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Research Article

Effect of Chopped Carbon Fibers Amount on the Mechanical and Tribological Properties of Polyester Matrix Composite

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ABSTRACT

In this study, the effect of the amount of short carbon fibers (SCFs) on the mechanical and tribological properties of polyester (PES) composite were investigated. Composites were produced with different weight fractions (0.5%, 1%, and 2%) of SCFs by the hand lay-up method. The flexural strength and flexural modulus of samples was studied by conducting 3-point bending tests, whereas the energy-absorbing performance was examined by performing the Izod impact test. Moreover, the wear resistance properties of samples were measured by applying a 20 N load. The scanning electron microscope was used to examine the morphology of broken and worn surfaces of specimens. Test results exhibit the flexural strength and flexural modulus of SCFs reinforced polyester composite was decreased with the increment of fiber contents. However, the same trend was not observed for the impact test. Thus, the addition of 2 wt. % SCFs onto pure polyester improves the energy absorbing of pure polyester nearly by 210%. The present study also reveals the wear resistance properties of SCFs reinforced polyester composites are indirectly related with of SCFs content. Hence, the highest wear resistance capacity was observed for PES0.5CF of about 1.51×10^{-3} mm^3/m. Therefore, the addition of small amounts of SCFs onto pure polyester attributes significant effects in tribological behaviors compared to mechanical properties.
Keywords: *Short Carbon Fibers, Polyester, Flexural Strength, Flexural Modulus, Impact Strength, Wear Resistance*

Kırpılmış Karbon Elyaf İçeriğinin Polyester Matrisli Kompozitlerin Mekanik ve Tribolojik Özelliklerine Olan Etkisi

ÖZET

Bu çalışmada, kısa karbon elyaf (SCFs) içeriğinin polyester (PES) kompozitin mekanik ve tribolojik özellikleri üzerindeki etkileri araştırılmıştır. El yatırması yöntemiyle ağırlıkça farklı oranlarda (%0,5, %1 ve %2) SCF'ler içeren kompozitler üretilmiştir. Numunelerin eğilme mukavemeti 3 noktalı eğilme testleri ile, darbe sönümleme performansları ise İzod darbe testi yapılarak incelenmiştir. Ayrıca numunelerin aşınma direnci özellikleri 20 N yük uygulanarak ölçülmüştür. Numunelerin kırık ve aşınmış yüzeylerinin morfolojisini incelemek için taramalı elektron mikroskobu kullanılmıştır. Test sonuçları, lif içeriğinin artmasıyla SCF takviyeli polyester kompozitin eğilme mukavemetinin azaldığını göstermektedir. Ancak, darbe dayanımı analizinde aynı eğilim gözlemlenmemiştir. Böylece, %2 SCF takviyesi ile PES2CF'nin darbe dayanımını, saf polyestere göre yaklaşık %210 oranında artmıştır. Bu çalışma aynı zamanda SCF takviyeli polyester kompozitlerin aşınma direnci özelliklerinin SCF içeriği ile dolaylı olarak ilişkili olduğunu ortaya koymaktadır. Dolayısıyla, en yüksek aşınma direnci (1.51×10^{-3} mm^3/m) PES0.5CF numunesi için görülmüştür. Bu nedenle, saf polyester üzerine düşük oranlarda SCF içeriğinin eklenmesi, mekanik özelliklere kıyasla tribolojik davranışlarda önemli etkiler göstermiştir.
Anahtar Kelimeler: *Kırpılmış Karbon Elyaflar, Polyester, Eğme Dayanımı, Darbe Dayanımı, Aşınma Direnci*

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I. INTRODUCTION

Fiber reinforced polymer matrix composites are produced of a polymer matrix reinforced fibers such as carbon, glass, and aramid. Epoxy, vinyl ester and polyester thermoset polymers are generally used as matrix materials. Polymer composite materials are used in many application areas such as in an automobile, aircraft, tire reinforcement, sports goods, and construction industries. This is due to their various mechanical and tribological properties include lightweights, corrosion and wear resistance, and higher strength [1]–[4]. Polyester matrices are reinforced with carbon fibers to produce carbon fiber reinforced polyester-based composites (CFRP). Carbon fiber reinforced polyester composites have many more application areas due to their higher stiffness properties; such as for structural components in rocket motor cases, boat hulls, and chemical reaction vessels [3]. On the other hand, the polyester matrix provides toughness and ductility for the CFRP materials. However, because of the characteristics of polyester polymers matrix, polyester-based composites have some drawbacks. They have comparatively low impact strength due to absorbing water very easily in the curing process [3]. Therefore, polyester matrices are usually reinforced with carbon fibers to improve their mechanical and tribological load withstand capacity [4]. The literature survey showed that so far different researches have been done to enhance the mechanical and tribological properties of carbon-reinforced polyester composites.

Nancharaiah and Anusha [5] investigate the mechanical properties of carbon fiber reinforced polyester composites at different weight percentages of 0.4-2 %. According to the test results, the impact strength of the carbon fiber reinforced polyester composite increases with the fiber loading. So, the highest impact strength of the composite was observed when 2 wt. % carbon fiber reinforced with pure polyester composite. In another study by Durairaj et al. [6], the effects of carbon and glass fibers on the mechanical properties of polyester matrix composites were investigated. Test results show the flexural strength of 5 wt. % carbon fiber reinforced composites was better than 10 wt. % carbon fiber reinforced composite. However, the impact strength of carbon fiber reinforced composite increases directly with the fiber loading content. Impact toughness which characterizes the behavior of the materials subjected to high-speed loading is among the important mechanical properties of materials for structural applications. In another similar study [7], it was reported to the impact strength of the composite improves with fiber content.

On the other hand, few studies were investigated on the effects of SCFs on the wear performance of polyester matrix composites. Xian and Zhang [8] in their studies revealed that there was a great reduction in the wear rate of polyetherimide (PEI) due to the lubricating effect of SCFs. Moreover, as reported by Akgul [9] the wear resistance properties of high-density polyethylene (HDPE) increase for lower SCFs contents. Thus, composites containing 10 wt. % SCFs showed the best wear performance in SBF fluid conditions than 20 wt. % SCFs inclusion composites. The effect of surface modification of carbon fibers on the interaction at the fiber-matrix interface in UHMWPE-based composites was studied in the works of Chukov et al. [10]. Results show that the increment on the carbon fiber reinforcement reduced the wear resistance properties notably.

As mentioned above, the effect of SCFs content on the tribological behavior of PES was not studied in previous studies [5]–[7]. Furthermore, past researches stated above were mainly concentrated on the mechanical properties of PES composites and did not consider the morphology of broken and worn surfaces of composites. Therefore, the present study aims to investigate the influences of different wt. % of SCFs on the mechanical and tribological properties of polyester-based composites. Moreover, the morphology of broken and worn surfaces of both composites and pure polyester samples was analyzed by scanning electron microscope.

II. EXPERIMENTAL PART

A. MATERIALS

Short carbon fibers (SCFs) with an average length of 3-6 mm were purchased from Dost Kimya, Turkey. Polyester resin and Cobalt catalyst and methyl ethyl ketone peroxide (MEKP) were supplied from Omnis Kompozit, Turkey.

B. FABRICATION OF PURE POLYESTER AND COMPOSITE MATERIALS

In the study, samples were coded and the composition of each of the specimens was shown in Table 1. To produce polyester composites, 1% Cobalt catalyst and MEKP as a catalyst were added to polyester. Composites were produced by hand lay-up using the molds shown in Figure 1. Samples used for flexural bending tests were fabricated with (158 × 13 × 5) mm dimensions. In addition, (80 × 10 × 10) mm dimension samples were also produced for the Izod impact tests.

Table 1. *Compositions of fabricated samples.*

Samples Code	Short Carbon Fibers (SCFs)	Polyester (PES)
	(Wt. %)	(Wt. %)
PES	0	100
PES0.5CF	0.5	99.5
PES1CF	1	99
PES2CF	2	98

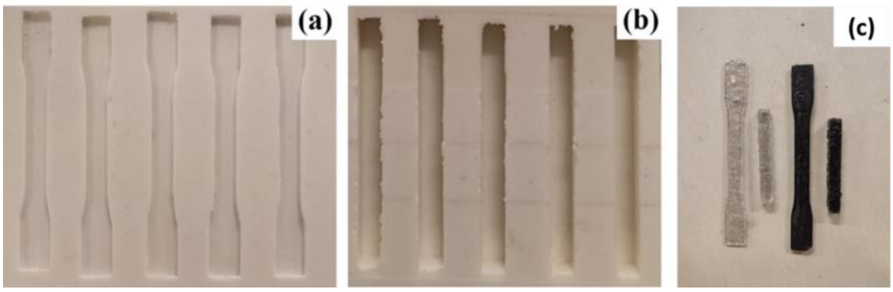

Figure 1. *Mold for (a) flexural bending test samples, (b) Izod impact test samples, and (c) images of produced samples.*

C. CHARACTERIZATION

Zwick Roell test machine with 600 KN capacity and 2 mm/min loading rate was used to perform 3-point flexural bending tests. The tests were conducted three times for each composite and pure polyester sample according to the ASTM D790 standard. The flexural bending strength "σ" of samples was calculated by Eq. (1).

$$\sigma = \frac{3\mathrm{FL}}{2\mathrm{b}a^2} \tag{1}$$

Where: 'F', 'L', 'b', and 'a' represent bending load (N), support span length (mm), a width of the sample (mm), and thickness of the specimens (mm), respectively [11]. A test device Zwick Roell RKP 450 with a loading capacity of 450J was used to perform Izod impact tests. Here, the tests were carried out three times for each sample according to the ASTM D256 standard, and the mean value of the result was considered.

On the other hand, UTS Tribometer T10/20 apparatus was used to investigate the wear resistance properties of composite and pure polyester specimens under dry-sliding conditions. Parameters such as; an applied load of 20 N, stainless steel ball diameter of 6 mm, a sliding distance of 150 m, sliding speed of 40 mm/sec, and a stroke length of 10 mm were used during the reciprocating wear analysis. The wear rate was calculated based on Archard approaches.

$$Wear\ Rate = \frac{Wv}{l} \tag{2}$$

Where: 'Wv' is volumetric wear loss and 'l' is the sliding distance [12]. Mitutoyo SJ-410 instrument was used to compute the volumetric wear loss of specimens according to the ISO 4287-1997 standard. Furthermore, broken and worn surfaces of samples were examined by using a scanning electron microscope (SEM) after being samples were coated with gold by a sputter coater (Quorum, Q150R ES Plus). Mechanical and tribological behaviors of samples were characterized by the testing devices represented in Figure 2. A flexural bending strength test of the PES sample was indicated in Figure 2(a). In addition, Izod impact and wear resistance properties were analyzed under Figures 2(b) and 2(c), respectively.

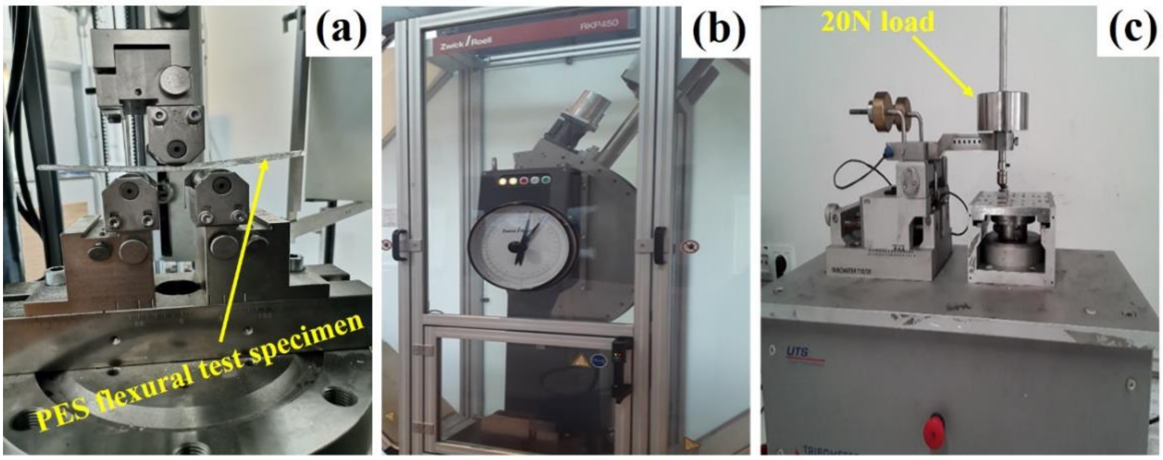

Figure 2. *(a) Flexural bending test, (b) Izod impact test, and (c) Pin-on-disc wear test.*

III. RESULTS AND DISCUSSION

A. MECHANICAL PROPERTIES

Figure 3 shows the flexural strength and impact resistance properties of composites and pure polyester samples at a different weighted percentage of chopped carbon fibers (0.5, 1, and 2 %). Also, the morphology of samples was examined by scanning electron microscope as indicated in Figure 4. This SEM study helps to observe both the distribution of SCFs in the polyester matrix and the interaction between fibers (SCFs) and the PES matrix.

The graph (Figure 3) represents when the addition of SCFs into pure PE increases from 0.5-2 wt. % attributes to the decrement in the flexural strength of resulted composites indirectly. The reason for the reduction of the flexural strength at high SCFs content was due to the presence of lower fiber-to-fiber interaction, pores, debonding, agglomeration, and poor dispersion SCFs into the polyester matrix [5]. In the course of the composite fabrication process, micro-pores were formed at the curing stages. In addition, more pores were appeared in the composite due to the viscosity in the sample created by the increment of SCFs content [13]. This incident was observed in Figures 4(c) and 4(d) when 1 and 2 wt.

% SCFs were added onto pure PES composite. Thus, during flexural strength tests, an externally applied load was responsible for the significant development of stress concentration around the porosity (voids). This stress results in the losses of interactions between SCFs and polyester matrix (Debonding). Hence, a weak interfacial bonding was shown in Figures 4(c) and 4(d) due to the presence of debonding. So, the force transferred from matrix to fiber is reduced significantly. Therefore, the presence of pores and debonding reduces the flexural load carrying capacity of the composite compared with the pure polyester sample [14]. The mechanical properties of all samples were expressed in Table 2.

Table 2. *Mechanical properties of fabricated samples.*

Sample	Flexural Strength (MPa)	Flexural Modulus (MPa)	Energy Absorption (J)
PES	23.73 ± 9.8	258 ± 120	0.20 ± 0.06
PES0.5CF	20.84 ± 8.1	361 ± 146	0.29 ± 0.06
PES1CF	16.28 ± 6.7	273 ± 118	0.37 ± 0.06
PES2CF	12.30 ± 5.6	240 ± 131	0.62 ± 0.1

According to test results, the maximum flexural strength was observed for pure PES material of 23.73 ± 9.8 MPa. Conversely, 12.30 ± 5.6 MPa was the lowest flexural bending strength of composite containing 2 wt. % SCFs. Moreover, the flexural strength of 0.5 wt. % SCFs added composite was better compared with 1 wt. % SCFs and 2 wt. % SCFs composites nearly by 28% and 69.43%, respectively. It was observed from past studies similar results were obtained in the work of Durairaj et al. [6] the flexural strength at the lower carbon fiber content of (5 wt. %) was better than (10 wt. %) carbon fiber reinforced polyester composite. Moreover, the flexural modulus of the composite was affected by the incorporation of chopped carbon fibers inside polyester matrix. Hence, addition of 0.5 SCFs into PES (PES0.5CF) enhanced the flexural modulus of pure PES nearly by 39.92% and thus, PES0.5CF was much more rigid composite material as compared to other samples.

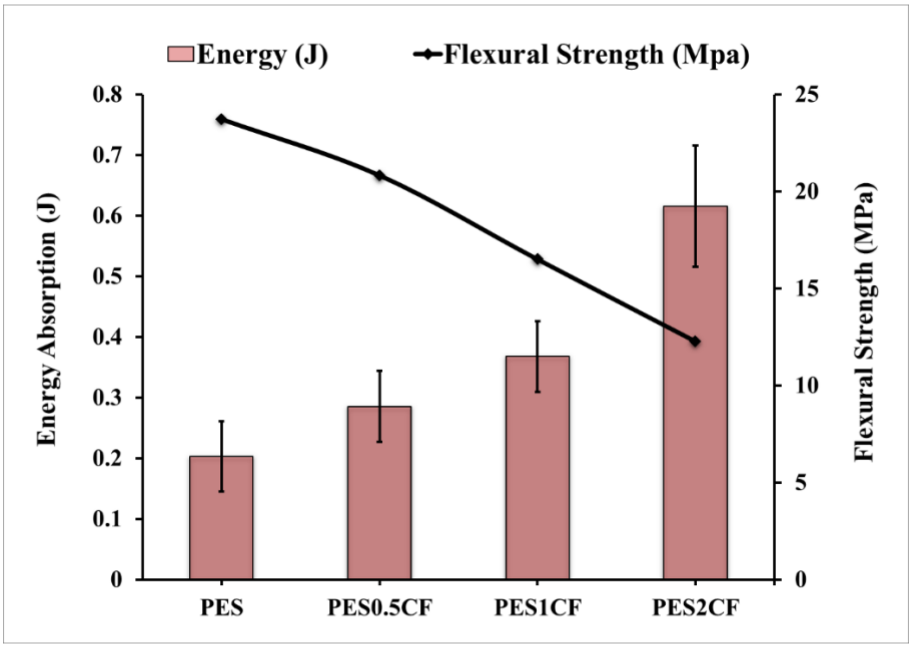

Figure 3. *Flexural Strength and energy absorption of samples.*

On the other hand, the analysis of the Izod impact test exhibits addition of SCFs onto pure PES matrix leads to improves energy absorption of the composite in direct proportion. This might be due to the increment in SCFs amount relatively enhancing the load to be effectively supported by the reinforcement due to increment in total fiber surface in contact with matrix [7]. Similar results were obtained by Wong et al., where increases in the fiber amount led to higher energy absorption of composites. Thus, composite with 2 wt. % SCFs (PES2CF) have higher energy absorbing characteristic value of nearly 0.62 ± 0.1 J. The energy absorption of (PES2CF) composite was better compared to PES0.5CF and PES1CF samples nearly by 113.79 % and 67.57 %, respectively. Whereas, energy absorbing performance of about 0.29 ± 0.06 J was observed for a composite (PES0.5CF) reinforced with 0.5 wt. % SCFs. It was also investigated that the lowest energy absorbing was noted for pure PES material with 0.20 ± 0.06 J.

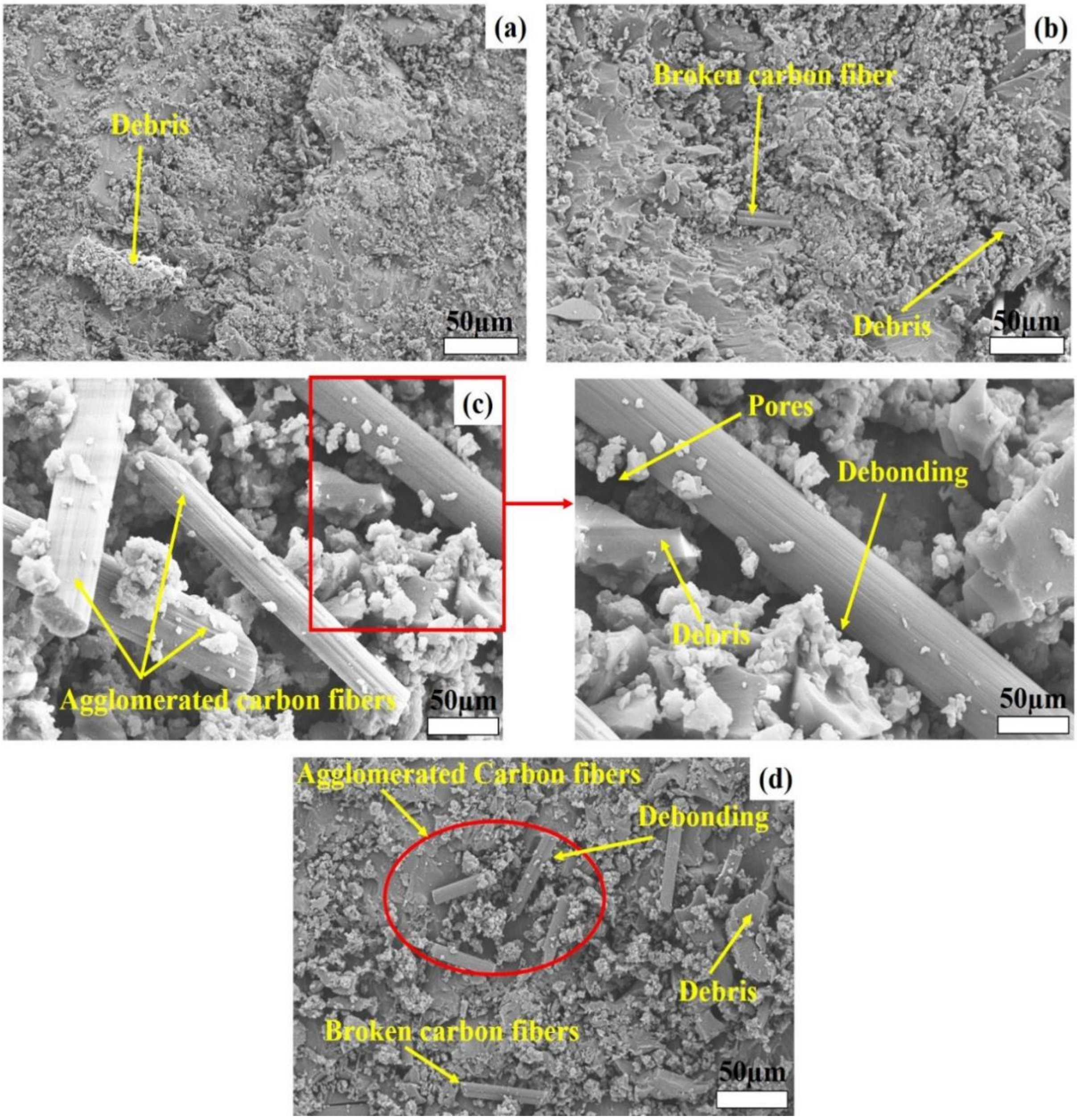

Figure 4. *SEM images of broken surfaces: (a) PES, (b) PES0.5CF, (c) PES1CF, and (d) PES2CF.*

B. TRIBOLOGICAL PROPERTIES

The wear resistance results of samples (PES, PES0.5CF, PES1CF, and PES2CF) were indicated in Figure 5. The highest wear resistance performance was observed when 0.5 wt. % SCFs were added to a pure polyester matrix (PES0.5CF). However, further increase in SCFs content to 2 wt % reduces the wear resistance behaviors of the composite. This might be due to poor SCFs-PES matrix bond strength which was indicated by SEM images designated in Figures 6(c) and 6(d). This poor interaction leads to high abrasion wear due to the ease of fiber cracking and partial chipping of SCFs from the worn surface or pull-out [8].

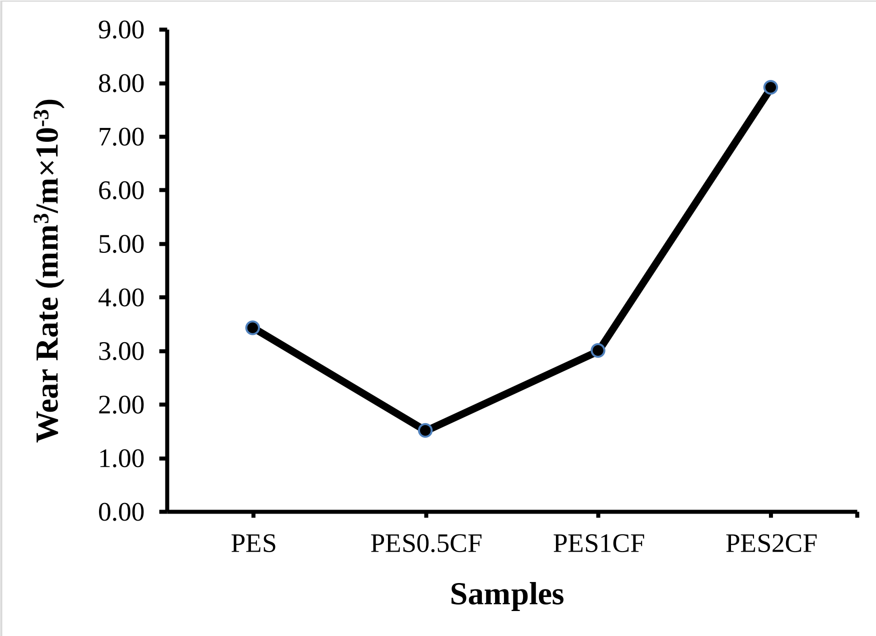

Figure 5. *Wear rate of samples.*

Moreover, the increment in SCFs content results in carbon fibers tending to agglomerate. This, agglomerations have more effects on the tribological behavior compared to the mechanical properties [9, 10]. Thus, from the wear analysis, it was computed that sample PES0.5CF has a wear rate value of 1.5×10^{-3} mm^3/m. Moreover, the wear resistance of PES0.5CF was better than PES1CF and PES2CF nearly by 98.60 % and 423.84 %, respectively. This is probably attributed to its rigidity showed in the flexural modulus. However, the lowest wear resistance was observed for 2 wt. % addition of SCFs onto pure polyester matrix (PES2CF) composite. On the other hand, the interaction between stainless steel balls and polyester surfaces increases the temperature at the contact surface. The increment in temperature causes polyesters to become more brittle and the friction load detaches the polyester component from the surface and hence, the wear resistance of PES material decreases notably [15].

Furthermore, a scanning electron microscope was used to analyze the worn surfaces of both pure PES and composite materials. It is observed that when 0.5 wt. % SCFs were added to the PES matrix, SCFs were embedded homogenously (Figure 6(b)). So, this results in an improvement in the wear resistance property nearly by 127.15 % compared to the pure PES sample. Also, the worn surface of the PES0.5CF composite was relatively smooth compared with all the samples. This may prove this sample has higher wear resistance characteristics. However, the addition of 1 and 2 wt. % SCFs into pure polyester matrix results agglomeration as indicated in Figures 6(c) and 6(d), respectively. Considering Figure 6(a) wear debris and cracked worn surfaces were observed for pure PES polymer materials. Whereas, in Figure 6(c) cracked worn surfaces, wear debris, and broken SCFs were noticed. As can be seen in Figure 4(c) the effects of agglomeration and debonding increased the wear rate tendency of the PES1CF composite. Moreover, the worn surface of composite PES2CF was represented in Figure 6(d). The wear debris size is bigger as compared to the wear debris size of all of the samples. Therefore, when 2 wt.% SCFs were added to the polyester matrix (PES2CF), which results in a composite having the lowest wear resistance (higher wear rate) property quantified value of 7.9×10^{-3} mm^3/m.

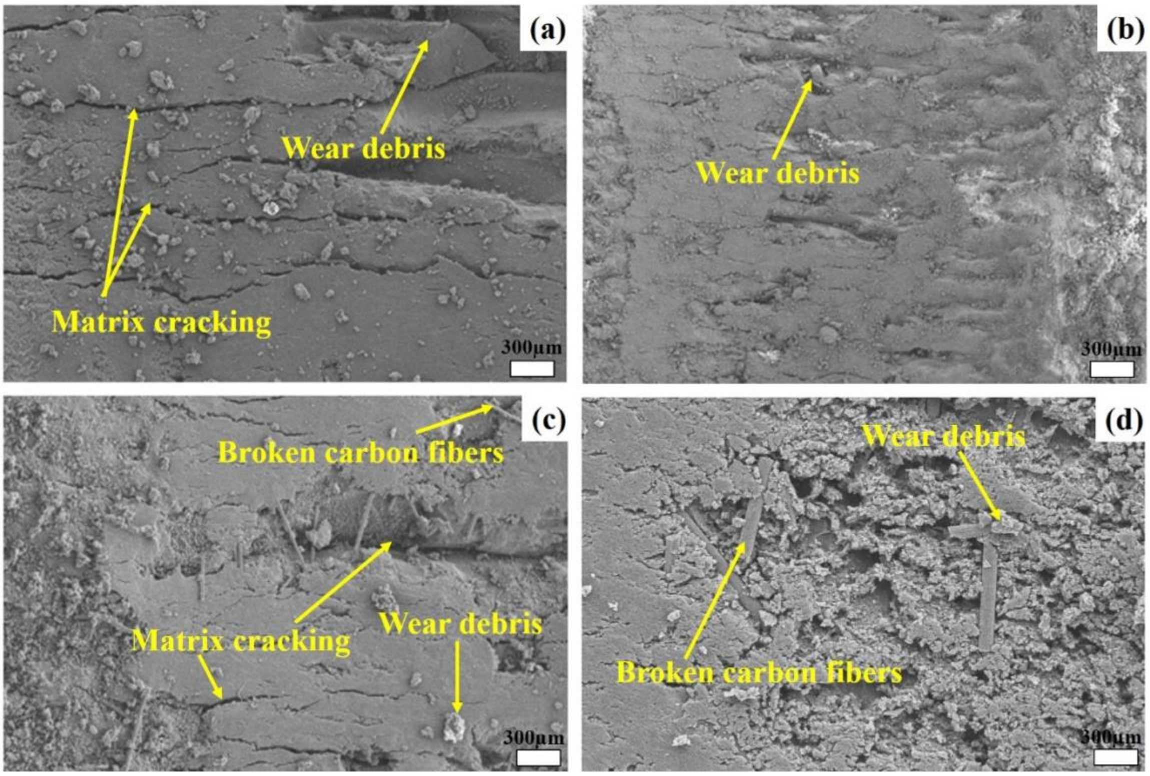

Figure 6. *SEM images of worn surface of the composites under 20 N: (a) PES, (b) PES0.5CF, (c) PES1CF, and (d) PES2CF*

IV. CONCLUSION

According to the test results, the flexural strength of specimens was negatively affected by the content of reinforced SCFs. The higher flexural strength was recorded for pure PES material with 23.73 ± 9.8 MPa. On the other hand, the flexural strength of 0.5 wt. % SCFs reinforced composite (PES0.5CF) were nearly 69.43% better than the flexural strength of 2 wt. % SCFs reinforced composite (PES2CF). The improvement in energy absorption of SCFs reinforced polyester composite is directly related to SCFs content. So, the maximum energy absorption was observed for 2 wt. % SCFs reinforced PES composite (PES2CF) of about 0.62 ± 0.1 J but 0.20 ± 0.06 J was the lowest evaluated energy absorption value of pure PES material. However, this trend was not observed for the tribological performance of samples. Here, the wear resistance was increased when the reinforcement SCFs contents were decreased. This was explained by the effect of agglomeration. Thus, polyester matrix reinforced by 0.5 wt. % SCFs (PES0.5CF) have the highest wear resistance capacity of 1.5×10^{-3} mm^3/m, whereas the lowest wear resistance performance was observed for sample reinforced with 2 wt. % SCFs (PES2CF) of about 7.9×10^{-3} mm^3/m. Moreover, the morphological studies on the worn surfaces of samples using scanning electron microscope show composites reinforced with 0.5 wt. % SCFs have smooth worn surfaces. Also, the morphology of broken surfaces indicates agglomeration, and debonding features were observed for PES1CF and PES2CF composites. This study also determined that the flexural modulus of lower SCFs contained polyester composites were remarkably higher as compared to composites with higher contents of SCFs. Finally, the most positively affected behavior regarding SCFs ratio was energy absorption whereas the flexural strength, flexural modulus, and wear resistance were decreased with the increment of SCFs.

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