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OPTIMIZED TRIBOLOGICAL BEHAVIOUR OF MUSA–BASALT–SiC HYBRID COMPOSITES USING RSM

OPTIMIZIRANJE TRIBOLOŠKIH LASTNOSTI HIBRIDNEGA KOMPOZITA NA OSNOVI VLAKEN MUSE, BAZALTA IN SILICIJEVEGA KARBIDA Z UPORABO METODE ODGOVORA POVRŠINE

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The study examines the influence of SiC additions on tribological properties of basalt–Musa fiber-reinforced hybrid composites with a phenol-formaldehyde matrix. The composite with 60 % of Musa, 26 % of basalt and 4 % of SiC (S5) had the highest mechanical properties, such as tensile, flexural and compressive strength of 38.8 MPa, 186.8 Mpa and 70.8 MPa, respectively, and was selected for wear testing. Experiments on tribological behaviors at different sliding velocities (2–6 m/s), contact pressures (0.25–0.75 MPa) and durations (60–180 s) indicated wear rates between 4.2×10^{-5} and 34×10^{-5} mm^3/m and a COF of 0.08–0.205. These results were well modelled using response surface methodology with R^2 values of 0.995 and 0.922, for wear rate and COF, respectively. It was found that the effect of the wear rate was governed by contact pressure and duration, while the COF was affected by all the factors together. The article emphasizes the wear properties of the Musa–basalt–SiC hybrid composite and determines the most favorable conditions in terms of improved tribological quality.

Key words: Musa–basalt hybrid composite, tribological performance, SiC reinforcement, friction coefficient optimization

Avtorji članka opisujejo študijo, ki je preučevala vpliv dodatka SiC na tribološke lastnosti hibridnega kompozita s fenol-formaldehidno matriko, ojačano z bazaltnimi vlakni in vlakni muse (Musa acuminate ali bananina lingoceluloza; vlakna pridobljena iz bananinih olupkov). Kompozit s 60 % muse, 26 % bazalta in 4 % silicijevega karbida (S5) je imel najboljše mehanske lastnosti. Ta kompozit je imel natezno trdnost 38,8 MPa, upogibno trdnost 70,8 MPa in tlačno trdnost 186,8 MPa. V nadaljevanju te študije so za tribološke preizkuse uporabili samo kompozit s to sestavo. Tribološki preizkusi so potekali pri različnih drsnih hitrostih (od 2 m/s do 6 m/s), kontaktnih tlakih (od 0,25 do 0,75 MPa) in trajanjih (od 60 do 180 sekund). Ugotovljene stopnje obrabe so se gibale med $4,2 \times 10^{-5}$ in 34×10^{-5} mm^3/m ter koeficienti obrabe (COF) med 0,08 in 0,205. Te rezultate so avtorji uspešno modelirali z metodologijo odziva površine (RSM; angl.: Response Surface Methodology) z R^2 0,995 in 0,922 za dano stopnjo obrabe oziroma koeficiente trenja. Avtorji članka so ugotovili, da na stopnjo obrabe vplivata kontaktni tlak in trajanje obremenitve, na COF pa vplivajo vsi dejavniki skupaj. Študija je določila obrabne lastnosti izbranega hibridnega kompozita Musa-bazalt-SiC in najugodnejše pogoje za izboljšanje njegovih triboloških lastnosti.

Ključne besede: hibridni kompozit na osnovi vlaken muse in bazalta, tribološka učinkovitost, ojačitev s SiC, optimizacija koeficienta trenja

1 INTRODUCTION

In the last few years, the number of vehicles produced has been increasing at an accentuated rate, and this has been mainly because of the ever-increasing global population. Such a trend has, in its turn, contributed to increased demand in the automotive spares. Composite materials are already used in the craft of bearings, shafts, seals, and gears.[1] Fibers and particles contribute to the reinforcement of the materials, optimizing and refining them so that they meet certain performance expectations. The use of polymer composites in cars has become imperative in recent few years. Composites made of natural fibers are highly used currently in automotive industries as they are affordable, environmentally friendly, and easily available to anyone.[2–4] When mixed with ceramic powders like SiC and Al_2O_3, fiber-reinforced composite materials have better wear resistance and friction resistance.[5–7] Currently, agricultural waste products are transformed into a variety of polymer composites, part of which is connected with the presence of the composites infused with ceramic particles applied in automotive engineering. Separation by abrasion and friction is also minimized by using mineral fibers. These wastes are chemically treated to obtain fibers that can be used to make composites, a process in which the lignin and wax components are discarded.[8,9] Treatment of natural fibers with CH_3COOH (acetic acid) also reduces the amount of wax on the surface and, thus, helps to establish a better bond between the fibers and the matrix, therefore leading to higher strength of the composites.

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The present study aims to prepare and optimize bio-ceramic hybrid composites that are reinforced with natural (Musa, basalt) and ceramic (SiC) materials in a phenol formaldehyde matrix to enhance mechanical strength and tribological stability for potential friction material applications. They were fabricated and tested for tensile, flexural, and compressive strengths using six formulations to determine the best composition. The best composite was analyzed using the response surface methodology (RSM) to determine the effects of wear time, sliding speed, and contact pressure on wear rate and coefficient of friction (COF), establishing the best values of these parameters and achieving high performance.

2 MATERIALS AND METHODS

2.1 Materials

The Musa fibers used in this research work were purchased at Eco Green Chennai in Tamil Nadu, India. The basalt fiber (5 mm short fibers) source was Fiber Source, Chennai, India. Phenol formaldehyde (PFR 301) resin was used as the matrix material, and it was obtained through Shivam Polymers, Maharashtra. Since PFR 301 is a self-curing thermosetting resin, no external catalyst or accelerator was used. The filler material used in the composite was SiC; its particles were fine, with a size of 220 mesh, procured cost-effectively through BGW India Manufacturing Private Limited, Chennai.

2.2 Chemical refinement of Musa fiber

The hydrophilic nature of Musa fiber alters the fiber and the matrix orientation, thus resulting in improper bonding, defects and low mechanical strength. The cellulosic components including Musa fiber, lignin, hemicellulose and wax are responsible for the material's poor adhesion; hence, chemical treatment of the fibers is required.[10] Acetic acid was originally used in this regard. In acetic treatment, the fiber is soaked in a 5 % acetic acid solution diluted with water and left to soak for 10 min after which it is washed many times with water.[11]

2.3 Composite fabrication

Composites were fabricated using a 30 Ton ACE compression molding machine[12,13] as illustrated in **Figure 1**.

First, Musa fibers and basalt fibers were cut to 5 mm in length and then weighed according to the proportions given in **Table 1**. The fibers were mixed with SiC particles and phenolic resin by mechanical stirring to ensure a truly random, homogeneous dispersion. Then the blended mixture was poured into a mold with a size of (300 × 300 × 3) mm. The mold was kept at a pressure of 2.6 MPa at 150 °C for 15 min for curing. The composite plate was then removed carefully, yielding a final composite measuring 300 mm in length, 300 mm in width, and 3 mm in thickness.

2.4 Wear characterization

A composite of Musa, basalt, and SiC was tested for its wear performance using a pin-on-disc tribometer (DUCOM TR20 model). The test specimens had a cross-sections of (8 × 5) mm and a length of 32 mm as per the ASTM G99 requirements of the pin-on-disc wear testing method. The test piece was placed on the machine and one of its sides was rubbed against an EN8 steel disc. The steel disc had a diameter of 110 mm and was 10 mm wide. EN8 steel was selected because of its wide use in industry, in frictional and sliding parts. The disc had a hardness of 220 HV (45 HRC) and was polished to 0.3 μm (Ra) using four-grade emery paper. The tests were all done in the dry condition with varying contact pressures of (0.25, 0.5 and 0.75) MPa.[14] The experiment was based on three sliding velocities of (2, 4 and

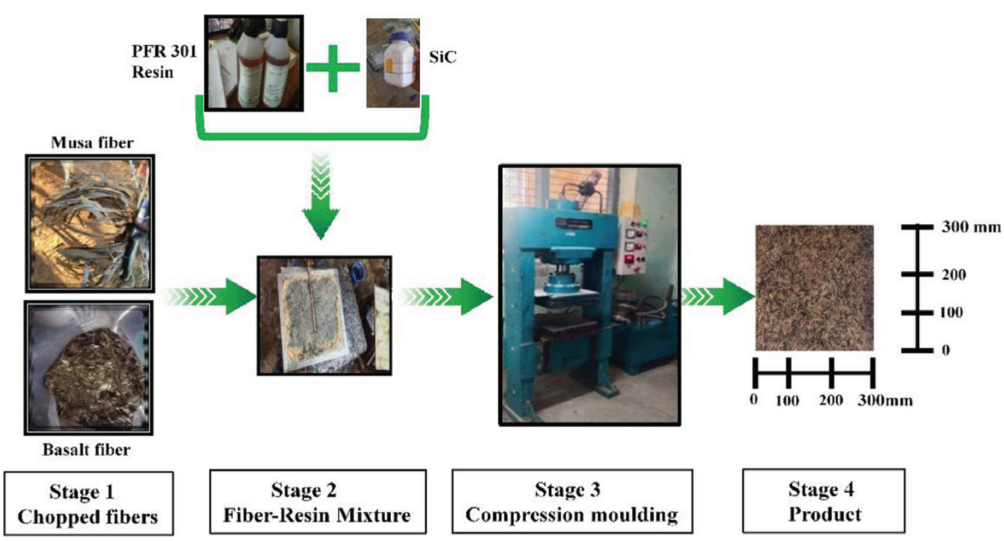

Figure 1: Process flow of Musa-basalt-SiC-reinforced phenol-formaldehyde composite fabrication

6) m/s. The wear duration varied between 60 s and 180 s, and the disparity between the tests was 60 s. The wear properties were determined by calculating the coefficient of friction (COF) and wear rate (WR) in mm^3/m.

Table 1: Matrix and reinforcement combination of hybrid composites

S. No.	Sample number	Matrix (%)	Reinforcement (%)		
			Musa fiber	Basalt fiber	SiC
1	S1	100	0	0	0
2	S2	60	40	0	0
3	S3	60	30	10	0
4	S4	60	28	10	2
5	S5	60	26	10	4
6	S6	60	24	10	6

3 RESULTS AND DISCUSSION

3.1 Influence of mechanical properties of the composite

The fabricated hybrid composites were characterized thoroughly in terms of their mechanical properties, and their key characteristics were noted. Table 2 shows the mechanical data and it can be seen that the best performance was given by specimen 5. A SiC reinforcement of 6 *w*t% resulted in particle agglomeration during fabrication. Excess SiC reduced dispersion uniformity and interfacial bonding, causing stress concentration and inferior composite performance. The acetic-acid-treated Musa fibers were more strongly bonded to the phenolic-based composition compared with untreated fibers; hence, acetic-acid-treated fibers tended to hinder fiber pull-out during mechanical testing. Sample 5 was, therefore, chosen to be further investigated in terms of its wear behavior. For this purpose, the pin-on-disc device was used, which allowed a detailed study of the wear characteristics of Sample 5.

Table 2: Mechanical characteristics of prepared hybrid composites

Sample number	Ultimate tensile strength (MPa)	Flexural strength (MPa)	Compression strength (MPa)
S1	3.71	13	2.21
S2	8.2	18.7	18.63
S3	15.3	27	25.48
S4	26.3	46.7	38.43
S5	**38.8**	**186.76**	**70.76**
S6	38.6	148.8	69.24

3.2 Design of experiments

This research evaluates the influence of the sliding velocities, contact pressure, and wear duration on the wear rate and coefficient of friction in the acetic-treated Musa fiber-, basalt fiber- and SiC-reinforced phenolic composites. The full factorial design was used to assess the interactions of the process parameters in three conditions: sliding velocities of (2, 4 and 6) m/s, contact pressures of (0.25, 0.5 and 0.75) MPa, and wear durations of (60, 120 and 180) s. Table 3 summarises the response values. The experimental setup was aimed at identifying the wear rate and coefficient of friction, which helped to identify the best tribological properties of the hybrid composites.[15,16]

3.3 Regression analysis

Design Expert 13 was used to analyze experimental data through RSM.[17] The relationships between the important process variables including sliding velocity, contact pressure, and wear duration, and tribological response parameters including wear rate (WR) and coefficient of friction, were examined in a quadratic regression model. The models were predictive and fitted well, with R^2 values of 0.9954 and 0.9221 for WR and COF, respectively. These findings indicate that quadratic regressions based on RSM can be used to describe the non-linear impact of processing conditions on the tribology of hybrid fiber-reinforced composite materials.

Table 3: Results of the wear rate and friction coefficient for SiC-reinforced hybrid composites

Trial number	Sliding velocity (m/s)	Contact pressure (MPa)	Wear duration (s)	Wear rate (mm^3/m) $\times 10^{-5}$	COF
1	2	0.25	60	4.2	0.08
2	2	0.25	120	6.6	0.085
3	2	0.25	180	9.2	0.09
4	2	0.5	60	6.1	0.125
5	2	0.5	120	8.4	0.135
6	2	0.5	180	11.8	0.15
7	2	0.75	60	8.4	0.148
8	2	0.75	120	10.2	0.158
9	2	0.75	180	14	0.17
10	4	0.25	60	9.1	0.135
11	4	0.25	120	12	0.145
12	4	0.25	180	16.3	0.16
13	4	0.5	60	11	0.15
14	4	0.5	120	14.5	0.16
15	4	0.5	180	18.6	0.18
16	4	0.75	60	13.7	0.162
17	4	0.75	120	18.6	0.175
18	4	0.75	180	22.4	0.195
19	6	0.25	60	15	0.158
20	6	0.25	120	18.2	0.168
21	6	0.25	180	22.5	0.178
22	6	0.5	60	18	0.195
23	6	0.5	120	21.8	0.18
24	6	0.5	180	26.9	0.162
25	6	0.75	60	22.4	0.17
26	6	0.75	120	28.6	0.19
27	6	0.75	180	34	0.205

3.4 Wear rate

Musa and basalt fiber-reinforced hybrid composites were systematically tested. This kind of process forms the basis for decision-making in material selection, formulation optimization, and tailoring of applications. A variance analysis is given in Table 4. The squared contributions of the sliding velocity (A), contact pressure (B), and wear duration (C) are A^2, B^2, and C^2, and the interaction terms are AB, AC, and BC. The p-value of 0.00001 and F-value of 411.38 indicate that at least one factor or interaction affects the wear rate, demonstrating the significance of the model. The most influential is the sliding velocity, with a p-value < 0.0001 and an F-value of 2405.73, explaining 64.68 %. The contact pressure is also an important predictor, as it has a p-value < 0.0001 and an F-value of 510.60, with a 13.72 % contribution. The p-value of the wear duration is less than 0.0001 and its F-value is 669.73, showing that it is also a significant factor for the wear rate, contributing 18 %. The interactions AB and AC also significantly affect the wear rate, with p-values < 0.0001; the variable BC has a minimal effect, with all its p-values > 0.0100. The non-linear relationships between these variables and wear rate are clearly indicated by the quadratic effects.

Figure 2a shows how wear rate varies with the sliding velocity at various pressures. The wear rate gradually increases with higher velocities. Higher pressures always

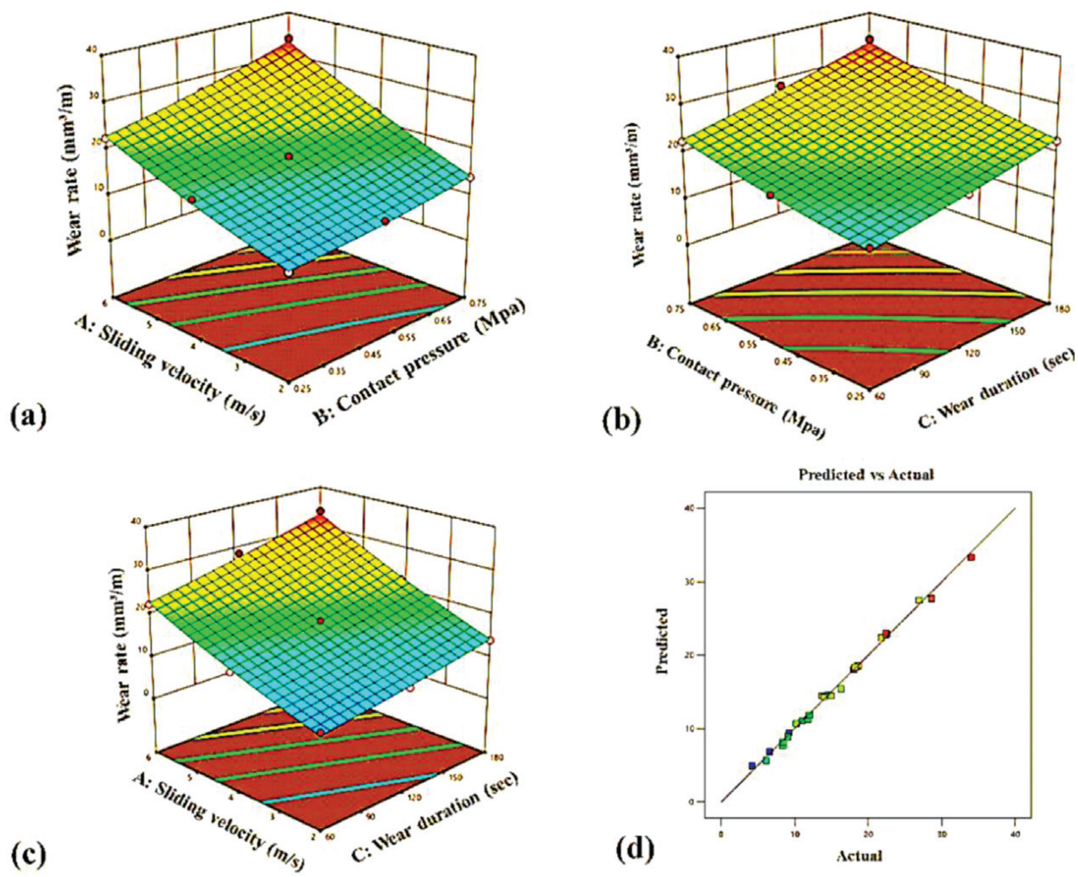

Figure 2: (a–c) 3D surface plots for the wear model; (d) actual vs predicted wear value

Table 4: ANOVA wear rate model

Source	Sum of squares	df	Mean square	F-value	p-value		Contribution %
Model	1411.80	9	156.87	411.38	<0.0001	Significant	
A–sliding velocity (m/s)	917.35	1	917.35	2405.73	<0.0001	Significant	64.68%
B–contact pressure (MPa)	194.70	1	194.70	510.60	<0.0001	Significant	13.72%
C–wear duration (s)	255.38	1	255.38	669.73	<0.0001	Significant	18%
AB	23.24	1	23.24	60.95	<0.0001	Significant	1.63%
AC	11.41	1	11.41	29.92	<0.0001	Significant	0.80%
BC	3.20	1	3.20	8.40	0.0100		0.22%
A^2	3.58	1	3.58	9.38	0.0070		0.25%
B^2	2.32	1	2.32	6.09	0.0245		0.16%
C^2	0.6230	1	0.6230	1.63	0.2184		0.043%
Residual	6.48	17	0.3813				
Cor. total	1418.29	26					

generate higher wear rates, demonstrating that normal force increases the removal of material.[18]

This correlation can be explained by the fact that speed affects the temperature in the contact zone: the faster the speed, the greater the heat, the softer the materials and the faster the wear. The interrelations that exist between contact pressure, wear time, and wear rate are illustrated in **Figure 2b**. It is seen that at low wear times, the wear rate is diminished considerably because of the low rate of interfacial engagement, leading to minimum material removal. As the contact pressure increases so does the wear rate of the material as a result of greater surface stress and thermal effects induced by friction, which combine to cause a greater degradation of the material. **Figure 2c** shows that the wear time has a far greater effect on the wear response than the sliding velocity because of the importance of the contact pressure and time of exposure that are dominant factors in determining the tribological response of the combination.[19]

The linear regression fitting of **Figure 2d** shows that there is a strong correlation between the experimental and predicted values, thus proving that the obtained wear

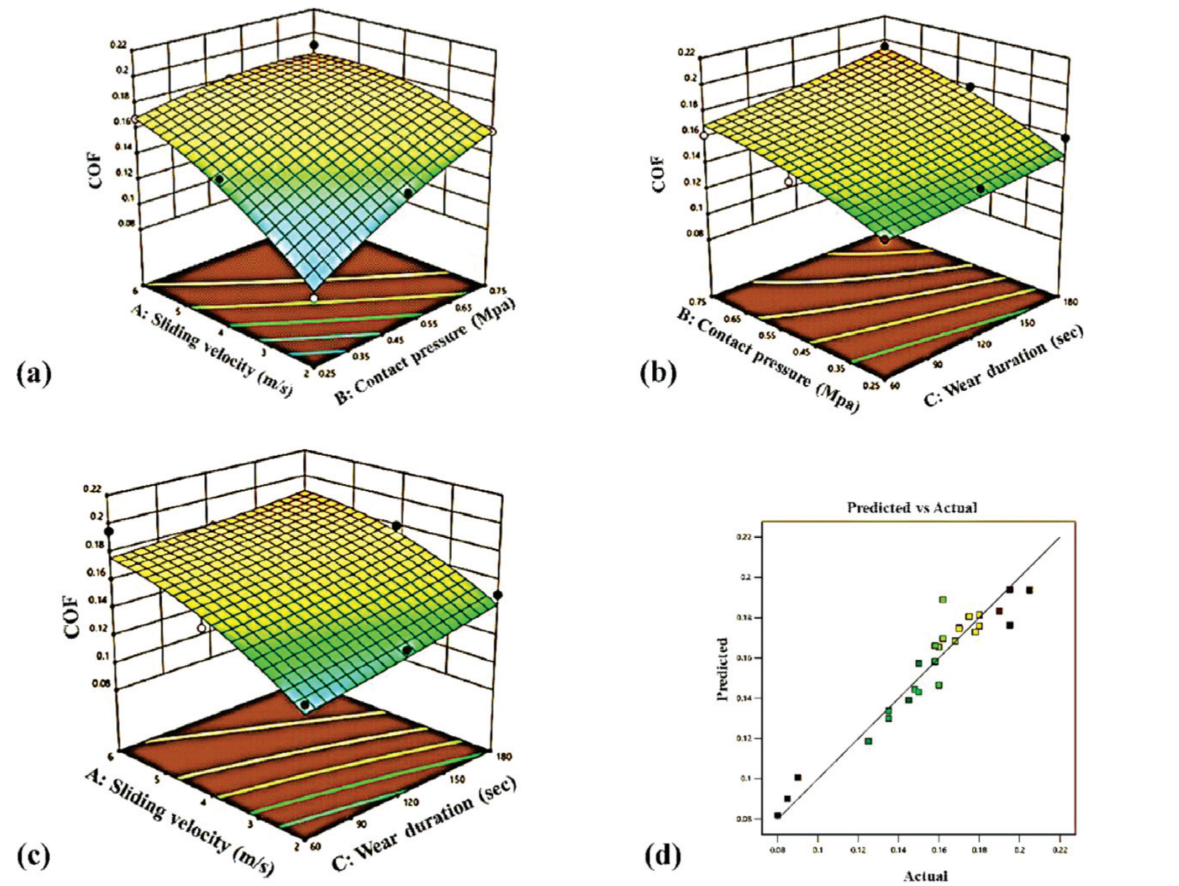

Figure 3: (a–c) 3D surface plots for the coefficient-of-friction model; (d) actual vs predicted coefficient-of-friction value

Table 5: ANOVA model of coefficient of friction

Source	Sum of squares	df	Mean square	F-value	p-value		Contribution %
Model	0.0245	9	0.0027	22.36	<0.0001	Significant	
A–sliding velocity (m/s)	0.0120	1	0.0120	98.87	<0.0001	Significant	45.28%
B–contact pressure (MPa)	0.0078	1	0.0078	63.96	<0.0001	Significant	29.43%
C–wear duration (s)	0.0015	1	0.0015	12.75	<0.0001	Significant	5.66%
AB	0.0021	1	0.0021	17.56	0.0006		7.92%
AC	0.0001	1	0.0001	0.8402	0.3722		0.37%
widctlparBC	0.0001	1	0.0001	0.8402	0.3722		0.37%
A^2	0.0006	1	0.0006	4.78	0.0432		2.26%
B^2	0.0002	1	0.0002	1.59	0.2249		0.75%
C^2	0.00001	1	0.0000	0.0672	0.7985		
Residual	0.0021	17	0.0001				
Cor. total	0.0265	26					

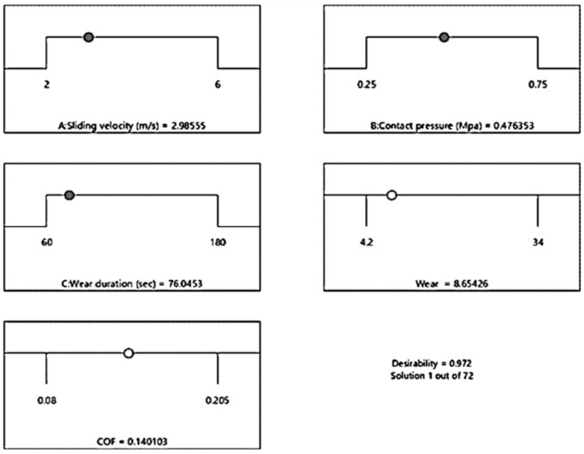

Figure 4: Confirmation of the location of input parameters

data can be very consistent. This kind of alignment without any visible curvature shows a linear relationship between the variables. This seamless and perfect alignment implies that the model can effectively recognize and depict the dataset's complex patterns and trends.

3.5 Coefficient of friction

Friction has a close relationship with the tribological performance and wear-resistance properties of natural-fiber polymer composites. The results of an analysis of variance (ANOVA) are given in **Table 5**. The p-value is much less than 0.0001, and the F-value is 22.36, showing that at least one factor or their interaction is affecting the response. The adjusted R^2 (0.9645) is higher than the predicted R^2 (0.9768), which shows that the model is reliable. Sliding velocity, which accounts for 45.28 % of the variance of the response variable, is very significant. Contact pressure is of great significance (F-value = 63.96, p-value < 0.0001), explaining 29.43 % of the variability. Wear duration is also important (F-value = 12.75, p-value < 0.0001), adding 5.66 % to the total. The AC and BC interactions are not significant, but the AB one is (p-value = < 0.0001), contributing 7.92 % to the re-

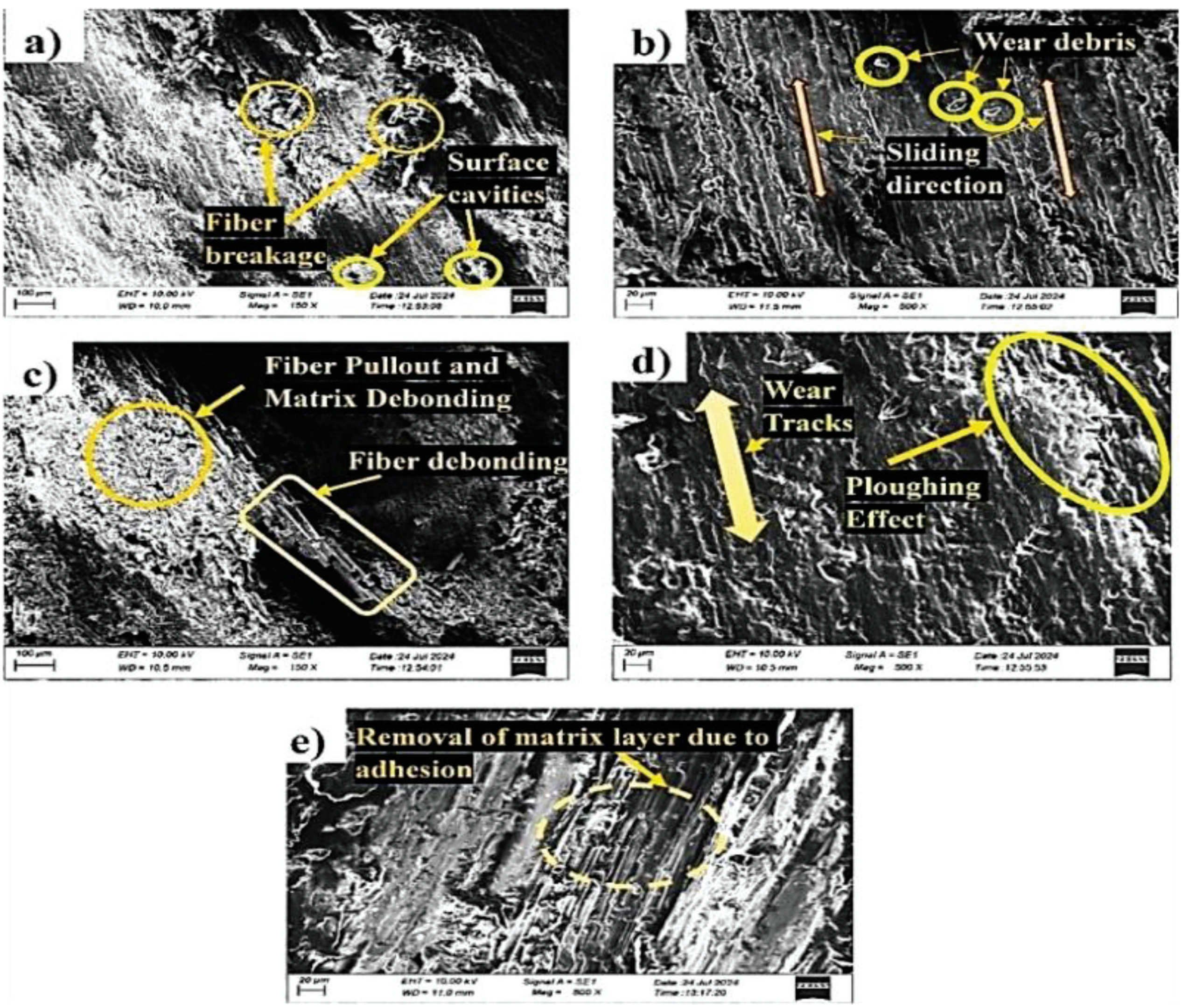

Figure 5: (a–e) SEM photos of the samples subjected to wear testing under different contact pressures

sponse. These results reveal that the predictive model is strong and precise. The relationship is shown in the sliding velocity, contact pressure, and friction interaction plot (**Figure 3a**). Sliding velocity and contact pressure exhibit a significant interaction, causing gradual variation in the coefficient of friction (COF). **Figure 3b** shows the RSM correlation between contact pressure, wear duration, and COF. A longer wear duration of (60–180) s reduces COF due to a stable tribo-film formation, while a higher pressure of (0.25–0.75) MPa increases COF by disrupting this layer. Moderate conditions ensure stable frictional behavior and balanced surface interaction. The interaction plot from **Figure 3c** also shows that sliding velocity has a significant effect on COF and is a key variable, controlling COF. Lastly, the straight line in **Figure 3d** is continuous, indicating consistent behavior and suggesting that the COF model is reliable. As a result, the model can be used to assess and optimize wear behavior due to its accuracy and predictability.[20]

3.6 Optimization of input parameters

Using the response surface methodology, the researchers identified the variables that needed to be optimized to maximize the response values. Both the statistical analysis of data and the formulation of an optimization strategy were done with the complex analytic capabilities of Design Expert 13. The multi-response strategy was aimed at the concurrent minimization of wear and friction. Based on the developed regression models, the minimum wear rate and stable coefficient of friction were obtained with the optimized material parameters. **Figure 4** shows that under fixed contact conditions including 2.98 m/s sliding velocity, 76 s wear duration and 0.47 MPa contact pressure, the corresponding wear rate and coefficient of friction were 8.6542×10^{-5} mm^3/m and 0.1401, respectively. These findings demonstrate that the optimization focused on the contact parameters. It was aimed at providing a trade-off between low wear rate, and high and constant friction. These altered conditions significantly enhanced frictional behavior, especially in regard to the wear rate and coefficient of friction. The example highlights the importance of choosing and optimizing the components of the process to obtain the best results.

3.7 Analysis of worn surfaces

The worn surface morphology of the 4 *w*/% SiC-reinforced Musa-basalt hybrid composite was examined by SEM to relate the wear mechanisms to the experimental tribological behavior. Micrographs for various sliding velocities, contact pressures and wear durations are shown in **Figures 5a–e**.

At 0.25 MPa and 2 m/s, the surface was relatively smooth, having only slight grooves indicating that there were mild adhesive wear and good fiber-matrix adhesion, as shown in **Figure 5a**. **Figure 5b** shows that increasing the contact pressure to 0.5 MPa and the velocity to 4 m/s resulted in observable ploughing of the surface and shallow matrix removal. **Figure 5c** represents the localized fiber rupture and interfacial debonding, indicating the onset of abrasive wear at 0.6 MPa and 4 m/s. **Figure 5d** reveals that severe deformation and fiber pull-out was noticed at 0.75 MPa and 6 m/s, attributed to greater contact stresses and heat generated by friction. After a prolonged wear test for 180 s, at the same condition, there was delamination of the matrix and heavy wear grooving, indicating that fatigue assisted the removal of the matrix material, as seen in **Figure 5e**. The SEM observations compliment the wear and COF analyses in confirming that with increased contact pressure, velocity and time of wear, the transition of mild wear to severe wear occurs, while moderate test conditions ensure a stable frictional response.[21]

4 CONCLUSIONS

The current study examined Musa fiber-, basalt fiber- and SiC-reinforced phenolic composites prepared by hot-press compression molding. The main findings are as follows.

1. Mechanical Performance: Incorporating 4 *w*/% SiC contributed greatly to the mechanical properties. The optimized composite (S5) exhibited a tensile strength of 38.8 MPa, flexural strength of 186.8 MPa, and compressive strength of 70.8 MPa, indicating that there is good synergistic contribution of the Musa and basalt fibers combined with SiC particles.

2. Tribological Behaviour: Wear tests and regression analysis revealed that the wear rate is dominated by the sliding velocity, whereas the coefficient of friction (COF) is affected by the sliding velocity, contact pressure, and wear time. The results of response surface methodology (RSM) were predictive models ($R^2 = 0.995$ wear rate and $R^2 = 0.922$ COF). The optimal conditions corresponded to a wear rate of 4.2×10^{-5} mm^3/m and a COF of 0.09, achieved at a sliding velocity of 2 m/s, a contact pressure of 0.25 MPa, and a duration of 180 s.

3. Microstructural Observations: SEM revealed the evidence of the enhancement of fiber-matrix bonding in acetic-acid-treated composites with 4 *w*/% SiC, as well as minimization of fiber pull-out, micro-cracking and adhesive failure, thus resulting in wear resistance.

4. Industrial Applications and Limitations: The resulting composites can be applied in automotive parts and wear-resistant parts, exhibiting enhanced performance in terms of durability and tribology. Weaknesses are processing problems (homogenous dispersion of fibers and particles) and scale problems of industrial production. One of the future studies should aim to overcome these challenges with practical applications.

The work shows the mechanical and tribological performance of hybrid fiber-SiC composites and demonstrates that RSM can be used to optimize processing parameters, which is important for both scientific studies and practice.

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