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Mechanical and Tribological Behaviors of Chopped Carbon/Glass Fiber Reinforced Hybrid Epoxy Composites

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KEYWORDS

Short carbon fibers;
Short glass fibers;
Flexural strength;
Impact strength;
Wear.

ABSTRACT

This study aims to examine the mechanical and tribological behaviors of short glass fibers (SGFs) and short carbon fibers (SCFs) reinforced single-layer hybrid epoxy composites. Here, the hybrid composites reinforced SGFs and SCFs in two different ratios (5 wt.% and 10 wt.%) were produced by the hand layup method. In addition, only glass or carbon fiber reinforced composites were produced in the same proportions to compare with hybrid composites. To investigate the flexural bending strength of composites (E5GF, E10GF, E5CF, and E10CF) and hybrid composites (E5GCF and E10GCF), 3-point bending tests were conducted. Izod impact tests were performed to analyze the impact energy absorbing behaviors of specimens. The wear performance of samples was assessed by using 10 and 20N loads. Moreover, the morphology of broken and worn surfaces of samples was analyzed by a scanning electron microscope. According to test results, E10GCF hybrid composites had nearly 27.36% and 29.67% better flexural strength and impact energy-absorbing compared to (E10GF) glass fiber reinforced composites, respectively. However, only 10 wt.% carbon-reinforced composites showed the highest wear resistance and smooth worn surface among all the samples. Therefore, for structural applications, hybrid epoxy composites can be the favorite but for tribological purposes reinforcing epoxy with only carbon fiber should be advantageous.

1. Introduction

Polymer matrix composites have a broad range of applications in the automobile and aerospace industries [1]. In recent days, great developments in the applications of fiber-reinforced polymer matrix composites such as polyurethane, epoxy, vinyl ester, and polyester have been observed [2]. Among them, epoxy resins are the most widely used polymer type due to their superior adhesion to substrates, low viscosity, dimensional stability, and chemical resistance [3]–[5]. However, the mechanical properties of this polymer matrix such as the strength, modulus, and toughness are drawbacks to its further industrial usage. Therefore, to improve its mechanical and tribological properties, the addition of fibers to the epoxy matrix is inevitable [5]. The most commonly used reinforcing synthetic fibers are glass and carbon fibers.

Glass fibers are the most widely used fiber types to reinforce polymers in the fabrication of polymer composites due to their tremendous chemical stability, lightweight, mechanical properties, and high-temperature resistance [6]. Thus, researchers are widely using glass-reinforced epoxy resins for construction and military applications. In the work of Ozsoy et al. [7], the effects of different contents of chopped E-glass fibers (10%, 20%, and 30%) on the mechanical and tribological properties of epoxy composites were investigated. According to test results, additions of chopped glass fiber had not increased the bending strength. However, the impact energy starts to increase as the amount of glass fiber reaches 30%. In another study, the consequences of different contents of short E-glass fiber (0%, 10%, 15%, and 20%) on the mechanical properties of the epoxy composite were investigated by Yadav et al. [8]. It was noticed from test results the flexural strength of

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composites increased with an increase in fiber loading up to 15 wt.% and then decreased with a further increase in the fiber loading. Furthermore, this study revealed that increment in strength enhanced the wear resistance behavior of materials, and it was found that epoxy composites with 15 wt.% E-glass fiber loading exhibit minimum specific wear rate among the samples for all the testing conditions. Moreover, the effect of different volume fractions (40%, 50%, and 60%) incorporation of glass fibers on the mechanical properties of the epoxy composite was examined experimentally by Swapnil et al. [9]. Test results indicated that better mechanical properties were observed with 50 wt.% glass fiber addition but the further increment in the fiber content caused delamination [9].

On the other hand, in addition to glass fibers (GF), carbon fibers (CF) are another type of synthetic fiber for reinforcing epoxy-polymer composites. Due to their high specific strength and stiffness, these fibers are extensively applied in various kinds of structural areas [1], [10]. Hence, various studies have been conducted to enhance the wear resistance and mechanical properties of epoxy-based composites with reinforcing CF [11]. Solomon et al. [12] study the effect of carbon fiber contents (30 wt.%, 35 wt.%, and 40 wt.%) on the epoxy matrixed composites. Test results exhibited that higher mechanical strength of the composites was observed for the carbon content of 35 wt.%. In another study, the tribological properties of short carbon fibers (SCFs) reinforced epoxy composites were investigated by Khun et al. [13]. Test results determined that addition of SCFs was an effective way to improve the tribological properties of the epoxy-based composites. However, carbon fiber (CF) suffers from low energy absorption rates and degraded impact resistance due to delamination [10]. Thus, further improvement on the strength while keeping the toughness of epoxy-based composites was crucial to boosting its application areas. Hence, scholars are studying the blended effect of glass and carbon fibers in the form of hybrid polymer composites. Soni et al. [14] investigated the mechanical characteristics of the multilayer (laminated) carbon-glass-epoxy hybrid composites. The flexural and impact properties of the specimen were maximum at 2 wt.% carbon fiber additions. Jesthi and Nayak [15] observed that the flexural strength and modulus of laminated type hybrid composite were improved by 46.1% and 49.5% respectively as compared to plain glass fiber reinforced polymer composites. Additionally, the test result revealed that among all the specimens laminated hybrid composite has shown the lowest wear rate of 18.8476×10^{-3} mm^3 Nm^{-1}.

As mentioned above, laminated (Fig. 1(a)) hybrid composites were studied in the previous studies. However, to the best of our knowledge, there is no study on the mechanical and tribological behaviors of single-layer (Fig. 1(b)) hybrids of chopped carbon and glass-epoxy composites. Furthermore, mostly only the mechanical properties of composites were investigated in previous studies. The present study examines the mechanical and tribological properties of SGFs and SCFs reinforced single-layer hybrid epoxy composites.

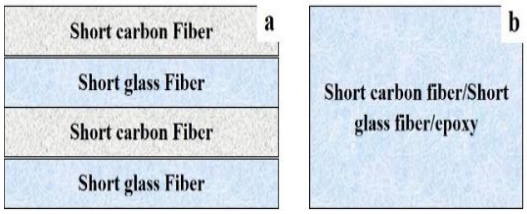

Fig.1. Schematic diagram of, (a) Laminated (multi-layer hybrid composite) and (b) single-layer hybrid composite

2. Experiment

2.1. Materials

Chopped glass fibers (SGFs) with an average size and diameter of 3.2 mm and 14 µm, respectively, and chopped carbon fibers (SCFs) with mean dimensions of 3-6 mm and 7 µm average fiber diameter were purchased from Omnis Kompozit and Dost Kimya, Turkey, respectively. Epoxy resin (DTE 1784) and hardener (DTS 1037) used were supplied from San Duratek Protective Equipment and Trade. Inc., Turkey.

Figure 2 shows scanning electron microscope (SEM) images of short carbon fibers (SCFs) and short glass fibers (SGFs). Short carbon fiber had good electrical conductivity, higher stiffness, low thermal expansion coefficient, and thermal conductivity. Whereas, good electrical conductivity, reasonable young's modulus, etc. are notable characteristic features of short glass fibers.

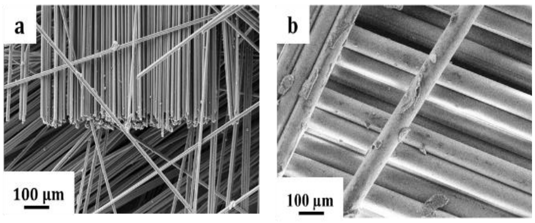

Fig. 2. (a) SEM images of short carbon fibers, and (b) SEM images of short glass fibers

2.2. Fabrication of Composites and Hybrid Samples

Pure epoxy (E) was produced when DTE 1000 and DTS 1100 were mixed in a ratio of 100:35.

The specimens were coded and the composition of each composite and epoxy hybrid polymer was shown in Table 1.

Table 1. Compositions of produced Composites

Sample Code	GF (Wt.%)	CF (Wt.%)	E (Wt.%)
E5GF	5	-	95
E5CF	-	5	95
E5GCF	2.5	2.5	95
E10GF	10	-	90
E10CF	-	10	90
E10GCF	5	5	90

Composites and hybrids were fabricated in two different weighted fractions of 5 and 10 wt. % using the hand layup method as indicated in Table 1. The fabrication process is taking place with the help of two different molds as illustrated in Fig. 3 at room temperature without any applied pressure. Hence, SGF/SCF reinforced epoxy-based hybrid composite (E5GCF) was produced when 63.33 g of DTE 1784 epoxy resin is placed in a beaker. Pre-prepared SGF and SCF each of them weighing 2.5 g are added to the beaker. Then, stir the blended composition firmly until a homogeneous mixture was obtained, and subsequently an amount of 31.66 g DTS 1037 hardener was added to the mixture after homogeneity was achieved. A quick mixing is carried out and then it took 24 hours for the curation to end and 48 hours were expected for the sample to be ready for tests. After the hardening reaction and waiting time is over, the redundancy is sanded with grit 240 pastes till the samples comply with the flexural and impact test standards by ASTM D790 and ASTM D256, respectively. These operations are carried out for each batch of composite and hybrid sample fabrication.

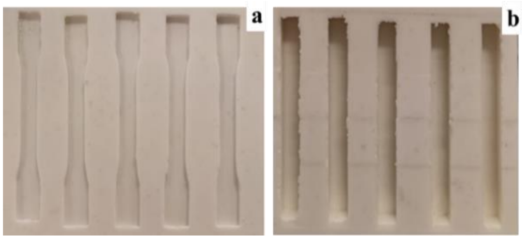

Fig. 3. Mold for, (a) Flexural composite samples and (b) Izod impact composite samples

2.3. Characterization

For flexural bending tests, specimens were produced with a dimension of (158 × 13 × 5) mm. The span length was taken 50 mm and the span to depth ratio is 10:1. The tests were conducted three times for each composite and hybrid specimen according to the ASTM D790 standard and the mean result was evaluated. 3-point bending tests were conducted on the loading capacity of the 600KN Zwick Roell test machine with a rate of loading of 2 mm/min. The flexural strength "σ" and flexural modulus "E_F" of samples were measured by Eq. (1) and Eq. (2), respectively.

$$\sigma = \frac{3FL}{2wt^2} \tag{1}$$

$$E_F = \frac{mL^3}{4wt^3} \tag{2}$$

where:

F - applied load [N],

m - the slope of the initial section of the load versus displacement curve,

L - span length [mm],

w - width of the sample [mm], and

t - thickness of specimens [mm] [15], [16].

Izod impact tests were performed on composites and hybrid composites fabricated with a dimension of (80× 10 × 10) mm. These tests were performed on the loading capacity of 450J Zwick Roell RKP 450 test apparatus. During impact tests, 3-Izod impact tests were executed for each sample according to ASTM D256 standard and the mean values were calculated. Moreover, wear resistance properties were investigated by UTS Tribometer T10/20 device under dry-sliding conditions. In the course of wear examinations, applied loads of 10 and 20N with a stainless-steel ball diameter of 6 mm, a sliding distance of 150 m, a sliding speed of 40 mm/sec, and a stroke of 10 mm were applied. The volumetric wear rate "wr" is calculated by Eq. (3).

$$Wr = \left(\frac{Wv}{dL}\right) = \left(\frac{2ab}{3}c \Big/ d\right) \tag{3}$$

where:

Wv - volumetric wear loss [mm^3/s],

a - wear width of sample [mm],

b - wear depth of sample [μm], and

c - stroke [mm] [17].

Eventually, after coating the samples with gold using a sputter coater (Quorum, Q150R ES Plus), damaged (broken and worn) surfaces of samples were analyzed using a Zeiss Ultra plus scanning electron microscope (SEM).

Figure 4 shows test machines that are applied to characterize the mechanical and tribological behaviors. Flexural strength experimenting with E5GF was seen in Fig. 4(a). The Izod impact and wear resistance properties were investigated using devices indicated in Figs. 4(b) and 4(c), respectively.

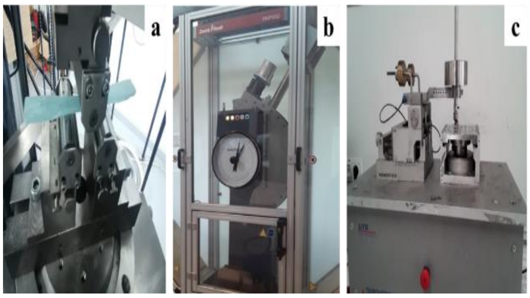

Fig. 4. (a) Flexural bending test, (b) Izod impact test, and (c) Pin-on-disc wear test

3. Results and Discussions

3.1. Mechanical Properties

The load versus deformation graphs of samples after the flexural bending tests were depicted below in Fig. 5. In response to an applied load, the deformation rises linearly upward for all samples. Then, there will be an initiation of compressive cracks on the upper surfaces of the E10CF sample. The propagation of the compressive cracks continues until the stress reaches the maximum peak load. After reaching the maximum load point, the tensile crack is initiated at the lower surface of the specimen and propagates in the direction of compressive cracks vertically upward through the mid-plane of the specimen. The propagation of the tensile crack accompanies delamination, which initiates and spreads widely. Eventually, the tensile cracks and compressive cracks continue their propagation and finally merge at a point that causes E10CF to break as indicated in Fig. 6(a) [18], [19]. This broken phenomenon of sample E10CF also similarly appeared in the rest of the samples. Fig. 6(b) indicates a broken sample of the E10CF sample after the Izod impact test.

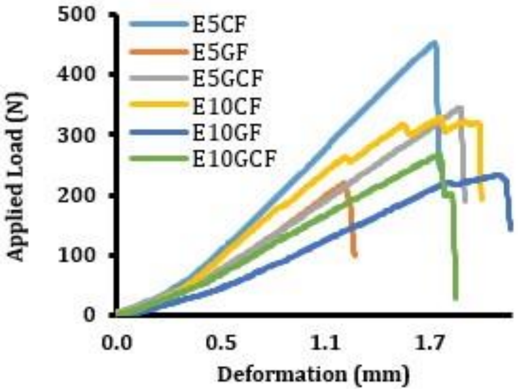

Fig. 5. Load versus deformation of samples

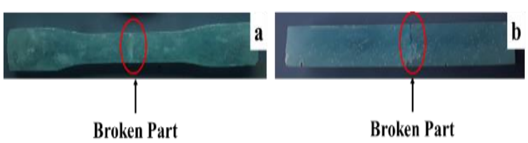

Fig. 6. (a) Broken E10CF by flexural bending and (b) E10CF after impact tests

The flexural strength and impact resistance characteristics of composites and hybrid samples were indicated in Fig. 7. The flexural bending tests for the first three samples E5GF, E5CF, and E5GCF were conducted. According to test results, hybrid composite E5GCF shows 24.11% and 6.65% improvement in the flexural bending strength compared to E5GF and E5CF, respectively. This might be due to the higher stiffness properties of both chopped carbon and glass fibers attributes for the enhancements of the flexural strength of hybrid composite [19], [20]. Likewise, the impact test results of E5GF, E5CF, and E5GCF reveal that sample E5GCF has the maximum energy absorbing characteristic value of nearly 0.95J. Whereas, the lowest impact resistance capacity of about 0.66J was observed in the E5GF sample. This is probably related to the morphological structure of the samples. The presence of river lines, cracks on epoxy matrixes, and pores cause weak interfacial bonding between SGFs and epoxy of E5GF composite as can be seen in SEM images of Fig. 8(a). Also, the delamination, cracks on matrixes, and debonding effects noticed under SEM images in Fig. 8(b) for sample E5CF reduce the amount of force transferred between SCFs and epoxy matrix. Hence, these were the factors responsible for the reduction of the impact strength of the composites [5].

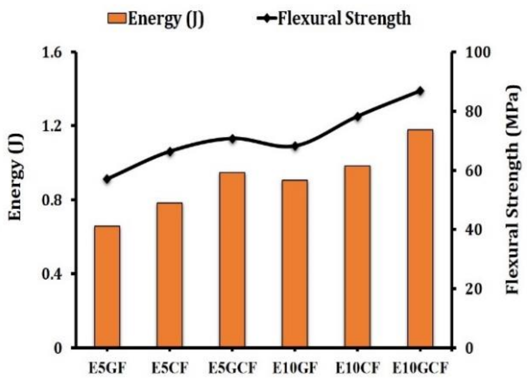

Fig. 7. Flexural Strength and impact resistance of samples

On the other hand, other flexural bending strength tests were conducted on the next three samples; E10GF, E10CF, and E10GCF. According to Fig. 7, the maximum flexural bending strength was observed for hybrid composite E10GCF with 86.76MPa whereas E10GF exhibits the least flexural strength value of 68.12MPa. Moreover, considering impact tests, the impact strength of E10GCF was nearly 29.67% and 20.41% better than E10GF and E10CF, respectively. This is probably because of defects in the morphological structures of composites E10GF and E10CF. Thus, the presence of agglomeration, delamination, and debonding was indicated in the SEM image of Fig. 9(a) for the E10GF specimen. Also, Fig. 9(b) indicated that agglomeration and debonding effects were observed in the E10CF composite. So, these might be an attribute for the decrement of impact strength [21]. Thus, mechanical tests exhibit that SGFs and SCFs reinforced epoxy-based hybrid composites show behavioral proportionality. Therefore, the linearity of the graph in Fig. 7 proves the direct proportionality of the flexural and impact properties of samples as a function of fiber content.

Previous studies also indicated that the addition of a limited amount of carbon and glass fibers into a fiber-matrix mixture results in an increment in the mechanical properties of composites [5], [6]. This might be because both SGFs and SCFs have higher strength and stiffness characteristics. So, E10GCF has better flexural and impact strength than E5GCF hybrid composite. These phenomena were also valid for both (E5GF and E10GF) and (E5CF and E10CF) composites. Thus, this result is in good agreement with past studies.

The SEM images shown in Fig. 8 and Fig. 9 indicate a comparison of fracture surfaces of samples. For all samples, a typical brittle fracture was noted. In addition, it was observed that there was a resemblance in the fracture mechanism for all samples and described by fiber pull out and debonding (Fig. 8(c), Fig. 9(a), and Fig. 9(b)), delamination and cracks (Fig. 8(c) and Fig. 9(a)), and fiber breaking (Fig. 9(c)).

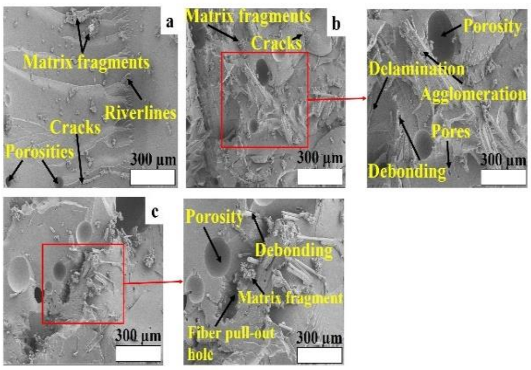

Fig. 8. SEM images of broken surfaces of samples, (a) E5GF, (b) E5CF, and (c) E5GCF

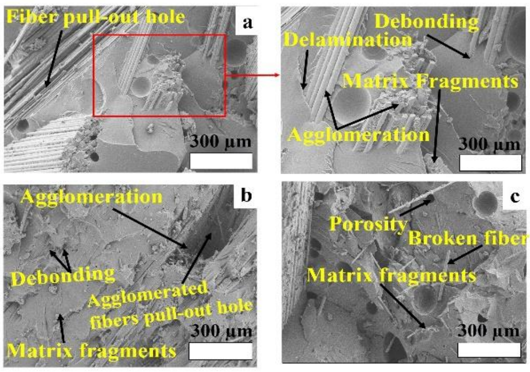

Fig. 9. SEM images of broken surfaces of samples, (a) E10GF, (b) E10CF, and (c) E10GCF

Figure 10 indicates the flexural modulus results of samples. It was noted that single-layer hybrid composite had a higher modulus compared to chopped carbon and glass epoxy reinforced individual composites. Considering 5 wt.% compositions the flexural modulus of E5GCF was better than E5CF and E5GF by 18.1% and 26.86%, respectively. This might be due to the higher stiffness characteristics of the chopped carbon fibers [1]. The aspect ratio also had notable effects on the flexural modulus. It was observed that when the aspect ratio of glass fiber (228.57) increases the flexural modulus is reduced. Similar results were also obtained in the works of Dong et al. [22]. In their study, it was determined that the increment in glass fiber content resulted in a decrement of the flexural modulus of carbon fiber reinforced plastic (CFRP). In another study by Dong and Davies, it was shown that increment in glass fiber resulted in flexural modulus reduction [23]. Whereas, for 10 wt.% compositions, the flexural modulus of E10GCF was 4146.6 MPa which is higher than E10CF and E10GF. Also, E10CF had a higher flexural modulus than E5CF. This was explained by the presence of higher stiffness and more carbon fibers. Similar results were observed in the works of Tsotra and Friedrich [24]. In their research work, it was revealed that the addition of higher contents of SCFs leads to a considerable increase of the flexural modulus of the neat epoxy.

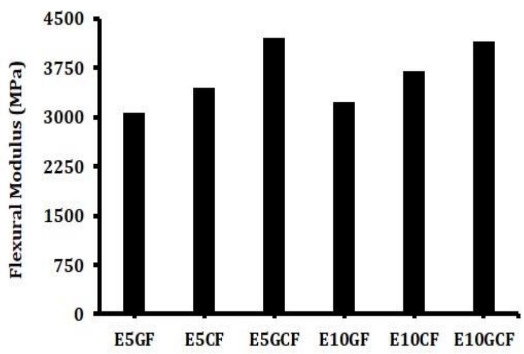

Fig. 10. Flexural modulus of samples

3.2. Tribological Properties

Figure 11 indicates the specific wear resistance properties of composites and hybrids under the applied loads of 10 and 20N. Whereas, the worn surface texture of composites and hybrid composites were noted in Fig. 13 using a scanning electron microscope (SEM).

For the first three samples (E5GF, E5CF, and E5GCF), wear tests were performed. Test results revealed that the highest specific wear resistance (SWR) property was observed for E5CF composite with 0.34×10^{-4} and 0.8×10^{-4} mm^3/m under the applied loads of 10 and 20N. Thus, it was observed that for higher loads the SWR increased. This was in complete agreement with the works of Jesthi et al. [25]. Although the mechanical properties of E5GCF were higher than E5CF, it showed lower SWR compared to E5CF. This is because short carbon fibers have self-lubricating properties [6], [13]. Thus, the wear properties of composites can be improved depending on the carbon fiber content and it can be noted that the SCFs were much more effective than SGFs on the tribological behavior of composites. In addition, SEM images in Figs. 13(i) and 13(j) indicate the worn surface of E5CF was relatively smooth with little wear debris. Hence, this confirms that E5CF has better wear resistance behavior. Subsequently, in Fig. 11 it was also observed that the lowest specific wear resistance property was noticed for E5GF composite with specific wear rate values of 0.75×10^{-4} and 1.7×10^{-4} mm^3/m under loads of 10 and 20N, respectively. Here, large wear debris sizes were observed in Figs. 13(a) and 13(b) under SEM images.

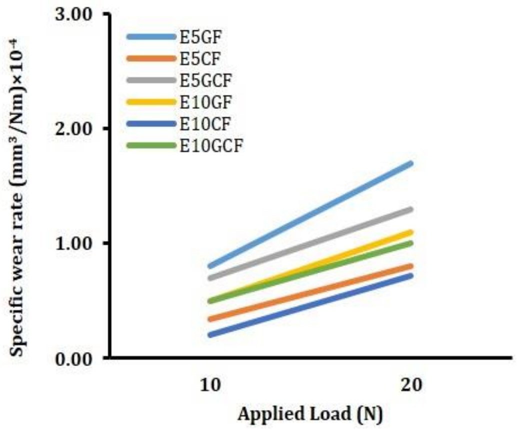

Fig. 11. Specific wear rate under the applied loads

Wear resistance tests were further examined on another batch of samples; E10GF, E10CF, and E10GCF. According to Fig. 11, the maximum specific wear resistance was observed for E10CF composite with 0.2×10^{-4} and 0.72×10^{-4} mm^3/m under 10 and 20N loads, respectively. Moreover, smooth worn surfaces were observed in Figs. 13(k) and 13(l). Hence, the specific wear resistance capacity of E10CF under a load of 20N was better than E10GF and E10GCF nearly by 52.78% and 38.89% respectively. Contrarily, a higher specific wear rate was recorded for E10GF composite with 0.5×10^{-4} and 1.1×10^{-4} mm^3/m under 10 and 20N loads, respectively. Agglomeration attributes for the poor interfacial adhesion at the higher fiber content of 10 wt.% SGFs and hence, the specific wear resistance behavior were reduced significantly [26]. Therefore, broken fibers and wear debris defects were detected in Figs. 13(e) and 13(f) for E10GF composite specimen due to less wear resistance.

On the other hand, it is said that the addition of different contents of carbon and glass fibers into the fiber-matrix mixture causes an enhancement in the mechanical properties. So, the increment in strength causes an improvement in the wear resistance properties of composites [8]. So, 10 wt.% SGFs and SCFs added E10GCF have better wear resistance characteristics than 5 wt.% SGFs and SCFs added E5GCF hybrid composites. This can also be explained by the morphology of surface textures, smooth surfaces were observed in the SEM images of E10GCF in Figs. 13(g) and 13(h). Whereas, higher wear debris was noticed on the worn surface of the E5GCF composite in Figs. 13(c) and 13(d). These phenomena were confirmed in Fig. 11 and are also valid for the other composites as well (E5GF and E10GF) and (E5CF and E10CF). Additionally, the loading value has a direct impact on the coefficient of friction during wear analysis. The coefficient of friction was measured for all samples at the maximum load of 20N and is depicted below in Fig. 12. Generally, the study confirmed that single-layer hybrid composites have a lower coefficient of friction values as compared with short glass fiber epoxy reinforced composites. This might be due to the presence of higher stiffness carbon fibers in the hybrid composite improving the specific wear resistance characteristics. Thus, a higher COF value of 2.75 was revealed for E5GF. However, the least coefficient of friction among all samples was 2.25 and recorded for E10CF. This was explained by the self-lubricating effects of short carbon fibers [6], [13]. This result was also supported by the results indicated in specific wear resistance tests indicated in Fig. 11.

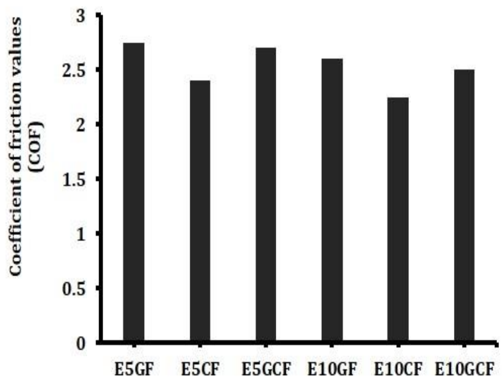

Fig. 12. Coefficient of friction values of samples at 20N

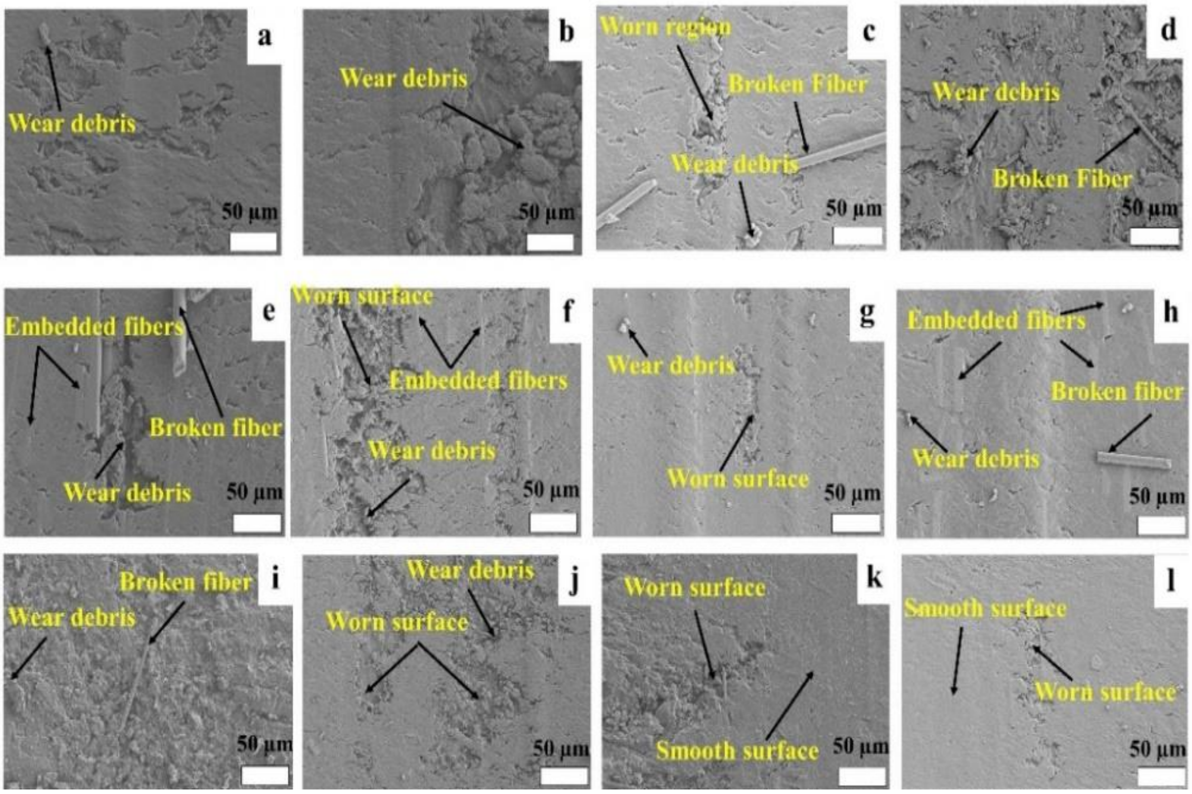

Fig. 13. SEM images of worn surfaces of samples, (a,b) E5GF, (c,d) E5GCF, (e,f) E10GF, (g,h) E10GCF, (i,j) E5CF, and (k,l) E10CF

Table 2. Past literature studies on short carbon-glass epoxy reinforced hybrid composites

No	Stacking sequence of hybrid	Number of plies	Results	Ref.
1	Group D (carbon/glass/carbon/glass/carbon)	5	Best tensile properties (382.7 MPa) were recorded and stacking sequence affects tensile loads.	[27]
2	0.1SCF-GE	-	Addition of 0.1 wt. % SCF into GE composite enhances the flexural strength by 16.08%.	[28]
3	Glass/epoxy, carbon/epoxy, 0^0 C/45^0 G/45^0 C/-45^0 G/-45^0 C/90^0 G/90^0 C	7	The flexural strength of hybrid composite (542.94 MPa) is significantly higher as compared to glass/epoxy (475.27 MPa) and carbon/epoxy (304.81 MPa) composite materials.	[29]
4	$[C]_8$, $[C2G2]_s$, $[CG3]_s$, $[CGCG]_s$, and $[G]_8$	3	The stacking sequence did not show a noticeable influence on the tensile properties but affected the flexural and compressive properties significantly.	[30]
5	[C/G/G/C/G/G/C] and [G/C/G/C/G/C/G]	7	Out of the two laminates tested, the one with carbon fabric positioned at exterior regions showed the highest tensile and flexural strength of 380.35 MPa and 615.48 MPa respectively.	[31]
6	C-G-G-G-G-G-G-G-G-C	10	The flexural strength of hybrid composites was found to improve by 10.5% as compared to neat glass composite (GFRP).	[32]

"-"indicates the number of plies is not specified.

4. Conclusions

In this study, the mechanical and tribological properties of SGFs and SCFs reinforced single-layer hybrid epoxy composites were investigated. Findings were summarized as follows:

- The present study confirmed that E5GCF had better flexural strength nearly by 6.65% and 24.11% than E5CF and E5GF while the E10GCF hybrid composite showed 10.97% and 27.36% improvements in the flexural strength than E10CF and E10GF composites, respectively.
- Also, the energy-absorbing values of samples showed the same trend as the flexural strength of samples. Thus, the E10GCF hybrid composite had the highest energy-absorbing value of 1.18J compared with E10CF and E10GF. However, the E5GF composite had the lowest energy absorbing capacity of 0.66J compared with all samples.
- On the other hand, the content of chopped carbon fibers had a significant effect on the tribological properties of chopped carbon fibers (SCFs) reinforced composites, and hybrid composites. Hence, the superior wear resistance property was observed for E10CF composite with 0.2×10^{-4} and 0.72×10^{-4} mm^3/m wear rates under 10 and 20N loads, respectively.
- Furthermore, the scanning electron microscope observation resulted in smoother worn surfaces for the E10CF sample.

To sum up, it was concluded that for structural application areas such as automobiles (i.e., automotive composite wheel, automobile door's internal structure) and construction areas (i.e., beams, partition walls) E10GCF hybrid composite can come forward while E10CF composite was much better for tribological applications.

Acknowledgments

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Conflicts of Interest

The authors declare that they have no conflict of interest.

Author's Contributions

YA and HC designed the structure. YAYA and AKE produced the samples and completed experimental studies. YA, HC and AKE wrote up the article. All authors have read and approved the final manuscript.

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