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TRIBOPERFORMANCE OF SILICON DIOXIDE FILLED GLASS FABRIC REINFORCED EPOXY COMPOSITES

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ABSTRACT

The article presents the results of experimental investigation on the mechanical and two-body abrasive wear behaviour of silicon dioxide (SiO_2) filled glass fabric reinforced epoxy (G-E) composites. Silicon dioxide filled G-E composites containing 5, 7.5 and 10 wt % were prepared by compression moulding technique. The mechanical properties such as tensile strength and modulus were investigated in accordance with ASTM standards. Two-body abrasive wear studies were carried out using pin-on-disc wear tester under multi-pass condition against the water proof silicon carbide abrasive paper. From the experimental investigation, it was found that the presence of SiO_2 filler improved the tensile strength and modulus of the G-E composite. Inclusion of SiO_2 filler reduced the specific wear rate of G-E composite. The results show that in abrasion mode, as the filler loading increases the wear volume loss deceases and increased with increasing abrading distance. The excellent wear resistance was obtained for SiO_2 filled G-E composites. Furthermore, 10 wt % filler loading gave a very low volume loss.

Keywords: silicon dioxide filled glass-epoxy, mechanical properties, two-body abrasive wear, scanning electron microscopy.

1. INTRODUCTION

Polymers and their composites are often required to move in contact with hard abrasive particles as countersurface. The demand for new materials which can operate in machine elements subjected to relative movement where no lubricant used is continuously increasing [1]. The advantages demonstrated by polymer matrix composites (PMCs), in addition to high strength, high stiffness, and low density, include corrosion resistance, long fatigue life, tailor made properties and the ability to form complex shapes. This has given an impetus to the industrial production of newer materials, for example, bearing components in automotive industry. Fiber reinforced polymer composites show mechanical properties similar to or higher than the conventional metallic materials. The introduction of particulate in the polymer materials enhances the thermal, physical, and mechanical properties. Even in fiber reinforced composites, the addition of microfillers has produced improvement in properties of the composites [2, 3].

Wear is defined as damage to a solid surface, generally involving progressive loss of material, due to relative motion between that surface and contacting substance or substances. The five main types of wear are abrasive, adhesive, fretting, erosion and fatigue wear, which are commonly observed in practical situations. Abrasive wear is the most important among all the forms of wear because it contributes almost 63% of the total cost of wear [4]. Abrasive wear is caused due to hard particles or hard protuberances that are forced against and move along a solid surface [5]. In two-body abrasion, wear is caused by hard protuberances on one surface which can only slide over the other. Polymer and their composites are finding ever increasing usage for numerous industrial applications such as bearing material, rollers, seals, gears,

cams, wheels, and clutches [6]. Different types of polymer show different friction and wear behaviour. However, neat polymer is very rarely used as bearing materials and wear-resistant materials because unmodified polymer could not satisfy the demands arising from the situations wherein a combination of good mechanical and tribological properties is required [7]. Among the wear types, abrasive wear situation encountered in vanes and gears, in pumps handling industrial fluids, sewage and abrasive-contaminated water, roll neck bearings in steel mills subjected to heat, shock loading; chute liners abraded by coke, coal and mineral ores; bushes and seals in agricultural and mining equipment, have received increasing attention [8]. The bidirectional fabric reinforcement offers a unique solution to the ever increasing demands on the advanced materials in terms of better performance and ease in processing [9].

The modification of tribological behaviour of fiber-reinforced polymers by the addition of filler material has been reported [10-13] to be quite encouraging. Most studies on the influence of filler material, in the case of polymer composites sliding against metallic counterfaces have reported on the reduction of wear rate and coefficient of friction. In addition to the higher mechanical strength obtained due to the addition of fillers in polymeric composites, there is direct cost reduction due to the less consumption of resin material.

A literature survey indicated that the short fiber reinforcement, in general, led to the deterioration in the abrasive wear resistance of the matrix [14]. Fabric reinforcement, on the other hand, improved the abrasion resistance of the polymers [15]. Many researchers studied the two-body wear behaviour for polymers in general and polymer composites in particular [16-21]. In some of the literature concerning abrasive wear of polymers, Evans *et*

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al., [16] tested about 18 number of polymers, low density polyethylene exhibited the lowest wear rate in abrasion against a rough mild steel but the highest wear rate in abrasion with coarse corundum paper. Shipway and Ngao [17] investigated the abrasive behaviour of polymeric materials in micro-scale level. They concluded that the wear behaviour and rates of polymers depended critically on the polymer type. Furthermore, the wear was associated with indentation type morphology in the wear scar and low values of tensile strain to failure. Cirino et al., [18, 19] investigated the sliding and abrasive wear behaviour of polyetheretherketone (PEEK) with different continuous fibers and reported that the wear rate decreases with increase in the fiber content. The abrasive wear behaviour of short carbon/glass fiber reinforced with PEEK/polyphenylene sulphide (PPS) polymers were studied by Lhymn et al., [20]. They have concluded that the wear rate is sensitive to the orientation of the fiber axis with respect to the sliding direction. The results showed that the addition of ultra high molecular weight polyethylene (UHMWPE) reduced the wear rate. Friedrich [21] investigated the abrasive wear behaviour of epoxy reinforced with carbon, glass and aramid fabrics and reported the wear performance of the fabrics in the order Aramid > glass > carbon. Bijwe et al., [22] tested polyamide 6, polytetrafluoroethylene (PTFE) and their various composites in abrasive wear under dry and multi-pass conditions against silicon carbide (SiC) paper on pin-on-disc arrangement. They concluded that the polymers without fillers had better abrasive wear resistance than their composites. Although, a good amount of work has been reported on abrasive wear behavior of PMCs as discussed earlier in this section, no literature could be cited on the two-body abrasive wear aspect of G-E and SiO_2 filled G-E composites.

Apart from experimental studies several number of models which attempt to relate the abrasive wear resistance of polymers to some mechanical properties of the material such as hardness and tensile strength have also been proposed. Budinski [23], Larsen-Basse [24] and Rajesh et al., [25] examined five of such models. Budinski indicated that the correlation proposed by all models between the abrasive wear behaviour and other mechanical properties of twenty one polymeric materials was poor. Larsen-Basse [24] argued that the mechanisms of wear differed depending upon the polymer type. Briscoe [26] in his review paper concluded that the models suppose a certain mechanism of material removal to prevail, and that changes in mechanism will tend to make the model predictions invalid. Budinski [23] noted that most of the studies on the abrasion resistance of plastics are inconclusive and tend to recommend further study. Thus, it can be seen that abrasive wear behaviour of polymeric material is complex and it is widely recognized that the processes of wear in polymers are not well understood.

To evaluate the possibility of improving the abrasive wear of glass fabric reinforced epoxy composites and elucidate the abrasive wear mechanisms, in the present study, the two-body abrasive wear behaviour of G-E

composite filled with SiO_2 micro particles were investigated under various external variables such as, normal load of 10 N, sliding velocity of 1 m/s, different abrasive papers 320 and 600 grit size and abrading distances of 7.5, 15, 22.5 and 30 m.

2. EXPERIMENTAL DETAILS

2.1 Materials and fabrication

Woven glass plain weave fabrics made of 360 g/m^2; containing E-glass fibers of diameter of about 12 μm have been employed. The epoxy resin (LAPOX L-12) was mixed with the hardener (K-6, supplied by ATUL India Ltd., Gujarat, India) in the ratio 100:12 by weight. The filler chosen was silicon dioxide. The average particle size of SiO_2 particles are about 10 μm. The details of the compositions including the density are listed in Table-1. As regards to the processing, on a Teflon sheet, E-glass woven fabric was placed over which the epoxy matrix system consisting of epoxy and hardener was smeared. Dry hand lay-up technique was employed to fabricate the composites. The stacking procedure consists of placing the fabric one above the other with the resin mix well spread between the fabrics. A porous Teflon film was again used to complete the stack. To ensure uniform thickness of the sample, a 3 mm spacer was used. The mould plates were coated with release agent in order to aid the ease of separation on curing. The cast of each composite after 12 h of impregnation and dried for 2 h at 100°C followed by compression molding at a temperature of 390°C and pressure of 7.35 MPa. The slabs so prepared measured 250 mm×250 mm×3 mm by size. To prepare different wt. % of SiO_2 filled G-E composites, besides the epoxy hardener mixture, additional wt. % of SiO_2 particles were included to form the resin mix. The details of the composites including the measured density are listed in Table-2. The percentage of the glass fiber in the composite is 60 by wt. %. Mechanical and abrasive wear test samples were prepared according to ASTM standard from the cured laminates using a diamond tipped cutter.

2.2 Physico-mechanical tests

Density of the composites was determined by using a high precision electronic balance (Mettler Toledo, Model AX 205) using Archimedes principle. Hardness (Shore-D) of the samples was measured as per ASTM D2240, by using a Hiroshima make hardness tester (Durometer). Five readings at different locations were noted and average value is reported. Tensile properties were measured using a Universal testing machine in accordance with the ASTM D-3039 procedure at a cross head speed of 25 mm/min and a gauge length of 50 mm. The tensile strength and modulus were determined from the stress-strain curves. Five samples were tested in each set and the average value was reported. The tensile test was carried out on a fully automated Lloyd LR-20 kN Universal testing machine connected to a computer with DAPMAT software.

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Table-1. Physical and mechanical properties of the constituents selected for the present work.

Property	Epoxy	Glass fibers	SiO$_2$ filler
Density (g/cm^3)	1.15	2.54	2.19
Tensile strength (MPa)	110	3400	110
Tensile modulus (GPa)	4.1	72.3	70

Table-2. Composites selected for the present study.

Sample name (Designation)	Epoxy (wt.%)	SiO$_2$ (wt. %)
Glass fabric reinforced epoxy (G-E)	40	-------
Silicon dioxide filled G-E (5SiO$_2$-G-E)	35	5
Silicon dioxide filled G-E (7.5SiO$_2$-G-E)	32.5	7.5
Silicon dioxide filled G-E (10SiO$_2$-G-E)	30	10

2.3 Two-body abrasive wear test

A pin-on-disc setup (as per ASTM G-99 standard, make: Magnum Engineers Bangalore) used for sliding wear and two body wear tests. The surface of 6 mm x 6 mm x 3 mm composite, specimen glued to pin of 6 mm diameter and 22 mm length comes in contact with a harden alloy steel with SiC abrasive paper. For the fabricated samples, the depth of first layer of the glass fabric happens to be 0.3 mm from contact surface. The samples ,in which the fabric perpendicular to SiC paper parallel and anti-parallel with respect to abrading direction and abrading plane (Figure-1) a constant normal load of 10 N was applied. Prior to testing the test samples were polished against 600 grit size SiC paper to ensure proper constant with counter face. The surface of both the sample and disc were cleaned with a soft paper soaped in acetone and thoroughly dried before the test. The pin assembly was initially weighed to accuracy of 0.0001g in electronic balance (Mettler Toledo). The composite sample was abraded against water proof SiC abrasive paper of 320 grit and 600 grit papers at a constant load of 10 N, speed of 175 rpm in multi-pass condition. The difference between the initial and final weights is the measure of sliding wear loss. Four samples were run for each combination of the test parameters employed. The results reported are thus the average of four readings and the relative deviation in wear loss was below 14%.

The wear was measured by the loss in weight, which was then converted into wear volume using the measured density data. The specific wear rate (K$_s$) was calculated from the equation:

$$K_s = \frac{\Delta V}{L \times D} \quad m^3/Nm \qquad (1)$$

Where ΔV is the volume loss in m^3, L is the load in Newtons and D is the abrading distance in meters.
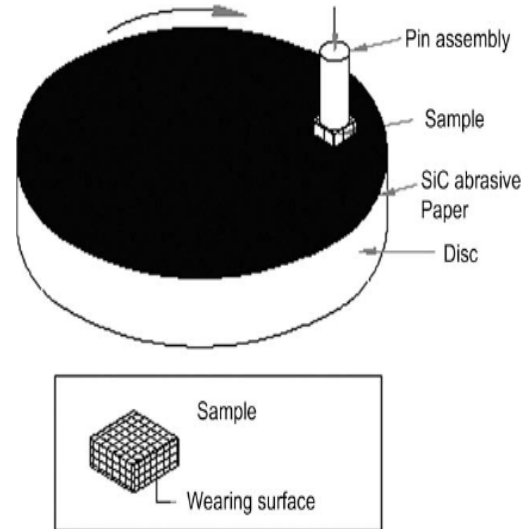

Figure-1. Rotating disc with SiC paper and composite sample.

3. RESULTS AND DISCUSSIONS

3.1 Effect of filler loading on density

The measured densities of the samples are listed in Table-3. Comparing the results it was observed that inclusion of ceramic filler into G-E showed higher density. The density of SiO$_2$ filled G-E is 2.19 which is highest when compared to other composites. This is because of the filler SiO$_2$ has higher density. The densities of all micro particles filled G-E is higher than the density of unfilled G-E composites.

3.2 Effect of filler loading on hardness

By using Duro-hardness tester, the hardness of the composites is measured; the values recorded are given in Table-3. The hardness of G-E composite increased with increase of micro particles filler loading.

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Table-3. Physico- mechanical properties of G-E and SiO_2 filled G-E composites.

Sample code	G-E	5SiO$_2$-G-E	7.5SiO$_2$-G-E	10SiO$_2$-G-E
Density, (g/cm^3)	1.984	2.06	2.15	2.19
Tensile strength, σ (MPa)	254	300	316.6	326.7
Tensile modulus, E (GPa)	8.34	9.43	9.53	9.57
Elongation, e (mm)	7.1	6.7	6.5	6.4
Hardness (Shore-D)	63	65	67	70

From Table-3, it can be seen that the SiO_2 filler greatly increased the hardness of G-E, which can be attributed to the higher hardness and more uniform dispersion of SiO_2 filler. The higher hardness is exhibited by the 10 wt % SiO_2 filled G-E compared to other microcomposites. The hardness of 10 wt % SiO_2 filled G-E composite is 70, which is highest among all the composites tested. 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, micro particles would undergo elastic rather than plastic deformation, as compared to unfilled G-E composites. The improvement in hardness with 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 SiO_2 filled G-E composites.

3.3 Tensile properties

The typical load-deformation curves of unfilled and particulate filled G-E campsites are shown in Figure-2 and the measured mechanical test results are listed in Table-3. The average ultimate tensile strength values for G-E composites with 0, 5, 7.5 and 10 wt % of SiO_2 filler are 254, 300, 316.6 and 326.7 MPa, respectively. The tensile strength of the SiO_2 filled G-E composites increased with increasing SiO_2 up to 7.5 wt %, because of the uniform dispersion of SiO_2 filler in G-E. However, the increase in tensile strength is marginal beyond 7.5 wt % of SiO_2 filler loading. This could be attributed the uniform dispersion of SiO_2 filler in G-E. The surface modified SiO_2 can interact with the fiber surface and hydrogen bonding increases and leads to the better interaction with glass fiber and epoxy. Addition of ceramic fillers increases the effective mechanical interlocking, which in turn increases the frictional force between the fiber and matrix.

It can be seen from Table-3 that the tensile modulus of SiO_2 filled G-E composites increases as the wt. fraction of the filler increases. Again there is a reduction in the elongation at break of the composites with increase in the wt. fraction of the filler. This is due to the fact that the SiO_2 filler is hard and also highly brittle. As the wt. fraction of SiO_2 filler increase, 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. fraction of filler is attributed to the high modulus of ceramic filler which are dispersed uniformly in the fabric layers of G-E composites. Adding SiO_2 did not alter the tensile modulus appreciably except at 5 wt % filler loading. The average Young's modulus values for composites with 0, 5, 7.5 and 10 wt. % SiO_2 are 8.34, 9.43, 9.53 and 9.57 GPa, respectively. 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.
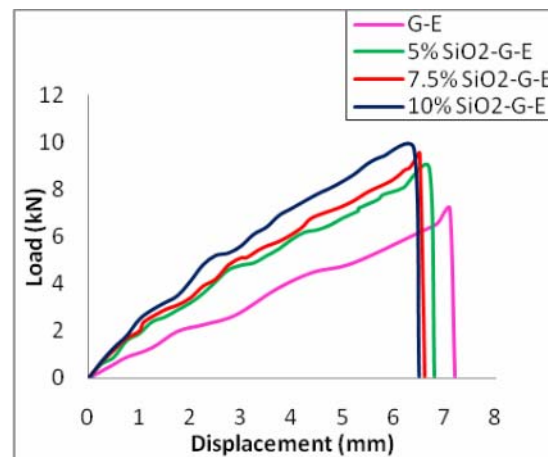
**Figure-2.** Typical load v/s displacement curves of G-E and SiO_2 filled G-E samples.

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. Also the effects of filler loading on the mechanical properties of particulate filled G-E composites were studied and it can be readily seen from the data given in Table-3 and Figure-1 at the filler loading 0-10 wt %. Comparing the results, it can be seen that SiO_2 filled G-E samples show improved mechanical properties, confirming the effect of SiO_2 filler inclusion. The addition of SiO_2 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

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where the dispersoid concentration is less leading to increased tensile strength, tensile modulus, and lower elongation.

3.4 Wear volume

The variation in abrasive wear volume of composites worn on 320 and 600 grit SiC paper under 10 N against abrading distance is shown in Figures 3(a) and (b), respectively. The wear data of the composites reveal that the wear volume tends to increase linearly with increasing abrading distance and strongly depends on the grit size of the abrasive paper. In Figures 3(a) and (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 SiO_2 filled G-E composites and also the wear volume decreased with increasing filler loading. In addition, the highest wear volume is obtained in specimens worn on 320 grit SiC paper (Figure-3b).
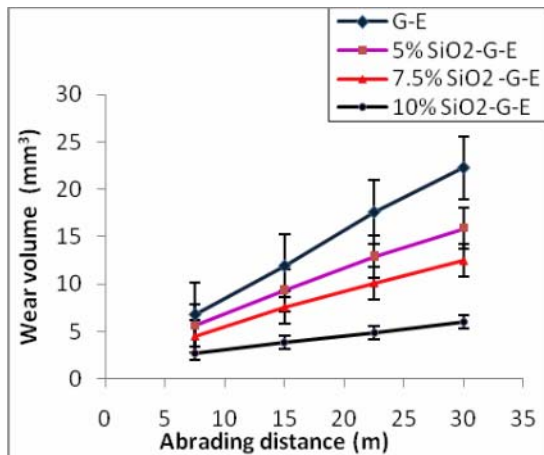
(a)
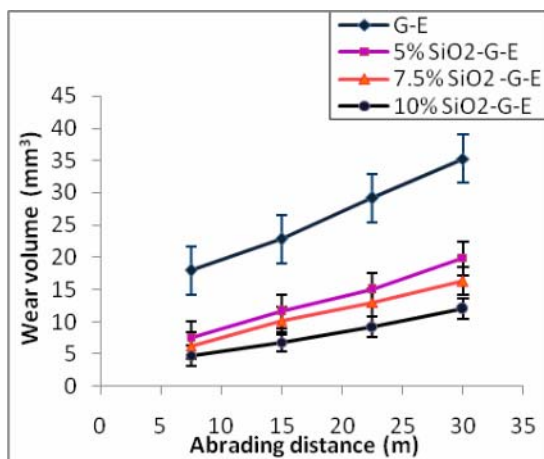
(b)

Figure-3. Wear volume loss of unfilled and SiO_2 filled G-E composites using (a) 600 and (b) 320 grit SiC papers.

As shown in Figures 2(a) and (b), the wear volume of composites is 2.5-3.75 times greater than that of unfilled G-E composite. In the specimen worn at a load of 10 N with 320 grit SiC, wear debris did not adhere to the SiC paper. However, in the specimen worn under same test conditions except the grit size of SiC (600 grit); 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. Therefore, the wear volume with 600 grit SiC paper decreased when compared to 320 grit SiC paper. 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. Also, G-E composites with SiO_2 filler addition, improves some of the mechanical properties listed in Table-3.
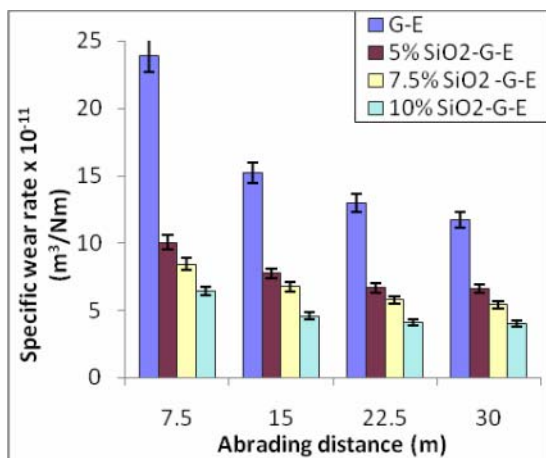
3.5 Specific wear rate

Figure-4(a) and (b) illustrates the variation of specific wear rate for G-E and G-E 5, 7.5 10 wt % SiO_2 composites with applied load under a range of abrading distance. It is clear from Figure-4 that the specific wear rate for G-E and SiO_2 filled G-E composites are increasing with abrading distance and decreased with increase in the grit size of the SiC paper. This figure also show 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. Above 15 m abrading distance (severe condition), the specific wear rate for G-E and SiO_2 filled G-E composite is following an increasing followed by stable 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 SiO_2 under two grit papers namely 600 and 320 are 2.01×10^{-11} and 4×10^{-11} m^3/Nm and the wear rate for unfilled G-E are 7.56×10^{-11} and 11.86×10^{-11} m^3/Nm. The addition of SiO_2 filler can cause a dramatic improvement in wear resistance of G-E composite. This behavior can be attributed to the presence of SiO_2, which is embedded within the matrix material, covers the packets of plain weave woven glass fabric and impart additional strength to the composite. Generally reinforcements in the form of fibers are sought to increase strength and specific modulus. This is so in conventional static and dynamic tests. In the case of wear, the interaction at the interface between the test specimen and the abrasive paper is a key factor. Lancaster [27] has shown the product of σ and e (where σ is the ultimate tensile strength and e is the ultimate elongation) is very important factor which controls the abrasive wear behaviour of composites. Generally fiber/filler reinforcement increases the tensile strength (σ) of neat polymer, they usually greatly decrease the ultimate elongation at break (e) and hence the product (σ x e) may become smaller than that of neat polymer. Hence, reinforcement usually leads to deterioration in abrasive wear resistance. How these values get changed in the

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context of filler is a point that needs further investigation. These parameters are different when the matrix is thermoplastic on the one end and thermoset on the other end. In the present work, the composite materials are thermoset and the reduction in specific wear rate with increase in SiO2 content in G-E composite can be attributed to the following reasons: (i) initially when the specimen is in contact with the abrasive paper the specific wear rate is high and (ii) with increase in abrading distance some of the worn particles clog the abrasive paper and slows down further wear. The amount of SiO_2 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 SiO_2. The glass fabrics strengthen the composite SiO_2 filler provide enhanced wear resistance because of their brittle nature.
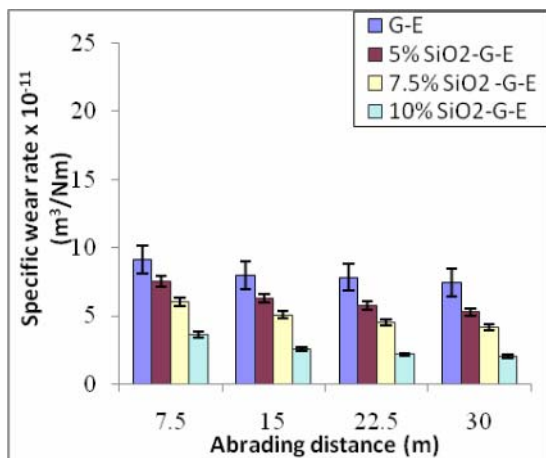
(a)

(b)

Figure-4. Specific wear rate of unfilled and SiO_2 filled G-E composites using (a) 600 and (b) 320 grit SiC papers.

4. CONCLUSIONS

The mechanical and tribological performances of G-E and SiO_2 filled G-E composite were investigated and the following conclusion were reached.

a) The silicon dioxide filler addition to G-E samples has exceptionally improved the abrasive wear performance and the mechanical properties like tensile strength, tensile modulus and hardness properties.

b) SiO_2 filled G-E composite exhibited high wear resistance as compared to unfilled G-E composite under similar testing conditions.

c) The SiO_2 filled G-E composites showed better abrasion resistance under different abrading distances and at given speed and load. This is because of filler-filler interaction and uniform dispersion of filler in G-E composites.

d) As the weight percentage of filler material increases in G-E composites the wear loss reduces in order of 10>5>0 %. This is because of brittle nature of glass fabric and filler materials. The average specific wear rate values for SiO_2 filled G-E is at the range of 2.5 to 4.9 x 10^{-11} m^3/Nm, while for the unfilled G-E is at the range of 8.3 to 16.2 x 10^{-11} m^3/Nm.

e) For the specific range of grit size of SiC paper and abrading distance explored in this study, the grit size of SiC paper has shown more influence on the wear behavior of G-E and SiO_2 filled G-E composite than the abrading distance.

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