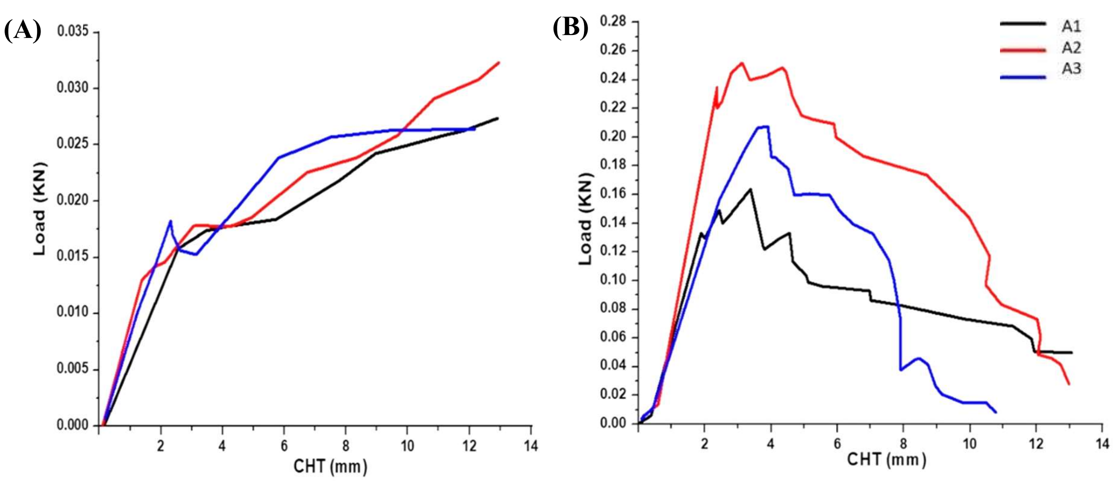

Figure 4 Effect of plain, twill, and sateen weave on flexural properties of composite (A) longitudinal direction (B) transverse direction.

Flexural strength is highest in both directions for composites twill fiber architecture fabric. This is due in part to the significant variation in the strengths of the reinforced yarns used in the two fabrics, as shown in Table 1, and part to the improved orientation of the twill weave fabric's fiber tows. The increased flexural strength of A2 can be attributed to better matrix compactness which is the result of better penetration of the matrix into the gap between two consecutive layers. This compactness resulted in a more even load distribution among the reinforced fibers. As a result, the flexural strength of the composites has improved. The same would have been applied to plain weave fabric composites. However, this is not the case. Plain weave fabrics fail with bundle pull-out, while sateen weave fabrics fail with shear-type failure with fiber pull-out.

The load-displacement curves turn out steeper in both directions as the fabric type progresses sateen-plain-twill. However, in this comparison, a distinct trend between longitudinal and transverse directions has been observed. Flexural load on the composite sample rises linearly in the transverse direction till the maximum load in the load-displacement curves. The load value on the samples then drops noticeably, which can be attributed to major numerous fiber breakages. Minor slip and stick failures are noted. When analysing force-displacement for the longitudinal direction, it is noticed that, unlike the transverse direction, the sharp drop in load is not as visible in these curves, but the curve maintains to rise at a lower slope and transcends the preceding maximum load. The reinforced fiber type in the loading axis is responsible for this variation in behavior between longitudinal and transverse directions. Figure 4b, load-displacement for transverse direction, shows brittle failure because the carbon fiber is along the loading of the axis. While in Figure 4a, the HDPE fibers are parallel to the load axis, which leads to ductile behavior. When the values of samples A1, A2, and A3 have been compared with carbon composites [4] it has been found to have comparable values in transverse direction. Figure 4 displays a few selected examples of samples both prior to and after being subjected to flexural deformation. When A0 and A1 are compared, it is observed that A0 displays greater flexural strength and flexural modulus in both directions than A1. The reason for this can be attributed to the bonding at the interface between the materials.

3.2.3 Impact strength

Weave structure's effect on carbon-HDPE epoxy composite's impact performance has been considered here. The samples A1, A2, and A3 were assessed for impact strength (Table 6).

Table 6 Impact properties of Carbon-HDPE epoxy composite.

Sample code	Longitudinal		Transverse	
	Energy absorbed J	Impact strength kJ/m^2	Energy absorbed J	Impact strength kJ/m^2
A0	0.636	45.854	0.953	81.336
A1	1.347	100.208	0.726	58.784
A2	1.151	73.688	0.773	46.541
A3	0.836	51.407	0.649	48.520

It demonstrates that fiber architecture has a significant influence on impact strength. The impact strength of all fiber architecture is greater in the longitudinal direction than in the transverse direction. The highest impact strength (100.21 kJ/m^2) has been observed in plain composite (A1) in longitudinal directions, followed by twill composite (A2-73.69 kJ/m^2) and sateen composite (A3-51.41 kJ/m^2). Plain composite (A1-58.78 kJ/m^2) has the maximum impact strength in transverse direction, as compared to that of other fiber architecture twill (A2-46.54 kJ/m^2) and sateen (A3-48.52 kJ/m^2) composites.

The presence of HDPE yarn in the longitudinal direction in carbon-HDPE composite accounts for the higher impact strength. Because HDPE is ductile, its impact strength is higher than that of carbon fibers. When assessing the impact strength for all the fiber architecture, plain-weaved composite demonstrated the highest strength. The plain weave is a structure with a square symmetry and most interlacement points. This explains why plain-weaved composite has a higher impact strength. A sateen weave has more floats and fewer interlacement points. Because of this, the yarn's binding to each other is less than in plain yarn. As a result, during impact, the fiber creates an effortless path for fracture propagation. The impact strength of hybrid composite is found to be much more than of carbon composite [4] especially that of plain weave. Thus, in applications where impact strength is one of the concerns such as automobile industry, hybrid composite can substitute carbon composite. There by, aiding in reducing the cost of vehicles. Figure 3 displays a selection of sample representatives that were tested before and after impact. On comparing A1 and A0, A1 has a higher strength of approximately 100 kJ/m2 in the longitudinal direction compared to A0. In A1, HDPE has a higher impact strength in the direction of loading due to its high ductility. This is supported by the fact that A1 also has a higher impact strength in the longitudinal direction.

4. Conclusion

From this study of Carbon-HDPE epoxy composite, maximum longitudinal tensile strength has been found in plain weave whereas maximum tensile in transverse direction is found in sateen. Maximum flexural strength has been seen in a twill weave in a longitudinal direction whereas in transverse direction sateen has the highest strength. The plain weave composite has maximum strength in both directions. Also, their properties are comparable with carbon composites and metals like steel & aluminium. Thus, hybridization, orientation of layers, and fiber architecture can help in exhibiting the desirable performance of composite and help in manufacturing a cost-effective composite.

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