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RESEARCH

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Evaluation of surface response of SiC and fly ash-filled *Prosopis juliflora* fibre-reinforced epoxy composites under dry sliding wear conditions using Taguchi method

Suresh Thirupathi[1], Ayyappan Solai[3], Shenbaga Velu Pitchumani[1], Venkatachalam Gopalan[2*] and Elango Mallichetty[1]

*Correspondence: gopvenki@gmail.com

[1] School of Mechanical Engineering, Vellore Institute of Technology, Chennai Campus, Chennai, Tamilnadu 600127, India
[2] Centre for Innovation and Product Development, Vellore Institute of Technology, Chennai Campus, Chennai, Tamilnadu 600127, India
[3] Department of Mechanical Engineering, Government College of Technology, Coimbatore, Tamilnadu 636011, India

Abstract

Prosopis juliflora (PJ) fibre-reinforced polymer composites are fabricated with fly ash and SiC as fillers with different weight percentages. Jute layers are also sandwiched for added strength in the structure. The wear behaviour is found for the prepared composition of samples. Pin-on-disc wear testing apparatus is used for the wear performance along with the design of experiments approach using orthogonal arrays of Taguchi's. The effect of the input parameters (load, sliding velocity, speed) is studied on wear resistance. The experimental design creates sliding wear evaluations based on Taguchi's L9 orthogonal array to identify the most dominating factors influencing the wear rate. This study demonstrates that the most important component affecting the sliding wear rate of the composite materials is followed by the sliding velocity, speed, and load. The result of the wear rate decreases with an increase in filler content and also increases with sliding velocity. The samples with fly ash and SiC fillers reportedly seemed to have the best wear rates.

Keywords: *Prosopis julifora*, Fly ash, Silicon carbide, Taguchi method, Wear

Introduction

People are becoming more conscious of and supportive of things made from natural resources. In many countries, environmental protection and the use of non-renewable resources in the manufacture of goods may raise substantial legal issues. Therefore, natural materials should be used whenever possible to create everyday things. In comparison to synthetic fibres, natural fibres offer several advantages such as being naturally recyclable, inexpensive, nonabrasive, lightweight, enhanced mechanical qualities, high crash absorbency, and superior flame retardance [1–6]. *Prosopis juliflora* (PJ) plants are prevalent in many areas. At the same time, it is difficult to grow crops since they take water and nutrients from the soil, rendering them unusable [7, 8]. Many studies are conducted to determine the best ways to utilise these plants for diverse applications. The activated carbon from PJ can be used in the food, oil and pharmaceutical trades by producing it chemically [9]. In our paper, PJ/glass fibre-reinforced composites were investigated, and it was discovered that the mechanical properties are improved as the glass fibre content rises. Additionally, they recommended using natural fibre instead of synthetic fibre [10]. The water absorption and mechanical and tribological properties of the novel composites need to be investigated thoroughly. By adding jute fibre and composites loaded with waste plastic and waste plastic particles in a 30-weight percent ratio, Sakthi Balan et al. found that the materials strongly resist water absorption [11]. In a study by Madhu et al., it was observed that treated PJ fibres' tensile and thermal properties are greater than those of untreated fibres [12]. The flexural strength, tensile strength and modulus of polymer composites, moreover their microstructure and molecular weight, all influence their performance characteristics [13–15]. According to Santhosh et al., the study of the shape and characteristics of PJ and rice husk-reinforced epoxy composites with filler materials can enhance mechanical qualities by 45% [16]. The wear resistance of natural and synthetic fibres is equivalent. By adding synthetic fibre reinforcement, natural fibre wear resistance can be raised [17]. A thorough analysis was conducted on the tribological application of polymer composites by Fredrich, who concluded that adding reinforcing fibres and micro- and nano-fillers would improve any polymer's tribological behaviour [18]. By means of chemically changing the superficial with $NaHCO_3$ and as well coating the surface of the fibre with PLA, the authors intended to boost the erosive wear resistance of the sisal composite. They found that both coated fibres and treated fibres provide the best wear resistance [19]. Designing experiments using the Taguchi method is beneficial. When analysing the effects of numerous process variables, materials scientists can benefit from it. The Taguchi method is used to analyse statistical composites made of polymers. Kumar and Reddy studied boron nitride reinforcement of Nylon composite using the Taguchi technique and discovered that it increased the composite's wear resistance [20]. Functionally graded polymer composites are a family of materials that are widely employed as components when friction and wear are important issues. These materials have beneficial qualities like high specific strength, high modulus, low weight, self-lubricating, minimal noise and ease of production [21, 22]. Adding silica sand filler improved the tribological and water absorption properties of plastic waste-reinforced glass fibre composite. In this study, Arthanarieswaran et al. enhanced epoxy composites' thermal and mechanical properties through NaOH treatment and added 20% fibres [23]. Ferdous et al. suggested employing the Taguchi design to examine the bond length and width used for greater strength in polymer-based composites [24]. According to Taguchi's full factorial design, the composite was made by mixing particles of waste plastic through the powder of PJ thorns and spraying it onto the surface. Trials were conducted using ASTM standards, and data from them was given as input into a software programme to allow for additional optimisation [25]. Recent studies focused on green fillers such as rice and maize husks, shell powders of coconut and cashew nuts and date seed powders. Natural fibres and fillers are employed in composite materials because these materials are lightweight, affordable, extensively accessible, decomposable and ecological [26].

Abrasive wear mechanisms of fibre-loaded epoxy composites can be established as the extensive literature review offers plenty of scopes. An effort is made in the current work to examine the wear behaviour of PJ fibre-reinforced epoxy-based composites using silicon carbide and fly ash filler materials. For increased structure, sandwich composite is fabricated using layers of jute mat fibres. Further work is carried out using Taguchi experimental design to perform a parametric analysis of the abrasive wear process.

Material selection

Prosopis juliflora (PJ)

Natural fibres are extracted from the barks of PJ from nearby areas of Coimbatore, India. Collected PJ bark is made to soak in water for 14 days and dried under the shadow in Fig. 1.

Jute fibre mat

The addition of coconut filler improves the mechanical features of jute fibre-woven mat epoxy-based reinforced composites. Fifteen percent coconut filler weight fraction is the optimum level. To enhance its mechanical qualities and use it for different structural applications, this coconut filler can be strengthened with any natural fibre mat polymer composite [27]. Jute mat, which improves the matrix formation and enhanced the composite material's mechanical properties, is employed in three layers in the epoxy resin-reinforced PJ's composite matrix.

Silicon carbide (SiC)

On the mechanical impact and hardness behaviours of chemically treated jute fabric reinforcement laminated composites, the effects of the SiC filling method with various percentages were examined by Reddy and Reddy (28). The test results indicated that the SiC particle size and the reinforcement amount impacted how the composite material performed mechanically [28].

Fly ash (FA)

Fly ash is the fine particulate residual outcome of burning pulverised coal mainly in coal-based energy generation plants. FA is used to improve the tensile strength of the material.

Fig. 1 PJ fibre

Epoxy resin

The epoxy resin is utilised to create the composite sample. The composite specimen is made with HY951 as the hardener.

Experimental

Fabrication method

Natural fibres are extracted from the bark of PJ and are made to soak in water for 14 days. A total of 500 g of PJ is obtained from the extracts and dried under the shadow. Different composite plates are fabricated as shown in Fig. 2, with each laminate containing 3 layers of natural fibre mats. Firstly, jute is placed on top of the plate, followed by an epoxy resin-hardener mix. Four hundred fifty grams of epoxy resin with 50 g of hardener is mixed for this work to obtain the matrix. Then, 100 g of fibre extracted from the dried barks of PJ is placed and sandwiched with another layer of jute. The sandwich is finally topped with an epoxy resin-hardener mixture and is covered with another plate. The whole setup is placed in the compression moulding machine. Once the compression action is complete, the whole plate is coated and finished with wax. It takes 60 min to fabricate one plate of the composite of dimensions 250 mm × 250 mm × 5 mm. The samples compositions are as follows:

- S1—100 g of PJ + 25 g of SiC + Epoxy
- S2—100 g of PJ + 12.5 g of SiC + 12.5 g of FA + Epoxy
- S3—100 g of PJ + 25 g of FA + Epoxy

Tribology test

The pin-on-disc wear testing apparatus is used to determine the composite abrasive wear. The specimen is prepared in conformance with ASTM G99 standards in Fig. 3. The testing is conducted using wear testing equipment with a maximum wear track diameter of 0.135 m and a maximum disc speed of 2000 rpm provided by DUCOM instruments. The specimen is subjected to a grinding distance of 500 m and a weight

Fig. 2 Specimen preparation

Fig. 3 Wear test samples (row-wise S1, S2, S3)

of 30 N. Its length is 5.930 m. The specimen is placed in the container and is kept around through the cantilever unit. The samples are evaluated before and after the tests.

The number of samples required to test the wear in the composites is calculated using Taguchi's method for wear testing. This method selects three levels low, medium and high of three distinct factors: load, reinforcement and sliding velocity. As a result, a total of 9 unique samples are created for this test in Tables 1 and 2.

Table 1 Process variables and their various stages

S. No	Variables	Unit	Stages		
			1	2	3
1	Load	N	10	20	30
2	Sliding speed	m/s	1	2	3
3	Speed	rpm	191	382	573

Table 2 Experimental values

S. No	Load (N)	Sliding speed (m/s)	Speed (rpm)	Time (min)	Wear (μm)	Frictional force (N)
1	10	1	191	8.3	4	2.7
2	10	2	382	4.16	7	2
3	10	3	573	2.7	3	1.1
4	20	1	382	4.16	5	5.7
5	20	2	573	2.7	22	4.9
6	20	3	191	8.3	37	4.1
7	30	1	573	2.7	19	3.5
8	30	2	191	8.3	16	4.7
9	30	3	382	4.16	5	4.1

Taguchi DOEs and optimisation

A full evaluation of the factors under consideration can be obtained by using a controlled and scientific process called DOE to collect and analyse enormous amounts of information, making it easier to analyse the impact of different input variables on the result of a process. Based on the Taguchi L9 orthogonal array for mixed levels of three factors design, the wear and friction tests of the composites are carried out. The created specimens are then evaluated, and the test results are input into the programme and run to determine the ideal values.

Based on our needs, optimisation is done on three concepts. The three basic interpretations used for the optimisation are higher is better, nominally well, and lesser is better. In some circumstances where wear and abrasion applications are present, hardness is necessary. The influencing factors that affect the hardness and the water absorption qualities are determined, including the type of fillers used, the PJ fibre and the epoxy resin. These parameters' ideal values are also identified and validations are carried out to determine how closely the actual results match the predictions.

Results and discussion

Wear test result

It is determined that the PJ fibre-filled-reinforced epoxy resin composite created besides tested in this work has the essential possible for a wide range of applications, particularly in dry sliding wear environments. Given their reasonably strong wear resistance, natural fibre-filled composites are to be preferred if the place of utilisation has adverse conditions for sliding wear. In general, these composites may also be suggested for uses such as fake ceilings, conveyer belt rollers, sliding door panels, lightweight vehicles, partition boards, linings for coal dust pipes and exhaust fan blades [29]. Therefore, depending on the strength and intensity of the wear assault, the amount of fibre in these composites should always be carefully determined.

Figure 4 shows that the wear rate tends to decrease as sliding distance, sliding speed and load increase. The fundamental effects plot for the wear rate with the lowest levels, with the mean value being shown on the Y axis then the levels of the wear rate are shown on the X axis. Higher sliding speeds are when this phenomenon is most apparent, as the composite transfer surface functions as a shield to reduce wear

Fig. 4 Main effect plot for minimum wear rate

rate. Furthermore, wear debris builds up between the pin and disc as the pressure increases during sliding wear, reducing the depth of active penetration [30].

The reduction of porosity, based on the presence of filler powder, is an essential aspect that influences the composite's wear resistance and hardness due to the increasing concentration of fillers [31]. There is a clear correlation between wear resistance and hardness [32]. Improved wear resistance is achieved by increasing the hardness, and increased wear resistance is provided by adding the filler material. Results for several composites and fillers made of polymers have been published by others [31, 33–35].

Figure 5 illustrates the particular wear rate recorded for each of the nine sets of test runs together with the matching S/N ratio. Utilising the MINITAB19 programme, several investigations are conducted. Figure 5 shows the plotting of the mean effect for the S/N ratios of respective control components. The 'smaller is better' features are used to estimate the response table for the S/N ratio. The interaction plot for the wear rate with the smallest wear is shown in Fig. 6. The most prevailing interactions occur between fly ash and SiC.

In this study, the sliding velocity and filler content are found to be the two most important factors. Other researchers have also reported that the content of filler materials and sliding velocity have a greater impact on the epoxy composites bonded with natural or other fibres showing dry sliding wear [36, 37] than sliding distance and normal load.

ANOVA

The experimental findings were analysed using the conventional statistical ANOVA technique to identify the significant parameter combinations influencing the output response, specifically the wear rate and coefficient of friction (COF). Tables 4 and 5 provide the experimental results for wear rate and COF using the design of experiments (DOE). The variance analysis enables the investigation of factors and interactions that significantly impact the response variables [38].

Table 3 denotes factors and response variable of wear experiment. The experimental results received analysis using ANOVA to determine the effect of several parameters on wear rate, including load, sliding speed and speed. This analysis found the dominant independent factor and its % contribution. The final section in Tables 4 and 5 shows the percentage contribution (Pr) of each parameter to the overall variance, demonstrating their level of effect on the outcome. The load is the most significant

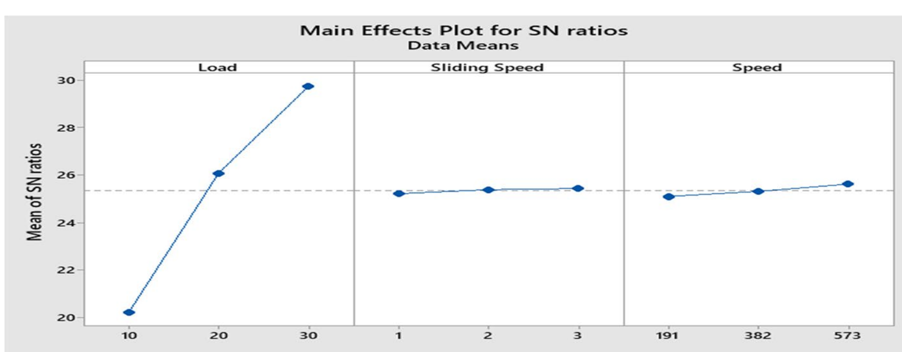
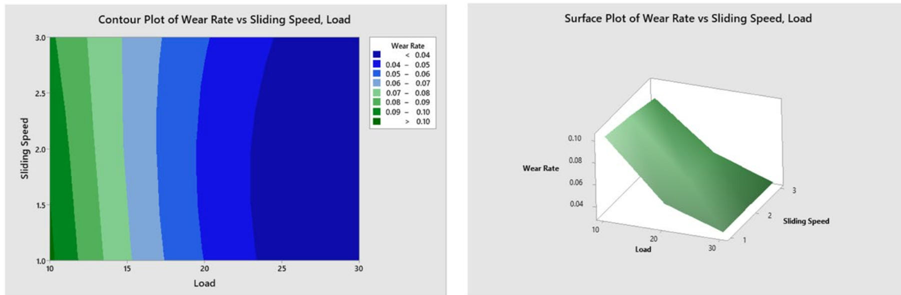
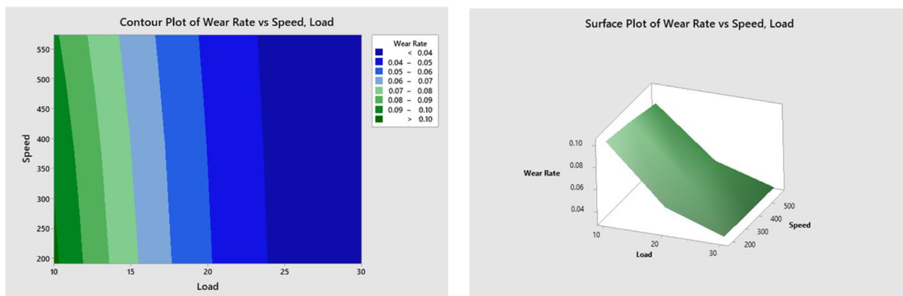


Fig. 5 SN ratio for wear rate



(a) Contour Plot and Surface Plot of Wear Rate Vs Load and Sliding Wear



(b) Contour Plot and Surface Plot of Wear Rate Vs load and Speed

Fig. 6 **a** Contour plot and surface plot of wear rate vs load and sliding wear. **b** Contour plot and surface plot of wear rate vs load and speed

Table 3 Taguchi's method—inputs and outcomes

S. No	Load (N)	Sliding speed (m/s)	Speed (rpm)	Wear rate (mm^3/m)	Coefficient of friction
1	10	1	191	0.1024	0.2700
2	10	2	382	0.0982	0.2000
3	10	3	573	0.0920	0.1100
4	20	1	382	0.0498	0.2850
5	20	2	573	0.0482	0.2450
6	20	3	191	0.0510	0.2050
7	30	1	573	0.0323	0.1170
8	30	2	191	0.0329	0.1570
9	30	3	382	0.0326	0.1370

Table 4 ANOVA for wear rate

Source	DF	Adj SS	Adj MS	*F*-value	Contribution%
Load	1	0.00632	0.00632	64.59	92.15515
Sliding speed	1	0.000014	0.000014	0.14	0.204141
Speed	1	0.000031	0.000031	0.31	0.452027
Error	5	0.000489	0.000098		7.130359
Total	8	0.006858			100

Table 5 ANOVA for coefficient of friction

Source	DF	Adj SS	Adj MS	*F*-value	Contribution%
Load	1	0.017185	0.004713	1.37	49.99
Sliding speed	1	0.008128	0.008128	2.36	23.64
Speed	1	0.004361	0.004361	1.27	12.68
Error	5	0.004713	0.003437		13.71
Total	8	0.034374			100

Table 6 Prediction

S/N ratio	Mean
30.1006	0.0287778

factor in the wear rate, when the load is increasing the wear rate decreases. The data shows that the load (92% on wear rate and 49.99% on COF) has the greatest influence on the wear rate. The wear rate decreases significantly as the load increases. This implies a significant inverse connection between applied load and consequent wear rate, implying that higher loads cause less wear over time.

Regression model

The diagrams in Fig. 6a and b depict the relationship between wear rate and its determinants, which include load, sliding speed and speed. Figure 6a depicts this relationship in two dimensions, whereas Fig. 6b provides a three-dimensional view, improving understanding of how these parameters interact to affect wear rate.

Minitab, a statistical software, was used to develop a multiple linear regression model. This model uses collected data to develop a linear equation that calculates the associations between various parameters. The regression model developed in this manner describes how critical parameters determined through ANOVA analysis—such as load, sliding speed and speed —influence the findings. The regression equation was specifically designed to calculate the wear rate's signal-to-noise (S/N) ratio [39–42].

$$\text{Wear Rate} = 0.1323 - 0.003245\ \text{Load} - 0.00150\ \text{Sliding Speed} - 0.000012\ \text{Speed} \tag{1}$$

$$\text{COF} = 0.3752 - 0.00280\ \text{Load} - 0.0368\ \text{Sliding Speed} - 0.000140\ \text{Speed} \tag{2}$$

Validation test

The verification test is intended to validate the predicted outcome. The displayed wear test result was calculated using Minitab based on the optimum conditions determined by the signal-to-noise (S/N) ratio study. Table 6 shows the expected value, which is 0.0287778, as recorded. Table 7 presents the validation results comparing experimental and optimal values, indicating an error margin of 6.39%.

Table 7 Validation test

S. No	Load (N)	Sliding speed (m/s)	Speed (rpm)	Wear rate (mm^3/m)	Error %
1	30	3	573	0.03062 (experimentation) 0.02878 (optimisation)	6.39

Table 8 Comparative analysis of wear test

S. No	Matrix	Reinforcement	Filler	Wear rate	Reference
1.	Epoxy	*Prosopis juliflora*	SiC and Fly ash	0.0287778 mm^3/m	Present work
2.	Epoxy	Kevlar, carbon and glass fibres	-	5.06×10^{-5} mm^3/m	[30]
3.	Epoxy-modified phenolic	*Prosopis juliflora*	-	2.58 mm^3 /brake application	[45]
4.	Epoxy	Kenaf	-	$1–1.9 \times 10^{-5}$ mm^3/Nm	[46]
5.	Polyester	Coir	-	$1.4–2 \times 10^{-5}$ mm^3/Nm	[47]
6.	Epoxy	-	Kenaf particles	$0.07–18 \times 10^{-5}$ mm^3/Nm	[48]
7.	Epoxy	Glass fibre	fly ash	1.34×10^{-2} mm^3 /Nm	[49]

Comparative analysis of wear test with previous work

Table 8 presents a comparative analysis of the wear rates observed in this study with those reported in earlier research. Polymer-based materials are widely used in tribological applications for their self-lubricating properties, wear resistance, low friction and corrosion stability. However, gaps in fundamental understanding and design challenges remain, due to the vast variety of polymers and composites used, the diversity of applications and the complexities in analysing the underlying tribological mechanisms [43]. Incorporating fibres and fillers, such as nanoparticles, into thermoset or thermoplastic matrices helps to reinforce the surface, thereby improving the tribological properties of polymers. This improvement is particularly noticeable in conditions of adhesive wear under dry contact [44].

Conclusions

The following details are drawn from the investigational analysis of the epoxy composites reinforced with natural fibres (PJ) and filler components:

- By using hot compression moulding, it is feasible to construct various polymer composites reinforced with PJ fibre and changing filler materials with different weight percentages (S1, S2, S3).
- The erosion wear resistance in fabricated composites is improved with an increase of proportionate fillers like SiC and fly ash, demonstrating good filler qualities.
- The filler content and sliding velocity have a significant impact on the erosion wear rate of the composite materials under investigation, while the effects of normal load and sliding distance are substantially less essential. In general, these composites may also be recommended for uses such as coal dust delivery pipes and conveyer belt linings [29, 50, 51].

- Fly ash is produced in India in excess of 80 million tonnes per year. So, its use in the creation of polyester matrix composites will only have a minimal impact on its overall consumption. Fly ash can be successfully working as filler in polyester matrix composites according to our study. Its filling improves the composites' erosion resistance but only slightly affects their mechanical qualities like hardness and tensile strength. The results of the trials indicate that the fly ash component of the composites has a significant impact on erosion properties.

Abbreviations

PJ	*Prosopis juliflora*
SiC	Silicon carbide
FA	Fly ash
DOE	Design of experiment

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Authors' contributions
TS provided draft manuscript preparation, SA provided conceptualization and data curation, PSV provided manuscript preparation, GV provided the data analysis and interpretation, and ME provided curation and interpretation. All authors have read and approved the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

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