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**Research Article**

# The Effect of Short Carbon Fiber and Hydrothermal Carbon Content on Impact and Wear Properties of Epoxy Composites

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**Abstract :** This study aims to investigate the effect of different weight fractions (3%, and 5%) of short carbon fibers (SCFs) and hydrothermal carbons (HTCs) on the impact and wear properties of epoxy matrix composites. The samples were fabricated using the hand lay-up method. Izod impact tests were applied to the unnotched samples. To investigate the wear properties of pure epoxy and composites, reciprocating wear tests were conducted. Also, a Scanning Electron Microscope has been used for observation of the morphology of the broken and worn surfaces of pure Epoxy and (SCFs and HTCs) reinforced epoxy-based composites. Results showed that HTCs have remarkable effects on improving the wear resistance rate as compared to SCFs reinforced composites. However, SCFs reinforced epoxy composites have better energy-absorbing effects compared to HTCs epoxy-reinforced composites.

**Keywords :** Short carbon fiber, Hydrothermal carbon, Epoxy, Impact, Wear.

## 1 Introduction

Nowadays novel materials are preferred for their properties of being lighter, stronger, or less expensive compared to traditional materials. Traditional materials like metals have been used in various application areas for many years and these material types are categorized under traditional materials as compared to recently discovered composite materials. Composite material is a novel material that replaces traditional materials due to their high strength and lightweight properties [1]. A composite material consists of two or more constituent materials such as matrix, reinforcement, and fillers with different physical and/or chemical properties. Matrixes are used to hold the fibers or reinforcements together and protect fibers from damage. On the other hand, the major function of the reinforcement component is to bear a load [2, 3]. Polymer matrix composites (PMCs) are one category of composites that has a wide range of applications in the aerospace, aircraft, and automobile industries [2], [4, 5, 6]. This might be due to their good combination of high specific strength and modulus [5, 6]. Although PMCs lack compression strength due to their fiber waviness, carbon fiber-reinforced epoxy composites show promising results in their mechanical properties [2].

Epoxy resin is a commonly used thermosetting polymer matrix composite with high strength and specific properties [7]. It is usually reinforced with carbon fiber, glass fiber, and aramid or particles such as ceramic powders to withstand high mechanical and tribological loads [8]. Carbon fiber has superior corrosion and bursting resistance compared to glass fiber or other polymer fibers at room temperature. Also, carbon fiber-reinforced composite materials have some attractive properties, notably their strength, stiffness, lightweight, and toughness [9]. It is evident from the literature that polymer matrix composites are used for structural applications such as for aerospace (e.g. wing box, tail, and stabilizer), bridge cables, body armors (e.g. rear and front ballistic carrier), automobile internal combustion engines (e.g. piston rings, connecting rod, pins, and cylinder block and head), and other industries may be passed through different environments usually subjected to different mechanical stresses. This may affect the mechanical performance of composite parts [10]. Therefore, reinforcing the epoxy matrix by using carbon fibers is inevitable.

Solomon et al. [11], investigate the effect of different contents of carbon fiber reinforced on the mechanical properties of epoxy-based composites. In their study, it was reported that the carbon fiber composites 35% carbon and 65% epoxy resin exhibit maximum tensile strength and hardness. In another study reported by Jagannatha and Harish [12], it was found that the hardness, flexural strength, and flexural modulus were improved as the carbon fiber reinforcement contents were 60% in the epoxy matrix material. Khun et al. [13] studied the effect of different SCFs contents on the tribological properties of SCF-reinforced epoxy composites. They determined that increasing SCFs content from 2.5 wt.% to 20 wt.% resulted in a decrement of the mean friction coefficients of the epoxy composites from 0.24 to 0.18 and from 0.53 to 0.24 for the normal load of 2 N

**Table 1: Past studies on the wear of composite polymers.**

| No | Sample Code | Applied load (N) | Sliding velocity (m/s) | Sliding distance (m) | Stroke distance (mm) | Wear test type | Ref. |
|---|---|---|---|---|---|---|---|
| 1 | UF, SF, & LF | 19.62 & 28.43 | 0.5 | 3000 | × | × | [21] |
| 2 | PE, PE-0.5HTC, PE-1HTC, & PE-2HTC | 20, 30, & 40 | × | 100 | 10 | Reciprocating | [22] |
| 3 | E5GF, E5CF, E5GCF, E10GF, E10CF, & E10GCF | 10 & 20 | 0.04 | 150 | 10 | Reciprocating | [23] |
| 4 | PA6 & CF/PA6 | 9 | × | × | 5 | Reciprocating | [24] |
| 5 | Pure EP, 0.3wt%BNNP/Epoxy, 0.5wt%BNNP/Epoxy, 0.7wt%BNNP/Epoxy, & 1wt%BNNP/Epoxy | 5 | 800 | 12000 | × | Reciprocating | [25] |

and 6 N, respectively. The effect of carbon fiber reinforcing epoxy matrix on friction and wear of composites was examined by Ibrahim [14]. In his study, it was shown that the friction coefficient of the tested composites slightly decreased with increasing carbon fiber content to 7.5%. It was also investigated that wear was drastically decreased with the increment of carbon fiber content to 7.5%.

In recent years, nano-sized carbon materials such as carbon nanotubes, graphene, and fullerene have become popular as reinforcement materials due to their mechanical properties [15]. These fillers (Graphene nanoplatelets (GNPs) and carbon nanotubes (CNTs)) act as a solid lubricant which results in a lower coefficient of friction compared to ceramic and metal fillers [16]. Due to their unique mechanical and tribological properties, numerous research is undergoing using GNPs and CNTs. Gojny et al. [17], examine the mechanical properties of double-wall carbon nanotubes (DWCNTs) in an epoxy matrix composite. Good dispersion of DWCNTs and carbon black in the epoxy matrix was observed. In addition, significantly improved fracture toughness, Young's modulus, and increased strength were observed at 0.1% content of nanotube. In another study, Yue et al. [18] explored the effects of CNT: GNP ratios on the mechanical and electrical properties of hybrid composites. The hybrid sample CNT0.8GNP0.2 exhibited remarkable improvement in both modulus and strength over CNT and GNP single filler composites. The tensile strength, compressive strength, tensile Young's modulus, and compressive Young's modulus were increased with the addition of MWCNT filler and were examined in the work of Srivastava [19]. Sakka et al. [20], also investigated that introducing fillers into epoxy resin greatly improved the tribological properties of the epoxy resin. Moreover, it was found that treated carbon nanotubes/epoxy composites have the best tribological behavior compared to other samples.

Furthermore, agglomeration of additives in a matrix occurred in carbon nanotube-reinforced composite due to the van der Waals bond and $\pi$-$\pi$ attractions. As a result of these the mechanical properties of the carbon nanotube-reinforced composite declined. Additionally, the production costs of CNT-based composites are quite high, and harmful chemicals are needed for their production. However, HTCs could be good alternative reinforcement to replace graphene and carbon nanotubes. Since fabricating HTCs needs low production costs, HTCs production is conducted without using any harmful chemicals and agglomeration will not be formed [15].

Therefore, this study aims to investigate the effect of different weight fractions (3%, and 5%) of SCFs and HTCs on the impact and wear properties of epoxy matrix composites. During tribological examination wear test process parameters were selected based on considering some literature studies as indicated in Table 1. Additionally, there has been limited research was conducted on the wear characteristics of epoxy composites reinforced with HTCs.

"×", indicates missing content. Where 'UF' stands for unreinforced epoxy, 'SF' is assigned for short carbon fiber, 'LF' is for carbon fiber reinforced epoxy, and 'PE' represents polyethylene. 'PE-0.5HTC', 'PE-1HTC', and 'PE-2HTC' designates reinforced polyethylene with 0.5, 1, and 2 wt.% HTC, respectively. Additionally, 'E10GF', 'E10CF', and 'E10GCF' indicate reinforced epoxy with 10 wt.% glass fiber, carbon fiber, and glass and carbon fibers, respectively. 'PA6' and 'CF/PA6' are polyamide 6, and carbon fiber reinforced PA6, respectively. Eventually, 'EP' is the shorthand form of epoxy, and 'BNNP', is for boron nitride nanoplatelets.

## 2 Experimental Methods

### 2.1 Materials

SCFs (3-6 mm length) were supplied from Dost Kimya, Türkiye. Epoxy resin (DTE 1784) and hardener (DTS 1037) were purchased from San Duratek Protective Equipment and Trade. Inc., Türkiye.

### 2.2 Preparation of HTCs samples

To fabricate HTCs, 1.5 g of glucose (Merck) was dissolved in 20 ml of distilled water. Then, the obtained suspension was poured into a stainless-steel autoclave. The autoclave was put into a furnace at 200 °C for 30 hours of residence time. After cooling, hydrothermal carbon products were separated by filter paper and dried in a furnace at 105 °C for 2 hours [26].

Table 2: Composition of composites.

| Sample Code | Epoxy (wt.%) | SCFs (wt.%) | HTCs (wt.%) |
|---|---|---|---|
| Epoxy | 100 | - | - |
| E3SCFs | 97 | 3 | - |
| E5SCFs | 95 | 5 | - |
| E3HTCs | 97 | - | 3 |
| E5HTCs | 95 | - | 5 |

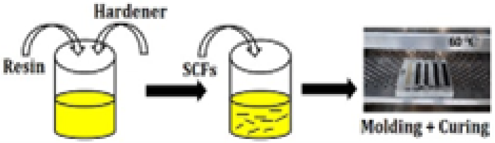

**Figure 1: Schematic of the production method of SCFs reinforced samples.**

## 2.3 Casting of samples

Resin and hardener were mixed in a ratio of 2:1 to produce pure epoxy. Afterward, SCFs were added to epoxy with different weight ratios (3 and 5 wt. %) according to Table 2.

Composites were cast by hand lay-up method using silicone molds. After molding, the curing of samples was held at 60 °C for 12 hours for the curing process. A schematic of the production method of SCFs reinforced samples is depicted below in Figure 1. The same method was also applied for HTCs reinforced composites.

## 2.4 Characterization

Izod impact tests were conducted on the unnotched samples with a cross-section dimension of (80× 10 × 10) mm. For each sample, impact tests were performed three times using the 450J Zwick Roell RKP 450 test machine indicated in Figure 2(a) and the mean values were calculated for each sample. The geometry of the impactor was schematically represented in Figure 2(b). The mass of the impactor and drop height are 32.5 kg and 1.369 m, respectively. On the other hand, wear tests were carried out on a UTS Tribometer device under 30 N loads for a 100 m sliding distance, using AISI 52100 steel ball, at a 5 mm stroke distance [22]. Also, the Tribometer device reciprocates at 2 mm/s sliding velocity. A schematic drawing of the wear test device is presented in Figure 3(a).

Wear rates ($W_r$) of samples were determined using the volume loss method and calculated using Equation (1):

$$W_r = \frac{W_v}{l} \tag{1}$$

Where '($W_v$)' is the worn volume of composites and 'l' is the sliding distance. The worn surface area was measured by the Mitutoyo SJ-410 instrument indicated in Figure 3(b). Here, the Mitutoyo SJ-410 measuring tool consists of 3 major components stylus, detector, and drive units. First, the worn surface area measurement is conducted by feeding the stylus into the detector and connecting the stylus to the surface of either Epoxy or SCFs-epoxy/HTCs-epoxy composites. Subsequently, the drive unit which holds both the stylus and detector pulls the assembly back and forth on the surface of the sample at this point the detector takes the movement and translates it into a digital signal that can be measured. 'Wv' was calculated by multiplying the worn surface area by stroke distance. Wear tests were performed three times for each sample and an average value was computed.

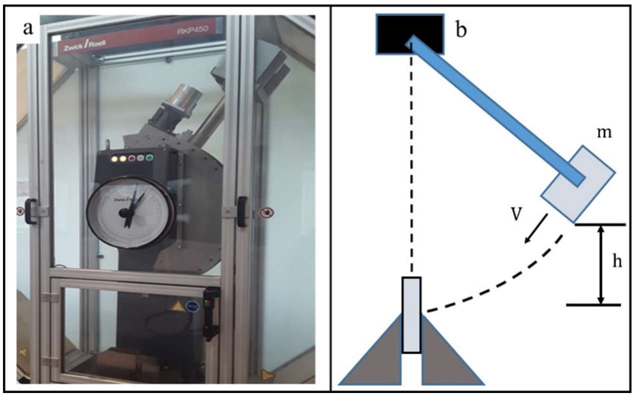

**Figure 2: (a) Impact testing device and (b) Schematic representation of the Izod impact test.**

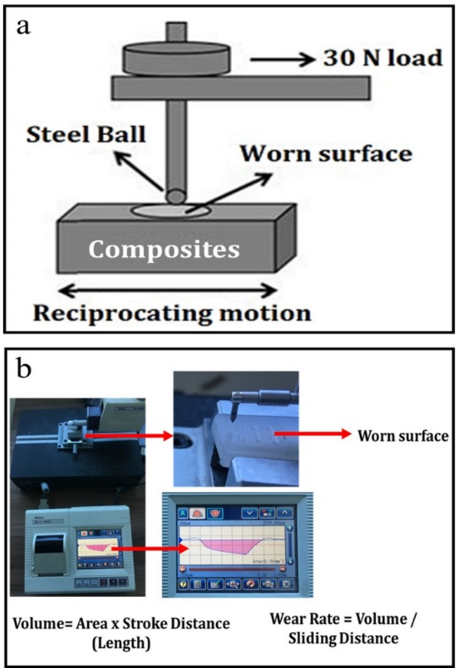

**Figure 3: (a) Schematic representation of the wear test device and (b) worn area measurement via Mitutoyo.**

Zeiss Ultra Plus Scanning Electron Microscope (SEM) was used for observation of the morphology of the broken and worn surfaces of pure Epoxy, SCFs-epoxy, and HTCs-epoxy composites after gold coating via sputter coater.

## 3 Results and Discussion

### 3.1 Impact test results

Figure 4 shows the impact test results of pure epoxy, epoxy reinforced-SCFs, and epoxy reinforced-HTCs samples. The addition of 3 and 5 wt.% SCFs into epoxy-reinforced composite have positive effects on improving the energy-absorbing behavior of epoxy-reinforced composite. So, for instance adding 5 wt.% of SCFs into pure epoxy (E5SCFs, 0.91 ± 0.36 J) boosted the energy-absorbing performance of the sample (Epoxy, 0.51 ± 0.32 J) approximately by 78.43%. This is probably because SEM images in Figure 5(a) show the presence of river lines and matrix cracks were responsible for the early failure of the Epoxy sample compared to other composites [23], [27]. Conversely, for the E5SCFs sample apart from small voids, no delamination and insignificant river lines were seen in the SEM morphologies. And hence, it exhibits better energy-absorbing capacity due to increased surface contact between SCFs fiber and epoxy matrix [28]. This result was in agreement with a previous study by Wong et al. [28], who also confirmed that an enhancement in energy absorption characteristics was noticed due to the increment in fiber contents of the reinforcement. Thus, this study found that composites with 5 wt.% SCFs (E5SCFs) have the highest energy-absorbing characteristics compared to Epoxy and HTCs-reinforced samples. On the contrary, incorporating HTCs into epoxy did not show any significant effects on the energy-absorbing characteristics of epoxy-based composite. The energy absorption of the E5SCFs composite was better than E3HTCs and E5HTCs samples nearly by 89.58 % and 68.52 %, respectively. Whereas, an energy absorbing performance of about 0.54 ± 0.12 J was noticed for E5HTCs composite. It was also investigated that the lowest energy-absorbing was noted for E3HTCs composites with 0.48 ± 0.18 J.

Moreover, the SEM morphological features of samples after destructive Izod impact tests are indicated in Figure 5. As can be seen from the SEM images taken at 250× magnification, Epoxy (Figure 5(a)) and HTCs epoxy-reinforced composite (Figures 5(d) and 5(e)) samples have relatively similar broken surface morphologies. But, the SEM images for SCFs integrated epoxy-reinforced composites (Figures 5(b) and 5(c)) revealed voids. This might be due to the formation of bubbles during the mixing of 3 and 5 wt.% contents of SCFs into epoxy composites. Therefore, after the Izod impact test, a 25 µm and 207.14 µm diameter void were noted in E3SCFs and E5SCFs, respectively. A chopped carbon fiber length of 71.43 µm was also seen in E3SCFs.

### 3.2 Wear test results

The specific wear resistance results of samples of pure epoxy, SCFs-reinforced epoxy (E3SCFs and E5SCFs), and HTCs-reinforced epoxy (E3HTCs and E5HTCs) were represented in Figure 6. A worn area of 0.304 mm2 was measured from wear track analysis of the Epoxy sample via Mitutoyo. Additionally, the lowest worn area was noted for the E5HTCs sample (0.154 mm2). This study confirmed that both reinforcements (SCFs & HTCs) have remarkable effects on the specific wear resistance

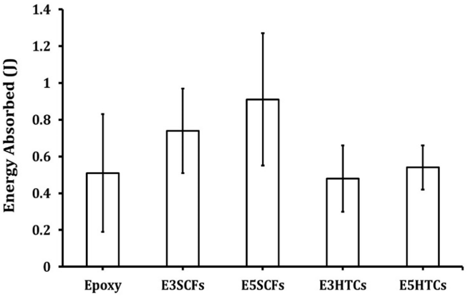

**Figure 4: The energy absorption capacity of samples.**

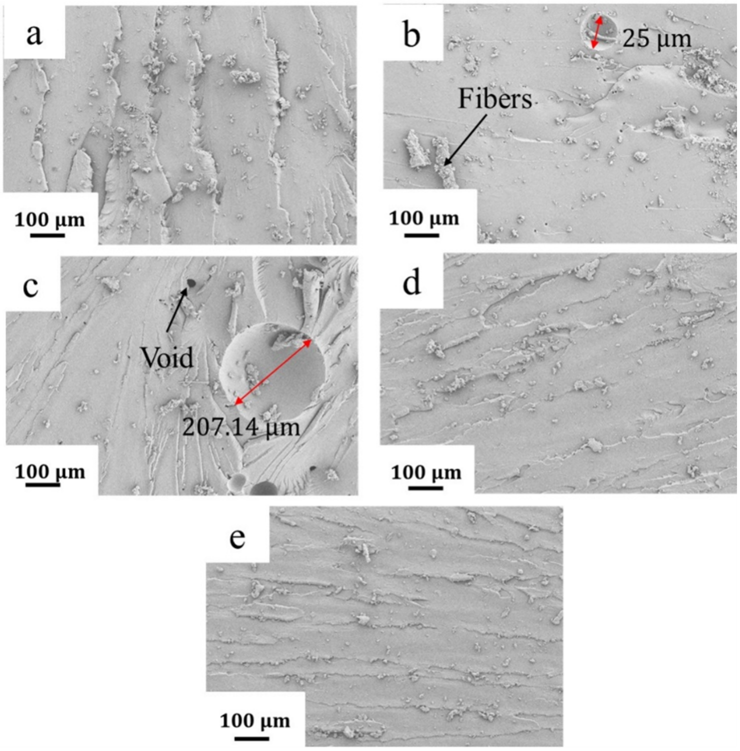

**Figure 5: SEM images of samples surface after impact test, (a) Epoxy, (b) E3SCFs, (c) E5SCFs, (d) E3HTCs, and (e) E5HTCs.**

properties of epoxy-based samples. The highest specific wear resistance was noticed when 5 wt.% HTCs were added to a pure epoxy matrix (E5HTCs). Conversely, the lowest specific wear resistance was recorded for the Epoxy sample nearly 0.51×10-3 mm3/N.m. Moreover, the incorporation of 5 wt.% of SCFs into pure epoxy enhanced the specific wear resistance of Epoxy by 41.77%. On the other hand, introducing 5 wt.% contents of HTCs into pure epoxy improved the specific wear resistance of Epoxy by 49.31%. This expressed that the addition of similar contents of SCFs and HTCs onto pure epoxy showed HTCs results in better influence in enhancing the specific wear resistance (lowest wear rate) of the epoxy-based composite compared to SCFs reinforced epoxy composite. Therefore, in this study, it was determined that the addition of 5 wt.% of SCFs and HTCs into pure epoxy significantly improved the specific wear resistance of pure epoxy. This is attributed to the self-lubricating effects of both SCFs and HTCs as noted in the study of Khun et al., and Xian and Zhang, respectively [13] [29]. Following the wear test it was visually observed that the Epoxy sample became more brittle and the epoxy component started to separate from the sample surface by the effect of friction load. Hence, this incident notably decreases the wear resistance of epoxy material. Similarly, a past wear test study by Ilhan and Feyzullahoğlu found that with the increment in temperature, the polyester becomes brittle and separated from the surface as a result of this its wear resistance properties get diminished [30].

Furthermore, the worn surfaces and details of wear morphologies in the wear regimes of Epoxy, E3SCFs, E5SCFs, E3HTCs, and E5HTCs were examined by using SEM at 250× magnification (Figure 7). Looking at Figures 7(b) and 7(c) embedded carbon fibers were noticed as compared to other samples. Also, the worn surface of the E5SCFs (Figure 7(c)) and E5HTCs (Figure 7(e)) composite was relatively smooth in contrast to all other samples. This may prove that these samples have higher wear

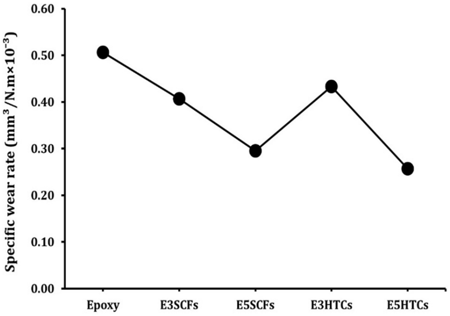

Figure 6: The specific wear rate of samples.

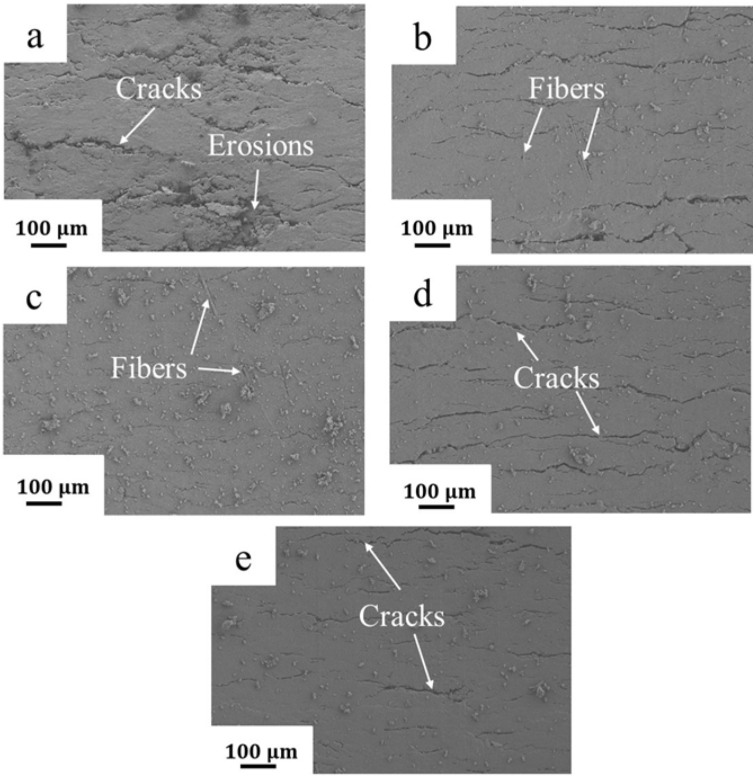

Figure 7: SEM images of worn surface of samples, (a) Epoxy, (b) E3SCFs, (c) E5SCFs, (d) E3HTCs, and (e) E5HTCs.

resistance characteristics. In addition, fewer sliding marks were noticed on their worn surfaces. Moreover, besides fewer sliding marks, compared to (Epoxy, E3SCFs, and E3HTCs) lesser matrix cracks were also noticed for E5SCFs and E5HTCs. Thus, the SEM image shows higher wear resistance was observed for 5 wt.% SCFs-epoxy (E5SCFs) and 5 wt.% HTCs epoxy-based composites (E5HTCs). On the other side, more scratches, cracks, and erosions were seen for the pure Epoxy sample. Here, in the pure Epoxy sample higher wear rates were observed probably due to the absence of reinforcement (SCFs or HTCs). Further, the SEM images of the worn surfaces gave information about the wear mechanism of samples. The presence of wear tracks (grooves) on the worn surface revealed that the abrasive wear mechanism contributes to the wear for all samples.

Figure 8 depicts the coefficient of friction (COF) observed during the wear behavior investigation of epoxy-based samples. The COF of composites E3SCFs, E5SCFs, E3HTCs, & E5HTCs at a constant normal load of 30 N and sliding speed of 2 mm/s is lower compared to the COF of the Epoxy sample. It is noted that increasing the weight percentage of both SCFs and HTCs fibers resulted in fibers being detached and stuck on the worn surface of the composites. Consequently, the presence of these fibers (SCFs and HTCs) between the composite samples and steel ball might reduce the COF due to the solid lubricant characteristics of SCFs and HTCs fibers. Therefore, as presented in Figure 8 the COF results determined for Epoxy and SCFs and HTCs reinforced epoxy composite samples are in complete agreement with some previous studies. Omrani et al. [31] found in their study the decrement of COF for 30%, 20%, and 10% amounts of carbon fiber-reinforced epoxy composites compared to pure epoxy. In another study, the COF of carbon fiber/epoxy composites was analyzed using a reciprocating pin on disc wear

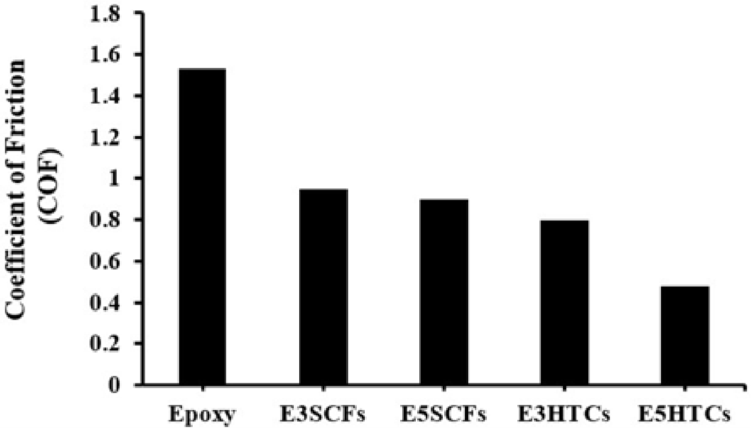

**Figure 8: Coefficient of friction values of different samples.**

tester device by Matsunaga et al. [32]. In their study, it was shown that the COF varied in the range of 0.10 - 0.25.

## 4 Conclusions

The present study confirmed that SCFs have positive effects on improving the energy-absorbing characteristics of epoxy-reinforced composites. Whereas, HTCs did not show any considerable effects on the energy-absorbing performance of epoxy-based samples. The SEM morphologies indicated that after the impact test, voids were noted for SCFs added epoxy-reinforced composites. Similarly, broken surfaces were seen for HTCs incorporated in epoxy-based composites and Epoxy samples. On the other side, wear on the matrix of the Epoxy sample, and cracking between fiber-matrix interfaces resulted in the pulling out of fibers from the matrix are the main wear mechanisms picked out from SEM investigation. Also, the SEM images for the worn surfaces indicated erosion and abrasive wear mechanisms were identified by the presence of wear tracks on the worn surfaces of composite samples. Here, under severe abrasive wear conditions, both SCFs and HTCs reinforced epoxy composites experience lower specific wear rates in comparison to the Epoxy sample. Thus, HTCs reinforced epoxy composites are the favorites to be used in tribological areas that need high wear-resistant properties at a load of 30 N. Also, the experimental results showed that the COF of E3HTCs and E5HTCs composite/steel pairs tested at 30 N load were in the range of 0.80 and 0.48, respectively. Also, it was observed that the COF decreases with the increment in SCFs and HTCs content. Therefore, utilizing E5HTCs may bring novel perspectives for tribological application areas. Contrariwise, the study suggests that using E5SCFs samples for structural areas, especially in beams, columns, partition walls, etc., is promising.

## Acknowledgments

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## Authors' Contributions

In this study, HÇ and YA created the idea, designed the structure, and evaluated the characterized results. Whereas SSMK and AKE performed a literature review, produced the samples, and completed experimental works. HÇ, YA, and AKE wrote up the article.

## Competing Interests

The authors declare that they have no conflict of interest.

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