Investigations on Mechanical and Erosive Wear Behaviour of Cenosphere Filled Carbon-Epoxy Composites

Mohammed Ismail, Suresha Bheemappa and Rajendra N

Abstract—Carbon fabric reinforced epoxy (C-E) composites filled with different weight proportions of fly ash cenosphere (CSP) were fabricated by hand lay up technique followed by compression molding. The solid particle erosion characteristics of the CSP filled C-E composites have been studied and the experimental results were compared with those of unfilled C-E composites. For this, an air jet type erosion test rig and Taguchi orthogonal arrays have been used. The findings of the experiments indicate that the rate of erosion by impact of solid erodent was greatly influenced by various control factors. The tensile modulus and flexural modulus of cenospheres-filled C-E composites showed good improvement compared with that of the unfilled C-E composites. Low density (0.6 g/cm$^3$) and higher silica content (60%) of cenospheres seems to be the reason for this observation. The comparative study indicates that the CSP filled C-E composites exhibit better erosion wear performance than that of the unfilled C-E composites. The CSP filled and unfilled C-E composites showed ductile erosion behaviour, with maximum erosion at 30° impingement angle. Overall the erosion rate was found to increase with impact velocity. Furthermore, the filler content is the powerful influencing factor followed by impact velocity, impingement angle, erodent size and erosion time during the erosive wear process.

Keywords—Mechanical properties, Polymer matrix composites, Solid particle erosion, Taguchi method.

I. INTRODUCTION

EPOXY is one of the extensively used thermoset resins due to its ease of handling, molding and curing.[1]. In composites technology, particulate organic and inorganic fillers are added into the polymers, may provide a good method to improve their stiffness, modulus and reduce costs [2–4]. Fillers affect the tensile properties according to their packing characteristics, size and interfacial bonding [5–8]. The maximum volumetric packing fraction of filler reflects the size distribution and shapes of the particles. Srivastava and Shembeker [8] showed that the fracture toughness of epoxy resin could be improved by addition of fly ash particles as filler.

Polymer composites are increasingly used in engineering applications such as gears, pump impellers where the components undergo erosive wear. However, these composite materials present a rather poor erosion resistance [8, 9]. Hence, it is essential to evaluate their strength as well as their erosive behavior. Solid particle erosion is the progressive loss of original material from a solid surface due to mechanical interaction between that surface and solid particles. Generally, variables influencing the erosive wear of composite materials are, mechanical properties of the composites, fiber content, filler content, eroding particle size, impingement angle and velocity. Solid particle erosion of polymers and their composites have not been investigated to the same extent as for metals or ceramics. In viewing past work on erosive wear of polymer composites, most efforts were focused on the study of the influence of the material properties rather than the operating parameters [10–14]. Srivastava and Pawar [15] studied the effect of additives and impingement angle and eroding particle velocity on erosive wear of neat E-glass fiber reinforced epoxy resin composite materials and composites with 2 and 4 g fly ash additive particles. They concluded that the erosive wear rate of glass fiber reinforced polymer composite with 4 g fly ash is the lowest and that the maximum erosion occurs at 60°. Finnie [16] and Barkoula and Karger-Kocsis [17] studied the influences of operating condition such as impingement angle and speed on the erosion of polymer composites under small particle erodes.

It is widely recognized that polymers and their composites have a poor erosion resistance. Their erosion rates are considerably higher than metals. Barkoula and Karger-Kocsis [17] summarized the behavior of polymer composite materials under erosion conditions in schematic diagram see Figure 1. However, elastomers and rubbers are being used as protective coatings for erosion resistance [18]. The erosion resistance of polymers is two or three orders of magnitude lower than that of metallic materials. Also, it is well known that the erosion rate of polymer composites can vary with the variation of erosion conditions. Häger et al. [21] carried out erosion test for several thermoset and thermoplastics composites and observed a semi-ductile behavior. Maximum erosion is observed at 60° impingement angle for most of the tested composites. A different observation was made by Tsiang [22] as using Al$_2$O$_3$ particles erosion sand. He concluded that in glass fiber reinforced
Fiber reinforced polymer composites represent the basic element of complex composite structures. Epoxy resins are superior to polyesters in resisting moisture and other environmental influences and offer lower shrinkage and better mechanical properties. Woven fabric reinforced polymer matrix composites are gaining popularity because of their balanced properties in the fabric plane as well as their ease of handling during fabrication. Also, the simultaneous existence of parallel and anti parallel fibers in a woven configuration leads to a synergetic effect on the enhancement of the wear resistance of the composite [31]. The role played by fly ash cenosphere in different matrices and fiber reinforced polymer composites, and its effect on friction and wear is of interest to material technologists. This is because of the ability of fly ash cenosphere which could act as a load bearing filler material. Therefore, study of their behaviour is an important component of the analysis of erosive wear of polymer composites. The objective of the present investigation was to study the solid particle erosion characteristics of fly ash cenosphere filled and unfilled C-E composites under various experimental conditions. A plan of experiments, to acquire the data in a controlled way has been designed on the basis of Taguchi technique.

II. EXPERIMENTAL PROCEDURE

Materials

The Carbon fabric reinforced epoxy laminates were prepared by hand lay up followed by compression molding technique using epoxy resin as the matrix material and carbon woven cloth as the reinforcement. The fly ash cenosphere particles of average size of about 25 to 50 µm were employed as filler material. The fly ash cenosphere particles were treated with 2% organo-reactive silane coupling agent. Table 1 gives the details in respect of designation and the wt% of epoxy, carbon fiber, and fly ash cenosphere filler used in this investigation. Erosion test specimens of geometry (50 mm×50 mm×2.5 mm) were cut from the laminates using a diamond tipped cutter.

<table>
<thead>
<tr>
<th>Material (designation)</th>
<th>Epoxy (wt. %)</th>
<th>Fly ash cenosphere (wt. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-epoxy (C-E)</td>
<td>40</td>
<td>--</td>
</tr>
<tr>
<td>Fly ash cenosphere filled C-E (2CSP-C-E)</td>
<td>38</td>
<td>2</td>
</tr>
<tr>
<td>Fly ash cenosphere filled C-E (4CSP-C-E)</td>
<td>36</td>
<td>4</td>
</tr>
<tr>
<td>Fly ash cenosphere filled C-E (6CSP-C-E)</td>
<td>34</td>
<td>6</td>
</tr>
</tbody>
</table>

Mechanical property measurements

Mechanical properties namely tensile strength, tensile modulus, flexural strength and flexural modulus for different compositions of the CSP filled C-E composites were measured according to ASTM D 638 and ASTM D 790 standards using Shimadzu Universal testing machine (Kyoto, Japan). The data reported here is the average of 4 to 5 trials taken for each composition. The experimental errors on the measured parameters are around 2%.

Erosion testing

Erosion testing were carried out as per ASTM G 76. The test is conducted for 2, 4, and 6 minutes and weighed to determine the weight loss. Samples of size (50 mm×50 mm×2.5 mm) were cut from the plaque. The conditions under which erosion tests were carried out are listed in Table 2. Using test data, the ratio of weight loss to the weight of the eroding particles causing the loss is then computed as a dimensionless incremental erosion rate. Samples were eroded with silica sand at different impingement angles (i.e. 30°, 60°, and 90°).

Experimental design

Erosion test specimens were cut from the laminates using a diamond tipped cutter. Erosion testing were carried out as per ASTM G 76. The test is conducted for 2, 4, and 6 minutes and weighed to determine the weight loss. Samples of size (50 mm×50 mm×2.5 mm) were cut from the plaque. The conditions under which erosion tests were carried out are listed in Table 2. Using test data, the ratio of weight loss to the weight of the eroding particles causing the loss is then computed as a dimensionless incremental erosion rate. Samples were eroded with silica sand at different impingement angles (i.e. 30°, 60°, and 90°).
Design of experiments is a powerful analysis tool for modeling and analyzing the influence of control factors on performance output. Therefore, a large number of factors are initially included so that non-significant variables can be identified at earliest opportunity. Exhaustive literature review on erosion behavior of polymer composites reveals that parameters viz., impact velocity, impingement angle, fiber loading, erodent size and stand off distance etc., largely influence the erosion rate of polymer composites. The impact of five such parameters are studied using $L_{27}$ (3^13) orthogonal array design. The operating conditions under which erosion tests are carried out are given in Table 2. In Table 4, each column represents a test parameter whereas a row stands for a treatment or test condition which is nothing but a combination of parameter levels. In conventional full factorial experiment design, it would require $3^5 = 243$ runs to study five parameters each at three levels whereas, Taguchi’s factorial experiment approach reduces it to only 27 runs offering a great advantage in terms of experimental time and cost. The experimental observations are further transformed into signal-to-noise (S/N) ratios. The S/N ratio for minimum erosion rate can be calculated as logarithmic transformation of loss function as expressed as “lower is better” characteristic, which is suitable for minimization of erosion rate. The equation shown below Smaller is the better.

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

Where $n$ is the number of observations, and $y$ the observed data. The lower is better (LB) characteristic, with the above S/N ratio transformation, is suitable for minimization of erosion rate.

<table>
<thead>
<tr>
<th>TABLE 2 LEVELS OF VARIABLES USED IN THE EXPERIMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control Factors</strong></td>
</tr>
<tr>
<td>A: Impact Velocity (m/s)</td>
</tr>
<tr>
<td>B: Filler Content (wt%)</td>
</tr>
<tr>
<td>C: Impingement Angle (degree)</td>
</tr>
<tr>
<td>D: Erosion Time (min)</td>
</tr>
<tr>
<td>E: Erodent Size (µm)</td>
</tr>
</tbody>
</table>

## III. Results and Discussion

### Density

The theoretical and measured densities of all composite samples along with the corresponding volume fraction of voids are presented in Table 3. It may be noted that the composite density values calculated theoretically from weight fractions using rule of mixtures and are not in agreement with the experimentally determined values. The difference is a measure of voids and pores present in the composites. It is clear from Table 3 that the percentage of voids in an unfilled C-E is negligibly small i.e. 0.20% and this may be due to the absence of any filler. With the addition of light weight fly ash cenosphere, the volume fraction of voids is found to be at about 1%.

### Mechanical Properties

The mechanical properties of carbon fabric reinforced epoxy (C-E) filled with different content of cenospheres (CSP) are shown in Figures 1 and 2. From these figures, it can be seen that the loading of CSP greatly decreased the tensile strength, flexural strength, and significantly increased the tensile modulus and flexural modulus of C-E composite, which can be attributed to the high modulus and hardness of the carbon fibers. In the experimental range, the best mechanical properties were obtained with the C-E composite with 4 wt.% CSP.

![Fig. 1 Mechanical properties of CSP-filled C-E. (a) Tensile strength, (b) Tensile modulus.](image)

![Fig. 2 Mechanical properties of CSP-filled C-E. (a) Flexural strength, (b) Flexural modulus.](image)
cerospheres-filled composites is high compared with unfilled C-E ones. In the present work, the cenospheres used are of bigger size particles with less specific surface area. Therefore, it is clear that for particles with micron size, the surface area seems to play an insignificant role in so far as the improvement in mechanical properties is concerned. Therefore, we are of the opinion that the density and higher silica content of cenospheres is responsible for the enhancement in tensile modulus and flexural modulus in cenospheres-filled C-E composites. Because of the low density (0.7 g/cm³), the cenospheres fillers provide good flow properties and hence results in uniform distribution in the C-E composite and this enhances more number of Si-O-Si interactions due to higher silica content (60%). Therefore, good interfacial adhesion between the cenospheres particles and the matrix occurs.

Erosion rate

Main effects plots for S/N ratios and their interactions of samples are shown in Figures 5 and 6 respectively. It can be seen that the erosion rate was a maximum at 30° impingement angle for both composites at the different impact velocities studied. It is known that impingement angle is one of the most important parameters for the erosion behaviour of materials. In the erosion literature, materials are broadly classified as ductile or brittle, based on the dependence of their erosion rate on impingement angle. The behaviour of ductile materials is characterized by maximum erosion rate at low impingement angles (15–30°). Brittle materials, on the other hand, show maximum erosion under normal impingement angle (90°). Reinforced composites have been shown, however, to exhibit a semi-ductile behaviour with maximum erosion occurring in the angular range 45°–60° [3]. However, in the literature mixed trends have been reported even for nominally brittle or ductile materials. According to Hutchings [20], materials can show either ductile or brittle behaviour. If the erosion conditions are changed, such as impingement angle, impact velocity, particle flux, erodent properties such as shape, hardness or size, etc. Tilly and Sage [25] investigated the influence of velocity, impingement angle, particle size and weight of impacted abrasive for nylon, carbon fiber reinforced nylon, epoxy, polypropylene and glass fiber reinforced plastic. Their results showed that, for the particular materials and conditions of their test, composite materials generally behaved in an ideally brittle fashion (i.e. maximum erosion rate occurred at normal impact). Miyazaki and Takeda [26], Miyazaki and Hamao [30], reported that the peak erosion rate for neat nylon, ABS and epoxy matrix occurs at around 30° impingement angle. However, in the case of carbon or glass fiber reinforced nylon, ABS, and epoxy composites the peak of the erosion rate shifts to a larger value of impingement angle (60°). Therefore, in the present study, peak erosion rate were observed at 30° for both composites. A possible reason for the erosion behaviour found in the present study is that high modulus carbon fiber was used as reinforcement for the epoxy matrix are typical semi-ductile materials, so that erosion is mainly caused by such damage mechanisms as micro-cracking due to the impact of solid particles.

Maximum erosion rates were at impingement angle of 30°, for all the composites tested. The S/N ratios given in Table 3 are in fact the average of two replications. The overall mean for the S/N ratios of composites reinforced with CSP, are found to be -59.40db. The analysis is made using the popular software known as MINITAB 14.

### Table 4
**Signal to Noise Ratio (S/N) Table for Erosion Rate**

<table>
<thead>
<tr>
<th>Level</th>
<th>Velocity (A)</th>
<th>Filler (B)</th>
<th>Angle (C)</th>
<th>Erosion time (D)</th>
<th>Erodent size (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-58.06</td>
<td>-66.76</td>
<td>-61.19</td>
<td>-59.44</td>
<td>-59.23</td>
</tr>
<tr>
<td>2</td>
<td>-58.59</td>
<td>-60.80</td>
<td>-57.78</td>
<td>-60.20</td>
<td>-60.70</td>
</tr>
<tr>
<td>3</td>
<td>-63.18</td>
<td>-52.26</td>
<td>-60.84</td>
<td>-60.18</td>
<td>-59.89</td>
</tr>
<tr>
<td>Delta</td>
<td>5.12</td>
<td>14.50</td>
<td>3.41</td>
<td>0.76</td>
<td>1.48</td>
</tr>
<tr>
<td>Rank</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

### Table 5
**Analysis of Variance for SN Ratios**

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velo</td>
<td>2</td>
<td>142.66</td>
<td>142.66</td>
<td>71.33</td>
<td>3.91</td>
<td>0.042</td>
</tr>
<tr>
<td>Filler</td>
<td>2</td>
<td>955.91</td>
<td>955.91</td>
<td>477.96</td>
<td>26.17</td>
<td>0.000</td>
</tr>
<tr>
<td>Angle</td>
<td>2</td>
<td>63.26</td>
<td>63.26</td>
<td>31.63</td>
<td>1.73</td>
<td>0.208</td>
</tr>
<tr>
<td>Erosion time</td>
<td>2</td>
<td>3.43</td>
<td>3.43</td>
<td>1.75</td>
<td>0.09</td>
<td>0.911</td>
</tr>
<tr>
<td>Erodent size</td>
<td>2</td>
<td>9.83</td>
<td>9.83</td>
<td>4.91</td>
<td>0.27</td>
<td>0.767</td>
</tr>
<tr>
<td>Residual Error</td>
<td>16</td>
<td>292.20</td>
<td>292.196</td>
<td>18.262</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>26</td>
<td>1467.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Before any attempt is made to use this simple model as a predictor for the measure 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. The effects of control factors on erosion rate for different filler materials are shown in Fig.3. The analysis of the result gives the combination of factors producing minimum wear of the
composites. These combinations are found to be different for different filler materials. For CE filled with CSP, the factor combination of A1, B3, C2, D1, and E1 gives minimum erosion rate. As far as minimization of erosion rate is concerned, factors B, A, C, and E have significant effects on the composites whereas factor D has the least effect. It is observed from Fig. 4 that the interaction (A x B) shows most significant effect on erosion rate.

![Interaction Plot for SN ratios](image)

**IV. CONCLUSIONS**

Based on the research presented in this paper the following conclusions are drawn:

1. Inclusion of cenospheres filler in the C-E composite decreases the tensile strength as well as the density. However, CSP filler loading into C-E greatly increased the tensile modulus and flexural modulus.
2. The addition of cenospheres filler in carbon fabric reinforcement epoxy composites have shown marked improvement in erosion wear behaviour.
3. Erosion characteristics of the composites have successfully analyzed using Taguchi experimental design. Taguchi method provides a simple, systematic and efficient methodology for the optimization of the control factors.
4. Factors like filler content, impact velocity, impingement angle, erodent time and erodent size are found to be the significant control factors affecting the erosion rate. The erosion time is identified as the least significant parameter as far as the wear of such composites is concerned.
5. From the Taguchi experimental design, Filler content is identified as the most significant factor influencing the erosion wear of cenosphere filled carbon fabric reinforced epoxy composite. Further, this investigation reveals that maximum erosion takes place at the impingement angle of 30°.

**REFERENCES**
