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Effect of Short Carbon Fiber Content on the Mechanical and Tribological Behaviors of Polyurethane Foam-Based Composites

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ABSTRACT

This study aims to investigate the effect of different weight fractions (0.5, 1.0, and 1.5%) of short carbon fibers (SCFs) on the mechanical and tribological properties of polyurethane (PU) foam composites. The samples were fabricated using the hand lay-up method. To examine the mechanical properties of neat PU foam and composites (PU-SCF), 3-point bending tests were conducted. Moreover, a 5 N load was applied to assess the wear resistance properties of samples. The result of this study revealed that the flexural strength of PU0.5SCF composite was higher than PU1.5SCF nearly by 9.46%. Whereas, the addition of 1.5% mass fractions of SCFs onto neat PU have improved the wear resistance property by 78.95%. Moreover, the study showed that incorporating higher contents of SCFs into neat PU resulted in a direct increment in the flexural modulus of the composite. Therefore, the study confirmed that as the addition of SCFs into PU increases, the flexural strength of PU-SCF composites decreases. This was explained by the poor dispersion of SCFs into the PU matrix. However, it was also revealed that the flexural modulus and tribological properties of the composites enhanced significantly along with the increment of SCFs content.

Keywords: *Flexural modulus, Flexural strength, Polyurethane, Short carbon fibers, Wear.*

Kısa Karbon Elyaf İçeriğinin Poliüretan Köpük Bazlı Kompozitlerin Mekanik ve Tribolojik Davranışları Üzerindeki Etkisi

ÖZET

Bu çalışma, kırpılmış karbon elyafların (SCFs) farklı ağırlık oranlarının (%0,5, %1 ve %1,5) poliüretan köpük (PU) kompozitlerin mekanik ve tribolojik özellikleri üzerindeki etkisini araştırmayı amaçlamaktadır. Numuneler kalıba döküm yöntemi kullanılarak üretilmiştir. Saf poliüretan (PU) köpük ve kompozitlerin (SCFs-PU) mekanik özelliklerini araştırmak için 3 nokta eğme testleri yapılmıştır. Ayrıca, numunelerin aşınma direnci özelliklerini değerlendirmek için 5N yük uygulanılmıştır. Bu çalışmanın sonucu, ağırlıkça %0,5 SCFs içeren PU köpük bazlı kompozitin eğilme mukavemetinin, ağırlıkça %1,5 SCF içeren numuneden yaklaşık %9,46 daha yüksek olduğunu ortaya koymaktadır. Bu nedenle, PU matrisine daha yüksek miktarda SCF eklenmesinin, SCFs-PU köpük kompozitlerinin eğilme özelliklerinde azalma ile sonuçlandığı söylenebilmektedir. Bununla birlikte, saf poliüretana ağırlıkça %1,5 SCF eklenmesi, aşınma direnci özelliğini yaklaşık %78,95 oranında iyileştirmiştir. Sonuç olarak, PU köpüğe eklenen SCFs içeriği arttıkça SCF-PU kompozitlerinin mekanik özelliklerinin azaldığı tespit edilmiştir. Bununla birlikte, kompozitlerin tribolojik özellikleri önemli ölçüde artmaktadır.

Anahtar Kelimeler*: Eğilme modülü, Eğilme mukavemeti, Poliüretan, Kısa karbon elyaflar, Aşınma*

1. INTRODUCTION

Composite materials, which have superior properties compared to traditional materials, consist of the combination of two or more components at a macroscopic level and without dissolving with each other [1]. Polyurethane (PU) based composites are thermosetting polymer composite types that have a wide range of application areas including biomedical, aeronautical, sports, industries, and automotive, due to higher properties of chemical stability, specific strength, low relative density, strong, good stiffness, and outrageous wear resistance [2–6]. Bulk (rigid) or foam-type PU matrixed composites are most popularly used as construction material, because of their elevated durability, great strength-to-weight ratios, and inflated corrosion resistance [5].

Numerous manufacturing techniques exist for producing homogeneous composite materials, including hand lay-up methods, electric hand blenders, dispersion techniques, foaming, dry processing, and the melt

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extrusion of polymer powders [7]. The hand lay-up technique produces a homogeneous composite; however, it can occasionally lead to an uneven distribution of fibers within the matrix. In contrast, the electric hand blender mixing method is likely to yield a more uniform composite structure due to the continuous motion generated by the motor, which effectively disperses the fibers throughout the matrix. This advantage is not observed in the hand lay-up method, where the interrupted motion contributes to the occurrence of non-homogeneity.

According to the works of literature, since PU materials have high elasticity, toughness, and rapid cure time properties, nowadays polyurethane-based composites are increasing their application areas more than ever in industries and are also responsible for part of solutions in modern science. Hence, the number of studies on PU-based composite is drastically increased [5]. Despite PU's huge applications, their weak mechanical properties have been the barrier to their further applications in construction, automobile bodies, and aerospace structures. Thus, researchers have been trying to raise the mechanical properties of PU by adding organic and inorganic fillers into the PU matrixes [5]. Many types of fillers have been employed as reinforcement to improve PU's mechanical and physical properties [5,8–10]. Carbon fibers (CF) are the most commonly used inorganic fibers, because of their lightweight, excellent chemical stability, high-thermal resistance, and good mechanical properties. Lately, CF-based composites have become a better alternative for a wide range of applications [5,11]. Previous findings exhibited that too-short fibers show no significant reinforcing effects on the composite due to the smaller contacting area, while too-long fibers resulted in bad mobility when PU agents and fillers were agitated. Therefore, studies showed that the optimum average length of carbon fibers reinforced into a PU matrix is 3-12 mm [12]. Further, in most cases, short carbon fibers have a stronger effect on the composites compared to too short or long carbon fibers [9].

The literature survey indicated that fewer studies were conducted on short carbon fibers and their impacts on the mechanical properties of PU matrixed composites. For instance, the study of Yakushin et al. [9], exhibited that the compression strength of the PU foam was boosted by 20% with the addition of 4 wt.% SCFs. However, a significant decrement in the elongation at the break of the PU foams was observed as the content of CF increased to 8 wt.%. In another study [13], the effects of different types of fibers and fiber contents of 10 to 20% on the tensile strength and bending performance of the PU matrix composites were examined. According to the test outcomes, higher flexural bending strength and higher energy absorption were obtained for 20% CF reinforced composites compared to the same content of jute felt, jute tablets, and glass fiber reinforced composites. For PU foam-added carbon fiber reinforced plastics (CFRP) composite tubes the peak force and threshold force were increased nearly by 132% for PU foam-based CFRP composite tubes than pure CFRP polymer was investigated [14]. In addition, the effect of hardener on the mechanical properties of carbon fiber-reinforced phenolic resin composites was also evaluated in the work of Sulaiman et al., [3]. Results revealed that composites containing 15% hardener (hexamine) content exhibit enhancements in flexural strength, due to the hardener amount increasing the crosslinks between phenolic resin and carbon fibers.

Furthermore, the influence of SCF's content on the wear resistance characteristics of PU foam-based composites was explained in a few research works. The work of Li and Cai [15] reported that CF-reinforced polypropylene (PP) composite (CF/PP) had superior tribological characteristics compared to pure PP. In another study by Khun et al., the wear rate and friction coefficient of epoxy-based composites were remarkably reduced with the increment of chopped carbon fiber content [16]. Moreover, Zhao et al., [17], studied tensile strength, wear, and friction properties of rigid-type PU composite reinforced with CF. Test assessment exhibited that chemically surface-treated CFs improved the tribological properties of PU composites. Also, the tensile strength is enhanced with the inclusion of CFs. The effects of different weight fractions of chopped carbon fiber on the effectiveness of wear resistance enhancement of high-density polyethylene (HDPE) were studied by Yasin et al., [18]. In their study, they found that 10 wt.% SCFs composites displayed supreme wear efficiency in SBF fluid conditions. Further, under the influence of seawater lubrication, the tribological behaviors of CF/PEEK were studied [19]. The result indicated that when the volume fraction of CF was about 10% then it greatly improved the wear and friction behaviors of the CF/PEEK composite. Additionally, Alagarraja et al., [20], studied the wear properties of composites using reinforced matrix via synthetic and natural fibers of carbon, PU, jute, sugarcane, glass, and banana. According to test results, foam-type sandwich materials' wear resistance characteristics built up when the foam and natural fibers materials were merged.

Therefore, nowadays different polymer-based composites are available in a broad range due to their crucial applications in various areas. The majority of past literature studies presented in Table 1 were mainly focused on carbon fibers reinforced bulk (rigid) polyurethane-based composites. However, in this study, the influence of SCFs-reinforced PU-foam-based composites was investigated. Here, the effects of different contents of SCFs (0.5, 1.0, and 1.5 wt.%) on the mechanical (flexural strength and flexural modulus) and wear resistance properties of PU-SCFs foam-based composites were examined. Moreover, the morphology of broken and worn surfaces of pure PU foam and PU-SCF composites was characterized by a scanning electron microscope (SEM).

Table 1. Summarized past studies

No	Sample Code	Results	Ref.
1	GF, SiC, and Al_2O_3-reinforced PU	Under an applied load of 5 and 10 N and sliding distance of 100 m, GF, SiC, and Al_2O_3-fillers enhanced the wear resistance properties of PU.	[21]
2	CFPC NP/PU	The application of the NP/PU nanocomposite coating resulted in notable enhancements in the flexural strength and impact resistance of the CFPC, with improvements of 9% and 14.7%, respectively.	[22]
3	SGF/PU	The wear performance of SGF/PU composites shows that wear volume increases with higher fiber content, while the specific wear rate decreases with increased load.	[23]
4	CFR-PU	The PU foam composite board reinforced with carbon fibers (CFR-PU) exhibits enhanced toughness and improved resistance to deformation.	[12]
5	DS-CFs/RPU	The tensile strength, impact strength, and interfacial shear strength (ILSS) of the dendritic short carbon fibers reinforced polyurethane (RPU) composites exhibited increases of 41.3%, 81.2%, and 28.9%, respectively, in comparison to pure RPU.	[24]

2. MATERIAL AND METHOD

2.1. Short Carbon Fibers

Short carbon fibers with an average length of 6-12 mm were purchased from Dost Kimya, Türkiye. Polyol and isocyanate used were supplied by Kimpur, Türkiye. The SEM images of short carbon fibers are depicted below in Figure 1.

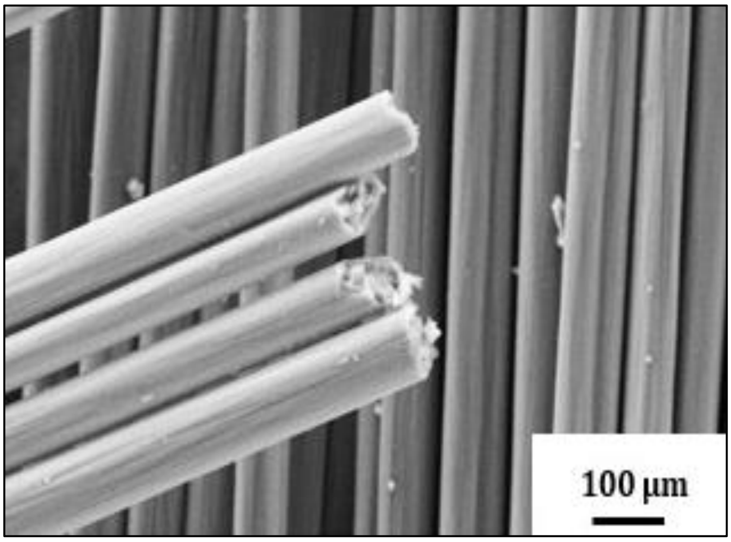

Figure 1. SEM images of short carbon fibers

2.2. Casting of Samples

Samples of PU-foam and PU-SCF composites were fabricated using a mold depicted below in Figure 2 depending on the compositions stated in Table 2. Different contents of SCFs (0.5, 1.0, and 1.5 wt.%) were homogeneously mixed with polymeric isocyanates in a beaker. Then, polyols that create curing are added to the homogenous mixture of SCFs and isocyanate. There was little time between homogenous mixing and casting of polyol. Thus, the composite mixture available in the liquid state was poured directly into the mold after a quick mixing. Samples were cast evenly in the casting mold using the hand lay-up technique. Here, during the sample's preparation via the hand lay-up technique, there might be some limitations related to agglomeration due to the inability to ensure a homogeneous distribution of SCFs in the PU matrix. Thus, great care must be imposed in the composite production methods. The foaming reaction starts after curating and an increase in volume was observed. After the reaction was over, the samples were removed from the mold and ground by 240 grit sandpapers to prepare the samples according to ASTM D790 standard for the flexural bending test. These processes were carried out repeatedly for the production of each sample.

Table 2. Composition of composites

Sample Code	Short Carbon Fibers (SCFs)	Polyurethane (PU)
	Percentage **(wt.%)**	
PU	-	100
PU0.5SCF	0.5	99.5
PU1.0SCF	1.0	99
PU1.5SCF	1.5	98.5

Figure 2. Mold for Flexural test samples

Figure 3 shows the fabricated samples of composites and pure PU foam. Figures 3(a)-3(c) indicate PU foam-based composites reinforced with 1.5, 1.0, and 0.5 wt.% SCFs, respectively. A pure foam-based PU polymer sample was indicated in Figure 3(d).

Figure 3. PU-SCF foam-based composites and pure PU foam

3. CHARACTERIZATION

To facilitate the characterization of the mechanical properties, samples were fabricated with dimensions according to standards. The flexural bending and wear tests were conducted using machines illustrated in Figure 4. According to Figure 4(a), the flexural strength tests were carried out three times for each sample having a dimension of 158 mm × 13 mm × 4.5 mm at a constant speed of 2 mm/min using a Zwick Roell 600KN test device. During the test, the span length for each specimen is 127 mm. Mathematically the flexural strength "σ" and flexural modulus "E_F" of samples were analyzed via Eq. 1 and Eq. 2, respectively [25].

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

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

Where F is the applied load (N), L is the span length (mm), w designates sample width (mm), t designates the thickness of the specimens (mm), and m is the slope of the linear section in the load versus deformation curve.

On the other hand, wear tests were carried out by UTS Tribometer T10/20 apparatus as can be seen in Figure 4(b) under dry-sliding conditions. In the course of the wear test, an applied load of 5 N along with a stainless-steel ball diameter of 6 mm, a stroke of 10 mm, a sliding rate of 40 mm/s, and a sliding distance of 25 m were used. In addition, theoretically, the volumetric wear rate can also be calculated using Eq. 3. A scanning electron microscope (Zeiss Ultra Plus) was used to examine the morphology of damaged (i.e., broken and worn) surfaces of samples after damaged samples were coated with gold using a sputter coater (Quorum, Q150R ES Plus).

$$W_r = W_v = \frac{2ab}{3}c \Big/ L \tag{3}$$

where W_v designates volumetric wear loss (mm3/s), a is the stroke distance (mm), b represents wear width (mm), L designates sliding distance (mm), and c indicates wear depth (mm) [26,27].

Figure 4. a) Zwick Roell flexural strength tester and b) UTS Tribometer T10/20 wear tester device

4. RESULTS AND DISCUSSION

4.1. Mechanical Properties

Figures 5(a) and 5(b) show the fracture surfaces of various contents of SCFs (1.0, and 0.5 wt.%) reinforced PU foam composites, respectively. In addition, the broken surface of neat PU foam is presented in Figure 5(c). The cause of the fracture is attributed to the existence of higher stress concentrations around a large number of pores resulting in PU matrix crack initiation. Also, it was said in the literature that the primary damage mechanism to appear is matrix crack initiation [14]. These micro PU matrix cracks originate from micro-pores formed during curing and tend to propagate and connect under applied load leading to SCF fracture and finally causing composite failure as can be noticed in Figure 5 [28].

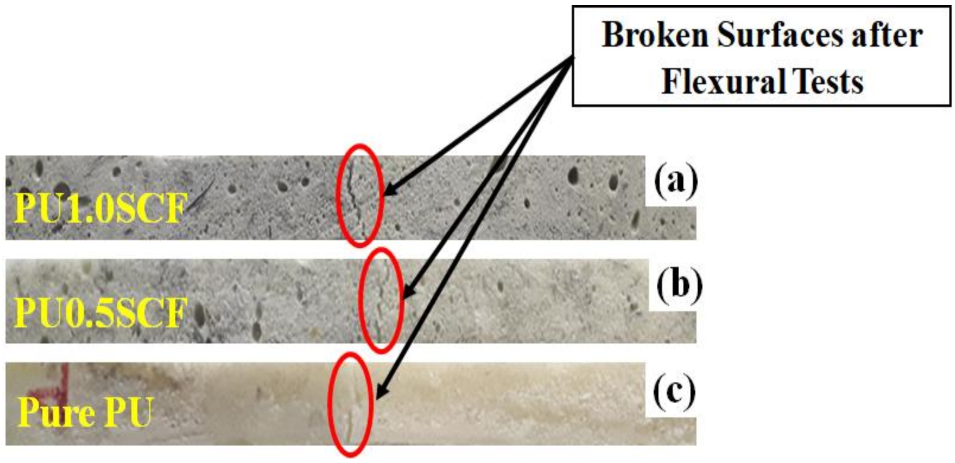

Figure 5. Flexural test results of pure PU foam and PU-SCF composites

Figure 6 expressed the force-deformation graphs of pure PU and PU composites reinforced with different contents of SCFs (0.5, 1.0, and 1.5 wt.%). As can be seen in the figures, a gradual increment in loading results in a notable increment in the load supporting of samples by gradual deformation. Thus, there were linear and nonlinear curves were noted in the load-deformation graph until the force reached its maximum peak value. After reaching the highest load point, the reinforced PU foam composites and PU-foam sample's force-deformation curve starts to decline considerably. This might be due to the presence of higher stress concentration and crack propagation factors around foam porosities [5]. Furthermore, as can be observed from the SEM image (i.e., Figure 7) the presence of weak interfacial bonding can be taken as a cause for the reduction of the load-carrying capacity of the PU-SCF composites compared with pure PU foam. And hence, these weak interfacial bonding between SCFs and PU matrix were responsible for the low load-carrying capacity of composites and also resulted in early deformation for SCFs incorporated composites than pure PU foam [14]. Thus, the maximum deformation of 5.95 mm was observed for pure PU foam at a peak load of nearly 142.33 N in contrast to all the samples illustrated in Figure 6. However, the addition of 0.5 wt.% SCFs into pure PU resulted in a deformation of 5.59 mm at a load of 61.62 N. Further adding of 1.5 wt.% SCFs in pure PU bring a reduction in the deformation by 37.21% compared to pure PU foam.

SEM observations were implemented on the fractured surfaces to verify the failure mechanism of samples. Figure 7(a) shows the presence of crushed PU matrix cells, porosities, and PU matrix cracks on the fractured surface of the PU foam sample. This is probably due to the absence of load-supporting fibers (SCFs). Figures 7(c) and 7(d) indicate the broken surfaces of PU1.0SCF and PU1.5SCF foam-based composites, respectively. Broken SCFs, PU matrix cracks, and broken composite pieces were noted for these samples after the flexural bending tests. On the other side, the PU0.5SCF composite (Figure 7(b)) has relatively better interfacial bonding between SCFs and PU matrixes as compared to both PU1.0SCF and PU1.5SCF. This might be due to as the contents of short carbon fibers increased; it was hard to mix them with the PU matrix because of the increase in viscosity. Hence, it resulted in poor dispersion of SCFs in the PU matrix. Also, voids are formed and shown in Figure 7(d) [5]. These defects are responsible for the reduction of the mechanical properties (flexural strength) of the composites.

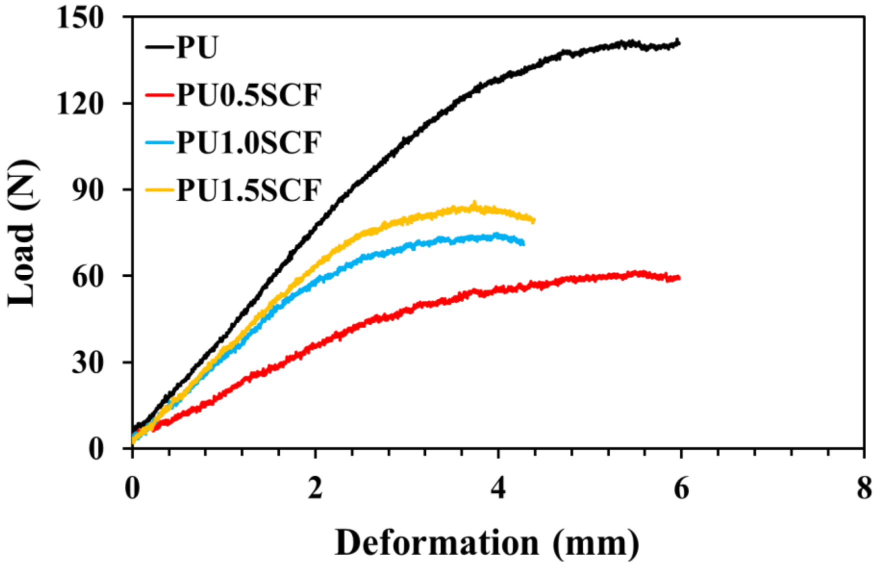

Figure 6. Load versus deformation curves for samples

On the contrary, when the fiber content is low, the possibility of diffusion of SCFs through the PU matrix is enhanced. Therefore, the probability of interfacial bond formation between fiber and matrix increased [28]. The SEM studies also indicate that in lower SCF-reinforced PU composites, damage to the matrix was more significant than fiber fracture. Conversely, in composites reinforced with higher SCFs, fiber damage was also notably evident.

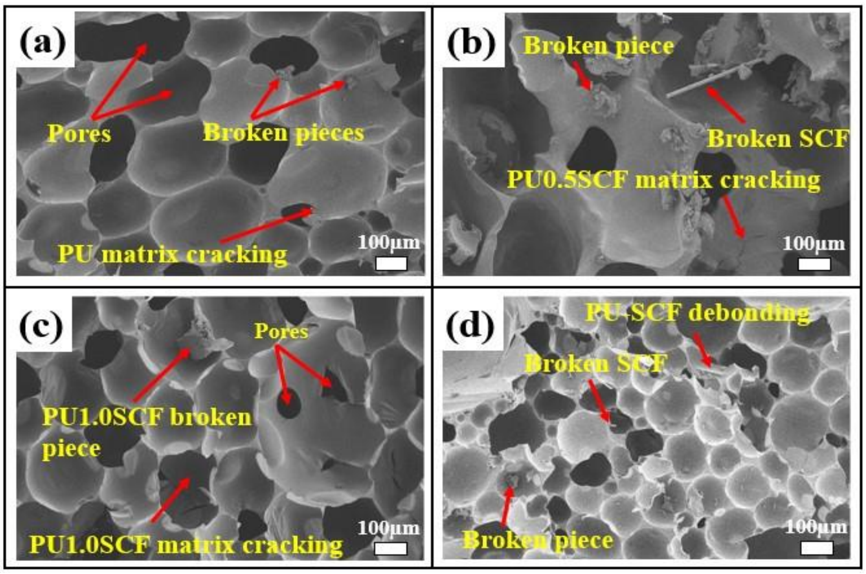

Figure 7. SEM images of broken surfaces of; (a) PU; (b) PU0.5SCF; (c) PU1.0SCF; (d) PU1.5SCF

Furthermore, the mechanical properties of the present samples were explained by conducting flexural bending tests. The flexural strength and modulus of pure PU polymer foam and PU-SCF composites are illustrated in Figure 8. As can be seen, it was determined that the maximum flexural strength was noticed for pure PU of 5.88 ± 1.57 MPa. In addition, the test result revealed the flexural strength of pure PU foam was better than PU0.5SCF and PU1.0SCF composite nearly by 15.52% and 173.5%, respectively. This might be due to, adding higher SCFs fillers as reinforcement into pure PU foam-based composites results in the agglomeration of fibers despite enormous care was given during the composite preparation, and hence, stress concentration increases around the irregular voids formed due to the agglomeration of fibers. Consequently, the mechanical strength of the material starts to deteriorate [5]. The other reason for the reduction in flexural strength with increment in SCF content is due to debonding, which occurs during the flexural bending test when the stress weakens the interactions between SCFs and the polyurethane matrix. This is shown in Figure 7(d), highlighting weak interfacial bonding. Consequently, the force transfer from the matrix to the fiber is reduced, negatively impacting the flexural load-bearing capacity of the PU-SCF composite compared to the neat PU sample. Similar results were reported in the research work of Akgul et al. [29]. In their study, it was shown that the flexural strength of SCFs reinforced Polyester composite decreases with the increment of SCFs. In another study, it was also revealed that better flexural strength was observed in 5 wt.% carbon fiber reinforced polyester composite as compared to 10 wt.% [30]. On the other side, it was seen that the addition of SCFs into pure PU enhanced the flexural modulus of the reinforced PU composites. So, the composite having a higher content of SCFs (1.5 wt.%) (PU1.5SCF) became stiffer than composites with fewer contents of SCFs. For instance, incorporating 1.5 wt.% of SCFs into pure PU improved the flexural modulus of pure PU nearly by 91.36%. The study also found that 192.32 ± 153.98 MPa was the highest flexural modulus of the PU1.5SCF composite. Whereas, the lowest flexural modulus was reported for pure PU foam (100.5 ± 5.01 MPa).

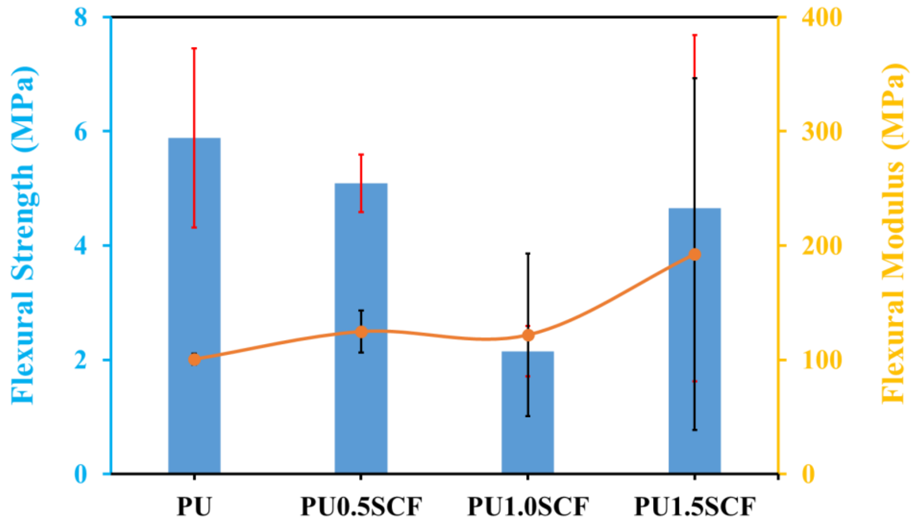

Figure 8. Flexural strength and flexural modulus of samples

4.2. Tribological Properties

The wear resistance results of pure PU foam and reinforced PU with different weight fractions of SCFs composites were indicated in Figure 9. According to test results, the highest wear resistance characteristics were noticed when 1.5 wt.% SCFs were added to the pure polyurethane matrix. This is attributed to the self-lubricating properties of short carbon fibers [16,18]. However, when the SCFs content decreased to 0.5 wt.% a remarkable reduction in the wear resistance was observed. This is due to the presence of lower contents of self-lubricating SCFs compared to samples with higher contents of SCFs (PU1.0SCF and PU1.5SCF). Additionally, as mentioned above the flexural modulus of the composite PU1.5SCF was improved by introducing higher contents of SCFs (1.5 wt.%) into pure PU compared to other samples. Thus, a higher modulus caused the sample to become stiffer and escalated wear resistance characteristics as well. So, as shown in Figure 9 the wear rate of PU1.5SCF was considerably lower in comparison to other samples.

SEM observations on worn surfaces of pure PU and PU-SCF foam-based composites were conducted and represented in Figure 10. The worn surface of the PU1.5SCF composite was relatively smooth and small size worn debris was examined as shown in Figure 10(d). This may prove higher SCFs content enhanced the wear resistance characteristics of composites. Therefore, when 1.5 wt.% SCFs were added to pure PU polymer foam; it led to an improvement in the wear resistance property approximately by 78.95%. Figure 10(c) shows, the worn surface of PU1.0SCF composite material. Here, delamination, wear debris, and broken short carbon fibers were observed. In addition, as depicted below Figure 10(a) indicates the worn surface of pure PU foam material. Here, higher contents of wear debris were noticed. Additionally, compared to all the samples the lowest wear resistance property was noticed for pure PU foam, (highest wear rate value of 0.228 mm3/m). This signifies SCF had a significant effect on the improvement of the wear resistance of composite materials. On the other hand, the worn surfaces of the PU0.5SCF composite are given in Figure 10(b). When 0.5 wt.% SCFs were added to the PU matrix, which resulted in a composite having a wear rate value of 0.164 mm3/m. The wear result of this study was in complete agreement with previous studies [16,18]. Further, the coefficient of friction (COF) created between contacting bodies had a notable effect on the wear properties of the contacted samples. Although applied load had a direct influence on the COF.

Nevertheless, in this study, the load value is constant for all experiments (5 N). However, the effect of COF can be defined as related to the content of SCF. Here, again considering Figure 9, it was shown because of an increment in SCF content led to a decrement in the COF. This might be related to the presence of a large number of stiff carbon fibers in the reinforced composite [25]. Thus, as demonstrated in Figure 9 the wear resistance characteristics of the composite samples are better than the pure PU foam. Therefore, the study investigates the least COF observed for PU1.5SCF with 1.52, while the highest COF of 2.22 noted for pure PU.

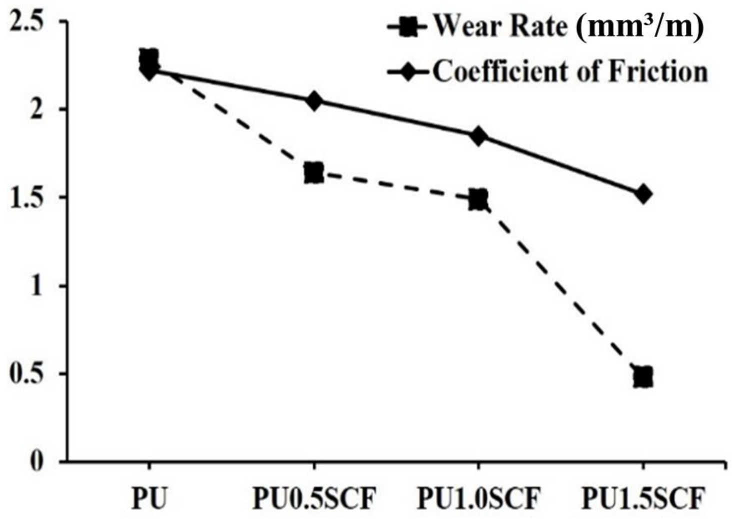

Figure 9. Wear rate and coefficient of friction values for different samples

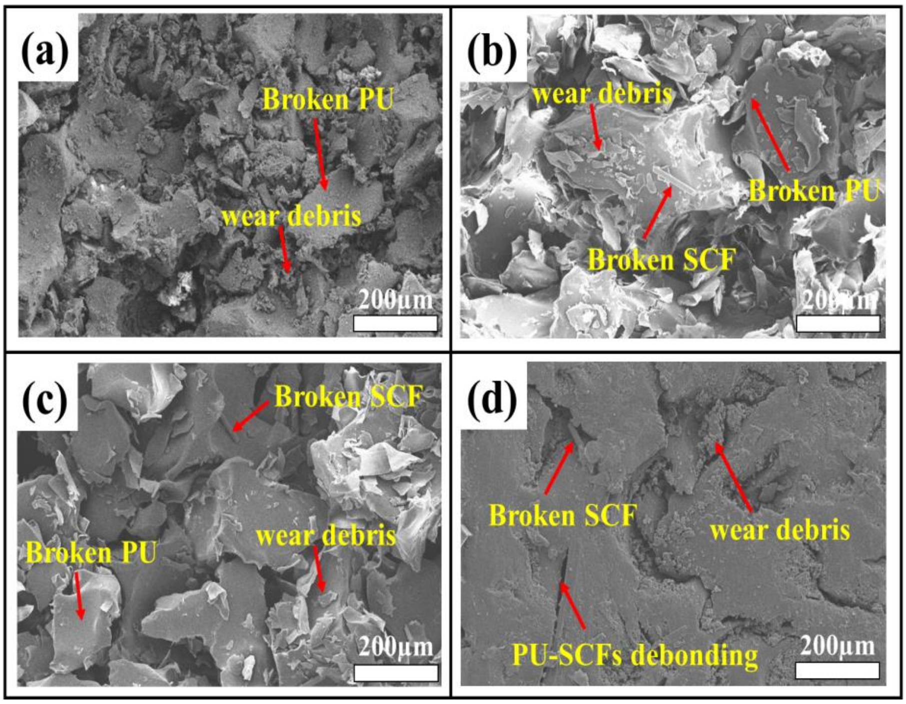

Figure 10. SEM images of worn surfaces of; (a) PU; (b) PU0.5SCF; (c) PU1.0SCF; (d) PU1.5SCF

5. CONCLUSIONS

The present study confirmed that the increment of short carbon fibers (SCFs) from (0.5-1.5 wt.%), resulted in a decrement in the flexural strength of SCFs reinforced polyurethane (PU) foam matrix composites. The addition of 0.5 wt.% SCFs into pure PU foam matrix cause higher flexural strength than 1.0 wt.% and 1.5 wt.% SCFs reinforced polyurethane foam composites. This was explained by the dispersion of SCFs in the PU matrix, stress concentration, and interfacial debonding factors. Whereas, incorporating various contents of SCFs into PU-based composite had a positive impact on enhancing the flexural modulus of the composite. Moreover, this study found that the content of short carbon fibers had significant effects on the tribological characteristics of polyurethane foam-based composites. The wear resistance of the composites was increased nearly by 78.95% with the addition of 1.5 wt.% chopped carbon fibers into a pure PU foam matrix. Thus, a superior improvement in the wear resistance property was noticed for the PU1.5SCF composite. However, the lowest wear resistance was recorded for pure PU foam. This was attributed to the missing of self-lubricating reinforcement fibers like SCFs. Furthermore, a short carbon fiber content of 1.5 wt.% reinforced pure PU foam matrix had smoother worn surfaces compared to the worn surfaces of both pure PU foam (PU) and composite materials (PU0.5SCF and PU1.0SCF).

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