CHAPTER 4

INVESTIGATION ON MECHANICAL AND TRIBOLOGICAL PROPERTIES OF HYBRID COMPOSITES

4.1 Introduction

This chapter presents the mechanical and tribological characterization of glass-fabric reinforced epoxy (G-E) composite filled with different proportions of SiO₂ and Al₂O₃ fillers. As a comparison, properties of unfilled G-E composite were also evaluated under identical test conditions. The experimental results of physico-mechanical properties such as density, hardness, tensile strength, tensile modulus, elongation at break and tribological behaviour of unfilled and SiO₂/Al₂O₃ filled G-E composites were discussed and presented. The analyses of the results are carried out using effect graphs and SEM micrographs.

4.2 Evaluation of Physical and Mechanical Properties

The physical and mechanical properties such as density, surface hardness, tensile strength, tensile modulus and elongation at break of unfilled and SiO₂/Al₂O₃ filled G-E composites are listed in Tables 4.1 and 4.2 respectively.

<table>
<thead>
<tr>
<th>Table 4.1 Physico-mechanical properties of G-E and SiO₂ filled G-E composites.</th>
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<tbody>
<tr>
<td>Sample code</td>
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<tr>
<td>Density (g/cm³)</td>
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<tr>
<td>Hardness (Shore-D)</td>
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<tr>
<td>Tensile strength, σ (MPa)</td>
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<td>Tensile modulus, E (GPa)</td>
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<td>Elongation, e (mm)</td>
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</table>
Table 4.2 Physico-mechanical properties of G-E and Al₂O₃ filled G-E composites.

<table>
<thead>
<tr>
<th>Sample code</th>
<th>G-E</th>
<th>5% Al₂O₃-G-E</th>
<th>7.5% Al₂O₃-G-E</th>
<th>10% Al₂O₃-G-E</th>
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</thead>
<tbody>
<tr>
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<td>2.12</td>
<td>2.23</td>
<td>2.3</td>
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<td>Hardness (Shore-D)</td>
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<td>69</td>
<td>72</td>
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<tr>
<td>Tensile strength, σ (MPa)</td>
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<td>324</td>
<td>343</td>
<td>352</td>
</tr>
<tr>
<td>Tensile modulus, E (GPa)</td>
<td>8.34</td>
<td>10.6</td>
<td>11.26</td>
<td>11.55</td>
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<tr>
<td>Elongation, e (mm)</td>
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<td>6.4</td>
<td>6.2</td>
<td>5.9</td>
</tr>
</tbody>
</table>

4.2.1 Effect of SiO₂ and Al₂O₃ Filler Loading on Density of G-E

The measured densities of all the samples are listed in Tables 4.1 and 4.2. Comparing the results it was observed that the inclusion of ceramic fillers into G-E showed higher density. The density of 10 wt. % Al₂O₃ filled G-E is 2.3 g/cm³ which is highest when compared to other composites. This is because of the filler, Al₂O₃ has higher density than that of epoxy matrix. The densities of all particulate filled G-E composites are higher than the density of unfilled G-E composites. Suresha et al. [57] studied the physico-mechanical properties of graphite filled C-E composites and they concluded that the densities of graphite filled C-E composites are higher than the density of unfilled C-E composite. The addition of 5% graphite as filler in C-E composite has resulted in the increase of density. This is because the filler, graphite has higher density than that of epoxy matrix.

4.2.2 Effect of SiO₂ and Al₂O₃ Filler Loading on Hardness of G-E.

By using the Duro - hardness tester, the hardness of the composites was measured, the values recorded and are given in Tables 4.1 and 4.2. The hardness of G-E composite increased with increase of SiO₂ and Al₂O₃ filler loading. From these tables, it can be seen that the Al₂O₃ filler greatly increased the hardness of G-E, which can be attributed to the higher hardness and more uniform dispersion of Al₂O₃ filler. The higher hardness is exhibited by the
10 wt. % of Al₂O₃ filled G-E compared to unfilled and SiO₂ filled G-E composites. It can also be seen that for a 10 wt. % of Al₂O₃ loading, there is 12.5 % increase in hardness of G-E composite. The increase in Al₂O₃ content results in an increase in brittleness of the composite. Hence this results in an increase in hardness value of the composite. Suresha et al. [57] evaluated the mechanical properties of graphite filled C-E composites and they concluded that regarding the hardness property, highest hardness is exhibited by the 10 wt. % of graphite filled C-E composite compared to unfilled and 5 wt. % of graphite filled C-E composites.

Particulate filled G-E composites with sufficient surface hardness are resistant to in-service scratches that can compromise fatigue strength and lead to premature failure. Therefore, under an indentation loading, microparticles would undergo elastic rather than plastic deformation, as compared to unfilled G-E composites. The improvement in hardness with the incorporation of filler can be explained as follows: under the action of a compressive force, the thermoset matrix phase and the solid fiber and filler phase will be pressed together, touch each other and offer resistance. Thus the interface can transfer load more effectively although the interfacial bond may be poor. This results in enhancement of hardness of Al₂O₃ filled G-E composites (Table 4.2).

4.2.3 Effect of SiO₂ and Al₂O₃ Filler Loading on Tensile Properties

The typical load-deformation curves of unfilled and particulate filled G-E composites are shown in Figures 4.1 and 4.2 respectively. The mechanical test results are listed in Table 4.1 and 4.2 respectively. It is clear from these tables the tensile strength is increasing with the increase in SiO₂ and Al₂O₃ content. As the investigation is mainly focused on filler content rather than G-E composite, taking the 10 wt. % of Al₂O₃ loading into G-E there is about 28% increase in tensile strength. Because of all added constituents are hard and brittle in nature in
comparison to epoxy therefore this is reflected by the mechanical properties of the composite as a hybrid one. Thus there is an increase in tensile strength of $\text{Al}_2\text{O}_3$ filled G-E composite with the increase in $\text{Al}_2\text{O}_3$ content. Suresha et al. [37, 38 and 57] evaluated the mechanical properties of $\text{Al}_2\text{O}_3/\text{SiC}/\text{graphite}$ filled glass fabric reinforced epoxy composites and they concluded that the tensile strength and tensile modulus of glass epoxy composites increased with increase in filler loading and decreased elongation at break.

Further, it could be attributed to the uniform dispersion of silane treated $\text{Al}_2\text{O}_3$ filler in G-E. Addition of a coupling agent can provide covalent bonding between epoxy/ $\text{Al}_2\text{O}_3$ hybrid materials, thereby enhancing the mechanical properties of the composites. The surface modified $\text{Al}_2\text{O}_3$ can interact with the fiber surface and hydrogen bonding increases and leads to the better interaction with glass fiber and epoxy. Addition of ceramic filler increases the effective mechanical interlocking, which in turn increases the frictional force between the fiber and matrix.

It can also be seen from Table 4.2, tensile modulus of $\text{Al}_2\text{O}_3$ filled G-E composites increases with increase in wt. % of $\text{Al}_2\text{O}_3$ content. It is clear from this table that the elongation at break is decreasing with the increase in $\text{Al}_2\text{O}_3$ content. This table shows that for a 10 wt. % increase in $\text{Al}_2\text{O}_3$ content there is 20 % decrease in elongation at break. The increase in $\text{Al}_2\text{O}_3$ content results in an increase in brittleness of the composite. Hence this results in a decrease of elongation at break. As the wt. % of $\text{Al}_2\text{O}_3$ filler increases, the tensile modulus of the G-E composites increases, but at the same time the system becomes more brittle. The increase in the tensile strength with wt. % of filler is attributed to the high modulus of ceramic filler which is dispersed uniformly in the fabric layers of G-E composites.
Figure 4.1 Typical load versus displacement curves for G-E and SiO$_2$ filled G-E composites.

Schewartz et al. [33] reported that the Young’s modulus is mainly dependent on the matrix deformation of the composite and increases as the slope of load-deformation curve at the initial stage and is practically not much influenced by the interfacial strength between fiber and the matrix. Generally, the addition of ceramic fillers and glass fiber reduces the
elongation at break because of the lower elongation at break values of ceramic fillers and glass fiber compared to that of epoxy matrix. The addition of Al$_2$O$_3$ particles causes a dispersion of these particles in the matrix which impede to the propagation of failure along the loading direction. Thus the failure would propagate easily in those directions where the dispersoid concentration is less leading to increased tensile strength, tensile modulus, and lower elongation.

### 4.2.4 Fractography of Unfilled and Particulate Filled G-E Composites

The SEM micrographs in Figures 4.3 - 4.5 show the tensile fractured surface of G-E, SiO$_2$ and Al$_2$O$_3$ filled G-E composites respectively.

![SEM micrographs of tensile fractured surfaces of unfilled G-E composite.](image)

The SEM micrographs revealed the linear elastic behavior and brittle type fracture for the test samples along with instant multiple fractures. The fracture is due to delamination between the layers of the composite samples and fiber-pull out (Figure 4.3a). For G-E sample, the fracture is ductile-brittle and can be explained by the plastic deformation of the matrix after fiber–matrix debonding. The SEM micrograph shown in Figure 4.3b supports
this failure mechanism because the fibers on fractured surfaces are clean, which shows brittle fracture. Other important failure mechanism of composites such as fiber–matrix debonding (marked ‘a’), fiber fracture (marked ‘b’), and cohesive resin fracture (marked ‘c’) are also observed in a SEM micrograph (Figure 4.3b). Generally matrix fracture was found to initiate at the surface of the fibers as indicated by the direction of river lines (marked by an arrow) and propagates into the resin on either side, where cracks extend from the surfaces of adjacent fibers simultaneously.

![SEM micrograph of tensile fractured surfaces of SiO2 filled G-E composite.](image)

**Figure 4.4 SEM micrographs of tensile fractured surfaces of SiO2 filled G-E composite.**

SEM characterization of the SiO2 filled G-E fractured surface shows (Figures 4.4a and 4.4b) that the fibers as well as SiO2 particles are adhered to the matrix very well (Figure 4.4b) and a qualitative indication of a greater interfacial strength. Disorientation of transverse fibers (Figure 4.4a), fiber bridging, fibers pull out (Figure 4.4a), and normal fracture of longitudinal fibers (Figure 4.4b), matrix debris, and matrix cracking (Figure 4.4b) is also seen. The improvement reported in terms of mechanical properties of the composites evaluated is mainly due to the enhancement of adhesion or interfacial interactions among the fibers, matrix, and SiO2 filler.
Figure 4.5 SEM micrographs of tensile fractured surfaces of Al₂O₃ filled G-E composite.

SEM characterization of the Al₂O₃ filled G-E fractured surface shows (Figures 4.5 a-b) that the fibers are more or less covered with the matrix and Al₂O₃ particles (marked by arrows) a qualitative indication of a greater interfacial strength. Disorientation of transverse fibers (marked ‘P’ in Figure 4.5a), fiber bridging (marked ‘Q’ in Figure 4.5a), fibers pull out, inclined fracture of longitudinal fibers (marked ‘R’ in Figure 4.5b), matrix rollers, and matrix cracking (marked ‘S’ in Figure 4.5b) is also seen. The improvement reported in terms of mechanical properties of the composites evaluated is mainly due to the enhancement of adhesion or interfacial interactions among the fibers, matrix, and Al₂O₃ filler.

4.3 Evaluation of Two-Body Abrasive Wear Behaviour

4.3.1 Two-Body Abrasive Wear Behavior of Unfilled and SiO₂ Filled G-E Composites

The variation in abrasive wear volume of composites worn on 320 and 600 grit SiC paper under 10 N load against abrading distance is shown in Figure 4.6 (a-b). The wear data of the composites reveal that the wear volume tends to increase linearly with increasing
abrating distance and strongly depends on the grit size of the abrasive paper. From figure 4.6 (a-b), it is obvious that the wear volume of composites worn on two different SiC papers increased with increasing abrading distance. Wear volume of unfilled G-E is much higher than those of SiO₂ filled G-E composites and also the wear volume decreased with increasing filler loading. The minimum wear volume loss of 10 wt. % of SiO₂ filled G-E composites is 2.71 mm³ which is nearly 60% less than that of unfilled G-E composites with 600 grit SiC paper under same test condition. The variation in abrasive wear volume of composites worn on various grit size SiC papers at different applied load and abrading distances under multi-pass condition. The wear data of the composites reveal that the wear volume tends to increase near linearly with increasing abrading distance and strongly depends on the grit size of the abrasive paper [53,56].

Figure 4.6 Variation of wear volume with abrading distance for unfilled and SiO₂ filled G-E composites: (a) 320 grit and (b) 600 grit SiC papers.

From the Figure 4.6 (a-b) the wear volume of unfilled G-E composites is 2.5-3.75 times greater than that of particulate filled G-E. In the specimen worn at a load of 10 N with 320 grit SiC paper, wear debris did not adhere to the SiC paper. However, in the specimen
worn under same test conditions using 600 grit SiC paper, some abrasive particles penetrated more into the matrix. The fine particles which were detached from the counter surface (SiC paper) fill the cavities and modified the specimen surface.

The wear volume loss is less in SiO$_2$ filled G-E composites and it can be attributed to inherent better mechanical properties and spherical shape of SiO$_2$. Further, the interaction between the SiO$_2$ particles and the epoxy matrix leads to better adhesion because of greater polymer-filler interaction.

![Graph](image)

**Figure 4.7 Variation of specific wear rate with abrading distance for unfilled and SiO$_2$ filled G-E composites: (a) 320 grit and (b) 600 grit SiC papers.**

Figure 4.7 (a-b) illustrates the variation of specific wear rate for G-E and particulate filled G-E composites with 5, 7.5 and 10 wt. % SiO$_2$ composites with applied load under different abrading distance. It is clear from Figure 4.7 (a-b) that the specific wear rate for G-E and SiO$_2$ filled G-E composites decreases with increasing abrading distance and grit size of the abrasive paper. This figure also shows that under higher abrading distance (30 m) the specific wear rate for G-E and SiO$_2$ filled G-E composite is following a decreasing trend. Generally there is large drop in specific wear rate for G-E with the addition of SiO$_2$ filler. The
lowest wear rate is for G-E with 10 wt. % of SiO₂ under two grit papers namely 600 and 320 are $2.01 \times 10^{-11}$ and $4 \times 10^{-11}$ m³/Nm and the wear rate for unfilled G-E are $7.56 \times 10^{-11}$ and $11.86 \times 10^{-11}$ m³/Nm.

Different types and concentration of fiber reinforcement and/or solid lubricants are known to improve many physical and/or mechanical and tribological properties of polymers. Harsha and Tewari [91] investigated two-body and three-body abrasive wear of polyaryletherketone (PAEK) composites. They concluded that the fillers such as PTFE and graphite were detrimental to abrasive wear resistance compared to glass fiber PAEK composites. The primary reason for adding the fillers is to increase the mechanical properties and the effect on tribo-behavior is not always beneficial. The filler type, shape, size, and chemical treatment play a major role on mechanical and tribological properties in fiber reinforced polymer composites.

The addition of SiO₂ filler can cause a dramatic improvement in wear resistance of G-E composite. This behavior can be attributed to the presence of SiO₂, which is embedded within the matrix material, covers the packets of plain weave woven glass fabric and impart additional strength to the composite. The amount of SiO₂ filler in G-E composites 5-10 wt. %, for this reason the filler loaded G-E wear loss were small and wear loss had been caused by matrix wear. The order of wear resistance behavior of composites is as follows: 10>5>0 % by weight of SiO₂ particles. The glass fabrics strengthen the composite, SiO₂ filler provide enhanced wear resistance because of their brittle nature.
4.3.2 Two-Body Abrasive Wear Behavior of Unfilled and Al$_2$O$_3$ Filled G-E Composites

The variation in abrasive wear volume as a function of abrading distance of neat G-E and Al$_2$O$_3$ filled G-E composites is presented in Figure 4.8 (a-b) for different grit sizes of SiC paper. A test conducted using coarse grit 320 having an average particle size of 36 µm resulted in a higher wear volume loss in all the samples tested. The abrasive wear performance of samples on grit 320 is poor due to the large sized abrasive particles, which removes more material during the abrasion process (Figure 4.8a). The material removal rate is high owing to the ploughing and cutting action of the grits. The wear volume data of all samples revealed that the wear volume tends to increase linearly with increasing abrading distance and strongly depends on both applied normal load and the grit size of abrasive paper. As the particle size decreases (600 grit having an average particle size of 16 µm), the material removal rate decreases as shown in Figure 4.8b. The wear volume loss is less in Al$_2$O$_3$ filled G-E composites for both grit sizes of SiC paper (320 and 600 grit size).
In addition it can be seen that as wt. % of Al₂O₃ filler increases then wear volume loss decreases for both grit size SiC papers and 10 wt. % of filler addition shows the less wear volume loss. The minimum wear volume loss of 10 wt. % of Al₂O₃ filled G-E composites is 2.14 mm³ which is nearly 68% less than that of unfilled G-E composites and 21% less than that of SiO₂ filled G-E composites on 600 grit SiC paper under same test condition. The effect of silicon carbide (SiC) particulate filler incorporation on two-body abrasive wear behaviour of G-E composites. The wear loss of the composites was found increasing with the increase in abrading distances. A significant reduction in wear loss and specific wear rates were noticed after incorporation of SiC filler into G-E composite. This result indicates that the significant influence of SiC filler allowing less wear of matrix during abrasion which in turn facilitates lower fiber damage, due to the presence of SiC particles on the counter surface, which act as a transfer layer and effective barriers to prevent large-scale fragmentation Mohan et al. [43].

The specific wear rate decreases with increasing abrading distance and grit size of the abrasive paper. Figure 4.9 (a-b) shows the specific wear rate of samples abraded against 320 and 600 grit SiC paper. Generally there is large drop in specific wear rate for G-E with the addition of Al₂O₃ filler. The lowest wear rate can be observed for G-E with 10 wt. % of Al₂O₃ under two grit papers namely 320 and 600 grit sizes. The addition of Al₂O₃ filler can cause a dramatic improvement in wear resistance of G-E composite. Also, G-E composites with Al₂O₃ filler addition, improves some of the mechanical properties listed in Table 4.2. The order of wear resistance behavior of composites is as follows: 10>5>0 % by weight of Al₂O₃. The glass fabrics strengthen the composite Al₂O₃ filler provide enhanced wear resistance because of their brittle nature.
Figure 4.9 Variation of specific wear rate with abrading distance for unfilled and Al$_2$O$_3$ filled G-E composites: (a) 320 grit and (b) 600 grit SiC papers.

The variations in the specific wear rate with abrading distance at 10N load for 320 and 600 grit SiC papers are shown in Figure 4.9 (a-b). The specific wear rate decreases with increasing abrading distance. The results revealed higher abrading nature of G-E composite compared to SiO$_2$ and Al$_2$O$_3$ filled G-E composites. The lowest wear rate is for G-E with 10 wt. % of Al$_2$O$_3$ under two grit papers namely 600 and 320 are $1.86 \times 10^{-11}$ and $2.39 \times 10^{-11}$ m$^3$/Nm and the wear rate for unfilled G-E are $7.56 \times 10^{-11}$ and $11.86 \times 10^{-11}$ m$^3$/Nm.

4.3.2.1 Surface morphology of specimen before the abrasion test

Figure 4.10 shows the SEM micrographs of unfilled and particulate filled G-E composites surface before conducting the two-body/three-body abrasion test and show the original distribution of fiber/filler in the resin before the abrasion wear test.
Figure 4.10 SEM micrographs of (a) Unfilled G-E (b) 10 wt. % of SiO₂ filled G-E (c) 10 wt. % of Al₂O₃ filled G-E composites before abrasion.

SEM micrograph of unfilled G-E composite figure 4.10 (a) shows the presence of voids on the surface of the sample, which reduces the mechanical as well as tribological properties of the composite. From figure 4.10 (b-c) it is clearly visible that the fibers as well as particles (SiO₂ and Al₂O₃) are adhered to the matrix very well and a qualitative indication of a greater interfacial strength.

4.3.2.2 Worn surface morphology

To correlate the wear data effectively, SEM micrographs of worn surfaces of G–E composite samples are shown in Figure 4.11 (a-b), Several mechanisms have been proposed to explain how material is removed from the surface during abrasion. Because of the
complexity of abrasion, no one mechanism completely contributes to all the wear loss. In general, the abrasive wear process involves four different mechanisms namely microploughing, microcutting, microfatigue and microcracking. Using SEM micrographs it is possible to identify qualitatively the dominant wear mechanisms under abrasion.

Figure 4.11 SEM micrographs of unfilled G-E composite: (a) 320 and (b) 600 grit SiC papers.

Figure 4.11a shows SEM micrograph of glass fiber reinforced epoxy samples abraded against 320 grit SiC paper. Figure 4.11a shows some ploughing marks on the surface, matrix damage and exposure of glass fibers. These exposed fibers tend to fracture and their removal from the surface of the composite. The matrix is heavily damaged by ploughing and cutting action by the higher sized SiC particles. Overall surface topography indicated more fiber pulverization, more fiber breakage and less fiber-matrix debonding. The SEM micrograph also indicates the crack propagation of the matrix, deterioration of the fiber-matrix adhesion due to repetitive mechanical stress and some fibers pull-out from the matrix is also visible.

Figure 4.11b shows SEM micrograph of unfilled G–E samples abraded against 600 grit abrasive papers. Further, few ploughing marks on the surface, matrix damage and very
little exposure of glass fibers are seen from the SEM micrograph. The matrix is damaged more and more microcracks in the matrix are also visible from the SEM micrograph. Further, smooth surface of the matrix and at some regions cracks and also voids are evident from the SEM micrograph. This is attributed to the finer abrasive particles get crushed as the abrading distance increases and the SiC particles become ineffective. The SEM micrograph also indicates the deterioration of the fiber-matrix adhesion due to repetitive mechanical stress and debonding of fibers from the matrix.

Figure 4.12 SEM micrographs of 10 wt. % SiO$_2$ filled G-E composite: (a) 320 and (b) 600 grit SiC papers.

Figure 4.12 (a-b) shows the abrasive wear surfaces of SiO$_2$ filled G-E samples at a load of 10 N and 30 m abrading distance. The deep furrows in the abrading direction owing to the ploughing action by sharp abrasive particles are seen on the surface (Figure 4.12a). The extent of damage to the matrix and fiber is less in SiO$_2$ filled G-E as compared to unfilled G-E composite under same test conditions. In this case there are significant interactions between fibers and SiO$_2$ filler resulting in better bonding with epoxy matrix. This result is in agreement with the SEM pictures 4.12 (a-b) shows that uniform dispersion of SiO$_2$ filler and fibers apparently are well bonded to the matrix material. Keeping the load constant, the
sample abraded against 600 grit SiC paper led to appearance of smaller-sized fiber with matrix debris adhered to the broken end of the fibers as seen in Figure 4.12b. Also, severe damage to the matrix, little fiber breakage and some fiber pull-out from the surface is noticed.

![Figure 4.13 SEM micrographs of 10 wt. % Al₂O₃ filled G-E composite: (a) 320 and (b) 600 grit SiC papers.](image)

Figure 4.13 (a-b) shows SEM micrographs of Al₂O₃ filled G-E composite abraded against 320 and 600 grit SiC abrasive papers respectively. In the sample abraded against a very rough abrasive paper (grit 320), the individual grains penetrate deeply into the surface of the material, subsequently removing material from the surface by micro-ploughing process. During this procedure the polymer matrix is highly plastically deformed before being separated owing to additional microcutting so that wear debris is formed. However, the worn surface of the same sample abraded against 600 grit abrasive paper (figure 4.13b) showed less damage to the surface and narrow grooves due to the smaller size of the abrasive particles. It is evident from the SEM micrographs comparing Figure 4.13 (a-b) with Figure 4.12 (a-b) and 4.11 (a-b) that 10 wt. % of Al₂O₃ filled G-E is showing lesser degree of worn surface features compared to unfilled G-E and SiO₂ filled G-E composites at 10 N load and 30 m abrading distance.
4.4 Evaluation of Three-Body Abrasive Wear Behaviour

The three-body abrasive wear behaviour of G-E and particulate filled G-E composites has been studied. Typical wear scars of the abraded composite specimens are as shown in Figure 4.14. In the initial stage of abrasion, a minimum number of abrasive particles are in contact with rubber wheel and composite. High contact pressure transferred to the abrasive has been shared by few sand particles, leading to maximum stresses at contact region. Hence, these stresses produced by an abrasive is sufficient to facilitate failure of matrix, leading to the matrix removal (Figure 4.14).

![Typical wear scars of unfilled and particulate filled G-E samples.](image)

4.4.1 Three-body abrasive wear behavior of unfilled and SiO$_2$ filled G-E composites

The three-body abrasive wear results of the unfilled G-E composite indicate that a poor wear performance as compared to SiO$_2$ filled G-E composites. G-E composite sample is fixed to a sample holder (as indicated in Figure 3.5). This way the mounted G-E sample is made to come in contact with a rotating rubber wheel. In this case, the abrasion started through contact with the softer phase (epoxy). First, from free fall, the sand particles gained
energy from the rubber wheel and then struck the composite surface, which would result in the formation of pits. Second, the abrasive particles were embedded in the rubber wheel, transforming the three-body abrasion into multi-pass two-body abrasion. Third, the particles roll at the interface, causing plastic deformation to the composite. In the present work, during abrasion, in the initial stage of abrasion, the particle penetrated the soft outer layer of the composite (matrix) due to the lower hardness. Once the matrix layer was removed, the harder phase of the composite (fibers) was exposed to the rubbing area, which acted as a protector, leading to a reduction in the removal of material. However, breakage, debonding and pull-out of fibers have been observed at longer abrading distances.

Figure 4.15 Variation of wear volume with abrading distance for unfilled and SiO₂ filled G-E composites: (a) 24 N and (b) 36 N.

Experimental data of wear volume are plotted for composites shown in Figure 4.15 (a-b) with wear volume as a function of abrading distance. The wear data reveal that the wear volume tends to increase near linearly with increasing abrading distance and strongly depends on the applied load for all the composites tested. Basavarajappa et al. [44] studied the effect of filler material on three-body abrasive wear behaviour of G-E composites and they
concluded that the weight loss increases with increase in load, sliding speed and abrading distance. The filler material (SiC) contributes a significant wear resistance of the G–E composites.

By increasing the load from 24 to 36 N, the wear volume of neat epoxy increased from 120.21 to 200.5 mm$^3$ and wear volume of 10 wt. % of SiO$_2$ filled G-E composite increased from 74.71 to 143.6 mm$^3$. It was observed that the wear performance is improved for G-E composite due to inclusion of different weight percentage of SiO$_2$ fillers for both the applied load. However, the wear performance of 10 wt. % of SiO$_2$ filled G-E composite showed higher abrasive wear resistance. Among the composites studied, the wear resistance trend occurred in the order: 10SiO$_2$-G-E > 7.5SiO$_2$-G-E >5SiO$_2$-G-E>0%G–E for composites at two different loads of 24 N and 36 N. Further from these figures for 10 wt. % of SiO$_2$ filled G-E composite there is an increase in abrasion resistance of 38% compared to unfilled composites.

Figure 4.16 Variation of specific wear rate with abrading distance for unfilled and SiO$_2$ filled G-E composites: (a) 24 N and (b) 36 N.
Figure 4.16 (a-b) shown as histograms, the comparative abrasive wear performance of G-E and SiO$_2$-G-E composites at 24 N and 36 N loads respectively. The specific wear rate data reveals that initially the specific wear rate tends to decrease with increasing abrading distance and further it strongly depends on the applied load for both samples. Also observed in the earlier noted fact that G-E composite exhibits the highest specific wear rate. It is interesting to note that for SiO$_2$-G-E composites, the specific wear rate is on the lower side.

The specific wear rate of unfilled and SiO$_2$ filled glass fabric reinforced epoxy (SiO$_2$-G-E) composites versus the abrading distance with different loads (24 and 36 N) at 200 rpm rotational speed are shown in Figure 4.16 (a-b). For all the composites tested, it is observed that the specific wear rate decreases with increase in filler content and increases with increase in the applied load. At all abrading distances the highest specific wear rate is for neat epoxy with a value of $2.25 \times 10^{-11}$ m$^3$/Nm at 36 N and the lowest value of $0.681 \times 10^{-11}$ m$^3$/Nm for 10 wt. % of SiO$_2$ filled epoxy composite at 24 N. The specific wear rate strongly depends on the applied load and abrading distance for all the samples. Among the composites studied, the abrasion resistance is higher for 10 wt. % of SiO$_2$ filled epoxy and lower for the neat epoxy. This is attributed to the fact that, in 10 wt. % of SiO$_2$ filled epoxy composite, the dispersion of filler is uniform and better adhesion between the matrix and the filler.

4.4.2 Three-body abrasive wear behavior of unfilled and Al$_2$O$_3$ filled G-E composites

Experimental data of wear volume are plotted for composites shown in Figure 4.17 (a-b) with wear volume as a function of abrading distance. The wear data reveal that the wear volume tends to increase near linearly with increasing abrading distance and strongly depends on the applied load for all the composites tested. Suresha et al. [52] investigated the effect of filler material on three-body abrasive wear behaviour of G-V composites and they concluded that for all the polymer composites used in the study there is a near linear wear volume loss.
with abrading distance. It indicates a steady-state wear with a constant wear rate. The highest wear volume is for unfilled G–V and the lowest is for SiC-filled G–V composites.

Figure 4.17 Variation of wear volume with abrading distance for unfilled and \( \text{Al}_2\text{O}_3 \) filled G-E composites: (a) 24 N and (b) 36 N.

By increasing the load from 24 to 36 N, the wear volume of neat epoxy increased from 120.21 to 200.5 mm\(^3\) and wear volume of 10 wt. % of \( \text{Al}_2\text{O}_3 \) filled G-E composite increased from 36 to 67.8 mm\(^3\). It was observed that the wear performance is improved for G-E composite due to inclusion of different weight percentage of \( \text{Al}_2\text{O}_3 \) filler. However, the wear performance of 10 wt. % of \( \text{Al}_2\text{O}_3 \) filled G-E composite showed higher abrasive wear resistance. This is because of the hard ceramic particles has high specific modulus compared to glass fiber and possesses higher hardness. Anand and Kumaresh [48] studied the three-body abrasive wear of Titanium Carbide (TiC) filled and unfilled E-glass-epoxy (G-E) was experimentally investigated and they concluded that the inclusion of TiC filler in the epoxy lead to a significant influence on abrasive wear resistance of G-E composites. The wear
volume loss of the composite has been determined and it increases with the increasing abrading distance.

Among the composites studied, the wear resistance trend occurred in the order: 10% Al₂O₃-G-E > 7.5% Al₂O₃-G-E > 5% Al₂O₃-G-E > 0% G-E for composites at two different loads of 24 N and 36 N. Further from these figures for 10 wt. % of Al₂O₃ filled G-E composite there is an increase in abrasion resistance of 70% compared to unfilled G-E composites and increase of 51% compared to 10 wt. % of SiO₂ filled G-E composites.

![Figure 4.18 Variation of specific wear rate with abrading distance for unfilled and Al₂O₃ filled G-E composites: (a) 24 N and (b) 36 N.](image)

Figure 4.18 (a-b) shows specific wear rate of unfilled G-E and different wt. % of Al₂O₃ filled G-E composites at different loads. The variations in the specific wear rate with abrading distance at 24 and 36 N loads are shown in Figure 4.18 (a-b). The specific wear rate decreases with increasing abrading distance but increases with increase in applied load. At all abrading distances the highest specific wear rate is for neat epoxy with a value of 2.25 x 10⁻¹¹ m³/Nm at 36 N and the lowest value of 0.502 x 10⁻¹¹ m³/Nm for 10 wt. % of Al₂O₃ filled epoxy composite at 24 N. The results revealed higher abrading nature of G-E composite.
compared to particulate filled G-E specimens. The phenomenon of decrease in specific wear rate is due to the nature of microparticles used. Suresha et al. [57] investigated on three-body abrasive wear behaviour of carbon-epoxy composite with and without graphite filler and they found variation in the specific wear rate. The specific wear rate data reveals the fact that it tends to decrease with increasing abrading distance from 270m to 1080m as well as load from 22 to 32 N. They showed decreasing trend and finally reached a saturation level for all the samples examined. However, the higher filler loaded, that is, 10 wt. % graphite filled C-E exhibited lowest specific wear rate at all loads and abrading distances.

Thus, in the initial stage of abrasion, abrasive is in contact with matrix and has less hardness compared to that of angular silica sand. At that particular instance, the ratio of $H_a$ (hardness of abrasive particles) to $H_s$ (hardness of the surface) is much more than unity, resulting in severe matrix damage and the rate of material removal is very high. Similarly, when glass fibers are in contact with abrasive particles bi-directional fibers provide better resistance to the process of abrasion.

It is seen that the specific wear rate for all the samples is higher at a lower abrading distance and low for higher abrading distance. This is attributed to the fact that at lower abrading distance low modulus matrix was exposed and at higher abrading distance high modulus fiber was exposed to abrasion. These exposed fibers, because of their high hardness values, provide better resistance against the abrasion and in turn, abrasive particles have to work more to facilitate failure in the fibers (i.e., much higher amount of energy is required to facilitate fiber failure). Thus, the rate at which the material is removed with respect to the abrading distance decreases. Unfilled G-E composite surfaces exhibited relatively high initial wear rate, when the surfaces are new, which decreases gradually to an almost constant value for abrading distance $>750$ mm. The fillers such as SiO$_2$ and Al$_2$O$_3$ were observed to be
beneficial to wear performance. The Al₂O₃ filler in G-E had better wear resistance as compared to SiO₂ filled G-E composites.

### 4.4.3 Worn surface morphology

SEM micrographs of the worn surfaces of unfilled and particulate filled G-E composite samples are shown in Figures 4.19 to 4.21. The worn surfaces of G-E composite samples abraded under high load, lower and higher abrading distance conditions are shown in Figure 4.19 (a-b). These composite SEM micrographs indicate that there is severe damage on the worn surface.

![Figure 4.19 SEM micrographs of abraded G–E composite at 36 N: (a) 250 m and (b) 1000 m abrading distance.](image)

Figure 4.19 (a-b) shows the abrasive wear surfaces of unfilled G-E composites at a load of 36N, 250 and 1000 m abrading distance, respectively. The deep furrows in the abrading direction due to the ploughing action by sharp abrasive particles are seen on the surface. At higher abrading distance, SEM micrograph shown in Figure 4.19b depicts severe damage to the matrix, more fiber breakage and some fibers are pulled-out from the surface. In this figure the brittle fracture of the material due to the cutting action by the abrasive particles
are apparent and the extent of damage to the matrix and fiber is severe compared to lower abrading distance (Figure 4.19a). The higher wear rate in G-E composite may be attributed to lower matrix ductility and poorer fiber–matrix adhesion. The fracture of fiber is due to abrasion and transverse bending by sharp abrasive particles, resulting in fragments of fibers torn from the matrix (Figure 4.19b). Once again, the micrograph shows poor adhesion between fiber and matrix.

![Figure 4.20 SEM micrographs of abraded 10 wt. % of SiO$_2$-G-E composite at 36 N: (a) 250m and (b) 1000 m abrading distance.](image)

Figure 4.20 (a-b) shows the SEM micrographs of abraded surface of SiO$_2$ filled G-E composites tested at a load of 36 N. At lower abrading distance (Figure 4.20a), severe matrix and fiber destructions were the characteristic features in the micrographs. Also the evidence of fiber cutting, small voids left by debonded fibers and fatigue damage of matrix can be seen on the surface. It is thought that the observed damaged fibers are the result of surface fatigue due to repeated abrasion by silica sand particles. The crack propagation through the fiber and interfacial debonding were also observed, because of the brittle nature of glass fibers, which fractures due to repeated abrasion by silica sand particles. The interfacial debonding is less because of finer SiO$_2$ dispersed uniformly in G-E composite and hence, the fibers are less
exposed to the abrasive medium resulted in the lower wear volume loss as compared to unfilled G-E composites.

It is evident from the SEM micrographs comparing Figure 4.19a with Figure 4.20a that the 10 % SiO$_2$ filled G-E is showing lesser degree of worn surface features compared to unfilled G-E sample at 36 N load applications. In the case samples subjected to 36 N load, one can see less number of broken fibers with less debris formation in the SiO$_2$ filled G-E sample (Figure 4.20a) whereas in the unfilled G-E sample (Figure 4.19a), de-bonding of the fiber with cleavage type of fracture is seen. Now, coming to the samples subjected to higher abrading distance (1000 m), masking of fibers are noticed in the SiO$_2$ filled sample (Figure 4.20b). On the other hand, the SEM picture of SiO$_2$ filled G-E composite abraded at higher distance (Figure 4.20b) clearly shows long cracks in matrix and fiber cutting are seen, predominantly along the wear direction. Evidence of fiber breakage, few SiO$_2$ particles and voids left by debonded fibers are observed. It is thought that the observed fiber damage is the result of surface fatigue due to inclusion of SiO$_2$ particles and repeated abrasion by sand particles. A layer of resin seems to be removed by microcracking resulting again from surface fatigue.

Figure 4.21 (a-b) shows the SEM micrographs of abraded surface of Al$_2$O$_3$ filled G-E composites tested at a load of 36 N. It is evident from the SEM micrographs that the Al$_2$O$_3$ filled G-E system shows less of matrix phase wear out in Figure 4.21a. The protrusion of the phase and resultant less wear out are seen in Figure 4.21b.

In Al$_2$O$_3$ filled G-E composite the samples, as it contains a combination of hard and soft phases, severity and extent of damage on the specimen surface becomes less, in the softer regions as noticed owing to the presence of hard Al$_2$O$_3$ particles. As the hard phases/regions
offer resistance to the damaging action of the abrasive, less of the damage is noticed in these systems. The spread of the matrix is distinctly seen in Figure 4.21b.

![SEM micrographs of abraded 10 wt. % of Al₂O₃-G-E composite at 36 N: (a) 250m and (b) 1000m abrading distance.](image)

The SEM micrographs amply demonstrate greater occurrence of debris that includes broken fibers when G-E system is subjected to wear. Thus this observation lends credence to the contention that the presence of Al₂O₃ particles allow less of matrix wear during abrasion which in turn leads to lower fiber breakage.

### 4.5 Chapter Summary

This chapter has provided:

- The mechanical characterization, two-body and three-body abrasive behaviour of the G-E composites with different particulate fillers (SiO₂ and Al₂O₃) and a comparison with a similar set of glass-epoxy composites.
- The effect of type and loading of filler, grit size of abrasive paper, constant applied load, different abrading distances and at a constant sliding velocity on two-body abrasive wear behaviour of composites.
The effect of type and loading of filler, different applied loads, abrading distances and at a constant sliding velocity on three-body abrasive wear behaviour of composites.

The fractured mechanical test samples and worn surface morphologies of abrasive wear composites using scanning electron microscopy.

The comparison of different particulate fillers with regard to the abrasion resistance of composites under similar test conditions.

The next chapter presents the drilling of composites and their statistical interpretation.