Optimization of Abrasive Wear Behaviour of Cenosphere Filled Basalt-Epoxy Composites Using Taguchi Approach

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Abstract. The current research work investigates the three-body abrasive wear analysis of cenosphere particulate filled chopped basalt fiber (40 wt.% constant) reinforced epoxy composites for developing light weight, low cost, and sustainable composite. The effect of cenosphere particulate on the composite was investigated. The composite laminates are fabricated by traditional open mold casting technique. The cenosphere particulate is mixed (0-15 wt.%, step of 5 wt.%) in the composites. Abrasive wear process input parameters like: filler loading, normal load, sliding distance, and abrasive size are optimize by using Taguchi design of experiments. From the results, it is clearly seen that 10 wt.% cenosphere filled basalt-epoxy composite (EBC 10) shows lowest abrasive wear rate in a steady state abrasive wear condition (with a variation in sliding distance and normal load). Taguchi experimental design technique is an effective optimization technique and gives a better outcome.

1. Introduction
Researchers are mostly used either synthetic or natural fiber as reinforcement in the fiber reinforced polymer based composites (FRCs). In the present researchers, mineral fiber has also been used by researchers in fiber reinforced polymer based composites for developing light weight, low cost, and sustainable composite. In the category of mineral fibers, basalt fiber is one of reinforcement (mineral fiber) having excellent strength and modulus. Basalt fiber is produced volcano (lava erupted from a volcano) [1-3].

For improving the strength, and wear resistance of fiber reinforced polymer composites, researchers are used ceramic fillers like: silicon oxide (SiO2), aluminum oxide (Al2O3), and magnesium oxide (MgO) etc. In the current research, solid industrial waste material like: Fly ash, Cenosphere, Red mud, Marble powder, Granite dust, etc. has also been used by researchers as filler material in fiber reinforced polymer based composites for developing better wear and friction resistant composite. Several research scholars worked to improve the wear and friction properties of composites by reinforcing with waste particulate materials [4-6].

The hollow microsphere fly ash particles are termed as cenosphere [7]. For reference purpose some important research work are here. Alkadasi et al. [8] investigates the mechanical characteristics of fly ash filled polybutadiene rubber based composite and reported that hardness, tensile strength, and tensile modulus improved with fly ash content. Sunil et al. [9] studied the tribological behaviour of submicron size cenosphere filled vinyl ester based composite and they found that cenosphere filler content improved the wear resistance of the composite. Chand et al. [10] investigates the tribological characteristics of cenosphere filled High Density Polyethylene (HDPE) based composite and they
reported that tribological performance of composite has been improved with cenosphere filler. Ray et al. [11] fabricated the fly ash filled (40 wt.% and 50 wt.%) vinylester based composites and result shows that composite with fly ash filler shows superior wear resistance than neat (without fly ash) composite. Suresha et al. [12] investigates the wear performance of cenosphere filled glass-epoxy composites and they found that sliding distance and normal load were most significant factors for wear loss.

In the present research work, fabricated the cenosphere (0, 5, 10, 15 wt.%) filled basalt fiber (40 wt.% constant) reinforced epoxy based composites via open mold casting technique for investigating the three-body abrasive wear behaviour of the composites and optimizing the process parameters by using Taguchi design of experiments.

2. Materials and Method

2.1 Required Materials and Fabrication of Composites

The details of raw materials and its absolute properties are listed in Table 1, while Figure 1 shows the formulation of composites and fabrication procedure by Open mold casting technique.

| Materials          | Density (g/cc) | Tensile strength (MPa) | Young’s modulus (GPa) | Thermal conductivity (W/mK) |
|--------------------|----------------|------------------------|-----------------------|-----------------------------|
| Epoxy Resin        | 1.19           | 52                     | 3.2                   | 0.35                        |
| Basalt Fiber (BF)  | 2.66           | 4500                   | 87                    | 0.031                       |
| Cenosphere (Grade ‘VA LD 300’) | 0.85 | -                       | -                     | -                           |
2.2 Three-Body Abrasive Wear Test Rig

The abrasive wear test (three-body) of fabricated composite samples is conducting on dry sand abrasion test rig. Model TR-50; supplied by MAGNUM Bangalore, INDIA; ASTM G65 standard. Figure 2 shows the illustration of abrasion test rig. Table 2 listed the control parameters and their levels for experiment. Composite sample dimension (75 × 25 × (10-12) mm³) in shape of rectangular is used for experiment. The sand particles are strike among the sample and rubber wheel through the nozzle at the feed rate of 255 + 5 g/min². The weight of composite samples before experiment and after experiment is measured using precision electronic balance and then weight loss (initial weight – final weight) during the experiment is calculated. Finally, abrasive wear rate is calculated by using following Eq.

\[
Ws = \frac{\Delta V}{\rho \times F_n \times S_s} \quad \text{(mm}^3/\text{N-m)}
\]  

Where,

- \( W_s \) = Abrasive wear rate (mm³/N-m).
- \( \rho \) = Actual density of fabricated composite samples.
- \( F_n \) = Normal load.
- \( S_s \) = sliding distance.
Figure 2. Three-body abrasion (dry sand) test rig.

Table 2. Dry sand abrasion test rig control parameter and their levels.

| Control factors | Levels | Units |
|-----------------|--------|-------|
|                 | I      | II    | III   | IV    |
| A: Filler loading| 0      | 5     | 10    | 15    | wt.%  |
| B: Normal load  | 20     | 40    | 60    | 80    | N     |
| C: Sliding distance | 500   | 1000  | 1500  | 2000  | m     |
| D: Abrasive size | 100    | 200   | 300   | 400   | μm    |

2.3 Taguchi’s Design of Experiment

Taguchi’s design of experimental technique is better alternate of conventional full factorial technique for finding the optimal results by reducing the number of experimental runs. Taguchi’s design of experimental technique helps to find out the optimal parameter. Table 2 shows the selected input parameters and their levels for analysis using Taguchi’s method. Taguchi analyses find out the input parameter, that is highly influence the response performance (abrasive wear rate). The experimental runs are simulated by software Minitab 17. There are four input parameters and four levels (see Table 2), so L16 (4^4 = 16) orthogonal array is selected for the analysis. For any component minimum abrasive wear rate (response/output) is better, so smaller-the-better type signal-to-noise ratio (S/N ratio) has selected for analysis [13].
\[ s = -10 \log \frac{1}{n} \sum Y^2 \]  

(2)

Where, \( n \) is the Number of observations and \( Y \) is the Observed data.

After the Taguchi analysis of observed data, the optimal process parameters are finding with the help of Analysis of Variance (ANOVA) tool. The influence of each process parameter and their optimal level on the output characteristics (Abrasive wear rate) is estimated.

3. Results and Discussion

3.1 Steady State Abrasive Wear Test for Prepared Composites

3.1.1 Abrasive Wear Rate of Composites as a Function of Sliding Distance

The steady state abrasive wear rate of unfilled (0 wt.%, virgin composite EBC 0) and cenosphere filled (5, 10, and 15 wt.% basalt-epoxy composites are analyzed by dry sand three-body abrasive wear analysis. The abrasive wear rate of unfilled and cenosphere filler basalt-epoxy composite samples with respect to sliding distance (500, 1000, 1500, and 2000 m) are depicted in Figure 3. Other parameters like sliding velocity (200 rpm), normal load (40 N), and abrasive size (300 μm) keeping as constant during the experiment.

The influence of sliding distance on abrasive wear rate of fabricated composites is depicted in Figure 3. From the figure it is clearly seen that the abrasive wear rate tends to decreased with sliding distance from 500 to 2000 m. Composite with 10 wt.% cenosphere (EBC 10) shows minimum abrasive wear rate: from \( 1.16 \times 10^{-2} \text{ mm}^3/\text{N-m} \) (for 500 m sliding distance) to \( 6.56 \times 10^{-3} \text{ mm}^3/\text{N-m} \) (for 2000 m sliding distance). Result shows that composite with 10 wt.% cenosphere (EGC 10) shows lowest abrasive wear rate than other composites. The reason for decreasing wear rate with filler can be, the filler (cenosphere) creates a hard surface of composite. At the lower sliding distance during abrasion, the sand particles are in contact with epoxy matrix and the epoxy has lower hardness than sand particles, so at lower sliding distance the ratio of material removal is high. After that, at higher sliding distance, the sand particles are in contact with fiber and filler (cenosphere) and fiber/filler act as a barrier to the process of abrasion. But, composite with 15 wt.% cenosphere filler does not show any improvement (in decreasing trend) in wear rate. So, from the analysis it is clear that cenosphere filler up to certain percentage, improves the wear rate (in decremented rate) of composites across the sliding distance range. Similar results were also stated by Arivalagan et al. [14] in their study of with and without fly ash filled carbon fabric reinforced epoxy composite.
Figure 3. Effect of sliding distance on Abrasive wear rate.

3.1.2 Abrasive Wear Rate of Composites as a Function of Normal Load

Figure 4 represents the steady state abrasive wear rate of unfilled (0 wt.%, virgin composite EBC 0) and cenosphere filled (5, 10, and 15 wt.%) basalt-epoxy composites. The abrasive wear rate is analyzed with respect to normal load (20, 40, 60, and 80 N) keeping other parameters as constant: sliding distance (1000 m), sliding velocity (200 RPM), and abrasive size (300 μm).

The wear rate of composite samples with respect to normal load (20, 40, 60, and 80 N) is depicted in Fig. 4. Result shows that wear rate of composite samples shows improvement (in decremented order) with increase in normal load. Also shows that, addition of cenosphere filler, improves the wear resistance of the composites. Basalt-epoxy composite with 10 wt.% cenosphere filler (EBC 10) shows lowest wear rate from $1.59 \times 10^{-2}$ mm$^3$/N-m (at 20 N normal load) to $1.23 \times 10^{-2}$ mm$^3$/N-m (at 80 N normal load) and the unfilled cenosphere (EBC 0) composite shows highest wear rate from $2.44 \times 10^{-2}$ mm$^3$/N-m (at 20 N normal load) to $1.77 \times 10^{-2}$ mm$^3$/N-m (at 80 N normal load). The hardness of the composite surface improves due to addition of cenosphere filler, and due to filler particles, adhesion between reinforcement and matrix becomes superior that’s prevents premature matrix failure. But higher percentage of cenosphere filler in composite (EBC 15) does not show any improvement (in decremented rate) in wear rate because higher percentage of filler creates more voids in composite, and due to voids, the bonding between matrix and reinforcement becomes poor. The order of wear rate for entire range of normal load is EBC 10 << EBC 15 << EBC 5 < EBC 0. Related results were also stated by Patnaik et al. [15] in their study of mechanical and abrasive wear characteristics of particulate filled glass-epoxy composites.
3.2 Taguchi’s Design of Experiments and ANOVA Analysis

$L_{16}$ Taguchi’s orthogonal array is used to conduct experimental runs. The experimentally evaluated abrasive wear rate and corresponding Signal to Noise (S/N) ratio value of fabricated composites are represented in Table 3. Figure 5 shows the main effect plot of S/N ratio. The mean value of S/N ratio for all experiment runs is 42.19 dB (see Fig. 5) and the control parameters like A: Filler loading (Level 3, S/N = 45.6174), B: Normal load (Level 1, S/N = 46.1859), C: sliding distance (Level 3, S/N = 46.6616), and D: abrasive size (Level 2, S/N = 44.8407) are designated minimum abrasive wear rate. 10 wt.% filler loading ($A_3$), 20 N normal load ($B_1$), 1500 m sliding distance ($C_3$), and 200 μm abrasive size ($D_2$) are the optimum control parameter combinations for minimum abrasive wear rate (see Fig. 5). Taguchi’s analysis also gives the ranking order; it is depicted in Table 4. As per Table 4 the ranking order of significant input parameters is: C: Sliding distance, B: Normal load, A: Filler loading, and D: Abrasive size.

Further, the percentage contribution of individual control parameter and their order of significance on the response (Abrasive Wear Rate) of composites are analyzed with Analysis-of-variance (ANOVA) tool. The ANOVA analysis is performed at 5% significance level and denoted by ‘p’. ANOVA analysis and p-value of each parameter depicted in Table 5. Lower value of ‘p’ for a parameter indicates, higher will be its contribution on the total variation of abrasive wear rate [16]. The order of significant control parameter and its percentage contribution ($P$) for abrasive wear performance of composite is: Sliding distance ($p = 0.016$ and $P = 50.99%$), Normal load ($p = 0.043$ and $P = 24.51%$), Filler loading ($p = 0.089$ and $P = 14.07%$), and Abrasive size ($p = 0.172$ and $P = 8.03%$). So, from the ANOVA analysis it is clearly seen that, sliding distance, normal load, and filler loading are most significant parameters for abrasive wear rate, respectively. The abrasive size is least significant parameter for abrasive wear rate.

Figure 4. Effect of normal load on abrasive wear rate.
Table 3. Taguchi’s L16 orthogonal array based experimental design.

| Exp. No. | Filler Loading (wt.-%) | Normal Load (N) | Sliding Distance (m) | Abrasive Size (μm) | Abrasive Wear Rate (mm³/N·m) | S/N Ratio (dB) |
|----------|------------------------|-----------------|----------------------|-------------------|-------------------------------|---------------|
| 1        | 0                      | 20              | 500                  | 100               | 0.0107580                     | 39.3654       |
| 2        | 0                      | 40              | 1000                 | 200               | 0.0100679                     | 39.9412       |
| 3        | 0                      | 60              | 1500                 | 300               | 0.0061733                     | 44.1897       |
| 4        | 0                      | 80              | 2000                 | 400               | 0.0062460                     | 44.0880       |
| 5        | 5                      | 20              | 1000                 | 300               | 0.0103009                     | 39.7425       |
| 6        | 5                      | 40              | 500                  | 400               | 0.0250950                     | 32.0083       |
| 7        | 5                      | 60              | 2000                 | 100               | 0.0079359                     | 42.0081       |
| 8        | 5                      | 80              | 1500                 | 200               | 0.0041982                     | 47.5387       |
| 9        | 10                     | 20              | 1500                 | 400               | 0.0019356                     | 54.2637       |
| 10       | 10                     | 40              | 2000                 | 300               | 0.0067632                     | 43.3970       |
| 11       | 10                     | 60              | 500                  | 200               | 0.0094290                     | 40.5107       |
| 12       | 10                     | 80              | 1000                 | 100               | 0.0060967                     | 44.2981       |
| 13       | 15                     | 20              | 2000                 | 200               | 0.0027002                     | 51.3721       |
| 14       | 15                     | 40              | 1500                 | 100               | 0.0092744                     | 40.6543       |
| 15       | 15                     | 60              | 1000                 | 400               | 0.0168799                     | 35.4526       |
| 16       | 15                     | 80              | 500                  | 300               | 0.0155896                     | 36.1433       |

Figure 5. Effect of input parameters on abrasive wear rate.
Table 4. Input control parameters ranking order of significance.

| Level | Filler Loading (wt.- %) | Normal Load (N) | Sliding Distance (m) | Abrasive Size (μm) |
|-------|-------------------------|-----------------|----------------------|-------------------|
| 1     | 41.90                   | 46.19           | 37.01                | 41.58             |
| 2     | 40.32                   | 39.00           | 39.86                | 44.84             |
| 3     | 45.62                   | 40.54           | 46.66                | 40.87             |
| 4     | 40.91                   | 43.02           | 45.22                | 41.45             |
| Delta | 5.29                    | 7.19            | 9.65                 | 3.97              |
| Rank  | 3                       | 2               | 1                    | 4                 |

Table 5. ANOVA results for abrasive wear rate.

| Input control factors | DF | Adj. SS | Adj. MS | F-value | p-value | P (%) |
|-----------------------|----|---------|---------|---------|---------|-------|
| A: Filler Loading     | 3  | 67.85   | 22.618  | 5.93    | 0.089   | 14.07 |
| B: Normal Load        | 3  | 118.19  | 39.397  | 10.32   | 0.043   | 24.51 |
| C: Sliding Distance   | 3  | 245.81  | 81.938  | 21.47   | 0.016   | 50.99 |
| D: Abrasive Size      | 3  | 38.75   | 12.916  | 3.38    | 0.172   | 8.03  |
| Error                 | 3  | 11.45   | 3.817   |         |         |       |
| Total                 | 15 | 482.06  |         |         |         |       |

4. Conclusions

In this study, basalt fiber reinforced epoxy matrix composites with or without cenosphere particulates are fabricated by open mold casting technique. Abrasive wear rate under steady state condition as a function of sliding distance and normal load increased shows improvement (in decreasing trend). 10 wt.% cenosphere filled basalt-epoxy composite (EBC 10) shows minimum abrasive wear rate. Taguchi experimental analysis was done with four input control parameters and their four levels. From the Taguchi analysis parameter sliding distance was most significant for abrasive wear rate followed by normal load, filler loading, and abrasive size.

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