

Statistical Modelling and Computational Optimization Using Response Surface Methodology

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Abstract: This paper investigates the development, characterization and erosion behavior of hybrid epoxy composites reinforced with coir and glass fibers and filled with fly ash particles. The composites were prepared by manual hand lay-up technique with 20 wt.% E-glass fiber and 10 wt.% coir fiber, while the fly ash content was varied at 0, 5 and 10 wt.%. The hardness of the composites increased progressively with filler content with incorporation of fly ash reaching 86 ± 1.5 at 10 wt% fly ash. Air-jet erosion test was performed to study the erosion behavior and the effect of reinforcement content, erodent velocity and impingement angle were investigated using response surface methodology (Box-Behnken Design). The obtained quadratic regression model was found to be in good agreement with experimental data ($R^2 = 96.80\%$, adjusted $R^2 = 91.04\%$) which was statistically confirmed by ANOVA. Erodent velocity was found to be the most dominant factor affecting the erosion rate followed by impingement angle and reinforcement content. The predicted minimum erosion rate of 0.0013883 g/min was observed at 5 wt.% reinforcement, 1.5 m/sec erodent velocity and 90° impingement angle. In general, the addition of fly ash in proper manner improved the hardness and erosion resistance of the composite.

Keywords: Polymer, glass fiber, erosive wear, fly ash, BBD

1. Introduction

Recent breakthroughs in materials science and engineering have led to a remarkable array of new materials. These developments are transforming the industrial sector by addressing the demand for lightweight, high-strength, wear-resistant and economical solutions. Among these engineering resources, composite materials are one of the most versatile. Today, composites hold critical importance in aerospace, automotive and structural engineering due to their exceptional strength-to-weight and modulus-to-weight ratios. As a result, global interest in their research and commercial use is growing exponentially. By definition, composites are heterogeneous materials formed by combining two or more distinct materials, typically reinforcing fibers or fillers embedded in a compatible matrix [1]. The matrix—metallic, ceramic or polymeric—provides the composite with its structural shape, surface finish and environmental resistance. The fiber reinforcement, meanwhile, bears the majority of the structural load. This combination results in a final material with excellent macroscopic stiffness and strength [2].

However, erosive wear caused by solid particles remains a significant challenge in several engineering applications. This wear mechanism occurs when solid particles in a fluid or gas stream impact a material surface, leading to material loss and surface degradation. It plays an important role in vital components such as compressors and turbine blades, fluid and gas valves, and the moving parts of ships and aerospace structures and automobiles [3]. Erosion behavior is regulated by various parameters, including impact velocity, particle size, impact angle and the mechanical properties of the erodent and substrate materials. The improvement of mechanical and tribological performances of fiber-reinforced polymer composites by incorporation of particulate fillers has been studied by many researchers.



Arivalagan et al. [4] have fabricated carbon fabric reinforced epoxy composites with silane treated fly-ash cenospheres and found that the wear volume and specific wear rate decreased progressively with increase in filler content and the improvement was ascribed to the enhanced resistance to abrasive degradation. Similarly, Shivamurthy et al. [5] reported that the inclusion of SiO₂ particulate filler in E-glass/epoxy composites leads to enhancement of the hardness and flexural strength of the material, where 3 and 6 wt.% silica loading resulted in the optimum combination of strength and sliding wear resistance. Suresha et al. [6] studied the effect of graphite particulate reinforcement on glass/epoxy composites and reported that the tensile strength was increased and the coefficient of friction and wear loss was decreased with the increase of graphite content.

In a related study, Suresha et al. [7] investigated the influence of SiC particulate reinforcement on glass/epoxy composites. The SiC filled composites were found to have lower wear losses than the unfilled composites and also better mechanical properties over the range of normal load and sliding velocity studied. Biswas and Satapathy [8] studied alumina filled glass/epoxy composites and found that the wear resistance was improved in comparison with unfilled composites but the mechanical properties were somewhat reduced. Raju et al. [9] studied SiO₂-filled glass-fabric/epoxy composites and reported that the addition of silica particles enhanced the mechanical performance and the two-body abrasive wear resistance of the composite compared to the unfilled composite.

Mohan et al. [10] studied the effect of tungsten carbide (WC) and tantalum-niobium carbide (Ta/NbC) fillers on glass-fabric/epoxy composites and observed that the wear volume loss and specific wear rate were reduced in comparison to the unfilled system under three-body abrasive wear conditions. The authors Ahmed et al. [11] reported that the incorporation of ceramic fillers especially Al₂O₃ significantly improved the wear resistance of jute/epoxy composites, and Al₂O₃ filled composites were found to be more effective than SiC filled composites. In the moisture related studies, Mohan and Kanny [12] reported that the incorporation of nanoclay (1, 3 and 5 wt.%) in sisal/epoxy composites greatly reduced the water absorption with 5 wt.% nanoclay composite showing nearly three times lower water transmission than the unfilled composite.

Similarly, Chow et al. [13] prepared epoxy/glass-fibre/OMMT nanocomposites by hand lay-up and observed the enhanced moisture resistance owing to the more tortuous diffusion path induced by the exfoliated nanoclay structure in the matrix. These findings together demonstrate that the judicious use of particulate fillers (ceramic, ash-based or clay-based) may significantly improve the mechanical strength, wear resistance and moisture resistance of fiber-reinforced polymer composites.

2. Material and methods

2.1 Matrix Material

Polymer matrices are the most widely employed matrix systems owing to their cost-effectiveness, ease of processability with low tooling requirements, and favorable properties at ambient temperature. They are broadly classified into thermoplastic and thermosetting resins, with epoxy, polyester, vinyl ester, polyurethane and phenolic resins being the predominant thermosets. Epoxy resin was selected as the matrix material for this study due to its superior adhesion to a wide range of fibers, high mechanical and electrical properties, good thermal stability, low cure shrinkage and excellent chemical resistance. Chemically, epoxy belongs to the epoxide family, commonly referred to as Bisphenol-A-Diglycidyl-Ether (DGEBA).

2.2 Fibers

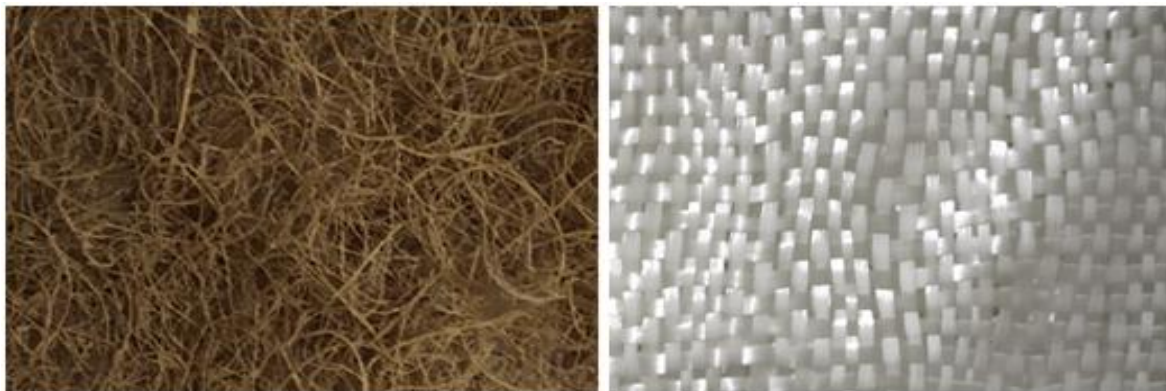


Figure 1: Coir fibre and glass fibre woven mat

Coir fiber, extracted from coconut husk along with the corky pith tissue, is a lignocellulosic fiber characterized by high lignin content, which imparts superior strength and durability relative to other natural fibers [14, 15]. Being abundantly available in India, biodegradable, low-density and cost-effective, coir fiber has gained increasing application in automotive, railway and public transport structural components, as well as in building and construction composites, driven by the demand for lightweight and fuel-efficient materials. E-glass fiber, selected as the synthetic reinforcement in this study, is the most extensively used fiber in polymer matrix composites owing to its high tensile strength, excellent chemical resistance, low cost and good electrical insulation properties.

2.3 Filler Materials

Filler materials are inert additives incorporated into natural fiber reinforced composites to modify the physicochemical properties of the matrix polymer, facilitate processability during fabrication, and enhance overall composite performance. They contribute to improved rigidity, wear resistance, dimensional stability and mechanical strength of the resulting structure. Among the various fillers investigated, fly ash an industrial by-product of coal combustion has gained significant attention owing to its ready availability, low cost, low density and high silica content. Incorporation of fly ash into polymer composites offers both technical and environmental benefits, enhancing stiffness, hardness, thermal stability and overall mechanical performance, while simultaneously enabling sustainable utilization of industrial waste as a value-added material [16]. The physical properties of fly ash are summarized in Table 1 and chemical composition of fly ash is summarized in Table 2.

Table 1: Physical characteristics of fly ash

Density (g/cm ³)	2.18
Bulk density (g/cm ³)	1.29
Melting point (°C)	>1200 °C
Moisture content	% 1.7
Colour	Gray

Table 2: Chemical composition of fly ash

Compound	SiO ₂	Al ₂ O ₃	CaO	MgO	Fe ₂ O ₃	SO ₃	Na ₂ O	K ₂ O
Composition (wt. %)	51.13	25.45	4.65	1.22	3.17	0.53	0.22	0.89

2.4 Composite Fabrication

Coir fibers were sourced locally, while E-glass fiber mat (Saint Gobain Ltd.) served as the synthetic reinforcement and epoxy resin (Ciba Geigy India Ltd.) as the matrix, cured with hardener at a 10:1 weight ratio as per

manufacturer specifications. Epoxy was selected as the matrix system owing to its low cure shrinkage and compatibility with both natural and synthetic fiber reinforcements.

Composite sheets (210 × 210 × 3 mm³) were fabricated by hand lay-up. Fly ash powder was mechanically dispersed into the epoxy resin prior to hardener addition to ensure uniform distribution and minimize agglomeration of filler particles. Glass fiber content was fixed at 20 wt.%, while fly ash content was varied at three levels to study its effect on the resulting composite properties; the composite compositions and designations are summarized in Table 3.

Post-casting, laminates were compressed under a 20 kg load for 24 h to eliminate voids and ensure proper consolidation, after which they were demolded and post-cured in air for a further 24 h to complete the curing process. Specimens of required dimensions were then cut from the cured laminates using standard cutting procedures for subsequent physical and mechanical characterization.

Table 3: Designation of composites

Samples	Compositions
C1	Epoxy(70wt%)+GlassFibre(20wt.%)+CoirFibre(10wt%)
C2	Epoxy (65wt %) + Glass Fibre (20wt. %) +Coir Fibre (10wt %) + Fly ash (5wt. %)
C3	Epoxy (60wt %) +Glass Fibre (20wt. %) +Coir Fibre (10wt %) + Fly ash (10wt. %)

2.5 Density Analysis

The density of the composite was measured by Archimedes principle. The principle states that the apparent weight of a body immersed in a liquid is reduced by the weight of the liquid displaced by the body. According to this concept, the density of the composite specimens was measured by the Archimedes drainage method as shown in Equation (1). This technique is widely used in testing the density of composite materials due to its simplicity, reliability and applicability to irregular-shaped specimens.

$$\rho_E = \frac{m}{(m-m_w)} \rho_w \dots \dots \dots (1)$$

Where ρ_E is the experimental density of the composites, m_w is the mass of the composites in distilled water, m is the mass of the composites in air and ρ_w is the density of distilled water. The density of distilled water at 20°C is 998 kg/m³.

2.6 Hardness Test

Hardness is an important mechanical property of a material, indicating its ability to withstand penetration, scratching and permanent deformation of the surface. It is usually measured by the depth of the indentation and the recovery of the material when an indenter is pressed into the surface under a constant load. In this study, the Shore D hardness test was used to measure hardness.

2.7 Erosive Wear Test

The erosive wear behaviour of the AMCs was investigated using an air jet erosion testing machine. The erosion rate of materials is evaluated by exposing the test specimens to a high-velocity air stream containing abrasive particles in an air-jet erosion tester. Air jet erosion tests were conducted on the AMCs using a Ducom Instruments air jet erosion tester (Model TR 471-600).

An erosion resistance test was performed in accordance with ASTM G76 [12]. The study was designed based on the BBD to evaluate the effect of independent variables on the erosive wear rate. The test conditions adopted for the solid particle erosion experiments are presented in Table 4.

Table 4 – Testing Parameters of air jet erosion experiments

Experimental Parameter	Specification
Erodent particle size	45-50micron
Erodent material	Alumina (Al ₂ O ₃)
Temperature	Room temperature
Standoff distance	10 mm
Test duration	5 min
Erodent feed rate	3gm/min
Specimen size	25mm x25 mm x5 mm

Experiments were carried out for different impingement angles, erodent velocities and reinforcement weight percentages. The erosion rate of the aluminium matrix composites (AMCs) was determined from the weight loss of each specimen measured at the beginning and end of the erosion test. The degradation rate of the composites was calculated as per equation (2).

$$E_r = \frac{(W_1 - W_2)}{T} \dots\dots\dots(2)$$

Where, T is the time in minutes, W1 is the specimen weight before erosion, W2 is the specimen weight after erosion, and Er is the erosion rate in grams per minute.

2.7 Regression Modelling and Optimization of Erosive Wear Parameters

The BBD was employed to evaluate the individual and interactive effects of fly ash weight fraction (R), impingement angle (A) and erodent velocity (V) on the weight loss per minute of the AMCs and base alloy. The experimental levels of the process parameters used in the air-jet erosion tests are presented in Table 5. Each parameter was coded as -1 for low, 0 for moderate and +1 for high.

Table 5: Levels of the parameters considered in the air jet erosion test process

Process Parameter	Notation	Unit	Levels		
			-1	0	+1
Filler	F	Wt. %	0	5	10
Impingement angle	A	Degree	30	60	90
Erodent velocity	V	Meter/second	44	72	100

The optimization process aimed to minimize the weight loss of the composites. The experimental design comprised fifteen experimental runs, as presented in Table 6. Analysis of variance (ANOVA) was performed to evaluate the influential parameters governing the developed regression model. The principal objective of ANOVA was to evaluate the influential process variables, determine the predominant factor affecting the response and evaluate the adequacy of the developed model. Regression modelling was carried out with Minitab software (20.3).

Table 6: BBD for air jet erosion test

Run	Filler (wt.%)	Impingement angle (Degree)	Erodent velocity (m/s)
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1	5	90	44
2	5	30	100
3	10	60	44
4	5	60	72
5	10	90	72
6	10	30	72
7	5	60	72
8	10	60	100
9	5	60	72
10	0	90	72
11	5	30	44
12	5	90	100
13	0	30	72
14	0	60	100
15	0	60	44

3. Results and Discussion

3.1 Density Measurement

The experimental density of composite components is determined based on Archimedes' Principle. The density of the composites increases with increasing weight percent of reinforcement. Experimental densities of composites are shown in Table 7.

Composites	Composition	Density (gm/cc)
C1	Epoxy (70wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %)	1.162 ± 0.015
C2	Epoxy (65wt %) + Glass Fiber Mat (20wt. %) +Coir Fiber (10wt %) + Fly ash (5wt. %)	1.173 ± 0.017
C3	Epoxy (60wt %) + Glass Fiber Mat (20wt. %) +Coir Fiber (10wt %) + Fly ash (10wt. %)	1.195 ± 0.016

Table 7 – Experimental densities of composites

Table 7 indicates a gradual increase in composite density with an increase in filler concentration. The density of the composites was observed to increase gradually from 1.162 g/cc for C1 to 1.195 g/cc for C3 with increasing fly ash content. The increase in density can be attributed to the replacement of a portion of epoxy resin with fly ash particles, which possess higher density than the polymer matrix. Furthermore, the incorporation of fly ash particles fills the voids present within the composite structure and enhances particle packing, resulting in a denser composite material [17]. Therefore, increasing fly ash content from 5 wt.% to 10 wt.% led to a corresponding increase in the overall density of the hybrid composite. The density increased by approximately 2.8% from C1 to C3 due to the addition of fly ash filler.

3.2 Hardness analysis

As shown in Table 8, the microhardness of the composites increased with increasing filler content. Compared to C1, the hardness of C2 increased by 8.1%, while C3 showed an increase of 16.2%. The increase in hardness is attributed to the presence of rigid fly ash particles within the epoxy matrix, which improve resistance to localized plastic deformation and enhance load transfer between the matrix and reinforcement. The fly ash particles also reduce matrix mobility and fill micro voids in the composite structure, resulting in improved surface hardness. Therefore, increasing fly ash content significantly enhanced the hardness characteristics of the hybrid composites [18,19].

Table 8: Microhardness of Composites

Composite	Composition	Hardness
C1	Epoxy (70wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %)	74 ± 1.2
C2	Epoxy (65wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %) + Fly ash (5wt. %)	80 ± 1.3
C3	Epoxy (60wt %) + Glass Fiber Mat (20wt. %) + Coir Fiber (10wt %) + Fly ash (10wt. %)	86 ± 1.5

3.3 EROSION WEAR ANALYSIS

Erosion tests were conducted at room temperature following the Box-Behnken Design matrix. Erosion rate values were calculated and presented in Table 9.

Table 9 Box–Behnken experimental design and response for air jet erosion test

Run	Filler (wt.%)	Impingement angle (deg.)	Erodent velocity (m/s)	Erosion rate (gm/min)
1	5	90	44	0.00136
2	5	30	100	0.00977
3	10	60	44	0.00220
4	5	60	72	0.00611
5	10	90	72	0.00993
6	10	30	72	0.00891
7	5	60	72	0.00699
8	10	60	100	0.01260
9	5	60	72	0.00622
10	0	90	72	0.00973
11	5	30	44	0.00142
12	5	90	100	0.01139
13	0	30	72	0.00531
14	0	60	100	0.01207
15	0	60	44	0.00129

3.1.1 Regression Analysis of Erosion Rate

The regression analysis was performed using Minitab software (20.3) and the quadratic regression equation was obtained for erosion rate as given below in Eq. 3.

$$\begin{aligned} \text{Erosion rate (gm/min)} = & -0.01120 - 0.000097 \text{ Filler (wt.\%)} - 0.000044 \text{ Impingement angle (Degree)} + \\ & 0.000323 \text{ Erodent velocity (m/s)} + 0.000062 \text{ Filler (wt.\%)*Filler (wt.\%)} + 0.000001 \text{ Impingement angle (Degree)*Impingement angle (Degree)} - 0.000001 \text{ Erodent velocity (m/s)*Erodent velocity (m/s)} - 0.000006 \text{ Filler (wt.\%)*Impingement angle (Degree)} - 0.000001 \text{ Filler (wt.\%)*Erodent velocity (m/s)} + 0.000001 \text{ Impingement angle (Degree)*Erodent velocity (m/s)} \end{aligned}$$

.....(3)

Fig. 2 Normal probability plot of residuals provides a clear indication of the statistical adequacy of the model. The residual points are seen to lie close to a straight line in this plot, which suggests that the residuals are approximately normally distributed. This agreement shows that the normality assumption is satisfied which is an important requirement for the validity of regression analysis. The closeness of the points to the reference line also indicates that there are no large deviations, outliers or systematic patterns in the residuals. This implies the errors are randomly distributed and the model can represent the underlying relationship between the process variables and the response with reasonable accuracy.

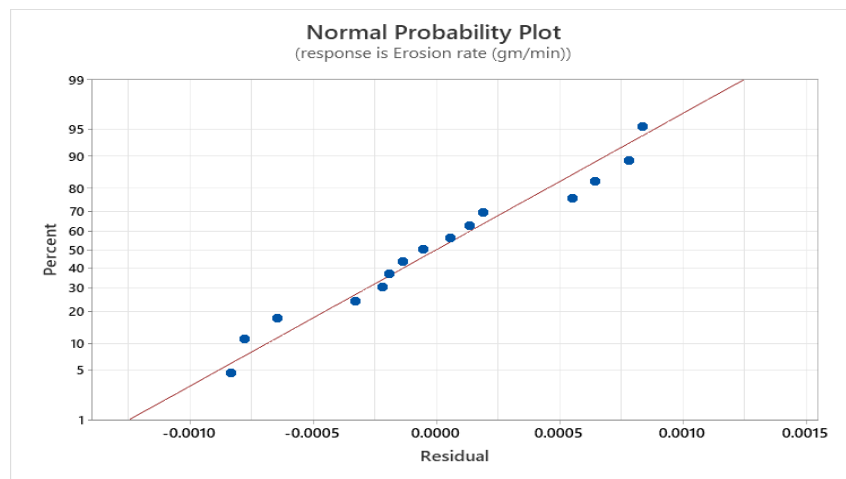


Fig. 2: Normal probability plot

The Analysis of Variance (ANOVA) of the regression model was performed using the Box–Behnken Design (BBD) in Minitab software, to evaluate the adequacy of the model and the significance of its coefficients. The results of the lack-of-fit test, sum of squares and overall model statistics are shown in Table 10. The p-value for the quadratic model is 0.003 based on the model statistics and is less than the threshold of 0.05. The low p-value suggests that the model is statistically significant at the 95% confidence level [20].

Also, Table 10 shows that the R² and adjusted R² of erosion rate are 96.80% and 91.04%, respectively, which indicates a good relationship between the experimental inputs and the predicted response. These values suggest that the model can account for a large proportion of the variation in the response [21].

Moreover, the regression model shows a F value of 16.81, which also confirms its significance. The high F-value shows that the variation explained by the model is significantly larger than the unexplained residual variation, and confirms that the model matches the experimental data well. The quadratic model is a good representation of the relationship between the input variables and the response in general [22]. Among the parameters studied in the erosive wear test, the erodent velocity was found to be the most influencing parameter followed by the impingement angle and the filler wt.%.

Table 10 - ANOVA of erosion rate

Source	DF	Adj SS	Adj MS	F-Value
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Model	9	0.000223	0.000025	30.77
Linear	3	0.000205	0.000068	85.11
Filler (wt.%)	1	0.000003	0.000003	4.27
Impingement angle (Degree)	1	0.000006	0.000006	7.62
Erodent velocity (m/s)	1	0.000196	0.000196	243.45
Square	3	0.000014	0.000005	5.69
Filler (wt.%)*Filler (wt.%)	1	0.000009	0.000009	10.93
Impingement angle (Degree)*Impingement angle (Degree)	1	0.000001	0.000001	1.09
Erodent velocity (m/s)*Erodent velocity (m/s)	1	0.000003	0.000003	4.08
2-Way Interaction	3	0.000004	0.000001	1.51
Filler (wt.%)*Impingement angle (Degree)	1	0.000003	0.000003	3.60
Filler (wt.%)*Erodent velocity (m/s)	1	0.000000	0.000000	0.04
Impingement angle (Degree)*Erodent velocity (m/s)	1	0.000001	0.000001	0.88
Error	5	0.000004	0.000001	
Lack-of-Fit	3	0.000004	0.000001	5.16
Pure Error	2	0.000000	0.000000	
Total	14	0.000227		
Summary of Model				
S	R²	R² (adjusted)	R² (predicted)	
0.0006706	98.23 %	95.03%	74.41%	

Fig. 3 shows the relation between the mean erosion rate and the input factors. The plots show a parabolic trend between the mean erosion rate and the three parameters studied which are the impingement angle, the erodent velocity and the reinforcement wt.%. Among these parameters, erodent velocity seems to be the most dominant factor controlling the erosion behavior of the composite.

It is well established that an increase in erodent velocity leads to a corresponding increase in the kinetic energy of the impacting particles, thereby intensifying material removal from the target surface. The higher velocity not only increases the impact energy, but also reduces the time interval between successive particle impacts, further contributing to surface degradation. Consequently, greater material loss is observed at elevated velocities due to the higher stress imposed on the target surface, even at relatively low angles of impact [23]. At low impingement angles, erosion is primarily dominated by abrasive action of the erodent particles. As the angle of impingement increases, the erosion mechanism shifts toward plastic deformation, resulting in enhanced material removal. At still higher impingement angles, brittle fracture may occur in the material, leading to a further rise in erosion rate [24].

The dependence of erosion rate on erodent velocity is described by a power-law relationship, as given in Eq. 4 [25].

$$E = kV^n \dots\dots\dots(4)$$

Here, E represents erosion rate at steady-state, V denotes the particle velocity, k is a constant and n is the velocity exponent. Generally, materials exhibiting ductile behavior typically have a value of n between 2 and 3, while materials that display brittle characteristics usually have a value of n between 3 and 5.

The filler content, erodent velocity and impingement angle have significant influence on the erosion behavior of the fly-ash-filled glass- and coir-fiber-reinforced polymer composite. As shown in Fig. 3, the erosion rate first decreases with the increase of fly ash content and reaches a minimum at about 4 wt.% fly ash. The reduction in these values can be explained by the increase in the hardness and stiffness of the composite material with the addition of fly ash particles. The rigid fly ash particles act as protecting barriers within the polymer matrix and inhibit penetration and cutting action of the erodent particles. The glass and coir fibers also help prevent material loss by absorbing and redistributing the impact energy. However, beyond the optimum fly ash content, the erosion rate increases. At higher filler concentrations agglomeration of particles and weak interfacial regions may develop, providing preferential sites for crack initiation and propagation. Thus, repeated impact of erodent particles can cause matrix cracking, fibre–matrix debonding, fiber breakage and removal of poorly bonded fly ash particles, which will increase the erosion rate [26].

The impingement angle also strongly affects the erosion behavior. The figure depicts a consistent rise in erosion rate with the rise of impingement angle from 30° to 90°. The erodent particles mainly slide and glance off the composite surface at relatively low angles of . Hence, the material removal is rather limited. As the angle of impingement increases, a greater fraction of the kinetic energy of the particle is directed normal to the surface. This leads to indentation, crushing of matrix, cracking, fiber damage and debonding at the fiber-matrix interface and hence more loss of material. The increase in the erosion rate at higher impact angle indicates that the present glass/coir fibre-reinforced polymer composite is significantly affected by the damage mechanism from the normal impact, especially at impact angle close to 90° [27].

Among the studied parameters, the erodent velocity has the most significant effect on the erosion rate as seen from the steepest slope in the main effects plot. The erosion rate increases dramatically with increasing erodent velocity. This behavior is related to the increase of the kinetic energy of the impacting particles, proportional to the square of their velocity. In this way high velocity erodent particles produce higher impact stresses and help in removal of matrix, formation of microcracks, fracture of fibers, debonding and dislodgement of fly ash particles. Therefore, the increase of the erodent velocity can accelerate the degradation of the composite surface greatly [28].

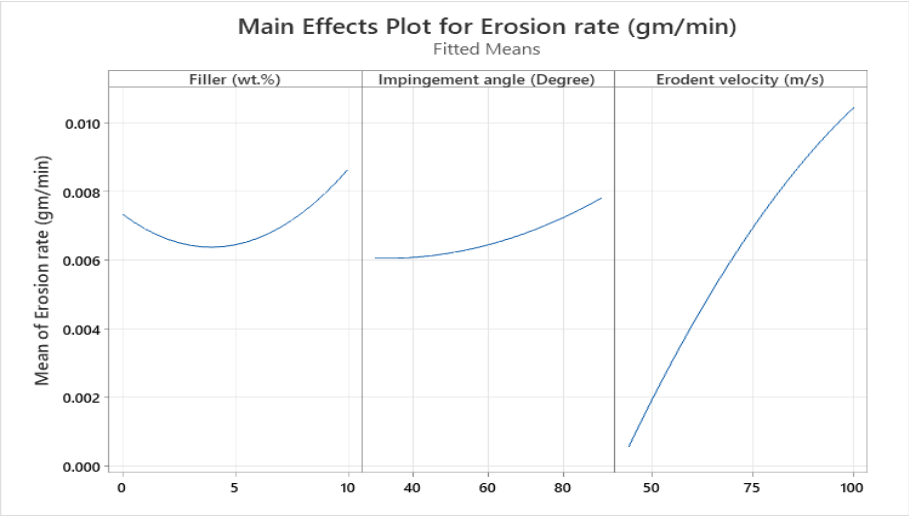


Fig. 3: Plot between mean of mean of erosion rate (gm/min) and impingement angle (deg.), erodent velocity (m/s) and filler (wt.%)

The erosion rate corresponding to different combinations of process parameters is presented through the surface response plots in Fig.4. The plots illustrate the combined effects of fly ash content, impingement angle, and erodent velocity on the erosion behaviour of the coir/glass fibre-reinforced polymer composite.

The surface plot exhibits a nonlinear variation at the constant erodent velocity of 72 m/s where the erosion rate decreases initially with the fly ash content up to an optimum concentration, beyond which it increases due to particle agglomeration and weakened matrix regions. Erosion rate also increases with impingement angle as the dominant normal impact component at higher angles promotes indentation, matrix cracking and fibre–matrix debonding.

At constant impingement angle 60°, erodent velocity has a strong influence and the erosion rate increases rapidly with an increase in kinetic energy of the impacting particles. Fly ash content also exhibits an initial decrease in erosion rate followed by an increase beyond the optimum loading which is due to the protective effect of filler particles at lower contents and interfacial deterioration/agglomeration at higher contents.

With a constant fly ash content of 5 wt.% the erosion rate rises with the angle of impingement and erodent velocity, reaching a maximum value at the highest combined values. Higher velocities lead to higher kinetic energy which along with a larger normal impact component at higher angles increases matrix deformation, fiber fracture, debonding and microcrack propagation. Lower values of both parameters cause lower erosion.

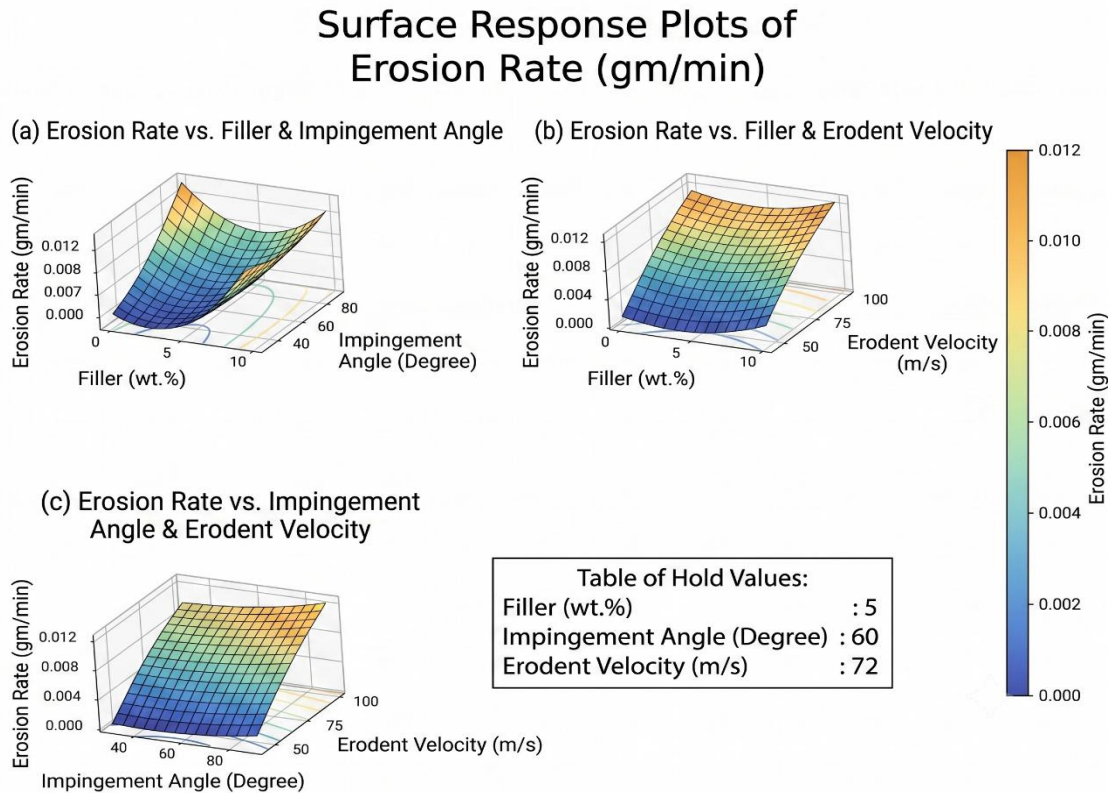


Fig. 4: Surface plots of erosion rate against impingement angle (deg.), erodent velocity (m/s) and fly ash (wt.%)

3.1.2 Optimization of Erosion Rate

The optimum process parameters were determined by desirability analysis for response optimization to minimize the erosion rate of the AMCs. The desirability analysis performed in Minitab (Fig. 5) shows the simultaneous optimization of the three variables i.e. reinforcement wt.%, erodent velocity and impingement angle. A composite desirability value of 1.000 indicates the selected factor levels are very effective in achieving the minimum erosion rate

in this study. The optimum combination was 2.5 wt.% reinforcement, 44 m/sec erodent velocity and impingement angle of 33.03° with erosion rate of 0.0001659 g/min.

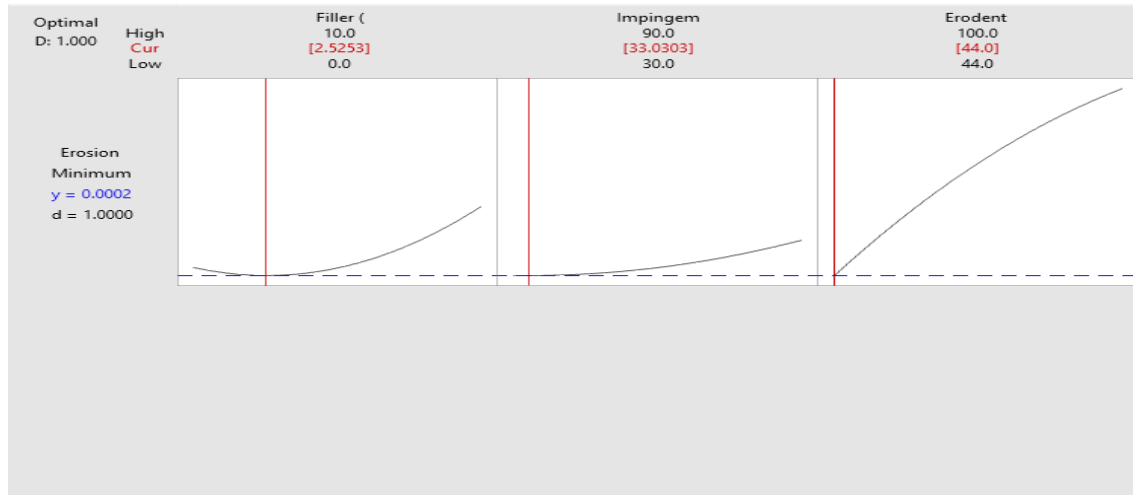


Fig. 5: Optimum response value of impingement angle (deg.), erodent velocity (m/s) and fly ash (wt.%)

3.1.3 Confirmation Test

A validation test was carried out to check the accuracy of the optimization method. The composite undergoes testing utilizing ideal settings. Table 11 displays the experimental results based on these ideal parameters, contrasting them with the optimized responses of the model. Since the error rate is under 6%, the proposed technique is dependable enough to function as a prediction tool for wear analysis.

Table 11 - Results of the confirmation test for erosion test

Filler (wt. %)	Erodent Velocity (m/s)	Impingement angle (deg.)	Experimental values of erosion rate (gm/min)	Modelled values of erosion rate (gm/min)	Error (%)
2.5	44	33.03	0.000162	0.0001659	2.41

4.1 Conclusions

In the present work, fly ash filler reinforced epoxy hybrid composites with coir fiber and glass fiber were successfully fabricated and their erosive properties were investigated. The experimental results indicated that the addition of fly ash had a great influence on the composite performance.

- Density of the composites increased with the increase in fly ash content due to the higher density and improved packing effect of fly ash particles.
- The addition of filler increased the hardness values due to the rigid nature of fly ash particles which increased resistance to localized deformation.
- Among the studied variables, the erodent velocity is the most dominant factor controlling the erosion behavior of the composite followed by impingement angle and filler weight percentage.
- As the erodent velocity increases, the erosion rate sharply increases. Higher velocities impart greater kinetic energy to the impacting particles, leading to higher impact stresses which accelerate matrix removal, microcrack generation, fiber fracturing, and displacement of fly ash particles.

- The erosion rate is parabolic with fly ash content. It decreases at first and reaches a minimum at about 4 wt.% fly ash, since the rigid particles act as protective barriers to prevent erodent penetration. However, at higher concentrations, the erosion rate increases due to particle agglomeration leading to weak interfacial regions where cracks can initiate and propagate. However, the erosion rate increases consistently as the impingement angle increases from 30° to 90°. At lower angles, erodent particles largely slide off the surface, while at higher angles the kinetic energy is directed normally to the surface creating more severe damage such as matrix crushing, indentation, and fiber-matrix debonding.

- The developed quadratic regression model by Box-Behnken Design is highly reliable and statistically significant to predict the wear with R-squared value of 96.80%.

- The desirability analysis showed that the optimal combination to achieve the minimum erosion rate (0.0001659 g/min) is 2.5 wt.% filler reinforcement, an erodent velocity of 44 m/s, and an impingement angle of 33.03°.

- This optimized model was validated with a confirmation test to have an error rate of 2.41% which proved that the model is a reliable predictive tool for wear analysis.

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