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Sliding wear analysis of natural fiber reinforced polymer composite

Amar Patnaik[1]*, Alok Satapathy[2], Sandhyarani Biswas[2]
[1]Mechanical Engineering Department, N.I.T.Hamirpur-177005, H.P., (INDIA)
[2]Mechanical Engineering Department, N.I.T.Rourkela-769008, Orissa, (INDIA)
E-mail : amar_mech@sify.com

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ABSTRACT

Natural fibres have long been used as cost cutting fillers in the plastics industry. Now a day, they are considered to be a potential replacement of glass fibers for use in composite materials. However, although natural fibres have many advantages, the most important being their low cost and low density, they are not totally free of problems. The present study focuses on the development, optimization and characterization of pine bark reinforced with polyester resin by the use of cement by-pass dust (CBPD) as a filler material. For this a standard pin-on-disc experimental test set up and Taguchi orthogonal array are used. This method not only determines the significant interaction and respective factors but also determines the significant interaction factor combination. Finally, Genetic Algorithm (GA), a popular evolutionary approach, is employed to optimize the factor settings for minimize specific wear rate under specific experimental conditions have been determined. The methodology described here is expected to be highly beneficial to manufacturing industries, and also other areas such as aerospace, automobile and tool making industries.
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KEYWORDS

Pine bark;
CBPD;
Polyester resin;
Taguchi method;
GA.

INTRODUCTION

In the recent years, the use of natural fibres as reinforcement is increasingly replacing the conventional inorganic fibres in polymer matrix composites. Especially, natural fibre- reinforced thermoplastics have a good potential in the future as a substitute for wood-based material in many applications. The development of environment-friendly green materials is because of natural fibre's biodegradability, light weight, low cost, high specific strength compared to glass and carbon, recycling and renewing natural sources of plants, such as bast, seed, leaf, wood and fruit. The jute fibre is an important bast fiber and comprises bundled ultimate cells, each containing spirally oriented micro fibrils bound together, which has similar structures of other natural fibres like hemp, flax, sisal etc.

Some aspects of plant fibre composites have gained considerable scientific interest, i.e. methods of extracting the fibre from the plants in order to preserve their good mechanical properties, methods to increase the compatibility between the polar lingocellulosic fibres and the nonpolar polymeric matrix, and measurements of interface properties[1-10]. Thus, so far, most studies have primarily focused on the fibre and matrix component of the composites, and ignored the existence of the third components, the porosity. Porosity, which is defined as air-filled cavities inside and otherwise continuous materials, is a most often un avoidable component in all composite materials, caused by the mixing and consolidation of two discrete materials components with most synthetic composite materials, such as glass/polyester and carbon/epoxy, considerable knowledge has been built up over the years in order to control and optimize the fabrication process, and consequently the porosity content is normally relative low (< 2%)[11]. However, with plant fibre composite, the fabrication techniques are not yet that developed, and the natural origin of the fibre component necessarily induces an element of variation into the composites; both factors cause the porosity component to make a note worthy contribution to the overall composite volume in plant fibre composites[12-14]. Knowing that porosity has a direct effect on composite physical and mechanical properties[15-18] under lines the need for more studies including this component into the overall material characterization. The quantities of bark available are substantial, since approximately 10-15 % of the volume of every log consists of bark. Bark and heart wood of some wood species contain large quantities of water soluble extractives of polyphenolic nature suitable as a starting material for the production of adhesives[19]. While some bark is used as fuel and in agricultural applications, a considerable amount of bark remains unused. Bark disposal becoming a serious problem because of the restriction on the incineration of bark residues[20].

A possibility that the incorporation of both particles and fibers in polymer could provide a synergism in terms of improved wear resistance has not been adequately addressed so far. Attempts to understand the modifications in the tribological behavior of the polymers with the addition of fillers or fiber reinforcements have been made by a few researchers[21,22]. The enhancement in tribological properties of Poly-phenylene-sulfide (PPS) with the addition of inorganic fillers[23] and fibers[24] has been reported. Bahadur et al.[25,26] reported that the fillers such as CuS, CuF_2, CaS, and CaO reduced the wear rate of polyamide but many other fillers such as CaF_2 increased the wear rate. But most of the above studies are confined to dry sliding and abrasive wear behavior of composites. The erosive wear aspects of polyester composites reinforced with fibers as well as particulates has not been adequately investigated. An inexpensive and easy-to-operate experimental strategy based on Taguchi's parameter design has been adopted to study the effect of various parameters and their interactions. This experimental procedure has already been successfully applied for parametric appraisal in wire electrical discharge machining (WEDM) process, drilling of metal matrix composites and wear behavior of polymer matrix composites[27-32] etc. The present study aims at studying the erosion behavior of particulate filled glass-polyester composites using Taguchi method. Further, the analysis of variance (ANOVA) is done to identify the most significant control factors and their interactions.

In view of the above, the present work studies the effect of inclusion of a variety of particulate fillers on the erosive wear behavior of pine bark-polyester hybrid composites under multiple impact conditions. Such multi-component hybrid composites form complex systems and there is an inadequate data available about phenomena behind the modified wear behavior due to the presence of particulates in the fiber reinforced polymer components. It is thus obvious that a further study in this respect is needed particularly with ceramic fillers both in view of the scientific understanding and commercial importance.

EXPERIMENTAL DETAILS

Specimen preparation

Natural fiber (Pine bark) are reinforced in cement by-pass dust (CBPD) filled unsaturated isophthalic polyester resin to prepare hybrid composites. The dough (polyester resin mixed with pine bark and cement by-pass dust) is then slowly decanted into the glass tubes, coated beforehand with uniform thin film of silicone-releasing agent. The composites are cast by conventional hand-lay-up technique in glass tubes so as to get cylindrical specimens (Φ 12 mm, length 120 mm). Composites of three different compositions (0 wt%, 8 wt% and 12 wt% pine bark content) are made and the cement by-pass dust remaining constant for all the three different samples. 2% cobalt nephthalate (as accelerator) is mixed thoroughly in isophthalic polyester resin and then 2% methyl-ethyl-ketone-peroxide (MEKP) as hardener is mixed in the resin prior to reinforcement. The filler material CBPD (average size 20 μm, density 1.75 gm/cc) is provided by solan cement industry, Ltd India. Pine bark and polyester resin have modulus of 19.5 GPa and 3.25GPa respectively and possess density of 963 kg/m^3 and 1350kg/m^3 respectively. The castings are put under load for about 24 hours for proper curing at room temperature. Specimens of suitable dimension are cut using a diamond cutter for physical characterization and erosion test.

Test apparatus

Sliding wear test

To evaluate the performance of these composites under dry sliding condition, wear tests are carried out in a pin-on-disc type friction and wear monitoring test rig (supplied by DUCOM) as per ASTM G 99.The schematic diagram of the experimental set up is as shown in Figure 1. The counter body is a disc made of

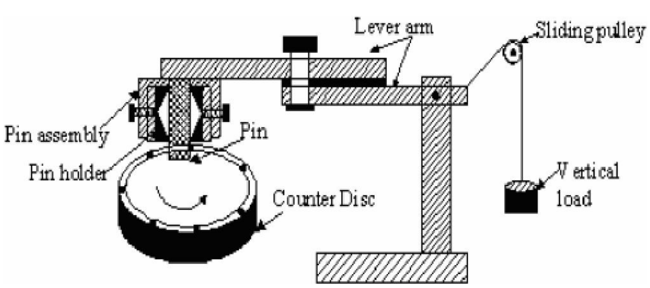

Figure 1 : Schematic diagram of a pin-on-disc set-up

hardened ground steel (EN-32, hardness 72 HRC, surface roughness 0.6 μ Ra). The specimen is held stationary and the disc is rotated while a normal force is applied through a lever mechanism. A series of test are conducted with three sliding velocities of 210, 261 and 314 cm/sec under three different normal loading of 10N, 20 N and 30N. The material loss from the composite surface is measured using a precision electronic balance with accuracy ± 0.1 mg and the specific wear rate (mm^3/N-m) is then expressed on 'volume loss' basis as

$$W_S = \Delta m/\rho t V_S.F_N \quad (1)$$

where Δm is the mass loss in the test duration (gm), ρ is the density of the composite (gm/mm^3), t is the test duration (sec)., V_s is the sliding velocity (m/sec), F_N is the average normal load (N).

The specific wear rate is defined as the volume loss of the specimen per unit sliding distance per unit applied normal load.

Experimental design

Design of experiment is a powerful analysis tool for modeling and analyzing the influence of control factors on performance output. The most important stage in the design of experiment lies in the selection of the control factors. Therefore, a large number of factors are included so that non-significant variables can be identified at earliest opportunity. The operating conditions, under which erosion tests carried out, are given in Table 1.

TABLE 1 : Control factors and levels used in the experiment

Control factor	Level			
	I	II	III	Units
A: Sliding velocity	210	261	314	cm/sec
B: Normal load	10	20	30	N
C: Fiber content	0	8	12	%
D: Sliding distance	3000	4000	5000	m

The tests are conducted as per experimental design given in Table 2 under room temperature. Four parameters viz., sliding velocity, normal load, filler content, and sliding distance each at three levels, are considered in this study in accordance with L_{27} (3^{13}) orthogonal array design. In Table 2, each column represents a test parameter and a row gives a test condition which is nothing but combination of parameter levels. Four parameters each at three levels would require 3^4 = 81 runs in a full factorial experiment. Whereas, Taguchi's factorial experiment approach reduces it to 27 runs only offering a great advantage.

The experimental observations are transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the type of characteristics. The S/N ratio for minimum erosion rate coming under smaller is better characteristic, which can be calculated as logarithmic transformation of the loss function as shown below.

Smaller is the better characteristic:

$$\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum y^2\right) \quad (2)$$

where n the number of observations, and y the observed data. "Lower is better" (LB) characteristic, with the above S/N ratio transformation, is suitable for minimizations of erosion rate. The standard linear graph by Glen[33] as shown in Figure 2, is used to assign the factors and interactions to various columns of the orthogonal array.

TABLE 2 : Orthogonal array for L_{27} (3^{13}) taguchi design

L_{27} (3^{13})	1 A	2 B	3 $(AxB)_1$	4 $(AxB)_2$	5 C	6 $(BxC)_1$	7 $(BxC)_2$	8 $(AxC)_1$	9 D	10	11 $(AxC)_2$	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

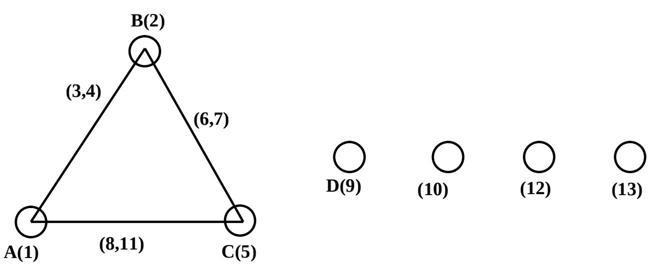

Figure 2 : Linear graphs for L_{27} array

The plan of the experiments is as follows: the first column is assigned to sliding velocity (A), the second column to normal load (B), the fifth column to fiber content (C), the ninth column to sliding distance (D) and the third and fourth column are assigned to $(A \times B)_1$ and $(A \times B)_2$, respectively to estimate interaction between sliding velocity (A) and normal load (B), the sixth and seventh column are assigned to $(B \times C)_1$ and $(B \times C)_2$ respectively, to estimate interaction between the normal load (B) and fiber content (C), the eighth and eleventh column are assigned to $(A \times C)_1$ and $(A \times C)_2$ respectively, to estimate interaction between the sliding velocity (A) and fiber content (C). The remaining columns are assigned to error columns respectively.

RESULTS AND DISCUSSION

From Table 3, the overall mean for the S/N ratio of the wear rate is found to be 83.88 db. Figure 3 shows graphically the effect of the four control factors on wear rate. The analysis is made using the popular software specifically used for design of experiment applications known as MINITAB 14. Before any attempt is made to use this simple model as a predictor for the measures of performance, the possible interactions between the control factors must be considered. Thus factorial design incorporates a simple means of testing for the presence of the interaction effects.

TABLE 3 : Experimental design using L_{27} orthogonal array

Sl No.	Sliding velocity A (cm/sec)	Normal load B (N)	Fiber content C (%)	Sliding distance D (m)	Wear rate W_s (mm^3/N-m)	S/N ratio (db)
1	210	10	0	3000	0.0006736	63.4320
2	210	10	8	4000	0.0005250	65.5960
3	210	10	12	5000	0.0000946	80.4790
4	210	20	0	4000	0.0000282	91.0000
5	210	20	8	5000	0.0001414	76.9930
6	210	20	12	3000	0.0002300	72.7650
7	210	30	0	5000	0.0002403	72.3850
8	210	30	8	3000	0.0000953	80.4150
9	210	30	12	4000	0.0001906	74.3980
10	261	10	0	4000	0.0000600	84.4440
11	261	10	8	5000	0.0000082	101.704
12	261	10	12	3000	0.0002183	73.2200
13	261	20	0	5000	0.0000034	109.475
14	261	20	8	3000	0.0000618	84.1790
15	261	20	12	4000	0.0002167	73.2820
16	261	30	0	3000	0.0000331	89.5910
17	261	30	8	4000	0.0000479	86.3970
18	261	30	12	5000	0.0002501	72.0380
19	314	10	0	5000	0.0000017	115.625
20	314	10	8	3000	0.0001476	76.6210
21	314	10	12	4000	0.0002893	70.7720
22	314	20	0	3000	0.0000098	100.199
23	314	20	8	4000	0.0000021	113.630
24	314	20	12	5000	0.0004016	67.9240
25	314	30	0	4000	0.0000128	97.8310
26	314	30	8	5000	0.0000116	98.6960
27	314	30	12	3000	0.0002576	71.7830

Analysis of the result leads to the conclusion that factor combination of A_3, B_2, C_1 and D_3 gives minimum wear rate. The interaction graphs are shown in Figure 4. As for as minimization of wear rate is concerned, factors A, C and D have significant effect whereas factor B has least effect. It is observed from Figure 4 that the interaction between A × B shows least significant effect on wear rate. Similarly, interaction between B × C also having second highest significant effect on the output performance as shown in Figure 5. But the factors A and C individually have greater contribution on output performance, and their combination of interaction with factor A and C is shown in Figure 6 have greater effect on wear rate and from this analysis the factor B has least effect on the specific wear rate but its effect in combination with other factor like factor C have significant effect on the output performance. Hence, factor B can not be neglected for further study.

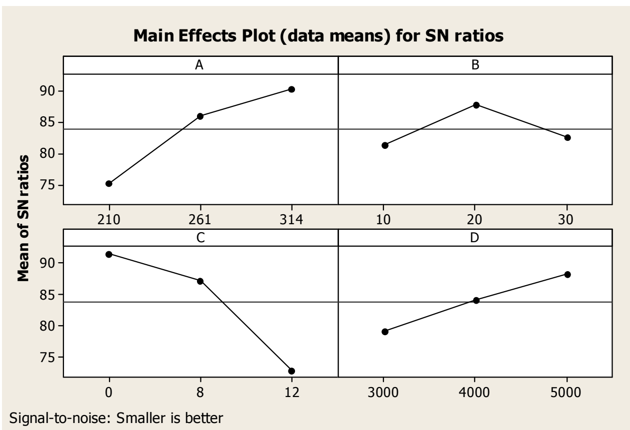

Figure 3 : Effect of control factors on wear rate

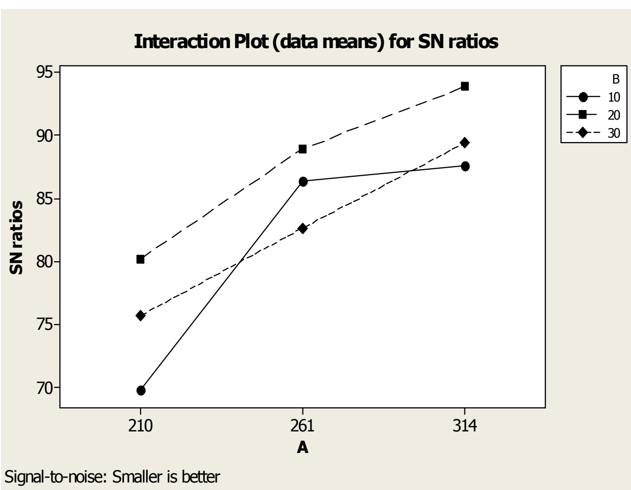

Figure 4 : Interaction graph between A×B for wear rate

ANOVA and the effects of factors

In order to understand a concrete visualization of impact of various factors and their interactions, it is desirable to develop analysis of variance (ANOVA) table to find out the order of significant factors as well as interactions. Table 4 shows the results of the ANOVA with the erosion rate. This analysis was undertaken for a level of confidence of significance of 5 %. The last column of the table indicates that the main effects are highly significant (all have very small p-values). From Table 4, one can observe that the fiber content (p=0.049), sliding velocity (p=0.107) and sliding distance (p=0.370) have great influence on wear rate. The interaction between sliding velocity × fiber content (p=0.288) and normal load × fiber content (p=0.743) show significance of contribution on the wear rate and the factor normal load (p=0.564) and sliding velocity × normal load (p=0.969) present less significance of contribution on wear rate.

TABLE 4 : ANOVA table for wear rate

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	1084.3	1084.3	542.2	3.33	0.107
B	2	205.8	205.8	102.9	0.63	0.564
C	2	1698.1	1698.1	849.1	5.21	0.049
D	2	384.7	384.7	192.4	1.18	0.370
A*B	4	80.5	80.5	20.1	0.12	0.969
A*C	4	1044.6	1044.6	261.2	1.60	0.288
B*C	4	320.8	320.8	80.2	0.49	0.743
Error	6	977.9	977.9	163.0		
Total	26	5796.8				

Confirmation experiment

The confirmation experiment is the final test in the design of experiment process. The purpose of the confirmation experiment is to validate the conclusions drawn during the analysis phase. The confirmation experiment is performed by conducting a new set of factor settings $A_1B_1C_3D_2$ to predict the wear rate. The estimated S/N ratio for wear rate can be calculated with the help of following prediction equation:

$$\bar{\eta}_1 = \bar{T} + (\bar{A}_1 - \bar{T}) + (\bar{C}_3 - \bar{T}) + [(\bar{A}_2\bar{C}_3 - \bar{T}) - (\bar{A}_1 - \bar{T}) - (\bar{C}_3 - \bar{T})] + (\bar{B}_1 - \bar{T}) + [(\bar{B}_1\bar{C}_3 - \bar{T}) - (\bar{B}_1 - \bar{T}) - (\bar{C}_3 - \bar{T})] + \left(\bar{D}_2 - \bar{T}\right) \quad (3)$$

$\bar{\eta}_1$ Predicted average, $\bar{T}$ Overall experimental average, $\bar{A}_1, \bar{B}_1, \bar{C}_3$ and $\bar{D}_2$ Mean response for factors and interactions at designated levels.

By combining like terms, the equation reduces to

$$\bar{\eta}_1 = \bar{A}_1\bar{C}_3 + \bar{B}_1\bar{C}_3 - \bar{C}_3 + \bar{D}_2 - \bar{T} \quad (4)$$

A new combination of factor levels A_1, B_1, C_3 and D_2 are used to predict wear rate through prediction equation and it is found to be $\bar{\eta}_1 = 74.97\,dB$. For each performance measure, an experiment is conducted for a different factors combination and compared with the result obtained from the predictive equation as shown in Table 5.

TABLE 5 : Results of the confirmation experiments for Erosion rate

	Optimal control parameters	
	Prediction	**Experimental**
Level	$A_1 B_1 C_3 D_2$	$A_1 B_1 C_3 D_2$
S/N ratio for wear rate (db)	74.9741	73.1147

The resulting model seems to be capable of predicting wear rate to a reasonable accuracy. An error of 2.48 % for the S/N ratio of wear rate is observed. However, the error can be further reduced if the number of measurements is increased. This validates the development of the mathematical model for predicting the measures of performance based on knowledge of the input parameters.

Factor settings for minimum wear rate

In this study, an attempt is made to derive optimal settings of the control factors for minimization of wear rate. The single-objective optimization requires quantitative determination of the relationship between erosion rates with combination of control factors. In order to express, wear rate in terms of mathematical model in the following form is suggested.

$$Ws = K_0 + K_1 \times A + K_2 \times B + K_3 \times C + K_4 \times D + K_5 \times A \times C + K_6 \times B \times C \quad (5)$$

Here, *Ws* is the performance output terms and K_i (i = 0, 1………..6) are the model constants. The constant are calculated using non-linear regression analysis with the help of SYSTAT 7.0 software and the following relations are obtained.

$$Ws = 1.899 - 1.550 \times A - 0.403 \times B - 1.592 \times C - 0.237 \times D + 1.826 \times A \times C + 0.335 \times B \times C \quad (6)$$

$$r^2 = 0.96$$

The correctness of the calculated constants is confirmed as high correlation coefficients (r^2) in the tune of 0.96 are obtained for Eq. (5) and therefore, the models are quite suitable to use for further analysis. Here, the resultant objective function to be maximized is given as:

$$\textbf{Maximize } Z = 1/f \quad (7)$$

f Normalized function for wear rate

Subjected to constraints:

$$A_{min} \le A \le A_{max} \quad (8)$$

$$B_{min} \le B \le B_{max} \quad (9)$$

$$C_{min} \le C \le C_{max} \quad (10)$$

$$D_{min} \le D \le D_{max} \quad (11)$$

The min and max in Eqs.8-11 shows the lowest and highest control factors settings (control factors) used in this study (Table 1).

Genetic algorithm (GA) is used to obtain the optimum value for single-objective outputs to optimize the single-objective function. The computational algorithm is implemented in Turbo C^{++} and run on an IBM Pentium IV machine. Genetic algorithms (GAs) are mathematical optimization techniques that simulate a natural evolution process. They are based on the Darwinian Theory, in which the fittest species survives and propagate while the less successful tend to disappear. Genetic algorithm mainly depends on three types of operators viz., reproduction, crossover and mutation. Reproduction is accomplished by copying the best individuals from one generation to the next, what is often called an elitist strategy. The best solution is monotonically improving from one generation to the next. The selected parents are submitted to the crossover operator to produce one or two children. The crossover is carried out with an assigned probability, which is generally rather high. If a number randomly sampled is inferior to the probability, the crossover is performed. The genetic mutation introduces diversity in the population by an occasional random replacement of the individuals. The mutation is performed based on an assigned probability. A random number is used to determine if a new individual will be produced to substitute the one generated by crossover. The mutation procedure consists of replacing one of the decision variable values of an individual while keeping the remaining variables unchanged. The replaced variable is randomly chosen and its new value is calculated by randomly sampling within its specific range. In genetic optimization, population size, probability of crossover and mutation are set at 50, 75 %, and 5 % respectively for all the cases. Number of generation is varied till the output is converted. Table 6 shows the optimum conditions of the control factors with optimum performance out put gives a better combination of set of input control factors.

TABLE 6 : Optimum conditions for performance output

Control factors and Performance characteristics	Optimum conditions
A: Sliding velocity (cm/sec)	209
B: Normal load (N)	24.75
C: Fiber content (%)	6.336
D: Sliding distance (m)	4710
Specific wear rate (mm^3/N-m)	0.000844

CONCLUSIONS

In this work, an attempt has been made to develop a hybrid composite (polyester, pine bark and cement by-pass dust as a filler) material to study the wear rate of the composite. Factors like sliding velocity, fiber content and sliding distance and their interactions have been found to play significant role for maximizations of wear rate. In order to optimize the objective, mathematical model is developed using non-linear regression method. The confirmation experiment shows that the error associated with specific wear rate is 2.48 % is observed. This study also used, Genetic Algorithm, a popular evolutionary approach, to optimize the factor settings for minimize specific wear rate under specific experimental conditions have been determined. The rationale behind the use of genetic algorithm lies in the fact that genetic algorithm has the capability to find the global optimal parameters whereas the traditional optimization techniques normally are stuck up at the local optimum values. In future, the study can be extended to find out better wear rate by using different work materials, and hybrid optimization techniques.

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