# Contrast on Tensile and Flexural Properties of Glass Powder Reinforced Epoxy Composites: Pilot Study

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**ABSTRACT:** Epoxy resin was filled with glass powder to optimize the tensile and flexural strength of the composite for structural applications by a research center in the University of Southern Queensland (USQ). To reduce costs, the center wishes to fill as much glass microspheres as possible subject to maintaining sufficient strength of the composites in structural applications. This project varies the percentage by weight of the glass powder in the composites. After casting the composites to the molds, they were cured at ambient conditions for 24 h. They were then postcured in a conventional oven and subjected to tensile and flexural tests. The contribution of the study was that if tensile and flexural properties were the most important factors to be considered in the applications of the composites, the maximum amount of glass powder can be added to the resin will be five (5) percent. It was also found that the fractured surfaces examined under scanning electron microscope were correlated with the tensile and flexural strength It is also hoped that the discussion and results in this work would not only contribute toward the development of glass powder reinforced epoxy composites with better material properties, but also useful for the investigations of tensile and flexural properties in other composites.


**Key words:** yield strength; tensile strength; Young's modulus; flexural strength; maximum flexural strain; flexural modulus; epoxy resin; glass powder

## INTRODUCTION

The most widely used and least expensive polymer resins are the polyesters and vinyl esters; these matrix materials are used primarily for glass fiber-reinforced composites. The epoxies are more expensive and, in addition to commercial applications, are also utilized extensively in polymer matrix composites for aerospace applications; they have better mechanical properties and resistance to moisture than the polyesters and vinyl resins.[1]

Epoxy-based materials have been widely used in coatings, as encapsulant for electronic components, as adhesives, as foams used to produce low weight castings for electronic applications and for coating textiles because of their outstand mechanical, thermal, and electrical properties.[2,3] However, highly cross-linked epoxy resins are rigid and brittle in nature and have poor crack resistance, which limit their many end-use applications, such as structural materials. Recently, a lot of attempts have been used to overcome these problems. Thus, a wide variety of fillers have been added to the epoxy resins to achieve an improvement of some properties, such as fracture toughness. Previously used fillers have included particulates, elastomers, and thermoplastics.[4–6] The addition of inorganic particles into epoxy resins can increase modulus, hardness, and fracture toughness. Although many studies of glass-reinforced epoxy composites have been described, relatively little work has focused on systemic studies of the physicochemical properties, such as surface free energies, thermal properties, glass transition temperature, electrical, and mechanical interfacial properties of hollow-glass microspheres-filled epoxy composites. Therefore, there is more interest related to the use glass powder spheres as fillers, due to low density, high stiffness, low thermal conductivity, and electrical properties.[7]

This research project is to investigate the yield strength, tensile strength, Young's modulus, flexural strength, maximum flexural strain, and flexural modulus of epoxy composites reinforced with varying percentage by weight of glass powder, the filler, with a view to finding out the optimum percentage by weight of the glass powder that can be added to the composites.

## MATERIALS AND METHODOLOGY

The epoxy resin used in this study is Kinetix R246TX Thixotropic Laminating Resin, an opaque liquid, and

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**TABLE I**
**Typical Properties of Hollow Glass Spheres**

| Shape | Spherical |
|---|---|
| Color | White |
| Composition | Proprietary glass |
| Density | 1.1 g/cc and 0.6 g/cc |
| Particle size | Mean diameter 11 and 18 microns |
| Hardness | 6 (Moh's Scale) |
| Chemical resistance | Low alkali leach/insoluble in water |
| Crush Strength | >10,000 psi |

the hardener used is Kinetic H160 medium hardener which has a pot life of 120 min. Other hardeners like H126, H128, H161, and H162 can also be used.[8] The glass powder was first mixed with epoxy resin, after this the hardener, kinetic H160 medium was added. The by weight ratio of resin to hardener used was 4:1.[8] The composite was then cast to molds of tensile and flexural test pieces and left to cure under ambient conditions for 24 h. The specimens were taken out of the molds and then postcured in oven at 40°C for 16 h, and then at 50°C for 16 h and finally at 60°C for 8 h. This is to ensure the heat distortion temperature (HDT) is above 63°C. To bring the ultimate HDT to 68°C, another 15 h of postcuring will be required.[8] The specimens were then subjected to tensile and flexural tests.

The glass powder used was SPHERICEL® 60P18 (spherical) hollow-glass spheres. They are used to enhance performance and reduce viscosity in paints and coatings and as lightweight additives in plastic parts. They are chemically inert, nonporous, and have very low oil absorption. Typical properties of the spheres are shown in Table I.[9] SPHERICEL® 60P18 glass powder products offer formulators flexibility in polymer composites. The addition of glass powder to fiberglass reinforced plastics (FRP), epoxy, compounds, and urethane castings can provide weight reduction, cost savings and improved impact resistance. Insulating features of glass powder also work to the chemists' advantage in thermal shock and heat transfer areas. Two densities available are 0.6–1.1 g/cc; it provides choices to best fit mixing and target weight requirements.[10] The density of the glass powder used in this research was 0.6 g/cc because the other filler, ceramic hollow spheres, or SLG used in similar study was 0.7 g/cc; this will give a better basis for comparison of results obtained in the future. No coupling agent has been used to modify the glass

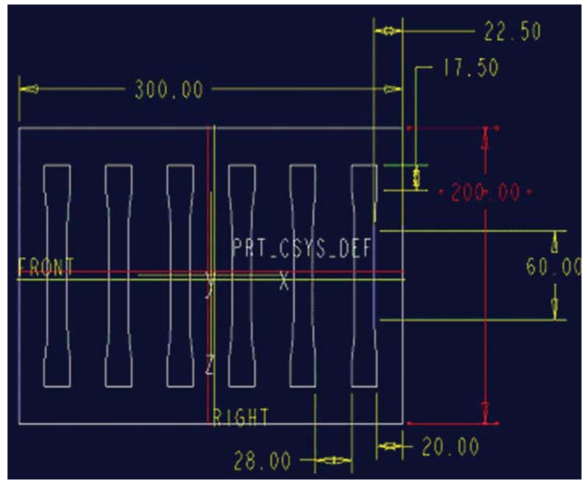


**Figure 1** The mold with dimensions. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

powder surface. When used in polymer concrete, hollow spheres provide a cost effective alternative without degrading physical properties. The particle size of the white glass powder ranges from 6 to 32 microns with an average size of 18 microns.[11] They are therefore micron fillers. These fused inorganic oxides are spherical and nonporous.

The reinforcement was glass powder particulates and they were made 0 wt % to 35 wt % in the cured epoxy composite. For each percentage by weight of filler, there were six samples. Above 35% by weight of filler, the slurry would be too sticky to be cast into molds. The resin was an opaque liquid and was first mixed with the hardener. After that the glass powder was added to the mixture of the resin and hardener, they were then mixed to give the uncured composite. Table II shows the mass in grams of resin, hardener, and glass powder required respectively, to make 1000 g of uncured composite of 20% by weight of glass powder.

The mixture of glass powder, resin, and hardener was blended with mechanical blender to ensure a more homogenous mixture. The mold for tensile test pieces was illustrated in Figure 1. They were clamped by nine screws and springy plastic clamps. This proved to be effective and no seeping of the slurry took place when the samples were cured under ambient conditions. The screwed and tightened mold combination was slightly vibrated to facilitate the escape of the gases and this will

**TABLE II**
**Weight of Materials Required to Make 1000 g of EP/GP (20%)**

| Parameters | Materials | Resin (R) | Catalyst (C) | R + C | Glass powder | Composite |
|---|---|---|---|---|---|---|
| Ratio by weight | | 4 | 1 | – | – | – |
| Percentage by weight | | – | – | 80 | 20 | – |
| Weight of materials in 1000 g of EP/GP (20%) | | 640 (g) | 160 (g) | 800 (g) | 200 (g) | 1000 (g) |

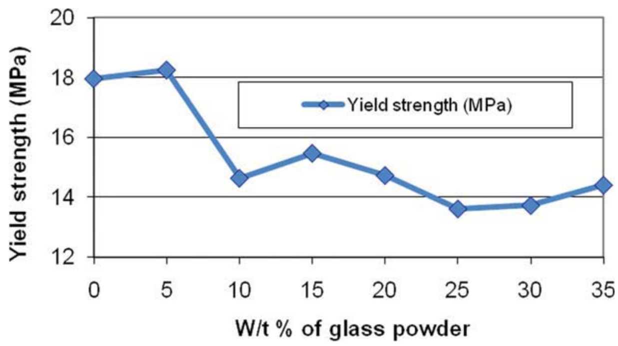


**Figure 2** Yield strength of epoxy composite reinforced with varying glass powder by weight. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

certainly reduce the porosity of the specimens. Finally, before pouring the uncured composite into the mold, the upper surface of the lower plate, the cavities of the mold, the two faces of the mold and the lower surface of the upper plate were sprayed with a releasing agent (wax) to enable easy release of the samples after curing. The uncured composite was then cast into the molds and cured in ambient conditions. The molds for flexural test pieces were similarly manufactured.

After initial 24-h curing when the test pieces were removed from the mold, they were postcured. This was achieved by curing the pieces in an oven. Oven temperatures and times were

- 16 h at 40°C
- 16 h at 50°C
- 8 h at 60°C

It was necessary to cure the samples with the above parameters because by curing the specimens for 16 h at 40°C, the HDT of the samples would become 53°C. By curing the specimens for 16 h at 50°C, the HDT of the samples would become 57°C. By curing the specimens for 8 h at 60°C, the HDT of the samples would become 63°C. The authors felt that with a HDT of 63°C, the samples should be safe to be flexurally tested at room temperature. The gauge length of the tensile test pieces was 60 mm and their other dimensions were shown in Figure 1. The dimensions of the flexural specimens were 250 mm × 10 mm × 4 mm and tested at a cross-head speed of 1 mm/min. The test pieces were then tensile or flexural tested in accordance with an Australian or ISO standards.[12,13]

## RESULTS AND DISCUSSIONS

Figure 2 illustrates the yield strengths of varying percentage by weight of glass powder reinforced epoxy matrix composites. The yield strength of the neat resin was 17.95 MPa, which was higher than those of the composites with any percentage by weight of glass powder other than 5 wt % (18.24 MPa) of glass powder. After dropping to 14.64 MPa at 10% by weight of filler, it remained stable up to 20% percent by weight of glass powder. After this, it dropped further to 13.62 MPa at 25% by weight of filler and remained so up to 35% percent by weight of glass powder. In general, the higher the percentage by weight of glass powder, the lower was the yield strength. Table III shows the values of yield strength mentioned above with their standard deviations in brackets.

Figure 3 shows the tensile strengths of epoxy composites with varying percentage of glass powder by weight. The tensile strength of the neat resin was 24.80 MPa, which was only lower than that (25.14 MPa) of composite with 5% by weight of filler, but higher than those of the composites with any percentage by weight of glass powder. At 10% by weight of filler, the tensile strength dropped to 17.79 MPa; it then remained the same up to 20 wt % of glass powder; after this glass powder reinforcement dragged the values of tensile strength further down; it dropped to 14.72 MPa when wt % of filler was 25% and remained so up to 35 wt % of glass powder. The variation of tensile strength with respect to percentage by weight of glass powder was the same as that of yield strength. Table III shows the values of tensile strength mentioned above with their standard deviations in brackets. It can be found that the trend for the graphs of yield and tensile strengths was the same and it can be argued that the results were correct in trend because the trend was the same with the graphs of yield and tensile strengths of other fillers reinforcing other resins.[14–16]

The addition of small amount (up to 5 wt %) of glass powder increased the yield and tensile strengths of the composites because the resin could encapsulate the glass powder particles easily. This resulted in strong matrix/filler interaction and participation of the filler particles in accommodating the deformation force was a lot in these composites. From 5 to 10 wt % of glass powder, the resin was not enough to encapsulate the glass powder particles completely, leading to the generation of a large number of voids. Due to the presence of these voids, the yield and tensile strengths of these composites became weaker and the composites can be argued to not only reduce in the stress bearing areas but also had the voids acting as stress concentrators, initiating the cracks. Sen and Nugay observed similar behavior for the tensile strength of fly ash filled epoxy resin composites. They concluded that the presence of voids and the formation of air bubbles were responsible for such lowering in strength.[17] Ray et al. also observed similar tendency for the flexural

**TABLE III**
**Yield Strength, Tensile Strength, and Young's Modulus of Epoxy Composite Reinforced with Glass Powder**

| Mechanical properties / W/t % of glass powder | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 |
|---|---|---|---|---|---|---|---|---|
| 0.05% Offset yield strength (MPa') | 17.95 (2.09)# | 18.24 (2.23) | 14.64 (2.73) | 15.47 (0.92) | 14.73 (1.00) | 13.62 (1.24) | 13.73 (2.67) | 14.41 (0.43) |
| Tensile strength (MPa) | 24.80 (4.44)# | 25.14 (4.75) | 17.79 (4.18) | 18.35 (2.44) | 18.13 (2.06) | 14.72 (1.18) | 15.04 (3.83) | 13.90 (1.17) |
| Young's modulus (GPa) | 2.91 (0.34) # | 2.92 (0.11) | 2.72 (0.12) | 2.63 (0.09) | 2.67 (0.14) | 2.70 (0.26) | 2.93 (0.17) | 3.02 (0.08) |

# Standard deviation.

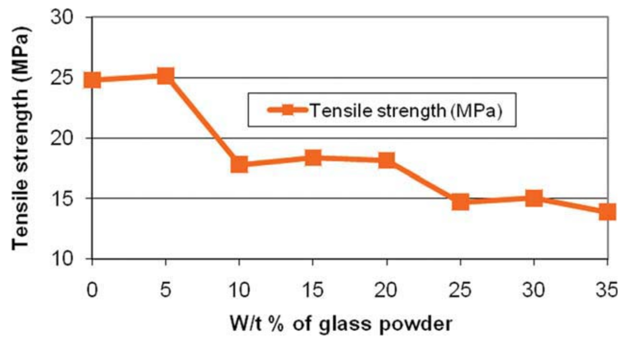


**Figure 3** Tensile strength of epoxy composite reinforced with varying glass powder by weight. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

strength of fly ash filled vinyl ester composites. They also blamed voids for the lowering in flexural strength.[18] Bose et al. also reported a lowering in tensile strength values of Nylon 6/fly ash composites with the increase in fly ash loading and in case of flexural strength, they observed an initial rise up to 20 wt % filler content, followed by a reduction in values. The latter was similar to that of this study.[19]

The tensile strength of neat resin used in the study (24.8 MPa) was much lower than that used by the studies of Nakamura et al. (77.3 MPa) and Radford (75.9 MPa). The former did not mention the epoxy resin used and the latter used anhydride-cured epoxy resin.[16,20] In this study, the pot life of the hardener is 120 min; therefore, the epoxy resin used must be amine-cured as well. Effects of particle size on the tensile properties of cured epoxy resins, filled with spherical silica particles prepared by hydrolysis of silicon tetrachloride, were studied by Nakamura et al.[16] Particles were sorted into five kinds of different mean sizes in the range from 6 to 42 microns. Static tensile tests were carried out. Tensile strengths were found to increase with a decrease in the particle size but with increase particle contents.[16] This trend was supported by the tensile strength results of epoxy/alumina trihydrate particulate composites in Table IV.[21] In this study, the tensile strengths were found to decrease with increase particulate loading and it can be argued that this happened

**TABLE IV**
**Tensile Strength of Alumina Trihydrate Filled Epoxy Composites**

| Particle size (microns) | Volume fraction (%) | Tensile strength (MPa) |
|---|---|---|
| Unfilled | 0 | 75.9 ± 8.8 |
| 1 | 10 | 58.0 ± 3.4 |
| 8 | 10 | 29.9 ± 1.7 |
| 12 | 10 | 27.2 ± 2.4 |

Adapted from Ref. 14.

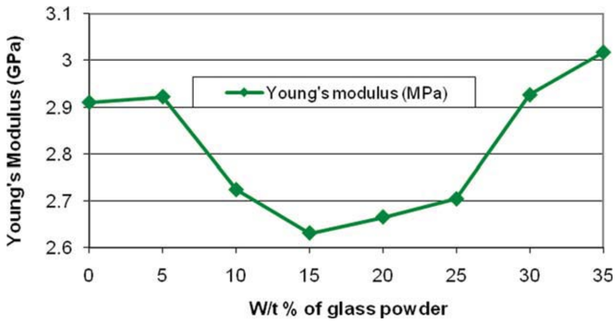


**Figure 4** Young's modulus of epoxy composite reinforced with varying glass powder by weight. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

because the glass powder particles had not been treated by hydrolysis of silicon tetrachloride or blended with coupling agent 3-glycidoxypropltrimethoxysilane (Markosi@ Silane KH-560).

Figure 4 shows the Young's modulus of varying by weight of glass powder reinforced epoxy matrix composite. The Young's modulus of the neat resin was 2.91 GPa and that of 5 wt % glass powder composite was 2.92 MPa; it dropped to 2.63 GPa when wt % of glass powder was 15%. It remained stable up until 25 wt % of glass powder. It then bounced back to 3.02 GPa at 35 wt % of filler. Table III shows the values of Young's modulus mentioned above with their standard deviations in brackets. From neat resin to 20 wt % of glass powder, the yield strength, tensile strength, and Young's modulus behaviors of the composites were more or less the same. From 20+ wt % to 35 wt % of the filler, values of yield and tensile strength decreased further with increasing particulate loading, while those of Young's modulus moved in the opposite direction. The Young's modulus of the neat epoxy used in this study was 2.91 GPa, while that used by Amdouni et al.[22] was 2.9 GPa. The latter used DGEBA/DDA network epoxy resin. It can be argued that the epoxy resins used in both studies were very similar in nature. The addition of a low $T_g$ (glass transition temperature) component as a dispersed phase in the thermoset matrix leads not only to a better fracture toughness but also to a decrease of the modulus.[22] This was true in this study as far as Young's modulus was concerned. The Young's modulus of the silane-treated and elastomer-coated glass beads reinforced epoxy composites increased with increase volume fraction of the filler as depicted in Table V.[22]

**TABLE V**
**Young's Modulus of Elastomer-Coated Glass Beads Filled Epoxy Composites**

| Material | Interlayer thickness (%) | Young's modulus (GPa) |
|---|---|---|
| 0 % vol | 0 | 2.9 |
| 10% vol silane treated | – | 3.5 |
| 20% vol silane treated | – | 4.6 |
| 30% vol silane treated | – | 5.6 |
| 10% vol | 4.2 | 3.45 |
| 20% vol | 4.2 | 4.45 |
| 30% vol | 4.2 | 5.4 |

Adapted from Ref. 19.

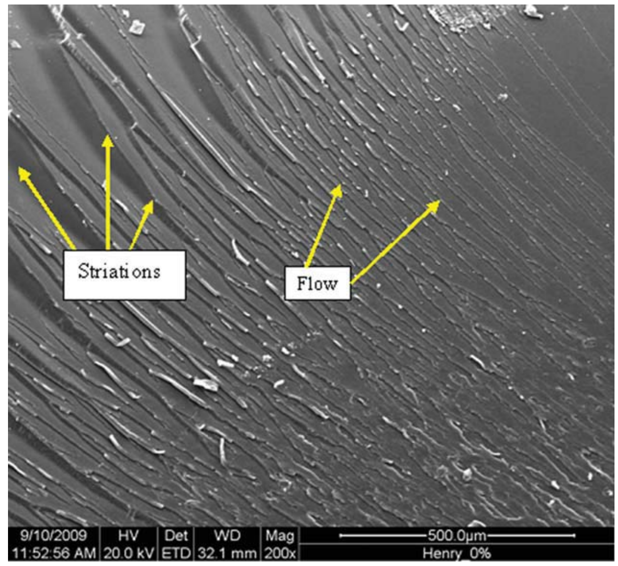


**Figure 5** SEM image of fractured neat epoxy resin, 200×. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The cost of the resin was \$14.5 per kg, while that of its hardener is \$29 per kg. The glass powder was \$3 per kg. For 5% by weight of glass powder, the cost of 1 kg of the composite = 0.76 × \$14.5 + 0.19 × \$29 + 0.05 × 3 = \$16.545. The reduction in cost = $\frac{\$16.86-\$16.55}{\$16.86}$ = 1%; while the increase in tensile strength = $\frac{25.14\text{MPa}-24.8\text{MPa}}{24.8\text{MPa}}$ = 1.5%. It can be found that a reduction in cost by one percent is followed by 1.5% increase in tensile strength. For other percentages by weight of filler, the loss in tensile strength will not be compensated by the reduction in cost. It can be argued that 5 wt % of filler is the best.

Figure 5 shows the scanning electron microscope image of neat epoxy resin postcured for a total of 40 h at 40°C, 50°C, and 60°C, respectively, at a magnification of 200 times. Faint striations followed by a "turbulent flow" can be found in the fractured surface of the neat resin. This shows that plastic deformation had taken place in the resin. Figure 6 illustrates the scanning electron microscope image of epoxy reinforced by 25 wt % of glass powder and postcured for the same number of hours and temperatures at a magnification of 200 times. Holes were spotted and this explained why the tensile strength (24.80 MPa) of neat epoxy resin was stronger than that (14.72 MPa) of epoxy composite with 25 wt % of glass powder. The holes were formed during the mixing process and the higher the

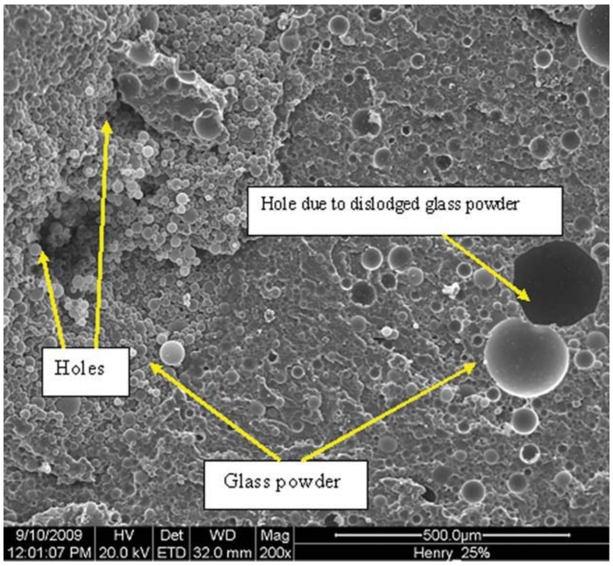


**Figure 6** SEM image of fractured 25% glass powder filled epoxy composite, 200×. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

percentage by weight of glass powder, the more holes would be expected.

Figure 7 shows the flexural strength of glass filled epoxy composites. The flexural strength of neat resin was 58.83 MPa and it rose to 59.32 MPa when wt %of filler was 5% but dropped slowly to 58.13 MPa when the particulate loading was 10%. The values of the flexural strength of the 5 wt %and 10 wt % were within the five percent markers of the neat resin as depicted in Figure 7. There was a sudden drop in flexural strength at 15 wt % to 36.87 MPa; after this the drop was gradual and the flexural strength at 35 wt % was 16.56 MPa.

Zee et al. made epoxy composites from EPON 828 epoxy resin (of Shell Chemical Company) and alumina powder (XA 3500 from Alcoa Company) by varying the percentage by volume of the filler. Anhydrite hardener was also used. Different anhydride curing agents were used and the flexural strength of neat epoxy resin was found to vary from 96.6 MPa to 117.3 MPa. The values dropped to a range of 55.2–62.1 MPa when the particulate loading was 10% but rebounded to values lower than those of the neat resin.[23] The flexural strength of neat resin used in Zee et al. study was high when compared with its counterpart in this study. The trend of the curves of the flexural strength of the composites of the two studies was different and this may be due to the different fillers used. It can be argued that some of the results of this study were better than that of its counterpart because by having 5 wt % of glass powder, the flexural strength was increased and there was a reduction in cost. On the other hand, the flexural strengths of the composites in this study with over 10% of filler were lower than their counter parts. This may be due to the devolatization and degassing processes used by Zee et al.

Park et al. synthesized a potential epoxy resin, i.e., epoxidized soybean oil to toughen the tetrafunctional epoxy resins (ESO). The ESO was blended with the epoxy resins to obtain a modified network having ESO content from 0 to 20 wt %. The neat epoxy resins and modified networks were characterized for thermal and mechanical properties. The thermal stability and glass transition temperature of the blends were slightly decreased with increasing ESO loading. This might be due to the reduction of cross-linking density of the epoxy network, which could be attributed to the incomplete curing reaction in the blend systems. The flexural strength of the neat resin was 112.6 MPa and it increased up to 6.8 wt % (133.8 MPa) ESO content. It then dropped back to 106.8 MPa at 20 wt % of SEO. This could be interpreted in terms of the addition of larger ESO molecule weight into the epoxy resins, resulting in increasing flexible properties of the epoxy resins. The results indicate that the ESO as an impact modifier was superior to the liquid rubbers in both the thermal properties and environmental compatibility.[24]

Fracture and impact behaviors of hollow-glass microsphere epoxy resin composites were studied. Volume fraction of microspheres for the composites was varied up to 65%. Specific flexural modulus marginally increased at some high volume fractions of microspheres but not the fracture toughness. The batch hollow microspheres used was soda-lime-borosilicate glass manufactured by 3*M*. It was found that the specific flexural strength decreased progressively with the volume fraction of the filler. The specific flexural strength of the neat resin was 23.46 MPa/g/cc. At a volume fraction of 65% of filler, the specific flexural strength of the composite was 4.62 MPa/g/cc.[25] The mixing and preparation of the samples were quite similar with those of this study but no pressure was required for compacting the microspheres because the wt % of glass powder used in

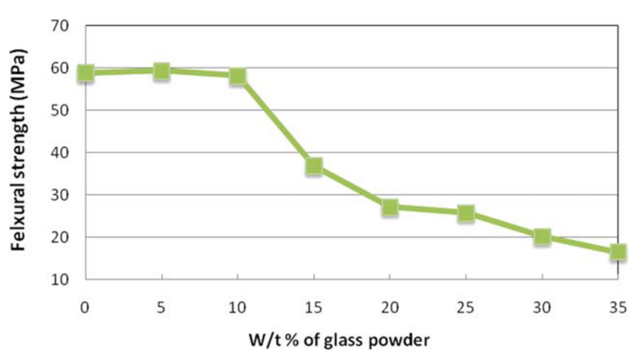


**Figure 7** Flexural strength of glass filled epoxy composites. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

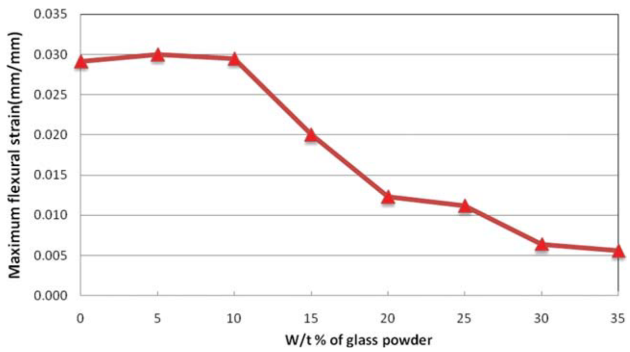


**Figure 8** Maximum flexural strain of glass reinforced epoxy composites. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

this study was not many. However, the flexural strength of the neat resin was low when compared with that of this study. In addition, the flexural strengths of composites in this study did not drop significantly up to 10 wt % of filler but those of Kim and Khamis dropped significantly with increasing filler loading. The difference might be due to the different resins and hollow-glass microspheres used.

Inubushi et al. determined the flexural strength of epoxy resin filled with mica flakes. Two types of epoxy resins were used; one was aminimide-cured epoxy resin matrix and the other was a conventional epoxy resin reference matrix. The intact mica flakes without surface treatment exhibit a substantial reinforcing effect on the flexural strength in the case of aminimide-cured epoxy resin composites. On the other hand, the reference epoxy resins behaved like conventional matrix resins, exhibiting 30–40% reduction in flexural strength when a small fraction of mica was added. In both cases, only up to 0.15 volume fraction of mica flakes were added.[26] In both cases of the study made by Inubushi et al., the values of the flexural strength (around 110 MPa) were much higher than that in this study (58.83 MPa).

Figure 8 shows the maximum flexural strain of glass filled epoxy composites. The maximum flexural strain of the neat resin was 0.0292. As with the flexural strength, the highest value of maximum flexural strain was 0.030 and this was at 5 wt % of glass powder and it dropped slowly to 0.0295 when wt % of glass powder was 10%. The values of the maximum flexural strain of the 5 wt % and 10 wt % were within the 5% markers of the neat resin. There was a sudden drop in maximum flexural strain at 15 wt % to 0.0183; after this the drop was gradual and the flexural strain at 35 wt % was 0.0054. The trend of the curve of Figure 8 was at par with its counterpart in Figure 7. It can be argued that since the trend for both curves was the same, their values are reliable. Table VI depicts the flexural strength, maximum flexural strain, and flexural modulus of epoxy composites filled with glass powder with their standard deviations.

TABLE VI
**Flexural Strength, Maximum Flexural Strain, and Flexural Modulus of Epoxy Composites Filled with Glass Powder**

| Mechanical properties / W/t % of glass powder | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 |
|---|---|---|---|---|---|---|---|---|
| Flexural strength (MPa) | 58.8 (4.3)# | 59.3 (3.3) | 58.1 (7.4) | 36.9 (5.7) | 27.2 (3.3) | 25.8 (1.1) | 20.28 (3.9) | 16.56 (2.9) |
| Maximum flexural strain | 0.0292 (0.0093) | 0.0300 (0.0041) | 0.0295 (0.0026) | 0.0183 (0.0005) | 0.0123 (0.0015) | 0.0110 (0.0005) | 0.0062 (0.0002) | 0.0054 (0.0006) |
| Flexural modulus (MPa) | 2318 (3.53)# | 2098 (199) | 2051 (250) | 1869 (306) | 2218 (153) | 2436 (218) | 3051 (385) | 2990 (138) |

# Standard deviation.

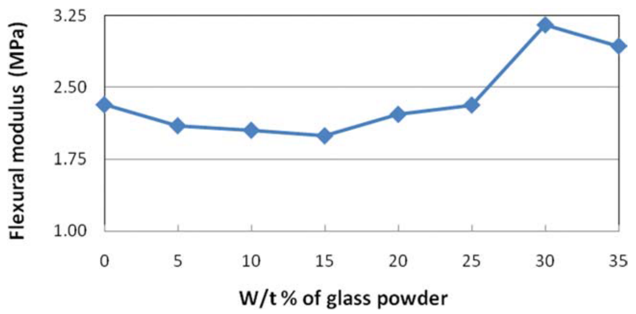


**Figure 9** Flexural modulus of glass powder filled epoxy composites. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 9 shows the flexural modulus of glass powder filled epoxy composites. The flexural modulus of the neat resin was 2318.4 MPa. It dropped slowly to 1869 MPa when the particulate loading was 15%. The drop in this range of particulate loading was 19.4%. The drop in stiffness was in line with that obtained by dynamic thermal analysis.[27] It then rose to a high of 3051 MPa when the percentage by weight of glass powder was 30% after this it changed not much. At higher particulate loading, the stiffness of the composites increased and the flexural modulus increased as well.

The flexural modulus of the work of Part et al. decreased slightly with increasing ESO loading. The flexural modulus of the neat resin was 3.64 GPa while that of 20 wt %of ESO was 2.99 MPa. The flexural modulus of the neat resin of this study was lower than that of Park et al. and this might be due to the different resin used and might also be due to the presence of some porosities inside the samples

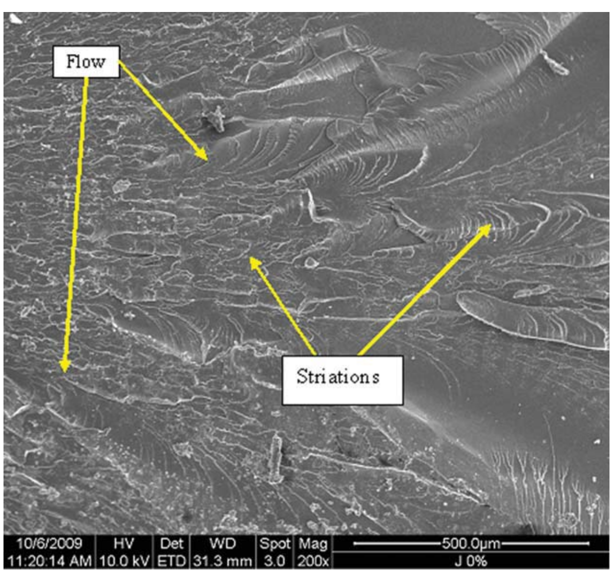


**Figure 10** SEM image of fractured neat epoxy resin from 3-point bending test, 200×. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

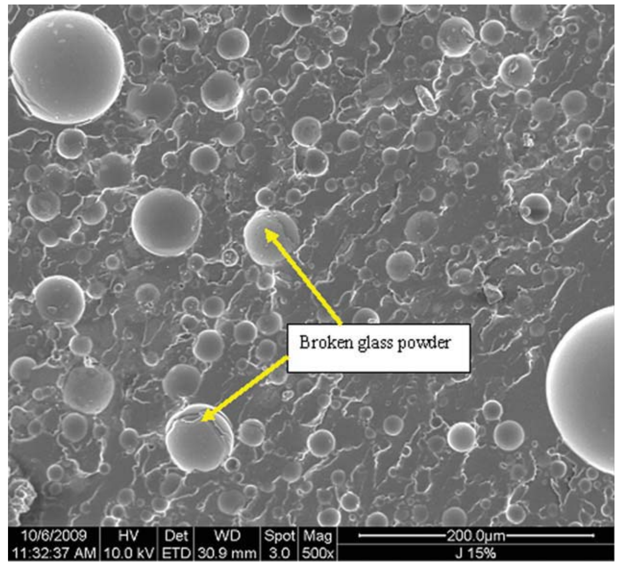


**Figure 11** SEM image of fractured 15% by weight of glass powder filled epoxy composite, 500×. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

because no degassing was performed with the uncured composites. The specific flexural modulus of neat resin obtained by Kim and Khamis was 3.10 GPa/g/cc; the specific modulus initially dropped slightly to 2.93 GPa/g/cc when the volume fraction of the filler was 30%; it then increased slightly to 3.64 GPa/g/cc when the volume fraction of the filler was 65%.[24] The flexural modulus of neat resin of this study was lower than that of Kim and Khamis. The flexural moduli of composites of this study were also lower than those of Kim and Khamis. However, the trend of the flexural modulus was the same in both cases (Fig. 9). The flexural modulus of aminimide-cured mica flakes reinforced epoxy resin composites increased exponentially with increasing volume fraction of the reinforcement, provided only up to 0.15 volume fraction of mica flakes were added.[26] The flexural modulus of neat resin was around 2.7 GPa, which was not far from the one (2.3 GPa) obtained in this study.[24]

Figure 10 shows the scanning electron microscope (SEM) image of fractured neat epoxy resin from 3-point bending test at a magnification of 200 times. Faint striations followed by a 'turbulent flow' can be found in the fractured surface of the neat resin. This shows that plastic deformation had taken place in the resin, on which failure took place. Figure 11 shows the SEM image of fractured 15 wt % of glass powder filled epoxy composite, 500X. A lot of fractured glass powder particles can be found and it can be argued that failure took place on the glass powder particles rather than on the resin; this is why the flexural strength of the 15 wt % was much lower than its neat resin counterpart. Figure 12 illustrates the SEM image of fractured 30 wt % of glass powder filled epoxy composite, 1000×. It can be found that there were a large number of glass powder particles as the particulate loading was 30%. Failure would have taken place on the glass powder and hence the flexural strength (16.56 MPa) was even lower than that of its 15 wt % peer (36.87 MPa). The drop was nearly 75% in flexural strength when compared with neat resin.

The cost of the resin was $14.5 per kg, while that of its hardener is $29 per kg. The glass powder was $3 per kg. For 5% by weight of glass powder, the cost of 1 kg of the composite = 0.76 × $14.5 + 0.19 × $29 + 0.05 × 3 = $16.545. The reduction in cost = $\frac{\$16.86-\$16.55}{\$16.86} = 1\%$; while the increase in flexural strength = $\frac{59.32\text{MPa}-58.83\text{MPa}}{58.83\text{MPa}} \approx 1\%$. It can be found that a reduction in cost by 1% was followed by 1% increase in flexural strength. For other percentages by weight of filler, the loss in tensile strength will not be compensated by the reduction in cost. It can be argued that 5% by weight of filler is the best.

By plotting the tensile and flexural properties together in Figure 13, it can be found that the trend of the yield, tensile, and flexural properties were the same and consistent. The maximum value of each of the three mechanical properties occurred at 5 wt % of filler. The value of the three mechanical properties dropped significantly at 15 wt % of filler. After this, the values remained more or less the same. From the above observations, it can be argued that the values were correct as the standard deviations of the values of those mechanical properties were low as well (Table VI).

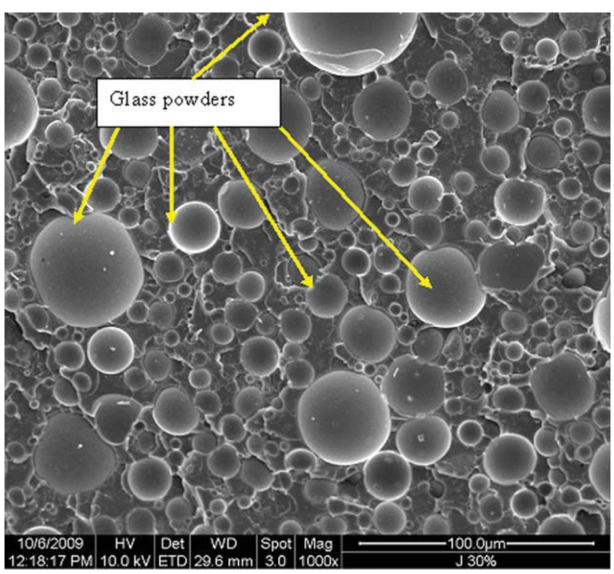


**Figure 12** SEM image of fractured 30% by weight of glass powder filled epoxy composite, 1000×. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

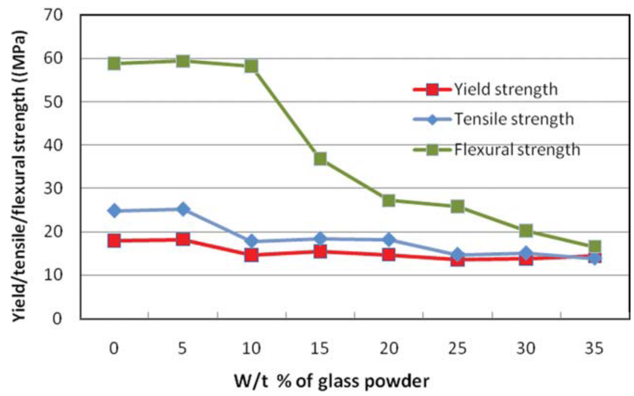


**Figure 13** Tensile and flexural properties of glass powder filled epoxy composites. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

## CONCLUSIONS

This study has evaluated the yield strength, tensile strength, Young's modulus, flexural strength, maximum flexural strain, and flexural modulus of varying percentage by weight of glass powder reinforced epoxy resin; in all cases, the fluidity of the slurry composite was high and could be cast easily into molds. The values with no filler had also been compared with those found by other studies but the tensile properties of some cases did not agree with this study and some did. Since the sizes of porosities of the composites found in this study were very small, it can be argued that the values of tensile properties obtained were very good and reliable as their standard deviations were low. Some air bubbles were found due to imperfect manufacturing of the samples. This can be improved by degassing the mixture before pouring it into the molds. The flexural strength of the glass powder filled epoxy composites, except at 5 wt %, decreased with increasing particulate loading and the trend was similar to other studies with epoxy resins but different fillers. It can be argued that the adhesion and interaction between epoxy resin (matrix) and glass powder (reinforcement) is improved by adding 3-glycidoxypropltrimethoxylina as coupler, its tensile and flexural properties at higher wt % of glass powder will be improved. As far as tensile and flexural properties are concerned, the best percentage of glass powder was 5 wt % as the 1.5% increase in tensile strength is followed by 1% decrease in cost as well as 1% increase in flexural strength is followed by 1% decrease in cost.

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