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An Investigation into the Mechanical and Wear Characteristics of Hybrid Composites: Influence of Different Types and Content of Biodegradable Reinforcements

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ABSTRACT

This research work focuses on the wear characteristics of hybrid composites prepared using Sisal fiber (SF) /Pineapple fiber (PF) and Pineapple fly ash (PA) in various wt.%. Linear reciprocating tribometer was used for determining the Specific Wear Rate (SWR) and Coefficient of Friction (CoF) of the hybrid composites. The XRF results of PA filler showed the existence of silica (64.43%) and aluminum oxide (10.03%) in a major percentage. The hybrid fiber combination of 30-50 wt.% showed improvement in Tensile Strength (TS), Flexural Strength (FS) and Impact Strength (IS) with the filler mixing up to 5 wt.%. The Taguchi optimization (SN graph) observed the combination with PA addition of 5 wt.%, hybrid fiber addition of 30 wt.%, sliding distance and load of 1500 m, 10 N having lower SWR. Similarly for lower CoF, fly ash of 1 wt. %, fiber of 30 wt.%, sliding distance and load of 500 m and 5 N, respectively, with high SN ratio is the best combination. SEM results showed a decrease in filler content, higher load conditions, higher reinforcement causing more surface deformations in the composites.

摘要

研究了剑麻纤维/菠萝纤维（PF）和菠萝粉煤灰（PA）在不同重量%下制备的混杂复合材料的磨损特性. 采用线性往复摩擦磨损仪测定了混杂复合材料的比磨损率（SWR）和摩擦系数（CoF）. PA填料的XRF分析结果显示二氧化硅（64.43%）和氧化铝（10.03%）占主要比例. 当填料掺量达到5 wt.%时，混杂纤维的拉伸强度（TS）、弯曲强度（FS）和冲击强度（IS）均得到改善. 田口优化（SN图）观察到PA添加量为5%，混杂纤维添加量为30%，滑动距离和载荷为1500m，10n的组合具有较低的SWR. 同样，对于较低的CoF，粉煤灰质量分数为1%，纤维质量分数为30%，滑动距离为500m，荷载为5n时，高SN比为最佳组合. SEM结果表明，填料含量的降低、载荷条件的提高、增强材料的增强作用使复合材料的表面变形增大.

KEYWORDS

Hybrid composites; wear; morphology; Taguchi optimization; ANOVA; reciprocating tribometer

关键词

混杂复合材料; 磨损; 形态学; 田口优化; 方差分析; 往复式摩擦计

Introduction

The necessity of using biodegradable resources is increasing daily due to the disadvantages of plastic usages. Natural fibers currently have a huge demand in the field due to its availability, eco-friendly nature, low cost, better wear properties, vibration and damping nature, low density and mechanical properties (Kavitha, Hariharan, and Rajeshkumar 2017; Li et al. 2020; Sumesh and Kanthavel 2019a). These reinforcements are used in acoustics, automobile interiors, civil construction, roof tiles, packaging sector and partition board

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applications (Kumar, Hariharan, and Saravanakumar 2019). Natural fiber reinforcement has lesser mechanical and chemical resistance properties comparing to man-made fibers such as glass, basalt, aramid and carbon (Nagaraja et al. 2020). Hybridization technique is used to enhance the properties of composites which can be done using addition of multiple fillers, natural fibers and natural and synthetic fibers into the resins (Mittal, Saini, and Sinha 2016). In particular, the researchers are focusing on the utilization of hybrid natural fibers and natural fiber along with filler to develop hybrid composites due to its merits (Sumesh, Kanthavel, and Kavimani 2020).

Pineapple fiber is obtained from the leaves which yield about 2–3% of fiber and it is one of the highly suitable reinforcement materials for fabricating polymeric composites (Rajeshkumar et al. 2020). Similarly, sisal fibers are also extracted from the leaves of the sisal plant and each leaf has about 1000 individual fibers (Naveen et al. 2019). Based on the abundant availability and tailored properties of individual fibers the hybrid composites were fabricated by combining these two fibers and investigated its machining characteristics (Sumesh and Kanthavel 2020a). The outcomes revealed that the hybrid composites perform better when compared to single fiber composites. Furthermore, in order to utilize these hybrid composites in machine tool, clutches, bearing cages, etc., applications a well understanding of tribological behavior of these composites becomes mandatory.

The tribological behavior of sisal fiber incorporated epoxy composites was studied by Maurya, Jha, and Tyagi (2017) by varying the parameters like load, sliding distance and speed. The results revealed that the incorporation of sisal fiber reduced the SWR and CoF of epoxy composites. On the other hand, Singh et al. (2020) compared the tribological performance of pineapple and Kevlar fiber-based composites and found that the tribological property of composites reinforced with 5 wt.% of pineapple fiber was comparable to the composites reinforced with 5 wt.% of kenaf fibers which shows that the pineapple fiber is a good alternative material for fabricating friction composites.

The literature analysis revealed that the tribological properties of abundant available sisal and pineapple hybrid fiber composites are to be explored more to suit it for wide range of tribological applications. A study reported that the addition of fly ash to sisal/pineapple fiber-reinforced composites enhanced its performance further (Sumesh and Kanthavel 2020a). Therefore, the present work has been planned to fabricate and investigate the tribological properties of sisal/pineapple/pineapple fly ash reinforced hybrid friction composites. To the best of author's knowledge, this is the first work reporting the wear characteristics of SF/PF/PA hybrid composites. Furthermore, Taguchi's optimization technique was adopted to design the experiments and the results were statistically studied through ANOVA. Additionally, XRF, XRD, SEM and mechanical tests were also carried out which supports the present study.

Materials and methods

Materials

The sisal and pineapple fibers were purchased from natural fiber extractors in Tamilnadu, India and the prepared pineapple fly ash was used as the filler material. Epoxy resin (LY566) with hardener (HY951) obtained from local retailers Coimbatore, India was used as the matrix.

Alkali treatment

Natural fiber usually has high hydrophilic nature which reduces the adhesion with hydrophobic matrix (Rajeshkumar 2020a; Todkar and Patil 2019) and the NaOH treatment helps to overcome this drawback. Initially, all the fibers were cleaned with the distilled water and then immersed in NaOH solution for 180 min. Mechanical stirring was done at a time interval of 20 min. Again the fibers were cleaned using distilled water for removing excess solution. Then, these fibers were kept in bright sunlight for 48 h and heated in an oven for 240 min with 65°C to remove the moisture content.

Fabrication of hybrid composites

In this work, the hybrid composites were fabricated using compression molding technique by reinforcing the sisal and pineapple fibers (1:1 ratio varied from 30 to 50 wt.%) and pineapple fly ash (1, 3 and 5 wt.%) into the epoxy matrix. During fabrication, the required quantity of SF and PF are mixed and placed in the mold and a mixture of matrix/PA filler was poured into the mold and given with required temperature (90°C) and pressure (14 MPa) to obtain composite plate (Sumesh and Kanthavel 2020d).

X-ray fluorescence spectroscopy (XRF)

Bruker model S4 pioneer X-ray spectrometer having X-ray tube (4 kW Rh) and collimators (0.25° and 0.46°) was used. Collimator device is used for narrowing the beam for finding the exact content in the specimen.

X-ray diffraction test (XRD)

In order to find the presence of silica in the PA filler XRD machine (BRUKER D8) having 10 deg/min scanning speed, 5–60° range was used.

Mechanical testings

The mechanical properties such as tensile (ASTM D 638), flexural (ASTM D 790), Charpy impact (ASTM D 256) and hardness (ASTM E 10) were experimentally determined for the fabricated hybrid composites. Archimedes rule was used to obtain the density of the composite (ρ_{ca}) using electronic scale reading of MP-5002 with ASTM D 792 standard and the theoretical density was computed by using the following equation (1) (Rajeshkumar 2020b).

$$\rho_{ct} = \frac{1}{(W_r/\rho_r) + (W_m/\rho_m)} \tag{1}$$

where ρ_{ct} is the theoretical density of composites in g/cm^3, W_r and W_m denote the weight fractions of reinforcements and matrix, respectively, and ρ_r and ρ_m correspond to the density of reinforcements and matrix, respectively, in g/cm^3.

The volume of voids (Vv) existing in the fabricated composites was computed by using the following equation (2).

$$Vv = \frac{\rho_{ct} - \rho_{ca}}{\rho_{ct}} \tag{2}$$

At least five samples were tested in each case and the mean value was recorded as the mechanical property of the respective samples.

Wear testing

Linear reciprocating tribometer was used to assess the tribological behavior of the composites (ASTM G 133–05). A chromium steel ball of 1 cm diameter was used as the ball specimen which reciprocates on the flat specimens of size $4 \times 4 \times 0.3$ cm^3. The steel ball and composite specimens were cleaned with mild liquid laboratory glassware cleaner prior to the experiment and subsequently they were cleaned using acetone and methanol. Then, the specimens were cleaned using cotton swabs. The sliding distance of 500, 1000 and 1500 m (covering 40 mm per cycle) and the load of 5, 10 and 15 N were considered for the experimentation. The following equations were used to compute the Sliding distance (X) (Eq. 3), and Specific Wear Rate (SWR) (Eq. 4).

Table 1. Factors and levels in Taguchi experiment.

		Levels		
Sl. No.	Factors	1	2	3
1.	Pineapple fly ash (wt.%)	1	3	4
2.	Hybrid fiber (wt.%)	30	40	50
3.	Sliding distance (m)	500	1000	1500
4.	Load (N)	5	10	15

$$X = 0.002\ \text{tfL} \tag{3}$$

where X is the sliding distance of alloy steel ball in m, t denoted the time in sec, f represents the oscillating frequency in Hz, and L is the stroke length in mm.

$$\text{SWR} = \frac{\text{WL}}{\rho \text{LSD}} \text{mm}^3/\text{Nm} \tag{4}$$

where WL is the loss in weight after wear testing for the specimen in g, ρ corresponds to density of natural fiber composite in g/cm^3, L is the load acting in N, and SD is the sliding distance in m.

SEM testing

SEM analysis was done using Hitachi SU660 tester to identify the filler morphology and to analyze the surface of wear tested samples to predict the wear mechanism.

Taguchi optimization

Taguchi method was utilized for analyzing all possible conditions to be carried out in the experiment with a minimum number of trials. In this research work, 4 factors with 3 levels experimentation were carried out using L27 orthogonal array. The factors considered are PA and hybrid fiber (SF/PF) contents, SD and L. For normalization procedure, all the readings were converted into a signal-to-noise (SN) ratio and the main motive of this research is to reduce SWR and CoF, so smaller the better ratios were accounted. All the results were tabulated using Minitab-16 software. Factors and levels in Taguchi experiment are given in Table 1.

Statistical analysis

The experimental results were statistically studied by Analysis of Variance (ANOVA) with a 95% confidence level. ANOVA evaluates the significance of various factors comparing the response variables at different factor levels and the percentage contribution of various factors was computed by the total sum of squared deviation from total S/N ratio mean.

Results and discussion

XRF result of PA filler

XRF result of PA filler is provided in Table 2 and it showed the major presence of silica (64.43%) and aluminum oxide (10.03%) and also revealed the existence of 94.05% of inorganic materials. Similar results with more than 50% of silica were observed for fly ash powders (Rodriguez et al. 2015). High content of inorganic materials in fly ash provides good mechanical and surface enhancement properties for the natural fiber composites (Vivek and Kanthavel 2019).

Table 2. XRF results of pineapple fly ash powder.

Chemical composition	Present study (%)	Data available in literature (Rodríguez-Díaz et al. 2015) (%)	Data available in literature (Vivek and Kanthavel 2019) (%)
SiO_2	64.43	75.46	50.40
CaO	4.08	4.42	18.90
Fe_2O_3	3.26	1.62	6.87
Al_2O_3	10.03	3.35	7.48
P_2O_5	2.27	2.18	2.47
K_2O	5.04	4.16	7.29
SO_3	2.44	2.99	1.94
MgO	1.54	3.04	1.61
TiO_2	0.5	0.19	1.28
Na_2O	0.26	0.30	0.33
Cl	0.20	-	0.59
MnO	-	0.06	0.23
Organic materials (%)	5.95	2.15	25.33
Inorganic materials (%)	94.05	97.85	74.67
Density (g/cm^3)	0.96	0.74	0.55
Loss on ignition (%)	1.86	2.15	-

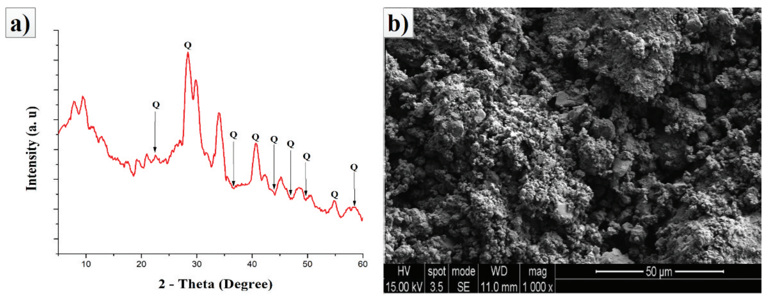

Figure 1. XRD (a) and SEM (b) results of PA filler.

XRD and SEM results of PA filler

The XRD result (Figure 1a) perceived quartz as a predominant element in PA filler. The obtained peaks match PDF card 331161 with a work-related to fly ash powder (Castaldelli et al. 2013; Pereira et al. 2018) and its presence was mainly because of the soil growth of plants (Vivek and Kanthavel 2019). The SEM analysis (Figure 1b) showed the morphological structure of PA filler. The particle size was found to be irregular and lightly bonded with other particles.

Effect of fibers and ash content on mechanical properties

Mechanical test results presented in Table 3, showed improved properties with the addition of PA filler. The TS enhanced from 26.19 MPa to 33.48 MPa with 30 wt.% SF/PF combination. Similarly, FS improved from 67.79 MPa to 73.07 MPa and IS from 55.31 J/m to 64.88 J/m for the same combination. The hybrid fiber combination of 40 and 50 wt.% showed improvement in TS, FS and IS with the filler mixing up to 4 wt.%, because filler addition enhanced the mechanical properties by reducing the gap between the interface (Sumesh et al. 2019). On the other hand, higher fiber addition created uneven fiber distribution in epoxy-based matrix which reduced the mechanical strength of composites. Similarly, hardness and density of the composites showed good improvement after the filler addition. Furthermore, it was noted that the theoretical and actual densities are not in agreement due to the existence of voids and it increased with the increase in filler content due to the entrapment of air during the fabrication process. Similar findings were reported for *Arundo Donax*/epoxy composites (Fiore et al. 2014).

Table 3. Mechanical properties of hybrid composites with different fiber and filler contents.

Hybrid composite	TS (MPa)	FS (MPa)	IS (J/m)	Hardness (HV)	ρ_{ca} (g/cm^3)	ρ_{ct} (g/cm^3)	Void (%)
HC1 (15% SF/15% PF/1% PA)	26.19	67.79	55.31	21.8	1.173	1.190	1.43
HC2 (15% SF/15% PF/3% PA)	29.35	71.23	63.19	21.85	1.182	1.202	1.66
HC3 (15% SF/15% PF/5% PA)	33.48	73.07	64.88	22.3	1.196	1.218	1.81
HC4 (20% SF/20% PF/1% PA)	23.28	66.52	53.27	20.2	1.169	1.187	1.52
HC5 (20% SF/20% PF/3% PA)	25.68	69.87	58.76	21.4	1.175	1.203	2.33
HC6 (20% SF/20% PF/5% PA)	26.98	69.03	60.32	21.9	1.179	1.211	2.64
HC7 (25% SF/25% PF/1% PA)	22.13	64.28	52.89	19.4	1.160	1.182	1.86
HC8 (25% SF/25% PF/3% PA)	24.89	67.04	55.25	20.3	1.168	1.198	2.50
HC9 (25% SF/25% PF/5% PA)	24.32	68.15	58.06	21.5	1.174	1.206	2.65

Table 4. Signal to Noise ratio for SWR and CoF.

Sl. No.	Combination designation	Pineapple fly ash (wt.%)	Hybrid fiber (wt.%)	Sliding distance (m)	Load (N)	SWR $\times 10^{-5}$ (mm^3/Nm)	SN ratio	CoF	SN Ratio
1	C1	1	30	500	5	20.32	-26.16	0.24	12.40
2	C2	1	30	1000	10	15.51	-23.81	0.27	11.48
3	C3	1	30	1500	15	23.31	-27.35	0.23	12.68
4	C4	1	40	500	10	18.76	-25.46	0.35	9.23
5	C5	1	40	1000	15	24.20	-27.68	0.35	9.20
6	C6	1	40	1500	5	30.17	-29.59	0.26	11.82
7	C7	1	50	500	15	24.38	-27.74	0.42	7.58
8	C8	1	50	1000	5	31.01	-29.83	0.34	9.33
9	C9	1	50	1500	10	28.16	-28.99	0.34	9.46
10	C10	3	30	500	5	11.59	-21.28	0.30	10.39
11	C11	3	30	1000	10	10.52	-20.44	0.31	10.28
12	C12	3	30	1500	15	18.18	-25.19	0.28	10.96
13	C13	3	40	500	10	14.62	-23.30	0.40	8.01
14	C14	3	40	1000	15	20.28	-26.14	0.38	8.47
15	C15	3	40	1500	5	21.30	-26.57	0.29	10.77
16	C16	3	50	500	15	22.33	-26.98	0.43	7.37
17	C17	3	50	1000	5	28.83	-29.20	0.35	9.11
18	C18	3	50	1500	10	25.00	-27.96	0.35	9.14
19	C19	5	30	500	5	4.10	-12.25	0.34	9.36
20	C20	5	30	1000	10	6.28	-15.96	0.34	9.27
21	C21	5	30	1500	15	12.43	-21.89	0.32	9.93
22	C22	5	40	500	10	10.34	-20.29	0.44	7.19
23	C23	5	40	1000	15	17.11	-24.67	0.42	7.48
24	C24	5	40	1500	5	27.09	-28.66	0.33	9.53
25	C25	5	50	500	15	16.71	-24.46	0.46	6.75
26	C26	5	50	1000	5	25.80	-28.23	0.39	8.27
27	C27	5	50	1500	10	16.44	-24.32	0.40	7.99

Taguchi optimization

Signal to Noise (SN) ratios for both SWR and CoF was calculated for 27 trials and presented in Table 4. The results disclosed lower SWR of 4.10×10^{-5} mm^3/Nm in 19th trial with 5 wt.% PA/30 wt.% SF/PF/ 1500 m SD/10 N L combination.

Effect of fibers and ash content on the wear rate

PA filler wt.% (SN ratio) ranging from 1, 3, and 5 increase the hardness of the composites thereby reducing the SWR (Figure 2a) (Joseph et al. 2020; Rajeshkumar 2020c). On the other hand, the increase in wt.% of hybrid fibers increased the SWR of composites irrespective of wt.% of PA filler added which could

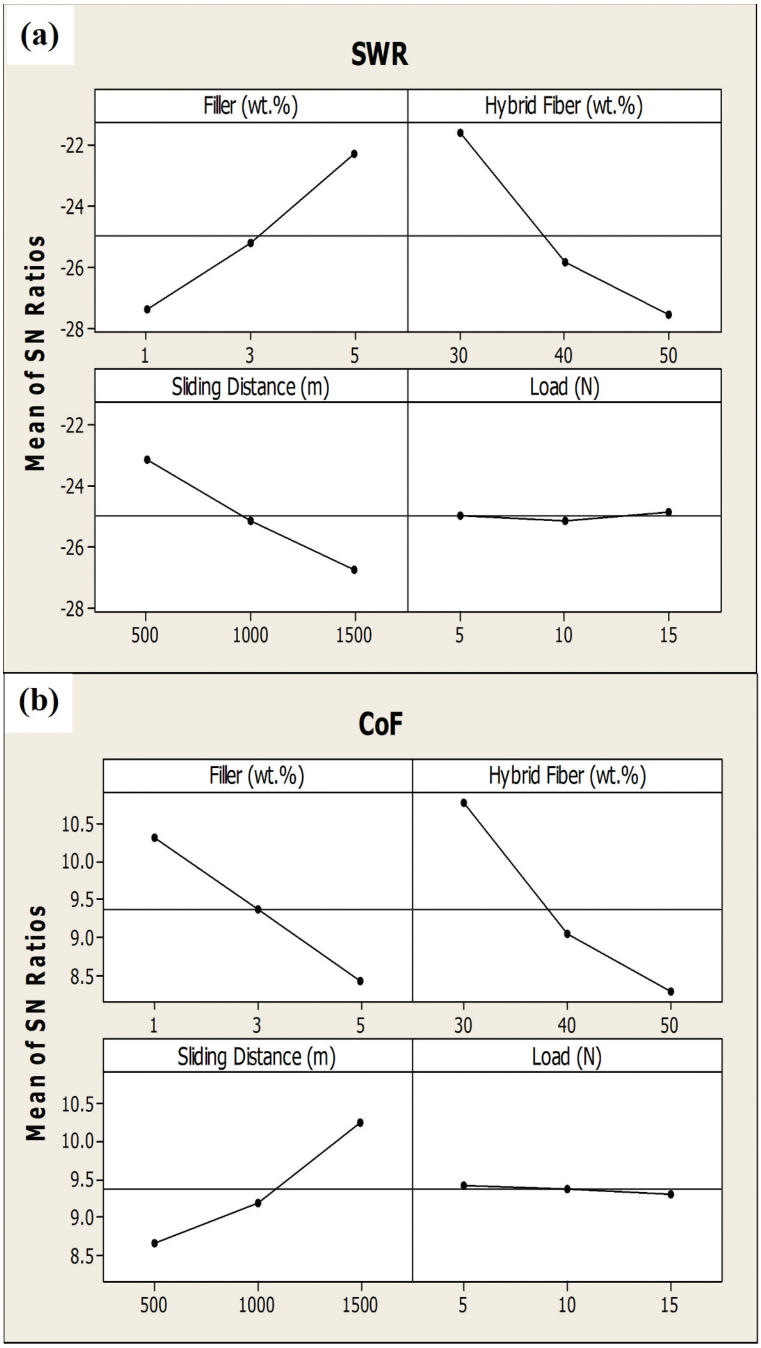

Figure 2. SN ratio of: (a) SWR, and (b) CoF.

be due to the poor bonding strength between the hybrid fibers and the matrix and surface deformations occur in the polymer composites (Rajeshkumar 2020d; Shuhimi et al. 2016). Furthermore, the sliding distance ranges from 500 to 1500 m also have noteworthy effect on the SWR of the composites.

Effect of load on the wear rate

Increase in load from 5 to 10 N reduces the SWR due to the optimum pressure exerted on the specimens, whereas an increase in the SWR was observed at 15 N load which could be due to high pressure exerted on the composites (Maurya, Jha, and Tyagi 2017). Moreover, at higher load tight adhesion force occurs between the specimens and steel ball surface, these atomic forces are much stronger than both the materials and thus breaking the bond leads to high SWR in weaker material (Nirmal, Hashim, and Megat 2015). In general, the wear loss occurs either due to abrasive or adhesive wear, in this experiment adhesive wear ensues between steel ball and composite specimen, producing a localized bonding between them with transfer of material for both the surfaces.

Delta values (Table 5) were tabulated by subtracting low range value from high range and it gives the rank of each factor in this experiment. It was noted that the hybrid fibers (SF/PF) have a huge impact on SWR of the composites with first rank. The adequate amount of fiber addition creates a barrier for protecting the epoxy matrix layer from the wear (Shuhimi et al. 2016). The addition of more fibers result in high wear rate due to pull out of fibers from the epoxy. The wt.% of PA was the second most influencing factor, filler addition improves the wear resistance by reducing the composite porosity and surface deformations (Fei et al. 2018). Sliding distance and load are in the third and fourth positions, respectively. The normal probability plot for SWR (Figure 3a) almost formed a straight line showing this regression analysis was good for predicting the results and a good correlation with the actual SWR responses was observed (Figure 3b).

The ANOVA table of SWR (Table 6) showed the significance of added fillers and fiber reinforcements on wear properties. Both the factors proved the significance range with the *P* value of 0.005 and 0.001, which is lesser than 0.05. On contrary, the sliding distance and load do not show significance on SWR of composites.

Effect of fibers and ash content on CoF

The second response, CoF decreased with the increase in wt.% of reinforcements (Figure 2b) and this could be attributed to the smooth film transfer on the counterface. Furthermore, the addition of reinforcement improved the hardness of the composites which was also responsible for lower CoF. The CoF value was influenced by the sliding distance, i.e. the CoF increased with the increase in SD. Similar trend of results was reported in the literature (Rajeshkumar 2020d).

Effect of load on the CoF

The applied load has a significant effect on the CoF of the composites (Figure 2b). In the present study, the CoF decreased with the increase in applied load which could be due to the development of thermal stresses at the interface when the test was performed under dry sliding conditions (Chauhan, Kumar,

Table 5. Response table for SN ratio of SWR and CoF.

Level	Pineapple fly ash (wt.%)	Hybrid fiber (wt.%)	Sliding distance (m)	Load (N)
1	−27.61	−22.44	−26.64	−25.88
2	−25.51	−26.41	−25.60	−24.83
3	−23.44	−27.72	−24.32	−25.85
Delta	4.17	5.28	2.32	1.05
Rank	2	1	3	4
1	10.260	10.733	9.520	9.566
2	9.307	8.933	9.359	9.297
3	8.358	8.259	9.047	9.062
Delta	1.902	2.474	0.473	0.504
Rank	2	1	4	3

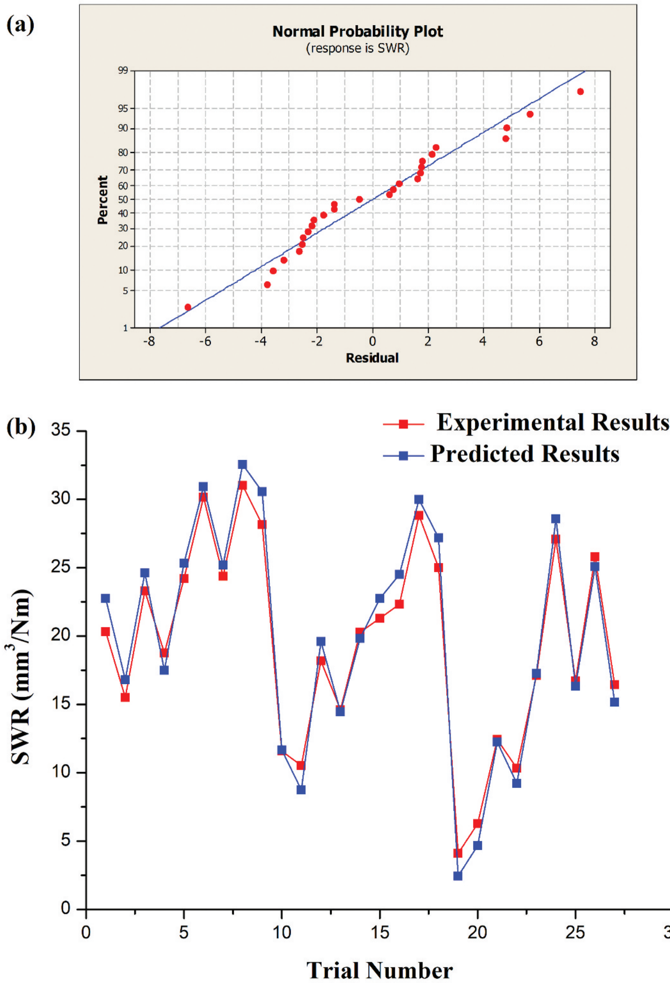

Figure 3. Normal probability plots (a), and Predicted and experimental results (b) of SWR.

Table 6. ANOVA table for SWR and CoF.

Source	DF	Seq SS	Adj MS	F value	P-value
Pineapple fly ash (wt.%)	2	351.98	175.99	7.26	.005
Hybrid fiber (wt.%)	2	529.93	264.97	10.93	.001
Sliding distance (m)	2	42.41	21.20	0.87	.434
Load (N)	2	2.26	1.13	0.05	.955
Error	18	436.22	24.23		
Total	26	1362.79			
Pineapple fly ash (wt.%)	2	0.024100	0.012050	7.05	.01
Hybrid fiber (wt.%)	2	0.040461	0.020230	11.83	.00
Sliding distance (m)	2	0.000643	0.000321	0.19	.83
Load (N)	2	0.001078	0.000539	0.32	.73
Error	18	0.030785	0.001710		
Total	26	0.097067			

and Singh 2010). These thermal stresses weaken the bonding between the reinforcements and matrix and ensure smooth transfer of film led to lower CoF. On the other hand, higher CoF at 5 N load was due to the interlocking of asperities which removes more material from the composites (soft materials).

Delta values (Table 5) were tabulated for finding the ranks of each factor which affects the CoF of the composites. It was noticed that the reinforcement content influenced more on the CoF of the composites, while the applied load and sliding distance have minimal effect on CoF. The normal probability plot for CoF almost formed a straight normal probability line (Figure 4a) showing this regression analysis is good for predicting the results and observed a good correlation with the actual CoF responses (Figure 4b)

ANOVA table for CoF showed the significance of reinforcements with *P* value less than 0.05. The other two operating parameters such as load and sliding distance do not prove the significance (Table 6).

Morphological analysis

The morphology of worn-out composites loaded with 5 wt.% of PA and 30 wt.% of SF/PF is shown in Figure 5a. It revealed that reinforcing less amount of hybrid fibers and high wt.% of filler has reduced the surface deformations in the composites. Filler addition created a tight

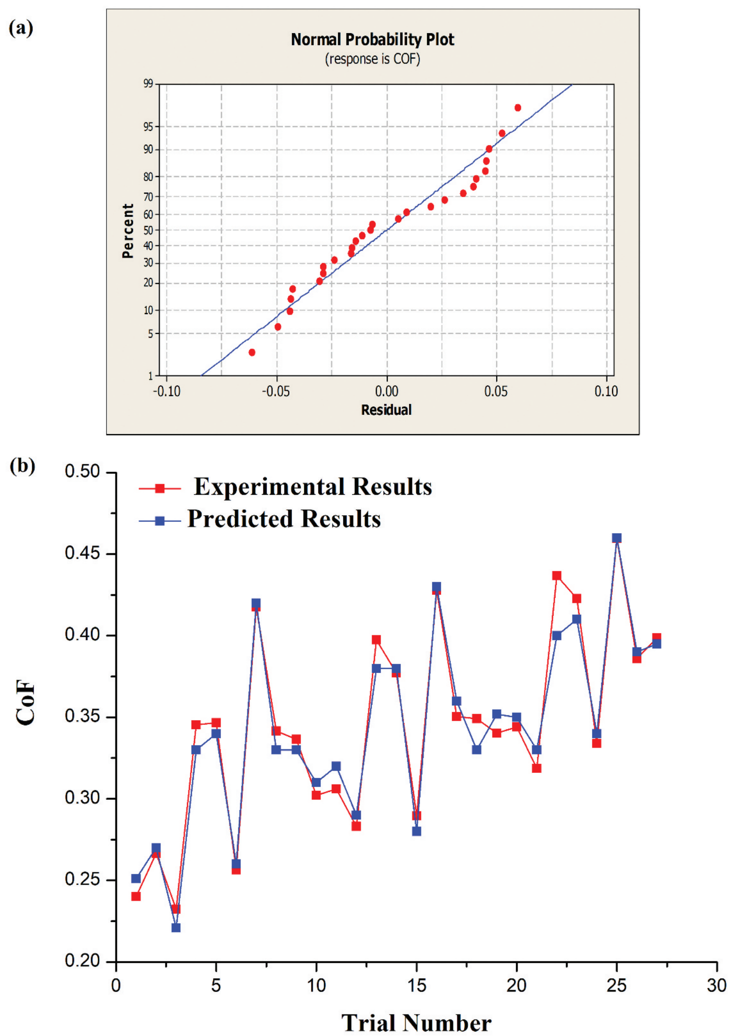

Figure 4. Normal probability plots (a), and Predicted and experimental results (b) of CoF.

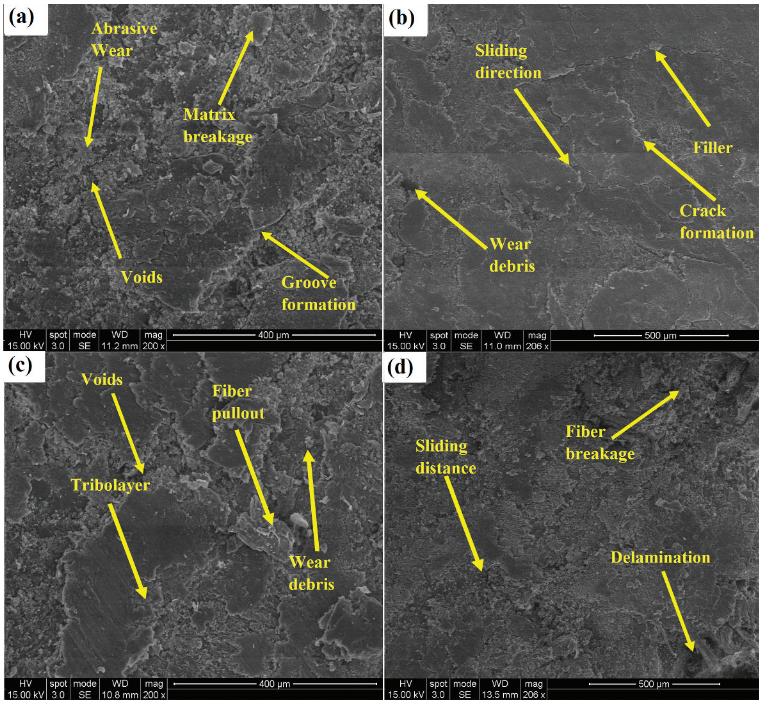

Figure 5. SEM results of composites with different content of reinforcements tested at different load conditions.

bond with the matrix, which reduces the amount of wear during sliding (Kumar et al. 2019; Ravikumar, Suresh, and Rajeshkumar 2020). On contrary, Figure 5b shows surface deformations such as voids, delamination exist in the composites added with 5 wt.% of PA and 50 wt.% of SF/PF. The addition of more hybrid fibers may be the reason for these deformations in the composite surface (Chang et al. 2019; Liu et al. 2019). The 50 wt.% of fiber incorporation created less bonding in the composites, resulting in high SWR which was confirmed from the obtained SWR results.

Figure 5c shows the fractograph of tested surface of the composites incorporated with 5 wt.% of PA and 30 wt.% of SF/PF at 15 N load. The imperfections such as matrix breakages, voids, groove formation and abrasive wear were observed in the SEM images, because of the increased temperature at the contact region due to high load. On the other hand, minute cracks and tribolayer visibility were observed for the similar specimen at 5 N Load (Figure 5d). Lesser load and optimum filler addition may be the reason for this phenomenon (Joseph et al. 2020; Nirmal, Hashim, and Ahmad 2015). Moreover, the minimum load created a low-pressure zone in the composite surface that reduced SWR (Nanda and Satapathy 2020; Kumar et al. 2019).

Conclusions

The main scope of this research work was to fabricate the hybrid epoxy composites using sisal and pineapple fibers and pineapple fly ash and to investigate the effect of content of these reinforcements on mechanical and tribological properties of hybrid composites. Three different compositions of fibers (10, 15 and 20 wt.%) and fly ash (1, 3 and 5 wt.%) were considered for the study. Based on the experimental outcomes the following conclusions have arrived.

- The XRF results showed PA filler consists of 64.43% of silica and 10.03% of aluminum oxide and 94.05% of inorganic materials. The XRD results disclosed the presence of quartz crystal in the filler.
- Mechanical test results revealed that reinforcing 30 wt.% of SF/PF improved the TS from 26.19–33.48 MPa, FS from 67.79–73.07 MPa, and IS from 55.31–64.88 J/m.
- The hybrid composites reinforced with 5 wt.% of PA enhanced the mechanical properties of the composites by improving the bonding between reinforcements and matrix.
- The Taguchi 27 trial results observed lower SWR of 4.10×10^{-5} mm^3/Nm in 19th trial with 5 wt.% of PA/30 wt.% of SF/PF/1500 m sliding distance/10 N Load combination. The results of CoF showed the minimum rate at 3rd trial with 1 wt.% of PA/30 wt.% of SF/PF/1500 m sliding distance/15 N Load combination.
- The Taguchi optimization (SN graph) revealed that the composites with 5 wt.% of PA and 30 wt.% of hybrid fibers have lower SWR. Similarly, the composites with 1 wt.% of PA and 30 wt.% of hybrid fibers show lower CoF.
- SEM results showed a decrease in filler content, higher load conditions, higher reinforcement causing more surface deformations in the composites.

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