Mechanics of Advanced Composite Structures 10 (2023) 211 – 220

Semnan University

Mechanics of Advanced Composite Structures

journal homepage: http://MACS.journals.semnan.ac.ir

Statistical Approach of Determining the Effect of Cenosphere on the Tribological Behaviour of Jute Reinforced Polymer Based Composite

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KEYWORDS

Jute;
Cenosphere;
Polymer Matrix Composite;
Wear;
Taguchi.

ABSTRACT

The current work involves the development of short jute fiber-reinforced polymer matrix composites (PMC) filled with Cenosphere. The short jute fibers were alkali-treated, and proposed composites with both untreated and alkali-treated fibers were prepared. Both kinds of composites have had their erosion wear behavior investigated. For the erosion investigation, an air jet-type test rig was used, and Taguchi's orthogonal arrays were used in the design of trials. The Taguchi technique was used to find the best parameter settings for minimizing erosion rate. The effect of input factors (angle of impact, velocity of impact, and filler percentage) on the erosion resistance of proposed composites was evaluated and statistically analyzed using ANOVA. The size of the erodent, impact velocity, impingement angle, and filler content all have a substantial impact on the wear rate of both types of composites, according to the findings. It is found that velocity of impact (p =0.089) and filler (p =0.246) have a significant impact on erosion wear rate for group A composites and standoff distance (p= 0.194) and filler content (p =0.391) had a significant impact on erosion rate for group B composites. With the addition of the Cenosphere, the erosion behaviour of the samples was significantly improved. The novelty of the present work lies in harnessing an industrial wast cenosphere into a useful filler for PMC in tribological applications.

1. Introduction

PMCs are emerging as potential substitutes for various metal components in different tribological applications and their demand is increasing day by day [1,2]. The PMC's unique qualities, such as low density, enhanced productivity, reduction in noise, and self-lubrication account for this [3–5]. Textile drying machine sliding elements, aggressive media pumps, and other applications are among them [6]. Due to their low density, environmental friendliness, and acceptable strength, natural fibers are an excellent reinforcement in these composites. Natural fiber composites are more environmentally friendly and have a wide range of applications in construction, packaging, and consumer product manufacture, among other things [7–10]. However, given the dusty working circumstances in various industries involved in manufacturing, assessing the erosion behavior of such composites is very much essential to judge their suitability for such applications. Due to its excellent thermo-mechanical and wear resistance qualities, economy, and availability, jute emerges as the most promising natural fiber among the numerous natural fibers available. As a result, jute-reinforced composites can be used in a variety of engineering applications [11–13], out of which tribological applications are one.

Fillers can drastically alter the characteristics of natural fiber composites. With natural fiber-reinforced polymer composites, various fillers such as graphite, silicon carbide, and fly ash have been widely employed [14]. Filler materials can also help minimize material prices, simplify manufacturing processes, and enhance tribo-mechanical behavior [15]. The interaction

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DOI: 10.22075/macs.2022.28671.1440
Received 2022-10-11; Received in revised form 2022-12-12; Accepted 2022-12-24.

between the matrix and the filler determines the improvement in characteristics. The filler dispersion in the matrix and the microstructural uniformity of the filler material determine the tribo-mechanical behavior of PMC [16]. Alumina, silicon carbide, and other fillers have been studied to see how they affect the mechanical and tribological properties of fiber-reinforced composites. A tribological analysis of composites reinforced with wastes from various sources was carried out [17].

In today's world, industries offer a great number of new products to society; yet, they also generate a significant amount of waste in the form of waste products [18]. This garbage is both a burden on society and a threat to the environment. Even though various approaches have been developed by researchers, the hunt for efficient industrial waste disposal mechanisms continues [19]. One of the best ways to recycle these waste materials while simultaneously improving the composite's properties is to use them as fillers in polymer composites [20]. For the manufacturing of composites, different naturally available fibers and waste products obtained from different industrial sources have been explored by researchers. Table 1 provides a breakdown of some of the most common combinations employed in tribological applications.

Table 1. Composites incorporating waste products

Natural fiber	Waste as filler	References
Bamboo-short	Slag from copper	[21]
Slag from copper	Redmud	[22]
Jute+Glass	Cenosphere Flyash	[23]
Coir	Alumina	[24]
Jute	Rubber crumb	[20]

The investigation of jute fiber and silicon carbide-reinforced polymer matrix composites was carried out [25]. The erosion wear characteristics of composites have been enhanced by silicon carbide, and the filler content influences the wear resistance in the composites. Erodent parameters such as the velocity of impact, reinforcement content, and angle of impingement also affect the wear rate due to erosion in the composites. *Aegle Marmelos* and shells of *Cocos Nucifera*-reinforced PMCs were assessed for their tribo-mechanical properties [26].

Cenosphere fly ash, one of the numerous industrial wastes, is abundantly available from thermal power plants. In India, 194 thermal power plants use coal or lignite and produce cenosphere fly ash as a by-product. As a result, the sector confronts a large disposal load. Because of its lower density, enhanced strength, and resistance to heat, cenosphere fly ash offers a wide range of industrial applications. It's a lightweight material that's also robust. Thus, it is used as one of the reinforcing materials in construction applications.

The erodent and fiber parameters can be adjusted to influence the erosion wear behavior of polymer composites. The erosion behavior of Jute-Glass hybrid composites loaded with cenosphere fly ash has been investigated. They have identified a variety of erodent and filler factors that can enhance the resistance against wear of the composites. Jena et al. [27] investigated the wear behavior of bamboo fiber-reinforced polymer composites with cenosphere filler due to solid particle erosion. Bamboo mats have been used as reinforcement. Short jute strands have been used as reinforcement in this study.

From the extensive literature survey carried out, it is found that the effect of alkali treatment on the short fiber and cenosphere-reinforced PMCs subjected to air jet erosion has not been studied.

Thus, the current research focuses on a unique material combination for composite production and erosion wear characterization. The focus of the current work is on the creation of cenosphere and short jute fiber-reinforced PMC. The effect of erodent and fiber characteristics on the tribological behaviour of composites has been put forth. To limit erosion wear, the Taguchi technique was employed to identify the optimal combination of parameters.

2. Materials and Methods

2.1. Materials

Short jute fibers were used in this experiment. The composite matrix was created using epoxy resin (LY556). The resin and hardener HY951 were purchased from Hindustan Ciba Geigy India Ltd. Composites were prepared using a 10:1 epoxy hardener ratio. The cenosphere, obtained from the nearest thermal power plant obtained through the flotation process is used as a filler in the composite. Its SEM image along with EDX is shown in Figure 1.

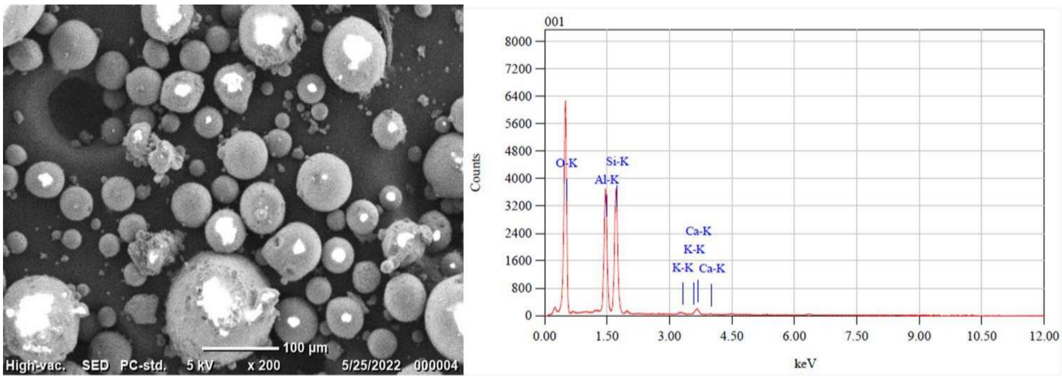

Fig. 1. SEM image of cenosphere and its EDX

2.2. Fabrication

Cenosphere, as filler; jute as fiber reinforcement and epoxy as the matrix was used in the proposed composites. Short fibers of raw jute (Group A) and jute fibers, which are alkali treated (Group B) were used to make two different groups of samples. Composites were made using the hand layup method.

To guarantee that an equal amount of cenosphere was distributed in each layer, We developed a new blend of short jute fiber, epoxy, and cenosphere fly ash in the required quantity and utilized it entirely. The alkali-treated jute composites were treated in the same way. Short jute fiber was initially treated with 5% NaOH in this case [27].

By weight percent, the jute and NaOH solution was kept at 1:25. Jute fibers were dipped in a 5 percent solution of NaOH for a day at room temperature during the process of their alkali treatment. Such fibers were rinsed with water 2-3 times after the alkali treatment to get rid of the alkali solution. Further, acetone was used to clean the fibers. The fibers were then sun-dried for 24 hours. The main purpose of subjecting the fibers to alkali treatment is to eliminate/minimize the lignin content thereby enhancing the adhesion between fiber and matrix. The characteristics of the composite samples created are listed in Table 2.

Table 2. Proposed composite configurations

	Designation	Composition (Excluding matrix)
Group A (Composites with untreated fiber)	U3	Short Jute fiber (30%)
	UC1	Short Jute fiber (30%) + 10 wt% cenosphere
	UC2	Short Jute fiber (30%) + 20 wt% cenosphere
Group B (Composites with treated fiber)	T3	Short Jute fiber (30%)
	TC1	Short Jute fiber (30%) + 10 wt% cenosphere
	TC2	Short Jute fiber (30%) +20 wt% cenosphere

2.3. Testing

Erosion experiments were carried out using air jet erosion equipment following ASTM G76. Particles were delivered into the mixing chamber through the particle feeder and combined with dry compressed air. A nozzle with a diameter of 3 mm was used to accelerate the mixture. Specimens were held at various angles during the experiment to expose them to the erodent particles from the nozzle. The particle feed rate was regulated by the standoff distance between the sample holder and the nozzle. The impingement velocity was measured using the rotating disc method, which was adjusted by varying the compressed air pressure. The experimental parameters for the Steady State Erosion Test are listed in Table 3, and the erosion test procedure is depicted in Figure 2.

Table 3. Experimental parameters for erosion test

Parameters	Values
Velocity of impingement	35 m/s to 65 m/s in increments of 10 m/s
Erodent	Quartz sand
The angle of impingement (°)	30 to 90 in increments of 15 degrees
Rate of feed	2.5-3.0 g/min
Loading of filler	10-20%
Stand-off distance	75 mm
Time	10 minutes
Temperature	Room temperature

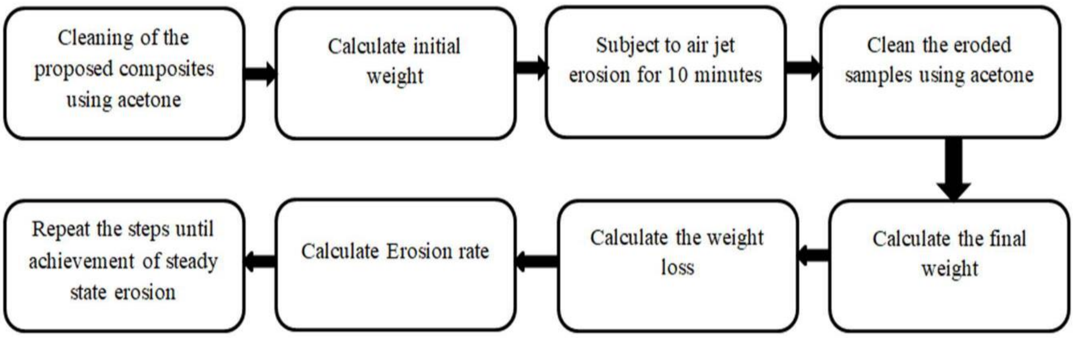

Fig. 2. Steps carried out in the erosion test

Eq. (1) has been used to compute the erosion rate of composites using the technique shown in Figure 1:

$$E_r = {}^{(\Delta W)}/_{W_e} \quad (1)$$

where ΔW is the mass loss of the sample and W_e is the erodent mass (testing time × feed rate).

The Taguchi Approach is a useful strategy for optimizing a collection of input parameters to get the desired output parameters. By performing trials, this method aids in determining the optimal configuration of design parameters based on performance. The steps for designing a Taguchi method are as follows:

(1) Setting up an orthogonal array (OA) with adjustable input components in mind
(2) Conduct the test using the OA
(3) Analyze the data using the experiments
(4) Using data analysis, determine the optimal situation.
(5) Optimize the parameter levels for the confirmation runs.

Biswas and Satapathy [28] conducted a systematic literature analysis to determine the elements that influence the composite erosion rate in an air jet erosion rig experiment. For the L27 orthogonal array design, it was discovered that the five most essential parameters, each at three levels, should be considered [22]. Table 4 shows these five factors and the three levels that they correspond to.

Table 4. Factors and levels were chosen for Taguchi's design

	Factors				
	A	B	C	D	E
Level	The velocity of impact (m/s)	Filler (%)	The angle of impingement (Degree)	Stand-off distance (mm)	Size of erodent (µm)
1	45	0	30	65	125
2	55	10	60	75	250
3	65	20	90	85	350

3. Results and Discussion

3.1. Steady-state Erosion

3.1.1. The effect of impingement angle on continuous erosion rate

Experiments were carried out under precise operating conditions (impact velocity of 45 m/s, stand-off distance of 75 mm, and erodent size of 250 m) were used to investigate the effect of filler content and impingement angle on erosion rate. Filler content enhanced hardness and lowered erosion rate, according to experimental data. Figure 3 depicts how the rate of erosion is been affected by the angle of impingements in the case of both composites from group A and group B. The erosion rate is highest for group A samples at a 45° impingement angle, while it is highest for group B composites at a 60° impingement angle. When these composites are put through a solid particle impact test, the findings show that they are neither ductile nor brittle. As a result, the behaviour is described as semi-brittle. However, when composites from both groups are compared, group B composites had a reduced rate of erosion. Furthermore, composites incorporating cenosphere in weight percentage of 20, have a reduced erosion rate than composites with no filler. This means that industrial trash is recyclable.

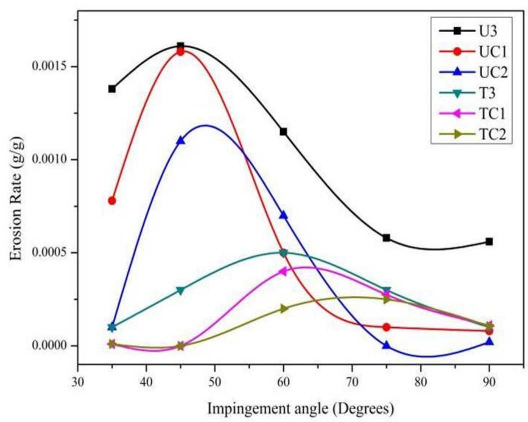

Fig. 3. Impingement angle's effect on the degradation rate

3.1.2. The effect of the velocity of impact on the composite's rate of erosion

The rate of erosion of the composites concerning impact velocity is presented in Figure 4.

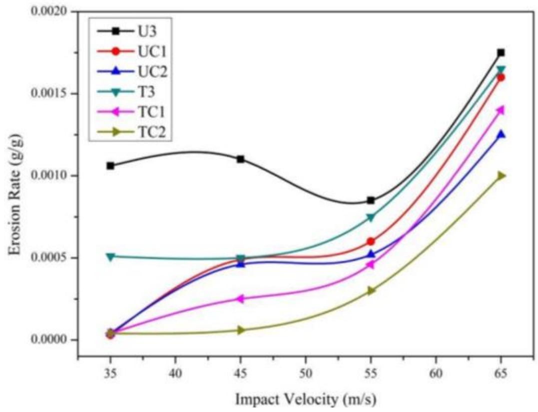

Fig. 4. The impact velocity's effect on erosion rate

Experiments were carried out under certain circumstances (angle of impingement: 60°, stand-off distance: 75 mm, size of erodent: 250 µm). With the increase in velocity of impact from 35 to 45 m/s, the sample erosion rate varies only slightly. However, the degradation rate of composites is most affected by an impact velocity of 65 m/s. The largest erosion rate was seen in U3 composites, as evidenced by the data. The rate of erosion increases as the impact velocity increases. Particles penetrate more deeply at high impact velocity, resulting in a larger number of particles being dispersed from the target surface. This diminishes erosion resistance and can result in greater surface damage as well as the formation of sub-critical cracks.

3.2. Taguchi analysis

The orthogonal array was tested 27 times following the Taguchi Analysis, with the findings reported in Table 5. In untreated samples, the mean S/N ratio was found to be 55.38 dB (with a standard deviation of 15.60), whereas, in treated samples, it was found to be 57.86 dB (with a standard deviation of 12.34). MINITAB 17 was used to conduct the analysis. To evaluate the interaction between input elements, a factorial design was used. The results show that for Group A samples, the lowest erosion rate is achieved by combining variables A (at level 1), B (at level 1), C (at level 3), D (at level 1), and E (at level 3) as seen in Figure 5a. For Group B Composites, the preeminent combination of factor settings to achieve the lowest erosion rate is A (at level 1), B (at level 2), C (at level 1), D (at level 2), and E (at level 2) as seen in Figure 5b.

Table 5. Erosion rate of untreated and treated composites

Exp. No	A (m/s)	B (wt%)	C (Degree)	D (mm)	E (µm)	Er (Untreated) (g/g)	S/N (dB)	Er (Treated) (g/g)	S/N (dB)
1.	45	0	30	65	125	0.000311	64.38	0.0011	57.85
2.	45	0	60	75	250	0.000476	67.63	0.000431	63.77
3.	45	0	90	85	350	0.000576	69.38	0.00196	59.01
4.	45	10	30	75	250	0.001110	57.52	0.00061	66.41
5.	45	10	60	85	350	0.001980	60.77	0.0002	72.32
6.	45	10	90	65	125	0.000415	62.51	0.000397	67.57
7.	45	20	30	85	350	0.002120	61.20	0.00206	51.14
8.	45	20	60	65	125	0.000059	64.45	0.000598	57.05
9.	45	20	90	75	250	0.002060	66.19	0.00767	52.30
10.	55	0	30	75	350	0.002150	51.85	0.00182	50.79
11.	55	0	60	85	125	0.001430	55.10	0.00123	56.71
12.	55	0	90	65	250	0.002100	56.85	0.00476	51.95
13.	55	10	30	85	125	0.003230	48.78	0.00311	53.16
14.	55	10	60	65	250	0.001130	52.03	0.000488	59.07
15.	55	10	90	75	350	0.005110	53.78	0.0031	54.32
16.	55	20	30	65	250	0.003140	46.96	0.000798	59.33
17.	55	20	60	75	350	0.012800	50.21	0.000876	65.25
18.	55	20	90	85	125	0.000870	51.96	0.000798	60.49
19.	65	0	30	85	250	0.002870	51.50	0.00155	56.99
20.	65	0	60	65	350	0.003100	54.75	0.00112	62.91
21.	65	0	90	75	125	0.000820	56.49	0.00072	58.16
22.	65	10	30	65	350	0.004100	42.45	0.00108	54.82
23.	65	10	60	75	125	0.004050	45.70	0.00352	60.73
24.	65	10	90	85	250	0.010000	47.45	0.000698	55.98
25.	65	20	30	75	125	0.011000	49.05	0.0101	49.04
26.	65	20	60	85	250	0.004980	52.30	0.00215	54.96
27.	65	20	90	65	125	0.000310	54.05	0.000897	50.21

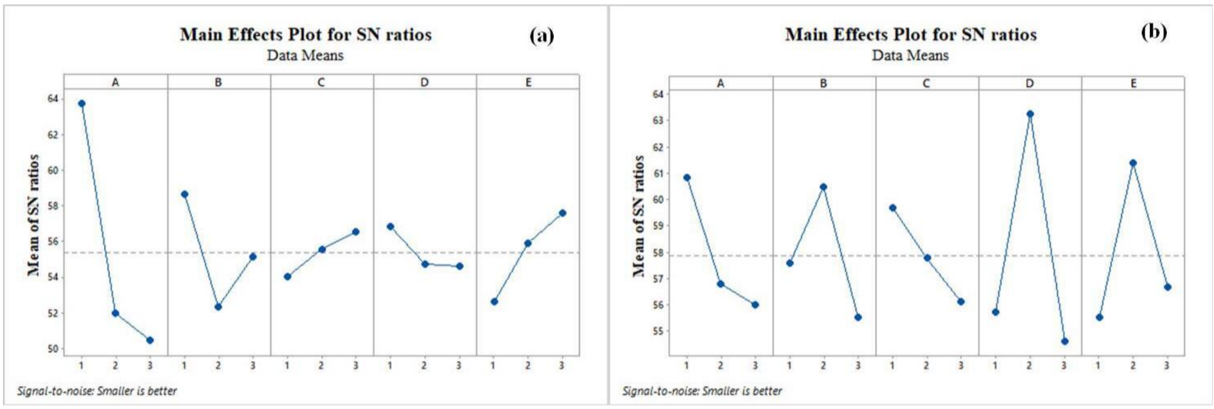

Fig. 5. The effect of control parameters on the erosion rate of samples from groups A and B

Erosion efficiency may be used to determine erosion wear processes. Table 6 depicts the relationship between the mechanism of wear and efficiency related to erosion.

Table 6. The relationship between mechanism of wear and efficiency of erosion.

Sl. No.	Erosion wear mechanism	Efficiency of Erosion
1	Micro-ploughing is ideal.	0
2	Micro cutting is ideal	1
3	Formation of Platelets (Ductile)	<1
4	Formation of spalling (Brittle)	>1

Eq. 2 can be used to compute the erosion efficiency (η_{normal}) when the impingement angle (α) is 90° [29].

$$\eta_{normal} = \frac{2E_r H_v}{\rho V^2} x100 \quad (2)$$

If the impingement angle (α) is not 90°, erosion efficiency (η) can be computed using Eq. (3)

$$\eta_{normal} = \frac{2E_r H_v}{\rho V^2 Sin^2\alpha} x100 \quad (3)$$

Table 7 shows the erosion efficiency computed using Eq (3) for both sets of samples. Many factors influence erosion efficiency, including hardness, the velocity of impact, and angle of impact which are not the material properties. The erosion efficiency of ductile materials is often quite low (less than 100 percent), whereas brittle materials have been shown to have values much higher than 100 percent [29]. According to the findings, Group A composites exhibit ductile and brittle behaviour when the angle of impact is 60° and 30° respectively, whereas Group B composites exhibit ductile and brittle behaviour when the angle of impact is 60° and 90° respectively.

To estimate the effect of the most relevant factors on the rate of erosion, the analysis of variance (ANOVA) approach can be utilized. ANOVA was used to analyze the experimental data for both sample groups. The results of this investigation are presented in Table 8 for Group A and Group B, respectively. The analysis was conducted with a 95% confidence level.

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Table 7. The erosion efficiency of composites from groups A and B.

Velocity of impact (m/s)	Angle of impact (degree)	Eroding material density (ρ) (kg/m³)	Eroding material hardness (Hv)	Er (Group A)	Er (Group B)	Erosion efficiency (η): Group A	Erosion efficiency (η): Group B
45	30	1110	34.45	0.000311	0.0011	0.9	3.4
45	60	1110	34.45	0.000476	0.000431	15.7	14.2
45	90	1110	34.45	0.000576	0.00196	1.7	3
45	30	1210	38.72	0.001110	0.00061	3.5	1.9
45	60	1210	38.72	0.001980	0.0002	67.3	6.8
45	90	1210	38.72	0.000415	0.000397	1.3	0.6
45	30	1275	40.16	0.002120	0.00206	6.7	6.5
45	60	1275	40.16	0.000059	0.000598	1.9	20
45	90	1275	40.16	0.002060	0.00767	6.4	11.9

55	30	1110	34.45	0.002150	0.00182	4.5	3.8
55	60	1110	34.45	0.001430	0.00123	31.5	27.1
55	90	1110	34.45	0.002100	0.00476	4.3	5.9
55	30	1210	38.72	0.003230	0.00311	7	6.7
55	60	1210	38.72	0.001130	0.000488	25.7	11.1
55	90	1210	38.72	0.005110	0.0031	10.8	4
55	30	1275	40.16	0.003140	0.000798	6.6	1.7
55	60	1275	40.16	0.012800	0.000876	286.9	19.6
55	90	1275	40.16	0.000870	0.000798	1.8	1
65	30	1110	34.45	0.002870	0.00155	4.39	2.3
65	60	1110	34.45	0.003100	0.00112	49	17.7
65	90	1110	34.45	0.000820	0.00072	1.2	0.7
65	30	1210	38.72	0.004100	0.00108	6.3	1.6
65	60	1210	38.72	0.004050	0.00352	66	57.3
65	90	1210	38.72	0.010000	0.000698	15.1	0.7
65	30	1275	40.16	0.011000	0.0101	16.8	15.4
65	60	1275	40.16	0.004980	0.00215	79.9	34.5
65	90	1275	40.16	0.000310	0.000897	0.4	0.9

Table 8. ANOVA table for group A composite erosion rate

Source	DF	Adj SS		Adj MS		F		P	
		Group A	Group B	Group A	Group B	Group A	Group B	Group A	Group B
A	2	0.000061	0.000003	0.000030	0.000001	2.82	0.25	0.089	0.780
B	2	0.000033	0.000011	0.000016	0.000005	1.53	1.00	0.246	0.391
C	2	0.000015	0.000008	0.000007	0.000004	0.68	0.70	0.522	0.510
D	2	0.000000	0.000020	0.000000	0.000010	0.00	1.82	0.997	0.194
E	2	0.000004	0.000009	0.000002	0.000005	0.21	0.84	0.815	0.452
Error	16	0.000172	0.000087	0.000011	0.000005				
Total	26	0.000285	0.000137						

The lower the P value, the more significant the results are [30]. The variables corresponding to impact velocity (p =0.089) and filler content (p =0.246) have a significant impact on erosion wear rate, according to Table 8 Similarly, parameters corresponding to standoff distance (p= 0.194) and filler content (p =0.391) had a significant impact on erosion rate for the samples in Group B, as shown in Table 8.

4. Conclusions

The effect of alkali treatment on the tribological behaviour of cenosphere-filled, short jute fiber-reinforced composites has been studied. The findings allow us to draw the following conclusions:

- The cenosphere concentration (as a percentage of weight) has a significant influence on the erosion wear behaviour of jute fiber-reinforced composites.
- Alkali-treated jute fibres in composite samples show improved erosion wear behaviour.
- The erosion rate is highest for group A samples at a 45° impingement angle, while it is highest for group B composites at a 60° impingement angle.
- The erosion rate of group B composites is found to be lower than that of group A samples. Furthermore, composites using 20% Cenosphere Fly ash have a reduced erosion rate than composites containing no filler. Industrial waste can therefore be recycled.
- The degradation rate of composites is most affected by the velocity of the impact of 65 m/s. The largest rate of erosion was seen in composites having no filler and fibers untreated.

- Both alkali-treated and untreated composites show a considerable rise in erosion rate as impact velocity increases.
- The velocity of impact ($p = 0.089$) and filler ($p = 0.246$) have a significant impact on erosion wear rate for group A composites and standoff distance ($p = 0.194$) and filler content ($p = 0.391$) had a significant impact on erosion rate for group B composites.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the authors have entirely observed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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