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Tensile and fracture properties of epoxy resin filled with flyash particles

V. K. SRIVASTAVA, P. S. SHEMBEKAR
Department of Mechanical Engineering, Institute of Technology, Banaras Hindu University, Varanasi – 221 005, India

The ultimate tensile strength, modulus of elasticity and fracture properties of epoxy resin filled with flyash particles have been evaluated by the tensile test. The tensile strength of epoxy resin filled with flyash particles decreases the fracture properties and the modulus of elasticity increases with increasing percentage of flyash. It is advisable to use flyash when the void formation cannot be controlled effectively.

1. Introduction

Epoxy resin is widely used as an electrical insulation material. However, its fracture behaviour is brittle compared with metals, therefore it is necessary to improve the fracture properties of epoxy resin by adding other materials. Low-cost particulate fillers are added to plastics in commercial production primarily for reasons of economy and improvement in moulding characteristics. In practice, except in rather specialized applications, the influence of the filler on mechanical properties is regarded as being of minor importance. The strength and toughness of a composite depends upon the shape and size of the filler, the amount which is compounded with the plastic, the bonding between the filler and the plastic, the toughness of the plastic, and sometimes the toughness of the filler. Fillers affect the tensile properties according to their packing characteristics, size and interfacial bonding. The maximum volumetric packing fraction of a filler reflects the size distribution and shapes of the particles. The space between the particles are assumed to be filled with matrix and no voids or air bubbles are present. Under these conditions, for a given system, the matrix volume is at a minimum and acts as individiual segments or pockets to support a tensile load [1].

1.1. Tensile strength

The simplest model for describing the tensile strength of bead-filled composites regards the matrix as being the only stress bearing component

$$\sigma_P = \sigma_m(1 - fV_f^{2/3}) \quad (1)$$

where σ_m is the tensile strength of the matrix and V_f the filler volume fraction. The value of f depends on the details of the model.

Ramsteiner and Theysohn [2] have shown for a glass bead-filled polypropylene system that the tensile strength, at higher temperature (about 70 °C), is independent of filler concentration, i.e. the model is valid at lower temperature where the matrix is brittle and the beads are not stress bearing. However, at a higher temperature corresponding to a tough matrix state, some stress can obviously be transferred from the matrix into the beads.

1.2. Modulus of elasticity

The elastic modulus has been the most widely studied and reviewed mechanical property of particulate composites. Using strain energy theorems, Paul [3] showed that the modulus of a composite should lie within the range given by

$$E_P E_m / [(1 - V_P)E_m + V_P E_P] \leqslant E_C \leqslant (1 - V_P)\, E_m + V_P E_m \quad (2)$$

where E_P, E_m, E_C are the moduli of elasticity of particulate phase, matrix phase and composite, respectively, and V_P is the volume fraction of particulate dispersion.

When the modular ratio, $m = E_P/E_m$ is small, i.e. $0.5 < m < 3$, the separation between these bonding solutions is small enough to obtain an estimate within 10% of the true modulus, providing that neither voids nor cracks are present. For composites of both high and low modular ratio, i.e. $m > 3$, the bonding solutions are too widely separated to obtain estimates of E_C. Approximate solutions by Kerner [4], Ishai [5] and others have been used to compare the predicted behaviour with experimental data. Ishai's relation is [5]

$$E_C = E_m [1 + V_P / [m/(m - 1)] - V_P^{1/3}] \quad (3)$$

Ishai and Cohen [6] reported that E_C of an epoxy-sand composite system ($m \simeq 36$) was in a good agreement with Ishai's solution for $V_P < 0.30$ and lay between Ishai's and Paul's solution for $V_P > 0.30$. The effect of particles size has also been investigated. Radford [7] reported that E_C is independent of particle size for an epoxy–Al_2O_3 and 3 H_2O system in which different composites were fabricated with different particle size dispersions.

1.3. Fracture energy

The fracture surface energies of epoxide and polyester resin and their resistance to crack propagation are

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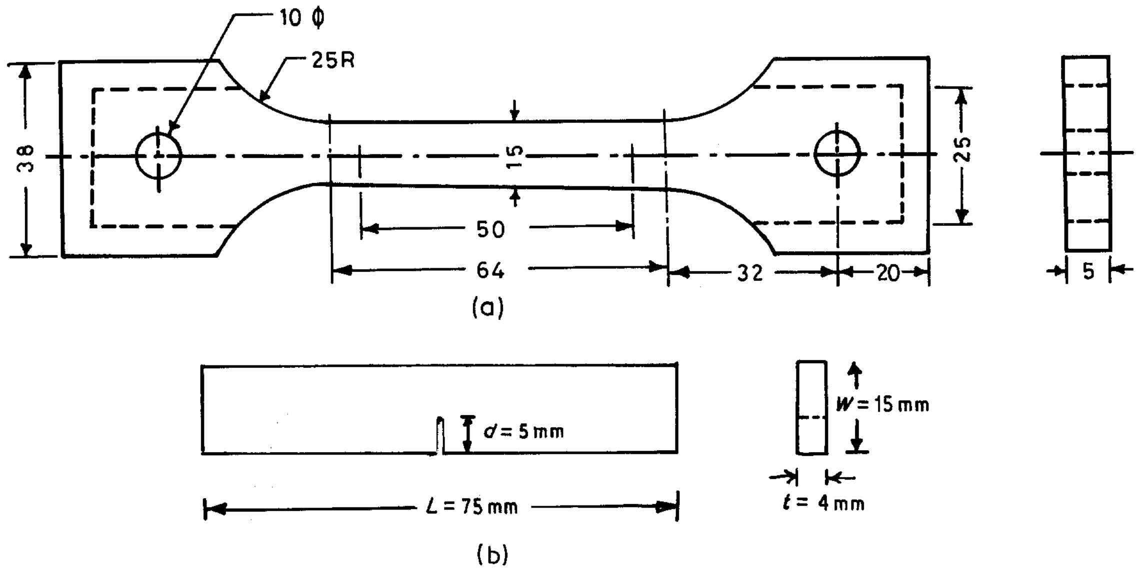

Figure 1 (a) Geometry of Tensile test specimen. (b) Geometry of fracture specimen, a is the crack length, L length, t thickness and w width.

relatively low. If a particulate filler is added to these brittle resins, the particles inhibit crack growth. As the volume fraction of filler is varied, the fracture energy increases until at some critical volume fraction it begins to decrease again. Broutman and Sahu [8] used glass beads of average diameter 30 μm in an epoxide resin to show such a variation. Hammond and Quayle [9] studied glass beads of two different average sizes in a polyester resin. Lange and Radford [10] showed the effect of particle size on the maximum toughness using alumina trihydrate in epoxide. Broutman and Sahu [8] have also reported that fracture energy was influenced by the degree of interfacial bonding between particulate phase and matrix. Lange [11] has reported the fracture energy behaviour of the silicon nitride–silicon carbide composite system. For brittle particles the Lange model explains the initial increase in fracture energy with increasing volume fraction.

In the present research program, the tensile and fracture properties of flyash-filled epoxy resin have been studied and the results reported here are very promising.

2. Experimentation

2.1. Flyash

The flyash collected by the mechanical precipitator in the Obra Thermal Power Station, Mirzapur, India, was used. It was sieved to obtain flyash mesh size (105 μm). Generally, flyash contains the different chemical constituents i.e. silicon oxide, aluminium oxide, calcium oxide, iron oxide and magnesium oxide. The density of flyash is 3.385 g cm^{-3}.

2.2. Epoxy resin

Epoxy resin contains the epoxide group, which is a three-membered oxide ring. The resin can be regarded as a compound which contains, on average, more than

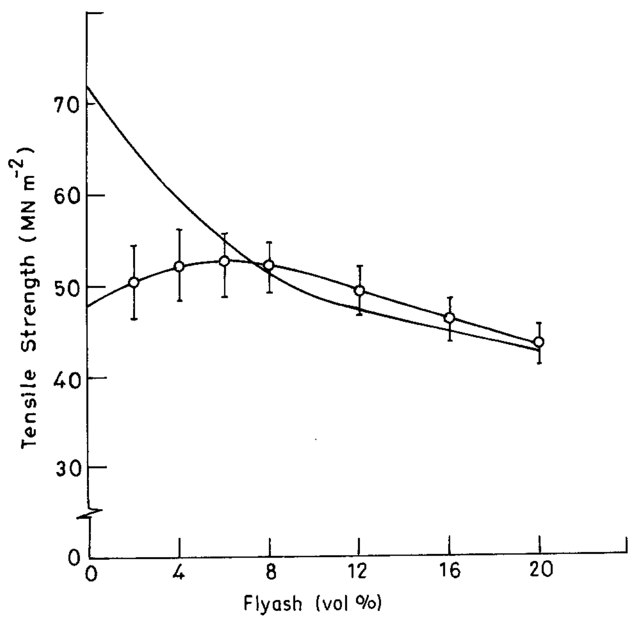

Figure 2 Variation of tensile strength of flyash-filled particulate composite with percentage of flyash by volume. The full curve is $\sigma_{fm} = \sigma_m(1 - 1.3V_f^{0.6})$.

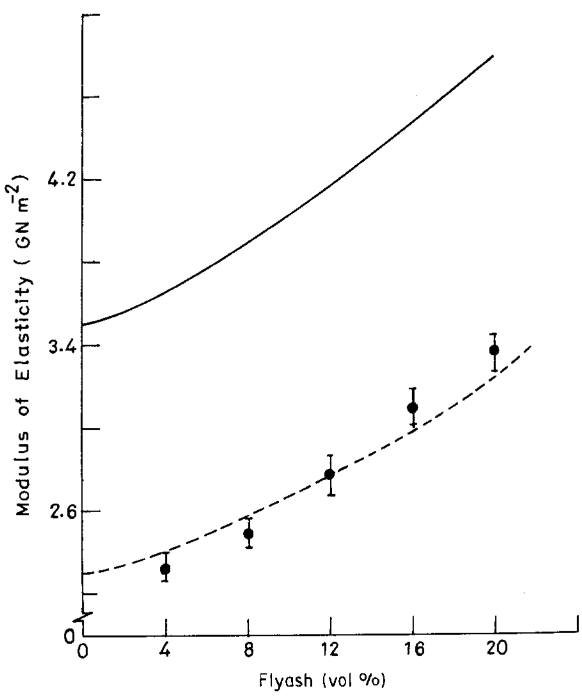

Figure 3 Variation of modulus of elasticity of flyash-filled particulate composite with percentage of flyash by volume. (—— Ishai relation, - - - Cohen–Ishai relation, ● experimental value).

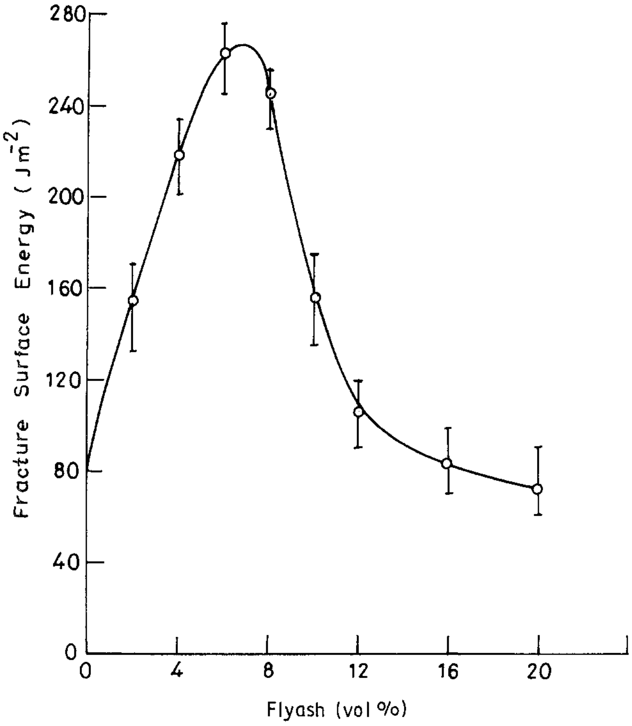

Figure 4 Variation of fracture surface energy of flyash-filled particulate composite with percentage of flyash by volume.

one epoxide group per molecule; and is polymerized through these epoxide groups, using a cross-linking agent to form a tough three-dimensional network. Araldite, CY-205 and Hardener, HY-951 were used as the matrix material.

Epoxy resin filled with different percentages of flyash particles (105 μm) was cast into the size of tensile and fracture specimens. The resin was heated to 50° C, then flyash was added in the required proportions and thoroughly mixed by hand for about 20 min. Then the hardener was added and was again thoroughly mixed for some time. Then it was poured into a mould to prepare particulate composite specimens. The geometry of the tensile and fracture specimens are shown in Fig. 1.

The tensile tests were conducted on commercially available Hounsefield Tensometer. The specimen was fixed in a suitable grip attached to the tensometer. The load elongation curve was obtained directly from the tensometer. From the load elongation curves tensile strength and modulus of elasticity with different percentages of the flyash were obtained as shown in Figs 2 and 3.

The slow three-point bend fracture test was carried out on the Hounsefield Tensometer. The single-edge notched specimen was suitably fixed on the tensometer. From, the load elongation curve, the fracture load was identified for each specimen. Finally, a fractography study was performed by scanning electron microscope (PHILLIPS PSEM - 500).

3. Results and discussion

Fig. 2 shows that the tensile strength of epoxy resin filled with flyash composite reduces with the percentage of flyash. The maximum tensile strength of epoxy resin filled with flyash is obtained at 6.5% of flyash by volume. Theoretically the tensile strength

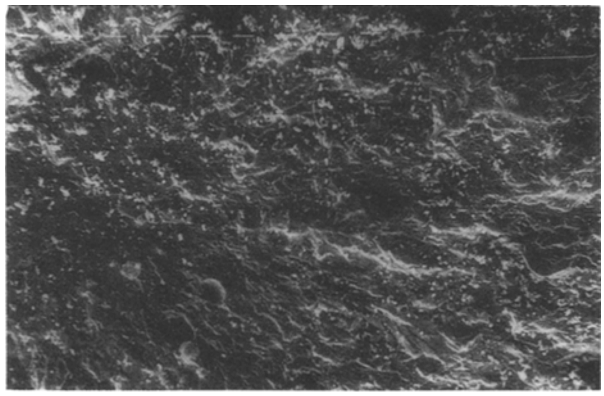

Figure 5 Fractograph of epoxy resin filled with flyash particles failed under tensile loading (× 32).

should vary as given by Equation 1. In the present study, the value of f in Equation 1 is found to be 1.3, giving

$$\sigma_P = \sigma_m(1 - 1.3 V_f^{2/3})$$

The experimentally observed behaviour is different to that given by the above equation, up to 7% of flyash. The variation in the observed behaviour is supposed to be the effect of the presence of voids. The formation of air bubbles and voids is practically unavoidable. The voids not only reduce the stress bearing area but also act as stress raisers, which initiate the cracks. The addition of flyash up to 6.5% is supposed to counter the effect of voids by crack pinning mechanism.

Fig. 3 shows that the modulus of elasticity of epoxy resin filled with flyash particles increases with an increase in the percentage of flyash. The experimental values are lower than those predicted by the Ishai [5] relation. The probable reason for the low modulus of elasticity is the presence of voids. For 19% of voids by volume, the Cohen and Ishai [6] relation gives values closer to those experimentally observed.

It is found that the fracture surface energy of epoxy resin filled with flyash composite reaches a maximum at 6.5% flyash by volume as shown in Fig. 4. The

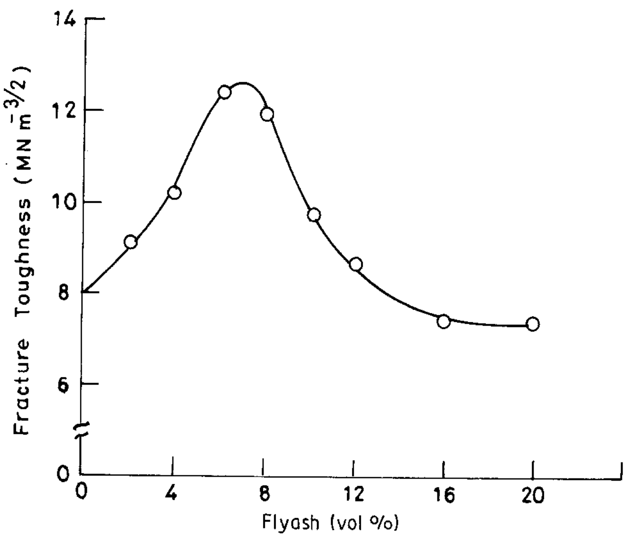

Figure 6 Variation of fracture toughness of flyash-filled particulate composite with percentage of flyash by volume.

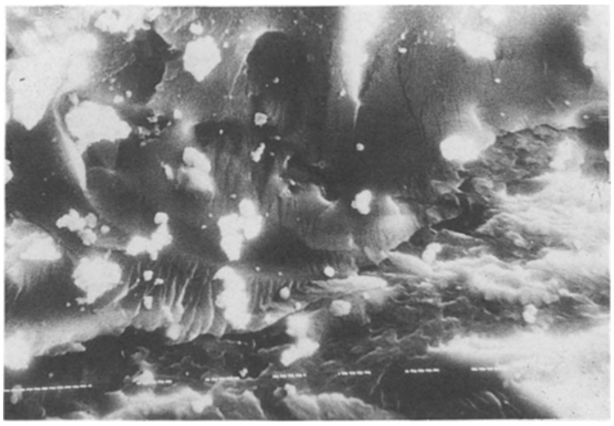

Figure 7 Fractograph of epoxy resin filled with flyash particles failed under tensile loading (× 514).

flyash particles pin the crack and inhibit its propagation as shown in Fig. 5. The micromechanical processes which increase the fracture surface energy of the composite in this case are; increased surface area of fracture faces due to an increase in surface roughness and interaction between the crack front and the dispersed phase. Fig. 6 also shows that the fracture toughness increases up to 6.5% and then it decreases with a further increase in flyash. As the toughness of the matrix is increased the relative contribution due to the pinning process decreases and the addition of flyash can reduce the toughness. This is because the contribution from the pinning process is less than the reduction due to the loss of tough matrix material.

Fig. 7 shows that the epoxy resin filled with flyash particles fractures in different planes. The step formation of the river pattern can also be seen in this figure. The crack front is momentarily pinned at the positions of the flyash particles as it moves through the matrix. Also, large steps are observed, associated with the flyash particles. These steps are characteristic of the interaction of crack front with the flyash particles and they are formed when the crack front 'wraps' around each inhomogeneity on slightly different planes as it breaks away.

4. Conclusions

The main significance of this paper is that the modulus of elasticity, fracture surface energy and fracture toughness of epoxy resin can be improved by filling with flyash particles, because, the crack front interacts with flyash particles, which increases the fracture properties. The flyash, being a waste product from Thermal Power Plants, is cheap and hence the cost of the materials, which will be beneficial for industry.

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