



Improvement in mechanical performance due to hybridization of carbon fiber/epoxy composite with carbon black

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Abstract

Many researchers are doing effort to investigate the effect of different particulates or fillers incorporated in the composite materials. In this investigation, the effect of the incorporation of different amounts of carbon black particulates on the mechanical performance of carbon fiber-reinforced epoxy composites has been studied. The carbon fiber-reinforced carbon black/epoxy hybrids were prepared with keeping constant weight fraction of carbon fiber and varying weight fraction of carbon black (0, 5, 10, and 15 wt%), using hand lay-up technique. After cure, the fabricated composite materials were cut and dimensioned into specimens as per the ASTM standards of testing and submitted to tensile, flexural, and impact tests. The microstructural characteristics and fracture surfaces of the composite were examined by scanning electron microscope (SEM). Increments of 65.78, 32.07, and 36.11% have been noticed in the tensile strength, flexural strength, and impact strength respectively for the hybrid composite (10 wt% carbon black) with respect to the conventional carbon fiber-reinforced epoxy composite. The experimental result has been validated with the numerical technique. This study represents that carbon black/epoxy composites reinforced with carbon fiber show higher mechanical performance than the conventional carbon fiber-reinforced epoxy matrix composites.

Keywords Carbon black particulate · Mechanical properties · PMC · Carbon fabric composite · Numerical analysis

1 Introduction

Today, there is an increasing demand for the advanced materials which can perform better and which are able to meet new requirements or to replace conventional materials. This demand has greatly contributed in the development of new polymer matrix composite. Epoxy resins are the major thermosetting polymer resins which are being used in the composite materials as a matrix. Due to its characteristics, such as low viscosity, good adhesion to the other materials, and less shrinkage problem during curing, epoxy resin is widely used

in the polymer matrix composite [1]. Previously research has well documented the high performance of carbon fabric-reinforced polymeric matrix composites. The epoxy matrix composites generally have excellent mechanical and tribological properties, good chemical and corrosion resistance, and excellent dimensional stability [2], but Cho et al. [3] suggested that the matrix-dominated properties such as interlaminar shear properties together with matrix stiffness, toughness, and hardness are still an area for research. Carbonaceous materials are being used as fillers in the polymer matrix composites in order to enhance their performances. Three types of carbonaceous fillers, which are most widely used in the composites, are carbon blacks, carbon fibers, and carbon nanotubes (CNTs) [4]. Incorporation of these fillers in the composites provides improvement in mechanical properties, low specific weight and ease of processing, etc. Toughening of the epoxy-based composite can be done by using a variety of materials including block copolymers [5, 6], graphite filler [7], grapheme [8], carbon nanotubes [9], and nanoclay [10].

Previously research by Cho et al. [3], Suresha et al. [2], Yasmin et al. [11], and Shokrieh et al. [12] has shown that

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the matrix-dominated properties of polymer matrix composites can be improved by incorporating different types of fillers. These improvements basically depend on the processing method, surface condition, concentration, and dispersion of the filler particles in the epoxy matrix. There is also a benefit of cost reduction of composite by the incorporation of the fillers, due to the lower consumption of epoxy resin [2]. In this investigation, the approach used to improve the mechanical properties of conventional carbon fabric-reinforced epoxy composite, consisted on the incorporation of carbon black particulates as a filler material in the epoxy resin. The overall purpose of this investigation is to develop a hybrid carbon fabric/carbon black-reinforced epoxy composite with better mechanical properties.

2 Experimental work

2.1 Materials used

Epoxy (epoxy resin LY-556 and hardener HY-951) is used as the matrix material in the fabrication of the composites. Carbon fabric (3k, 200 gsm, bi-directional) is used as reinforcing material, and carbon black particulate obtained from the pyrolysis process of waste automobile's tire is used as a filler material with different weight percentage (wt%) to enhance the mechanical properties of conventional carbon fabric/epoxy matrix composite.

2.2 Method of fabrication

Hand lay-up technique Hand lay-up is the oldest, simplest, and most commonly used method for composite production. Mold and hand tools are the basic need of hand lay-up fabrication method. The same method has been used for the present hybrid composite fabrication. Before starting lay-up, the wooden mold is coated with a mold release agent to ensure that the fabricated composite sheet would not adhere to the mold surface. Carbon fabric for the entire lay-up should be dimensioned before the mixing of epoxy is started because epoxy has a limited usable pot life. After applying the first layer of epoxy over the release agent-coated mold surface, reinforcing fibers are layered one on top of the other. The layers should be laid wet in wet which means that consecutive layers are laid on top of the others before the epoxy has gelled to promote bonding between the layers. A brush and roller can be used to impregnate the fibers with the resin properly. After the part has cured, it can be de-molded. Care must be taken to ensure that the curing of composite has completed. The fabricated composite sheet has the following dimensions: sheet length = 300 mm, sheet width = 150 mm, sheet thickness = 2 mm.

Depending on the epoxy system used and the properties required, post-curing may be necessary to obtain maximum

strength of the final product. Post-curing of the prepared composite samples has been done in the oven by the application of heat. The temperature of oven was maintained at 80 °C and the time period of post-curing in the oven was 2 h for each sample. The oven used was electrically heated. It features normal duty construction, in standard and medium capacity up to 150 °C. A micro-processor-based digital instrument is used for accurate temperature management. A separate high-limit instrument with manual reset provides over-temperature protection.

The composite samples A₁, A₂, A₃, and A₄ have been fabricated with varying the wt% of carbon black particulate and keeping the wt% of carbon fabric and epoxy constant. These composite samples have been fabricated containing the following percentage of carbon black shown in Table 1.

2.3 Mechanical testing

Mechanical testing of composite materials is important for the evaluation of their fundamental properties, as well as to develop different materials and for controlling their quality so that they can be utilized in various design applications. For these reasons, a number of experimental techniques for the mechanical testing of composite materials, subjected to different types of loading, have been developed.

Under mechanical testing, three mechanical tests, i.e., tensile test, flexural tests, and Izod impact test, have been performed.

2.3.1 Tensile test

A computerized universal testing machine (UTM) DAC System (Series 7000) has been used for conducting the tensile test and flexural test for the fabricated composite material. Tensile testing is a way to determine how a material reacts when it is pulled apart, i.e., when a tensile load is applied on it. The test has been done on the same UTM at room temperature according to the ASTM D638. The feed rate was chosen as 5 mm/min. The mechanical properties which can be directly measured through a tensile testing are ultimate tensile strength, maximum elongation, and reduction in area.

Table 1 Composition of samples

S. no.	Sample	Matrix	Reinforcement
1	A ₁ (0_90_0%)	Epoxy	[0/90] bi-directional carbon fabric
2	A ₂ (0_90_5%)	Epoxy + 5 wt% carbon black	[0/90] bi-directional carbon fabric
3	A ₃ (0_90_10%)	Epoxy + 10 wt% carbon black	[0/90] bi-directional carbon fabric
4	A ₄ (0_90_15%)	Epoxy + 15 wt% carbon black	[0/90] bi-directional carbon fabric

ASTM D638 test method is used to determine the tensile properties of any unreinforced and reinforced plastics or composite in the form of standard dumbbell-shaped (dog bone shape) specimens tested under the defined conditions of temperature, humidity, and testing machine feed rate. This test method can be utilized for testing materials of any thickness up to 14 mm. Basically five types of standard dumbbell-shaped (dog bone shape) specimens are used under this standard, i.e., TYPE-I, TYPE-II, TYPE-III, TYPE-IV, and TYPE-V with different dimensions. TYPE-I specimen is used for the reinforced composite material, including highly orthotropic laminates. As the fabricated hybrid composite is the laminated composite of carbon fiber and carbon black reinforcement, so the TYPE-I specimen has been used for tensile testing. Test specimens have been prepared by die cutting from the composite sheet.

2.3.2 Flexural testing

A three-point bending test has been performed on the same ultimate testing machine as per the ASTM D790 standards (at room temperature) to determine the flexural strength of composite samples. The testing has been performed at a feed rate of 1 mm/min. ASTM D790 test method is used to determine the flexural properties of unreinforced as well as reinforced plastics and composites in the form of rectangular bars molded directly or cut from sheets, plates, or molded shapes of the material. The flexural strength is calculated by the following formula.

$$\text{Flexural strength, } \sigma = 3FL/2bt^2$$

where, F is the maximum load, L is the distance between two supports, i.e., span length, b is the width of the specimen, and t is the thickness of the specimen. The dimension of the specimen for the test was $127 \times 16.5 \times 2$ mm and the span length was 64 mm.

2.3.3 Impact testing

Impact testing is also an important mechanical testing. A collision of any two objects can often result in damage to one or both of them and this damage may be in the form of scratch, crack, and fracture. So a design engineer needs to know how the materials behave under impact loading and the magnitude of load which they can sustain. Impact energy absorbing capacity, i.e., toughness of the fabricated composite material, has been determined by measuring the energy absorbed in the fracture of the specimen. For this purpose, Izod impact test has been carried out over fabricated composite material. This test has been done on TINUS OLSEN-104 according to ASTM D256 standard.

2.3.4 Characterization

Scanning electron microscope (SEM) has been used for analyzing the interaction of reinforcements and matrix as well as the fracture behavior of the fabricated hybrid composite material. A scanning electron microscope is a type of microscope that produces the images of an object by scanning the surface of the object with a focused beam of electrons. The electron beam interacts with atoms in the object, producing various signals that contain information about the object's surface and composition. The fractured surface as well as the flat surface of the fabricated hybrid composite sample has been examined by scanning electron microscope ZEISS EV0, MA10. Composite samples were washed and cleaned thoroughly and were coated with platinum in JEOL sputter ion coater as the PMC is not a conductive material. The fractured surface has been observed through SEM at 20 kV, 14.5 mm of working distance with three different magnifications of $\times 313$, $\times 1.23K$, and $\times 1.69K$.

3 Results and discussions

“Results and discussions” deals with the result obtained from the experimental testing. The changes in mechanical properties with the change in the wt% of carbon black in the fabricated hybrid composite are explained. The mechanical tests of the fabricated hybrid composite have been conducted only in one direction as the composite is considered as nearly isotropic. Under characterization, SEM of the fabricated composite has been discussed.

3.1 Mechanical tests

3.1.1 Tensile properties

Tensile strength of the fabricated composite samples A₁, A₂, A₃, and A₄ has been measured on UTM DAC System (Series

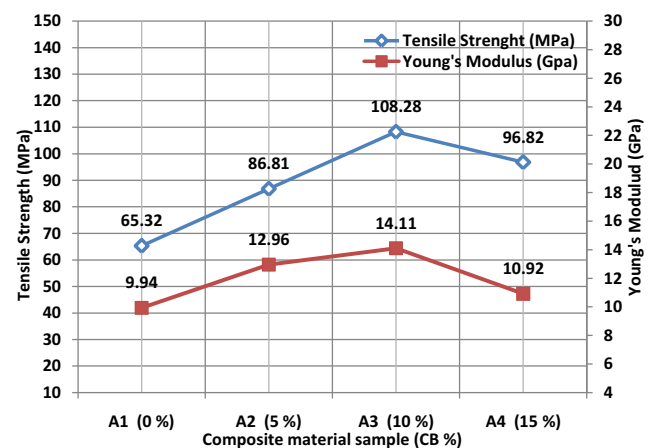


Fig. 1 Tensile strength and Young's modulus for different compositions of composites

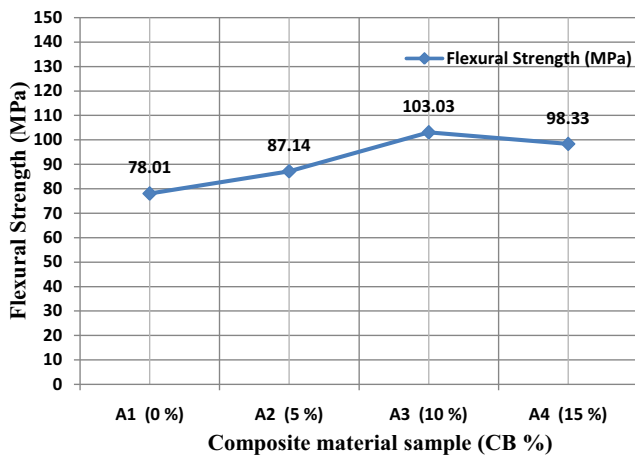


Fig. 2 Flexural strength of composites

7000). Basically, the tensile strength of the composite materials depends on its fiber strength as well as on the percentage of the particulate, used as reinforcement or filler in it. So, in this investigation, a variation in the fabricated composite strength has been observed with the varying percentage of the carbon black particulate. A₁, A₂, A₃, and A₄ are the four composite samples which have been fabricated by varying the percentage of carbon black particulate in the composite. The fiber and matrix interface plays an important role in determining the mechanical properties of the composite.

The tensile test result shows that there is gradual increase in the tensile strength of the composite from 65.32 to 108.28 MPa with increase in the percentage of carbon black particulate in the composite from 0 to 10 wt% (Fig. 1). The tensile strength of the fabricated hybrid composite increased significantly up to 108.28 MPa corresponding to 10 wt% of carbon black particulate in it. Beyond 10 wt% of carbon black in the composite reduces the tensile strength of the composite as the poor interface adhesion of carbon black with epoxy matrix occurs due to a greater amount of carbon black in the same amount of epoxy binder. The tensile strength of the

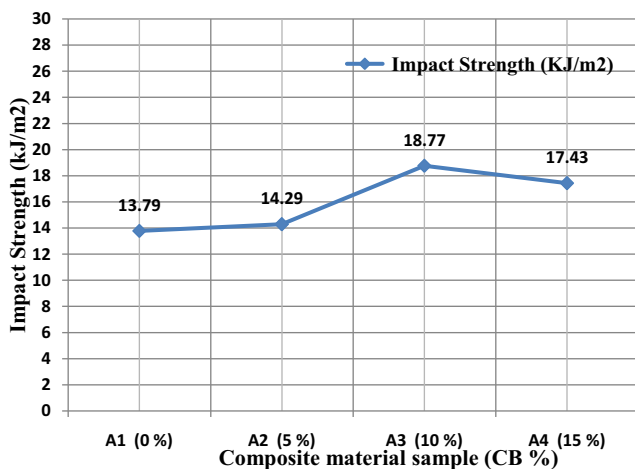


Fig. 3 Impact strength of composites

Table 2 Percentage change in the mechanical strengths of the hybrid composite with respect to mechanical strengths of simple carbon fabric-reinforced epoxy composite

Sample	% change in tensile strength	% change in flexural strength	% change in impact strength
A ₁ (0_90_0%)	–	–	–
A ₂ (0_90_5%)	32.91	11.71	3.63
A ₃ (0_90_10%)	65.78	32.07	36.11
A ₄ (0_90_15%)	48.23	26.04	26.40

composite noticed at 15 wt% carbon black is 96.82 MPa which is less than the corresponding value of tensile strength at 10 wt% of carbon black. Valente et al. [13] with LDPE/glass/wood flour and PP/glass/wood flour composites has also obtained approximately similar behavior.

Figure 1 also shows the variation in Young’s modulus of the composite samples A₁, A₂, A₃, and A₄ which are having different percentages of carbon black particulate (wt%). The maximum value of Young’s modulus obtained for composite sample A₃ (epoxy + carbon fabric + 10 wt% carbon black) is 14.11 GPa. Further addition of carbon black (above 10 wt%) in the composite sample reduces the Young’s modulus of the composite. The value of Young’s modulus corresponding to 15 wt% of carbon black particulate in the composite (sample A₄) is 10.92 GPa. The increasing trend of Young’s modulus up to 10 wt% of carbon black particulate in the composite is due to the strong interfacial bonding among carbon fiber, epoxy, and carbon black particulate. Also the decreasing trend above 10 wt% of carbon black in the composite is due to poor adhesion among epoxy and carbon black particulate.

Overall tensile test result shows an increasing trend of tensile strength and Young’s modulus of the fabricated composite material up to 10 wt% of carbon black compositions. Both tensile strength and Young’s modulus are maximum for the composite sample A₃, which is having 10 wt% of the carbon black particulate.

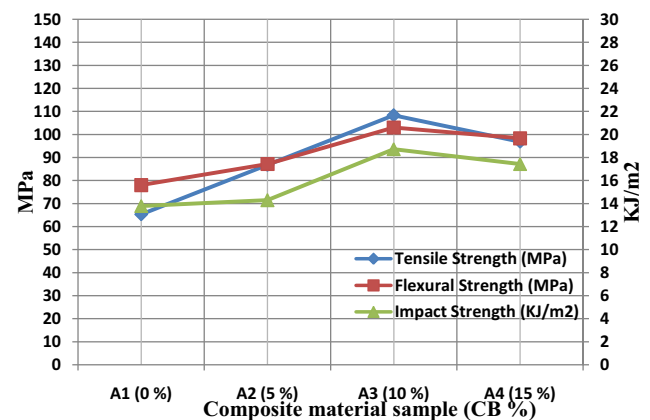
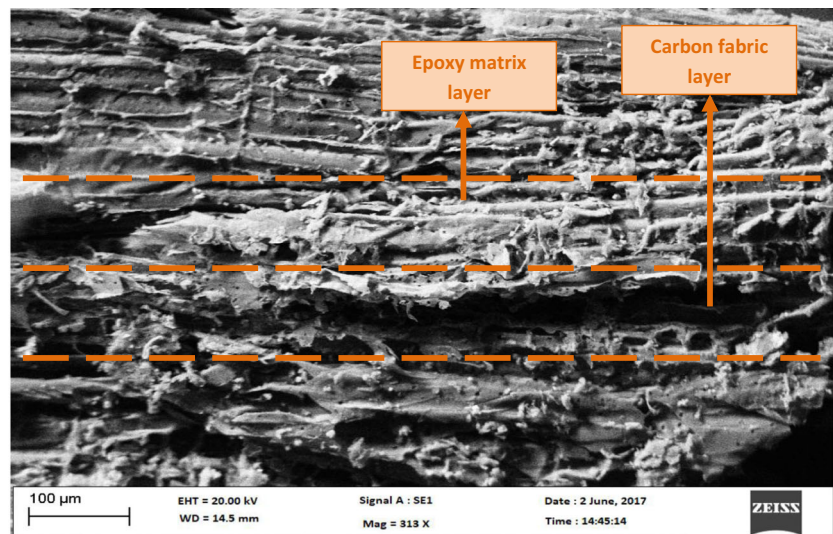
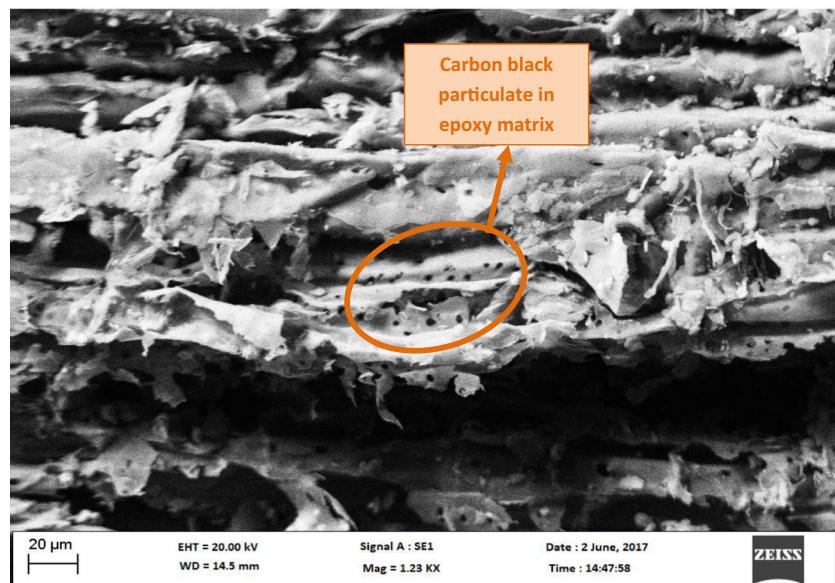


Fig. 4 Comparison of mechanical properties

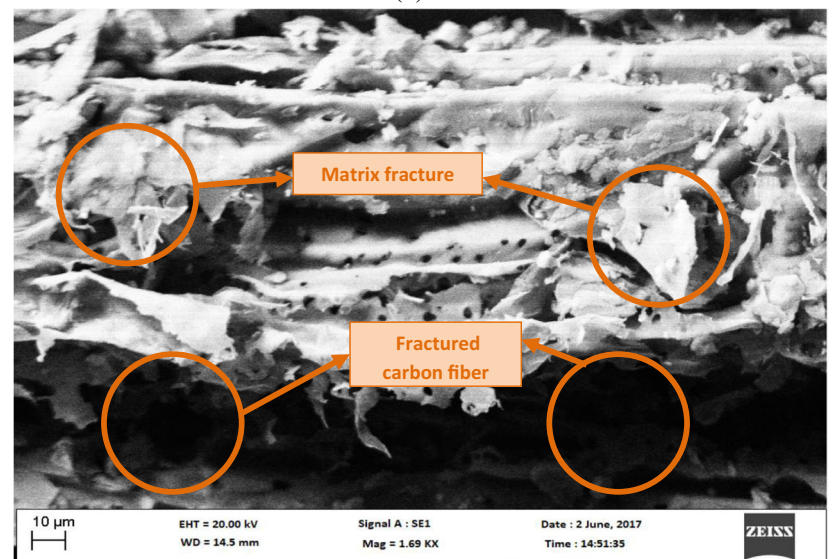
Fig. 5 **a** SEM image of the hybrid composite ($\times 313$ magnification). **b** SEM image of the hybrid composite ($\times 1.23$ K magnification). **c** SEM image of the hybrid composite ($\times 1.69$ K magnification)



(a)



(b)



(c)

3.1.2 Flexural strength

The bending strength of the fabricated composite samples with different wt% of carbon black particulate has been measured on the same UTM machine.

Figure 2 shows the flexural strength of composite samples A₁, A₂, A₃, and A₄. The flexural test result shows that there is gradual increase in flexural strength of the composite from 78.01 to 103.03 MPa with increase in the percentage of carbon black particulate in the composite from 0 to 10 wt%. Flexural strength of the fabricated hybrid composite increased significantly up to 103.03 MPa corresponding to 10 wt% of the carbon black particulate in it, which is the result of the good bonding property of carbon black with epoxy matrix. Carbon black particulate acts as a mechanical interlocking between carbon fiber and epoxy. This strong interfacial bonding contributes to good flexural properties.

Beyond 10 wt% of carbon black in the composite reduces the flexural strength of the composite as the poor interface adhesion of carbon black with epoxy matrix and some other fabrication defects occur due to a greater amount of carbon black in the same amount of epoxy binder. The poor dispersion of carbon black particles in the epoxy matrix and possibility of the existence of voids in the sample A₄ due to increased wt% of carbon black particulate may be another reason for decrement in the flexural strength.

The flexural strength of the composite noticed at 15 wt% carbon black is 98.33 MPa which is less than the corresponding value of flexural strength at 10 wt% of carbon black. Previously done investigations have shown that Valente et al. [13] got the similar results for PP/glass/wood flour and LDPE/glass/wood flour composites.

3.1.3 Impact strength

The Impact strength of the fabricated composite samples with different wt% of carbon black particulate has been measured on the impact tester.

Figure 3 shows that the resistance to impact loading of conventional carbon fabric epoxy matrix composite improves with addition of carbon black particulates.

It has been noticed that the impact strength of the composite increases to 14.29 and 18.77 KJ/m² with the 5 and 10 wt%

addition of carbon black respectively and then it decreases to 17.43 KJ/m² with addition of 15 wt% of carbon black particulate. Cui and Tao (2009) has also observed the similar behavior for glass fiber-reinforced wood plastic composites.

Many of the carbon microfibrils are formed at the time of impregnation by the friction between carbon fiber and carbon black particles. Then a special kind of three-dimensional hollow structures forms among the constituents of composite (i.e., carbon fiber, epoxy, and carbon black particulates). The carbon black particulates filled the cavity in the three-dimensional microstructure. Thus, a very strong framework is generated in composites which effectively restrict the crack propagation and increases the impact strength. The decreasing trend of impact strength above 10 wt% of carbon black in the composite is due to the poor adhesion among epoxy matrix and carbon black particulate as greater amount of carbon black mixed in the same amount of epoxy binder.

3.1.4 Comparison of overall mechanical properties

In the present investigation, hybridization of the conventional carbon fabric-reinforced/epoxy matrix composite has been done with the carbon black particulates. So through this hybridization, the percentage increments in the tensile strength of the hybrid composite (with 5, 10, and 15 wt% of carbon black addition) over tensile strength of conventional carbon fabric-reinforced epoxy composite (0% carbon black) are 32.91, 65.78, and 48.23% (Table 2).

Similarly, the percentage increments in the flexural strength of the hybrid composite over the simple carbon fabric composite are 11.71, 32.07, and 26.04% for 5, 10, and 15 wt% respectively of carbon black addition.

Also, the impact strength of conventional carbon fabric composite increases up to 3.63, 36.11, and 26.40% for 5, 10, and 15 wt% respectively of carbon black addition in the composite. Here it should be noticed that the percentage increment in the impact strength due to the addition of carbon black in the conventional carbon fabric composite is lesser comparatively to the tensile and flexural strengths. The reason behind it is that the particulate reinforcements generally are not so effective in improving the fracture resistance of composite material but they are beneficial for enhancing the stiffness of the composite up to a limited extent.

Table 3 Analytical result of tensile test

Sample	Composition	Applied maximum load (N)	Equivalent max. stress (MPa)
A ₁ (0_90_0%)	Epoxy + carbon fabric	1070	67.52
A ₂ (0_90_5%)	Epoxy + carbon fabric + 5 wt% carbon black	1420	89.59
A ₃ (0_90_10%)	Epoxy + carbon fabric + 10 wt% carbon black	1750	110.43
A ₄ (0_90_15%)	Epoxy + carbon fabric + 15 wt% carbon black	1592	100.50

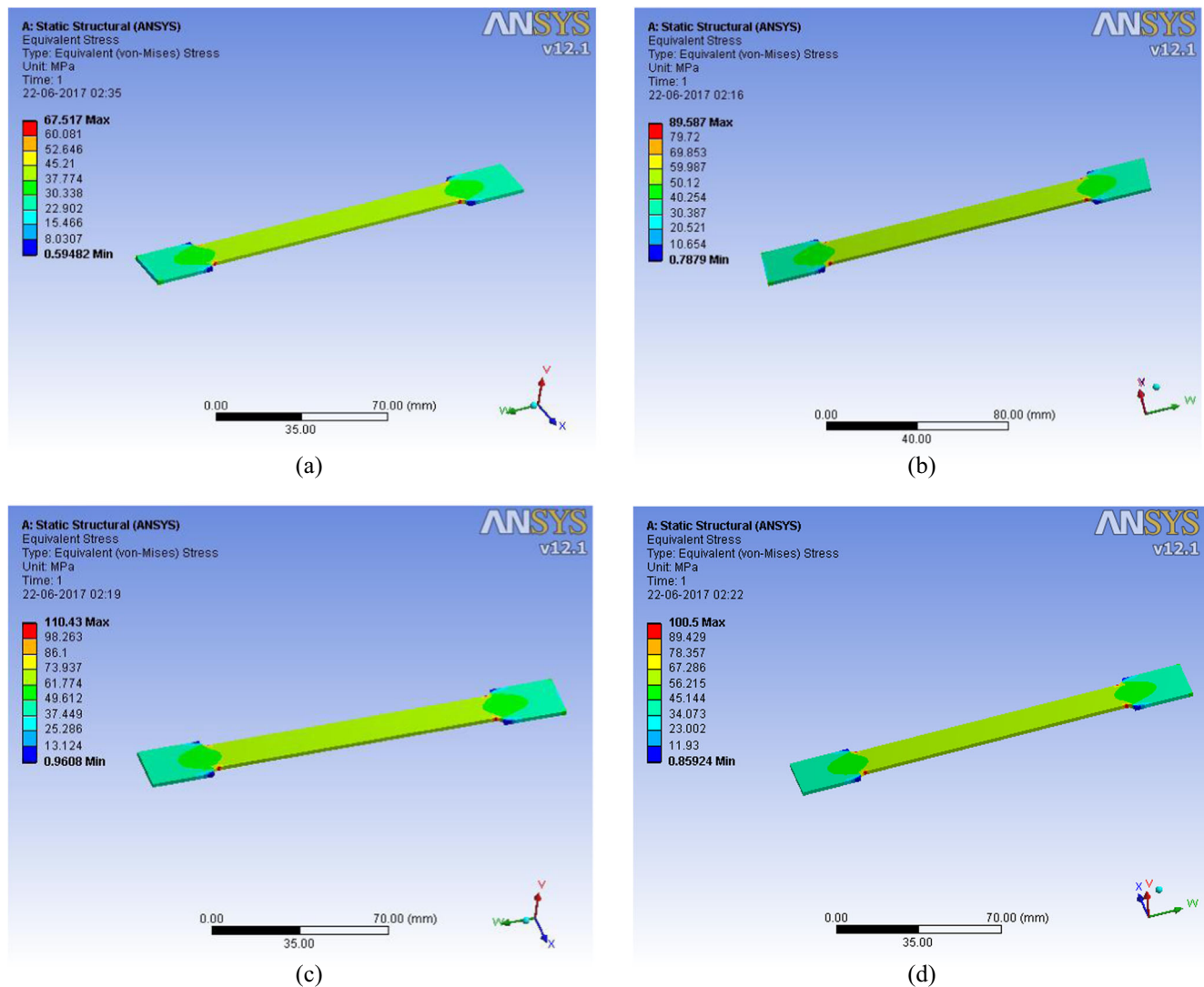


Fig. 6 **a** Stress distribution of composite composition A₁ (tensile test). **b** Stress distribution of composite composition A₂ (tensile test). **c** Stress distribution of composite composition A₃ (tensile test). **d** Stress distribution of composite composition A₄ (tensile test)

The comparison of all these three mechanical properties, i.e., tensile strength, flexural strength, and impact strength, is shown in Fig. 4.

3.2 SEM characterization

The SEM images of the composite sample have been produced as a result of electron-sample interaction. As the sample of composite having two major components, i.e., reinforcement (more dense) and matrix (lesser dense) in the form of lamina, has been fabricated by hand lay-up technique, so the layered structure can be easily distinguished in the SEM characterization.

Figure 5a, b, c shows the SEM images of fractured surface of the hybrid composite A₃ (epoxy+ carbon fabric + 10 wt% carbon black) based on three different magnification ranges $\times 313$, $\times 1.23K$, and $\times 1.69K$ respectively.

Different layers of carbon fabric and epoxy matrix can easily be seen in Fig. 5a. River line markings and sharp edges on the fractured surface are the evidence for the brittle fracture of the composite. These river lines formed due to the crack propagation.

The carbon black particulates are well dispersed in the epoxy matrix, although some small agglomerates are present in the composite. These images show that a good bonding between epoxy/carbon fiber and carbon black has been formed.

The interaction or mixing of carbon black particulate in the epoxy matrix is pointed out in Fig. 5b. The fiber breakage and matrix fracture due to the fracture of the composite are clearly observed in Fig. 5c. This figure also indicates the fractured edges of the carbon fibers in the specimen and also the fiber dislocation due to fracture of the composite.

Table 4 Analytical result of flexural test

Sample	Composition	Applied maximum load (N)	Equivalent max. stress (MPa)
A ₁ (0_90_0%)	Epoxy + carbon fabric	352	79.48
A ₂ (0_90_5%)	Epoxy + carbon fabric + 5 wt% carbon black	422	90.33
A ₃ (0_90_10%)	Epoxy + carbon fabric + 10 wt% carbon black	498	106.22
A ₄ (0_90_15%)	Epoxy + carbon fabric + 15 wt% carbon black	472	99.56

4 Analytical analysis

4.1 Tensile test analysis

The analytical result of tensile test analysis is based on specimen configuration, applied maximum load with value of experimental tensile modulus, and Poisson ratio of each composition of the composite. Tensile

strength obtained from the post-processor is shown in Table 3.

Figure 6a–d shows each composition of the composite under tensile test. These figures clearly represent that the numerical result of stress distribution in all the compositions of the composite is nearly same as the experimental results. Maximum stress is developing at the fillet edges due to the stress concentration, which is covered by red color in all images.

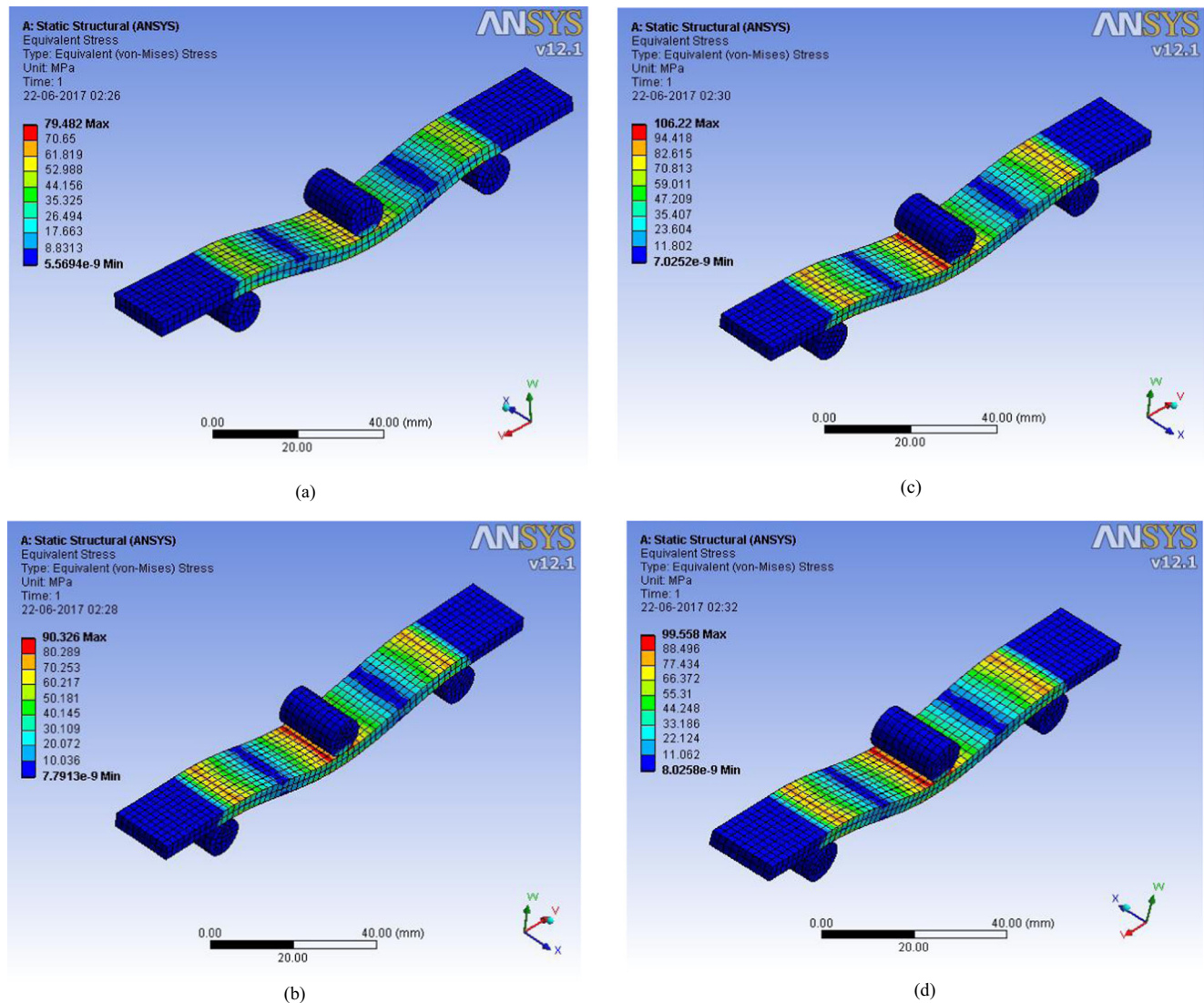


Fig. 7 a Stress distribution of composite composition A₁ (flexural test). b Stress distribution of composite composition A₂ (flexural test). c Stress distribution of composite composition A₃ (flexural test). d Stress distribution of composite composition A₄ (flexural test)

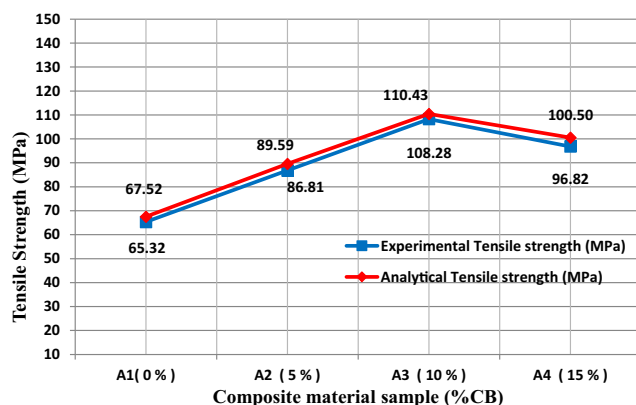
Table 5 Comparison between experimental and analytical results

Sample	Composition	Experimental tensile strength (MPa)	Analytical tensile strength (MPa)	Experimental flexural strength (MPa)	Analytical flexural strength (MPa)	Percentage error in tensile strength (%)	Percentage error in flexural strength (%)
A ₁ (0_90_0%)	Epoxy + carbon fabric	65.32	67.52	78.01	79.48	3.37	1.88
A ₂ (0_90_5%)	Epoxy + carbon fabric + 5 wt% carbon black	86.81	89.59	87.14	90.33	3.19	3.65
A ₃ (0_90_10%)	Epoxy + carbon fabric + 10 wt% carbon black	108.28	110.43	103.03	106.22	1.98	3.09
A ₄ (0_90_15%)	Epoxy + carbon fabric + 15 wt% carbon black	96.82	100.50	98.33	99.56	3.80	1.25

4.2 Flexural test analysis

A three-point bending test has been performed in ANSYS to analyze the flexural behavior of the different compositions of the composite. Specimen configuration and the applied maximum load for flexural test on each composition of the composite have been used in analysis. Analytical flexural strength of the four compositions of the composite, with corresponding maximum load, is tabulated in Table 4.

Figure 7a, b, c, d represents the flexural stress distribution in the fabricated composite samples A₁, A₂, A₃, and A₄ respectively. All images show almost the same stress distribution for all the compositions. Two roller supports are provided at the bottom of the specimens and the load has been applied at the middle of the top surface of the specimens. Failure region is occurring at the middle portion of the composite samples. This is because in three-point bending test, samples are subjected to load which are acting at the middle of the span. At the supports, the deflection is zero and at the middle portion where the load is acting, maximum deflection has occurred. So failure occurred at the middle point of the total gauge length.

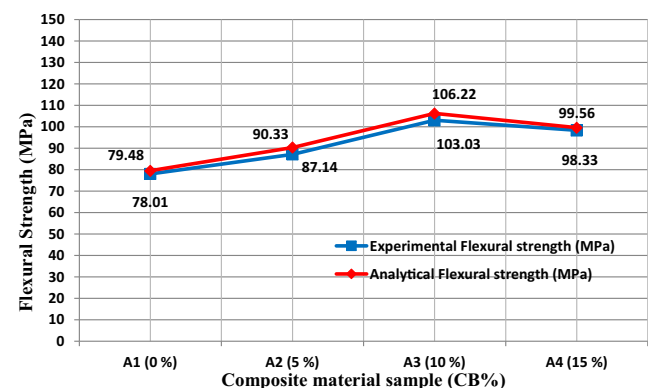
**Fig. 8** Comparison of experimental and analytical tensile strength

4.2.1 Validation of experimental result

The result for tensile test and flexural test obtained from the numerical analysis has been compared with the experimental result. Table 5 shows the comparison of experimental and analytical results of tensile and flexural tests. The percentage difference between two approaches is also given.

Figure 8 represents the percentage variation in tensile strength between experimental and analytical results for the different composite samples A₁, A₂, A₃, and A₄. The maximum positive deviation occurs with analytical result for the composite sample A₄ (epoxy + carbon fabric + 15 wt% carbon black), which is 3.8%. Composite samples A₁, A₂, and A₃ show 3.37, 3.19, and 1.98% positive deviation for analytical results. As the hand lay-up method has been used for the composite fabrication, so some voids have developed in the fabricated composite samples. Also, FEM gives the approximate results. So the abovementioned difference occurs between analytical and experimental results.

Similarly, Fig. 9 represents the percentage variation in flexural strength between experimental and analytical results for the different composite samples A₁, A₂, A₃, and A₄. The maximum positive deviation occurs with analytical result for the composite sample A₂ (epoxy + carbon fabric + 5 wt% carbon black), which is 3.65%. Composite samples A₁, A₃, and A₄

**Fig. 9** Comparison of experimental and analytical flexural strength

show 1.88, 3.09, and 1.25% positive deviation for analytical results. Formation of microvoids during fabrication is the reason for percentage deviation between analytical and experimental results of flexural strength.

5 Conclusions

Epoxy-based four composites samples A₁, A₂, A₃, and A₄ have been fabricated. Out of the four sample A₁ is conventional carbon fabric-reinforced epoxy composite and the remaining samples are hybrid composite which have been fabricated with keeping constant weight percentages of carbon fabric and with varying weight percentage of carbon black 5, 10, and 15% respectively. This work demonstrates that the hybridization of conventional carbon fabric-reinforced epoxy composite with carbon black is successfully achieved by hand lay-up fabrication technique. The tensile test results show that for composite A₃ (epoxy + carbon fabric + 10 wt% carbon black), tensile strength increases by 65.78% as compared to tensile strength of conventional carbon fabric-reinforced epoxy composite. In flexural test, 32.07% improvement in the flexural strength is observed for hybrid composite A₃ (epoxy + carbon fabric + 10 wt% carbon black) when compared to conventional carbon fabric-reinforced epoxy composite. Impact strength of hybrid composite A₃ also increases by 36.11% with 10 wt% addition of carbon black in the epoxy-based carbon fabric-reinforced composites. Under SEM characterization matrix fracture, fractured carbon fiber and the dislocation of the carbon fiber have been noticed due to the composite fracture. A good intermingling of the carbon black with the epoxy matrix has also been noticed. Finally, the optimum mechanical properties (tensile strength, flexural strength, and impact strength) are obtained for the composition of composite A₃ (epoxy + carbon fabric + 10 wt% carbon black). Experimental results have been validated with the numerical analysis. Comparison of experimental and analytical results shows a deviation of 3.37, 3.19, 1.98, and 3.8% in the experimental and analytical tensile strength and 1.88, 3.65, 3.09, and 1.25% deviation in the experimental and analytical flexural strength for composites samples A₁, A₂, A₃, and A₄ respectively.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Carolan D, Kinlocha AJ, Ivankovic A, Sprenger S, Taylor AC (2016) Mechanical and fracture performance of carbon fibre reinforced composites with nanoparticle modified matrices. *ECF 21. Procedia Struct Integr* 2:096–103
2. Suresha B, Chandramohan G, Renukappa NM, Siddaramaiah (2007) Mechanical and Tribological Properties of Glass–Epoxy Composites with and Without Graphite Particulate Filler. *J Appl Polym Sci* 103:2472–2480
3. Cho J, Chen JY, Daniel IM (2007) Mechanical enhancement of carbon fiber/epoxy composites by graphite nanoplatelet reinforcement. *Scr Mater* 56:685–688
4. Sumfleth J, Adroher XC, Schulte K (2009) Synergistic effects in network formation and electrical properties of hybrid epoxy nanocomposites containing multiwall carbon nanotubes and carbon black. *J Mater Sci* 44:3241–3247
5. Hydro RM, Pearson RA (2007) Epoxies toughened with triblock copolymers. *J Polym Sci B Polym Phys* 45:1470–1481
6. Chong HM, Taylor AC (2013) The microstructure and fracture performance of styrene-butadiene-methylmethacrylate block copolymer-modified epoxy polymers. *J Mater Sci* 48:6762–6777
7. Baptista R, Mendao A, Guedes M, Marat-Mendes R (2016) An experimental study on mechanical properties of epoxy-matrix composites containing graphite filler. *XV-PCF. Procedia Struct Integr* 1: 74–81
8. Chandrasekaran S, Sato N, Tolle F, Mulhaupt R, Fiedler B, Schulte K (2014) Fracture toughness and failure mechanism of graphene-based epoxy composites. *Compos Sci Technol* 97:90–99
9. Hsieh TH, Kinloch AJ, Taylor AC, Sprenger S (2011) The effect of silica nanoparticles and carbon nanotubes on the toughness of a thermosetting epoxy polymer. *Appl Polym Sci* 119:2135–2142. <https://doi.org/10.1002/app.32937>
10. Sivasaravanan S, Bupesh Raja VK, Manikandan (2014) Impact Characterization of Epoxy LY556/E-Glass Fibre/Nano Clay Hybrid Nano Composite Materials. 12th GCMM. *Procedia Eng* 97:968–974
11. Yasmin A, Daniel IM (2004) Mechanical and thermal properties of graphite platelet/epoxy composites. *Polymer* 45:8211–8219
12. Shokrieh MM, Esmkhani M, Shahverdi HR, Vahedi F (2013) Effect of Graphene Nanosheets (GNS) and Graphite Nanoplatelets (GNP) on the Mechanical Properties of Epoxy Nanocomposites. *Sci Adv Mater* 5:1–7
13. Valente M, Marra FS, Tirillo J, Pulci G (2011) Hybrid recycled glass fiber/wood flour thermoplastic composites: Manufacturing and mechanical characterization. *Compos Part A* 42:649–657