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Mechanical properties of E-glass fibre reinforced nylon 6/6 resin composites

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The tensile strength, tensile modulus, compressive strength, interlaminar shear strength and residual tensile strength of E-glass fibre reinforced nylon 6/6 resin composite with the variation of fibre volume fraction are characterized. The results are in line with the required limits of theoretical values.

1. Introduction

The use of glass fibre reinforced unsaturated polyesters is well known and is a major growth area. Many other polymers are, however, gaining ground in new and existing application areas where polymers replace traditional materials, such as glass fibre reinforced nylon and polyphenylene oxide. Composites have been reported in automobile radiator parts where they have fulfilled temperature and pressure requirements [1]. Nylon 6/6 resin, itself is a fairly tough material and is in fact, among the toughest engineering plastics. It is resistant to corrosion and chemicals, but its application is limited due to low rigidity and strength, dimensional instability (i.e. higher coefficient of thermal expansion) and moisture absorption. On the other hand, E-glass fibre is extremely strong, having a low coefficient of thermal expansion and good rigidity but is brittle and susceptible to environmental attack [2]. When they are combined they form a fibre composite with high strength, rigidity, toughness and stability at elevated temperatures.

1.1. Tensile strength

The simplest relations of tensile strength for fibre reinforced composites are based on the rule of mixtures

$$\sigma_u = n\sigma_f V_f + \sigma_m(1 - V_f) \tag{1}$$

where σ_u is the tensile strength, σ_f and σ_m the tensile strength of fibre and matrix, respectively, V_f the fibre volume fraction and n Krenchel's efficiency factor ($n = 0.5$ for cross-ply fibre composites).

This expression is not valid below a certain limiting fibre volume fraction, if the matrix material shows any feature of the stress–strain curve corresponding to work hardening in metals. It is strictly valid only for composites in which fibre and matrix have identical Poisson's ratio [3, 4]. It has been found on the basis of statistical analysis that for commercial E-glass fibres the average of fibre strength is about 1.42 times that of the bundle strength. The composite strength can, therefore, be approximated [5] as

$$\sigma_u = 0.7\sigma_f V_f \tag{2}$$

Dow and Rosen [6] have also analysed the strength of composites reinforced by fibres with a statistical strength

$$\sigma_u = \sigma_r V_f[(1 - V_f)^{0.5}/V_f^{0.5}]^{-1/2\beta} \tag{3}$$

where σ_r is a reference stress level that is a function of fibre and matrix properties and β a statistical parameter of Weibull distribution of fibre strength equal to 7.7 for commercial E-glass fibre.

1.2. Tensile modulus

Paul [7] has derived the upper and lower limits of modulus of elasticity for continuous fibre composites by assuming that the composite is loaded in uniform tension

$$\frac{1}{E_L} \leqslant n\frac{V_f}{E_f} + \frac{(1 - V_f)}{E_m} \tag{4}$$

and

$$E_U \leqslant nV_f E_f + E_m(1 - V_f) \tag{5}$$

where E_L and E_U are the lower and upper limits of modulus of elasticity, E_f and E_m are modulus of elasticity of fibre and matrix, respectively, Ekvall [8] has obtained a modified shape of rule of mixtures for upper and lower limit of modulus of elasticity

$$E_U = E_f V_f + E'_m(1 - V_f) \tag{6}$$

and

$$E_L = \frac{E_f E'_m}{E'_m V_f + E_f(1 - \mu_m^2)(1 - V_f)} \tag{7}$$

where

$$E'_m = \frac{E_m}{1 - 2\mu_m^2} \tag{8}$$

and μ_m is Poisson's ratio. These modifications of the previously derived expression are not, however, significant for $\mu_m \leqslant 0.25$.

1.3. Compressive strength

Dow *et al.* [9] have suggested that the mode of failure for a unidirectionally fibre-reinforced composite in compression is similar to the buckling of a column on an elastic foundation. Both Rosen [10] and Schuerch [11] have considered a two-dimensional model of a uniaxial composite. Fibre composites have failed under two modes and their strengths are given as

$$\sigma_{ce} = 2V_f[V_f E_m E_f/3(1 - V_f)]^{0.5} \quad (9)$$

where σ_{ce} is the compressive strength in the extension mode. The compressive strength of fibre composites in shear mode is also given as

$$\sigma_{cs} = \frac{G_m}{(1 - V_f)} \quad (10)$$

where G_m is the shear modulus.

Lager and June [12] have compared the theoretical prediction with experimental results for boron–epoxy composites. The theory appears to correlate well with the data if the matrix module in Equations 9 and 10 are multiplied by 0.63, that is,

$$\sigma_{ce} = 2V_f[V_f(0.63E_m)E_f/3(1 - V_f)]^{0.5} \quad (11)$$

and

$$\sigma_{cs} = \frac{0.63G_m}{(1 - V_f)} \quad (12)$$

1.4. Interlaminar shear strength

In continuous fibre composites, the interfaces between strong fibres and weak matrix are potential lines of weakness. Any stress system that imposes shearing forces along these lines of weakness may, therefore, initiate shear failure. Interlaminar shear strength in three-point bending beam is given as [1]

$$\tau_1 = \frac{3P_1}{4BD} \quad (13)$$

where P_1 is the fracture load and B, D the width and depth of the specimen, respectively.

The interlaminar shear strength in the lap shear test is given as

$$\tau_1 = P_1/lb \quad (14)$$

where l and b are the gauge length and width of slits, respectively.

Hancock and Cuthbertson [13] have found that the interlaminar shear strength of glass-reinforced epoxy composites is obtained from

$$\tau_1 = x\tau_i + (1 - x)\tau_m \quad (15)$$

where τ_i is the interfacial shear strength, τ_m the matrix shear strength and x the fraction of the fracture surface area which consists of fibre resin interface relative to the total surface area of one of the fracture faces. Their results also show that the composite shear strength decreases with the presence of voids.

1.5. Residual tensile strength

In view of the applications of composite materials to highly stressed aeronautical structures, a knowledge of their impact behaviour is necessary. Caprino [14] has observed that the damage induced in a composite by impact behaves as stress concentration when the material is loaded. In this work a model is presented, based on FM concepts by which the residual tensile strength of a laminate can be calculated as a function of the kinetic energy of the impacting body

$$\sigma_{rs} = \sigma_0\left(\frac{U_0}{U}\right)^m \quad (16)$$

where σ_{rs} is the residual tensile strength after impact, σ_0 is the un-notched strength, U the impact energy of notched specimen and U_0 and m constants. Broutman and coworkers [15, 16] performed their studies on glass fibre-reinforced epoxy and polyester resin composites. For a fibre-reinforced polymer it is expected that the impact behaviour will be time dependent. Agarwal and Narang [17] charpy impact test results on composites with all unidirectional fibre indicate that the impact energy continuously decreases with increase of fibre orientation. Minimum impact energy is observed at 90°. The impact energy observed by the cross-ply composite is consistently higher than that for the unidirectional composites except at $\theta = 0°$, at which it absorbs higher energy.

In the present paper, the ultimate tensile strength, tensile modulus, compressive strength, interlaminar shear strength and residual tensile strength of cross-ply and unidirectional E-glass fibre reinforced nylon 6/6 resin composite have been studied and the results verified with the theoretical model here are very promising.

2. Experimentation

2.1. Materials and their preparation

Commercially available E-glass fibre and Nylon 6/6 resin (Beads form) are used for present study. Nylon 6/6 is a thermoplastic polyamide and has better mechanical properties than other members of its group.

The mould used for the fabrication of the composite sheet consisted of one middle frame, in which two plates were fitted, one from the top and the other from the bottom as shown in Fig. 1 and composite rod was fabricated from the other mould as shown in Fig. 2.

E-glass fibre-reinforced nylon 6/6 resin composite (cross-ply) sheets were moulded by the hand lay-up technique. To maintain uniform thickness of the moulded composite, two square pieces were placed on

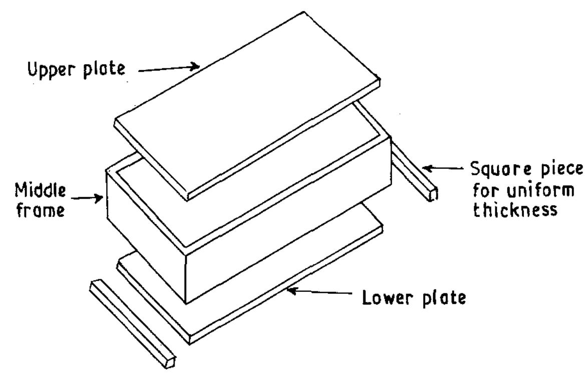

Figure 1 Moulding set-up for composite sheets.

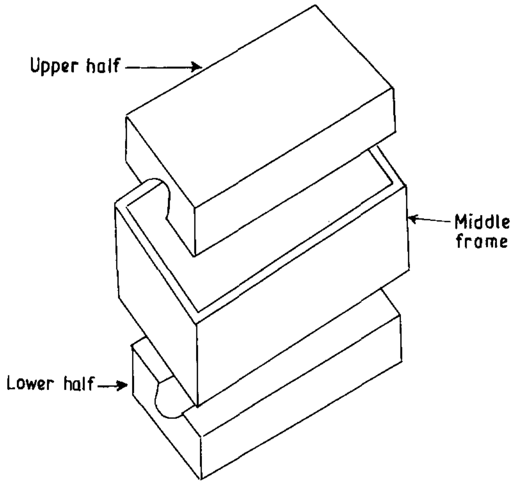

Figure 2 Moulding set-up for composite rods.

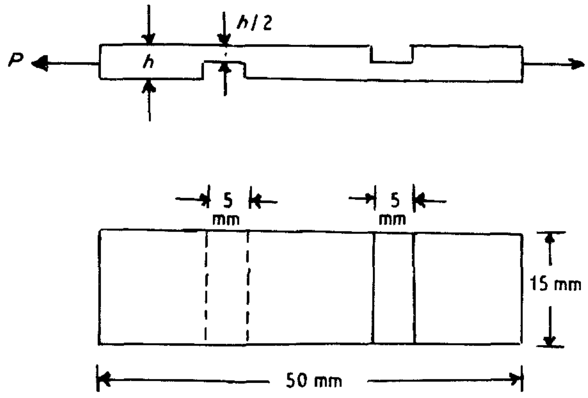

Figure 3 Specimen for lap shear test.

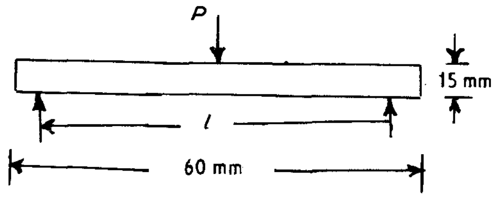

Figure 4 Specimen for short beam shear test.

two ends of the lower plate before pouring the material into the mould. The moulding box was kept inside an electric furnace chamber under a load of 2.5 kg on top of the mould at a temperature of 280 °C for 15 min. The excess nylon 6/6 resin was squeezed out from the mould. The moulding box was removed from furnace and cooled down for 20 h. Similarly, unidirectionally E-glass fibre-reinforced nylon 6/6 composite rods were moulded with the help of the second type of mould. The thicknesses of the fabricated composites specimen were 1.5 mm (2 ply), 3 mm (4 ply), 3.5 mm (6 ply), 4 mm (8 ply) and 5 mm (10 ply) with fibre volume fractions 0.15, 0.225, 0.30, 0.375 and 0.45, respectively. Using these composite sheets and rods, tensile, compressive and impact specimens were prepared for experimentation.

2.2. Tensile and compressive tests

The tensile and compressive specimens were used with the geometry of 6 mm gauge width, 30 mm gauge length, 20 mm maximum width, 5 mm thickness and 70 mm length (tensile specimen) and 8 mm diameter and 32 mm height of compressive specimen.

The tensile tests were conducted on a 5 ton Instron Universal Testing machine. The extension rate was kept at 1 mm s^{-1}. The load–elongation curves were plotted and tensile modulus, tensile strength, tensile stress and percentage strain were calculated with the help of these curves. The results were recorded for each type of tensile specimen. Compression tests were also conducted and the crushing load recorded for evaluation of compressive strength.

2.3. Interlaminar shear and impact tests

The specimen used for lap shear and the three-point bending (short beam shear) tests are shown in Figs 3 and 4. The composite specimens were cut from 6, 8 and 10 ply laminates. The tests were conducted on a Haunsfield Tensometer and results were recorded for calculation of interlaminar shear strength by Equations 13 and 14.

A special apparatus was fabricated for creating impact damage in composite specimens as shown in Fig. 5. The dimension of the specimen were 70 mm length, 20 mm width, 10 mm radius of central double notched and 10 plies. A striker of 0.350 g weight with a tap diameter of 6 mm was allowed to fall and strike the specimen in the middle, from various heights (20 cm, 40 cm and 60 cm). The energy of impact was 1.03, 2.05 and 3.08 J, respectively. This was repeated five times at each height, so that a visible impression is made on the face of the specimen. After impacting each specimen, the residual tensile strengths were recorded by Hounsfield Tensometer. The value of un-notched strength is 99.6 MPa and the values of constant U_0 and m are 3 and 0.25, which is obtained from the load–displacement value of un-notched specimen.

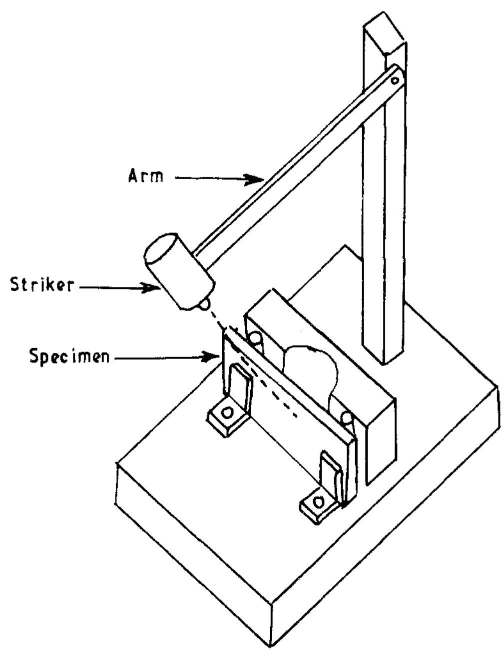

Figure 5 Set-up for impact test.

3. Results and discussion

The experimentally observed behaviour ot the stress–strain curve (Fig. 6) of nylon 6/6 and cross-ply E-glass fibre reinforced nylon 6/6 resin composite shows that up to 5% strain, the slope of the curve is higher or say in this range, nylon 6/6 resin specimen requires more stress for deformation. The yielding starts at about 18% of strain and material flows plastically upto the point of fracture. The stress–strain curve of E-glass fibre-reinforced nylon 6/6 resin (2 ply, 4 ply, 6 ply, 8 ply and 10 ply) laminates does not show any definite point of yielding but the slope of curve is almost constant upto 10% of strain and afterwards slope reduces slowly upto the point of fracture.

Fig. 7 shows that the theoretical and experimental predictions for ultimate tensile strength increases with increase of fibre volume fraction. As can be seen, the experimental results nearer to the predicted values from Equation 2. Weibull [5] has considered that the bundle strength may be as low as 70% of the mean fibre strength. The predicted values from Equations 1 and 3 are greater than the experimental values, since the strength of fibre and matrix are both considered in these equations. The behaviour of nylon 6/6 resin based fibre composites is, however, highly hygroscopic and there may be a definite percentage of moisture content in the composite at the time of experimentation, which affects the strength and stiffness.

The upper and lower limits of tensile modulus for the cross-ply E-glass fibre reinforced nylon 6/6 resin composites are presented in Fig. 8. The results show that the predicted values from Equations 4 and 5 and experimentation increases with increase of percentage of fibre volume fraction. The experimental values are much closer to the lower limit due to the lack of, for example, orientation of fibre and lay-up order. The experimental results are, however, in line with the observation of Paul [7]. The results also show that the differences in theoretical values and experimental values are a minimum at lower fibre volume fraction which may be due to increase of percentage of defects at the time of moulding.

In Fig. 9, the results show that the compressive strength increases with increase of fibre volume fraction. The experimental results are compared with the theoretical predicted values from Equations 11 and 12. The experimental results are lower than the predicted values from Lager and June, Equation 12. The

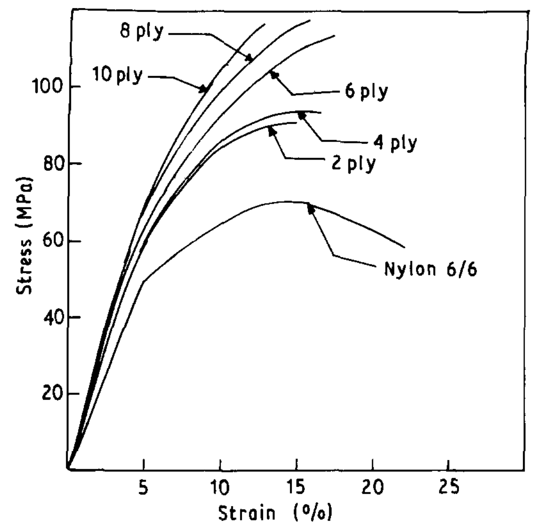

Figure 6 Stress plotted against percent strain.

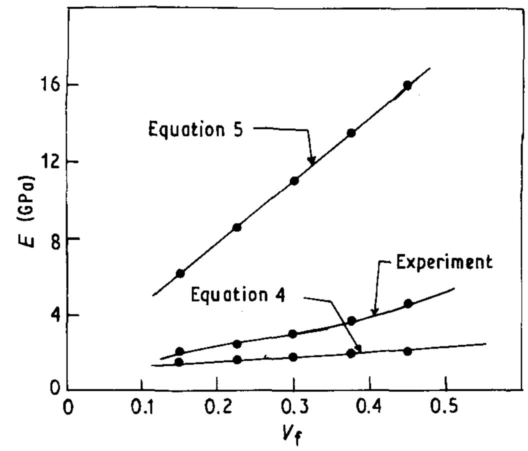

Figure 8 Tensile modulus plotted against fibre volume fraction.

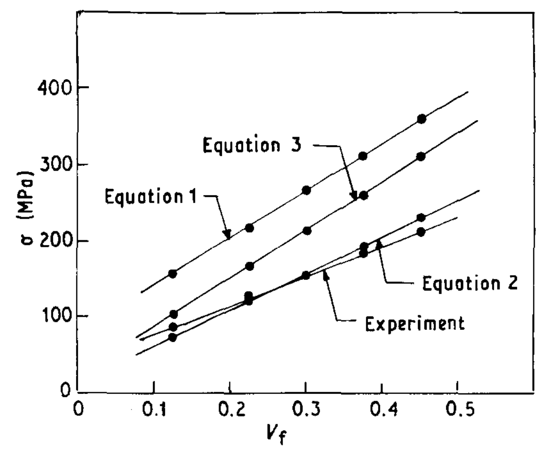

Figure 7 Ultimate tensile strength plotted against fibre volume fraction.

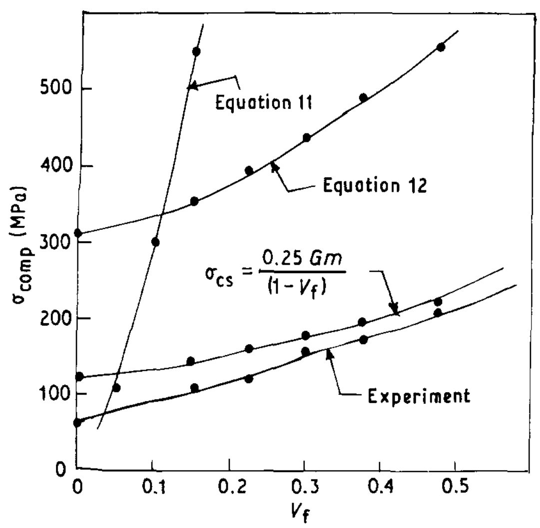

Figure 9 Compressive strength plotted against fibre volume fraction.

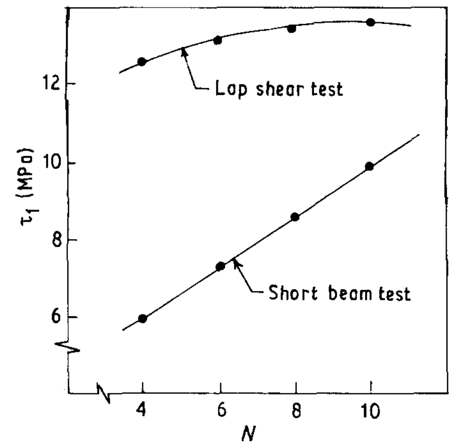

Figure 10 Interlaminar shear strength plotted against number of plies.

theory appears to correlate well with the experimental data if the nylon 6/6 resin moduli in Equation 12 are multiplied by 0.25 instead of 0.63. The nylon 6/6 resin-based unidirectional composites buckle inelastically and elastically. The influence coefficient (0.25) is believed to be a function of the matrix modulus. The results also suggest that for low fibre volume fraction (< 0.1) the extension mode gives lower failure strength. For higher volume fractions, the shear mode prevails. These results are in line with the Rosen [10] results. The interlaminar shear strength increases with the number of plies of cross-ply E-glass fibre reinforced nylon 6/6 resin composites as shown in Fig. 10. The difference in interlaminar shear strength by lap shear and short beam test shows that more energy is required to fracture the specimen due to an increase in the number of plies. In the lap shear test, however no fibre fracture usually takes place due to delamination of fibre. The lap shear test, hence, gives the information about bonding strength of fibre and matrix. The interlaminar shear strength is almost independent of the number of plies.

It is found that the residual tensile strength of cross-plied (10 ply) E-glass fibre reinforced nylon 6/6 resin composites reduces with increasing impact energy as shown in Fig. 11. The theoretical values of residual tensile strength are also compared with experimental results. The results show a continuous reduction in strength with increase of impact energy due to the cumulative damage law [14]. In fact, it is natural to infer that the caprino model will fail for kinetic energy rather than for the complete penetration threshold. Beyond this limit a constant residual strength can be expected.

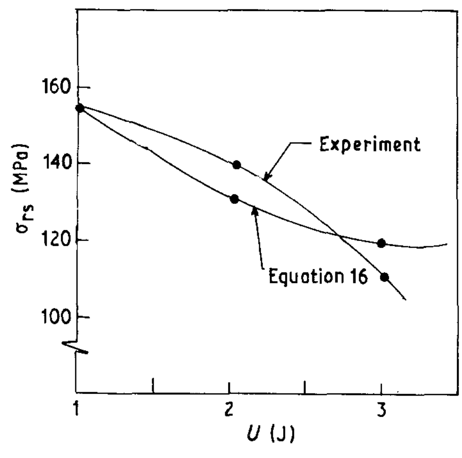

Figure 11 Residual tensile strength plotted against impact energy.

4. Conclusions

From the experimental and theoretical observation, the following conclusions can be made.

1. Tensile strength, tensile modulus and compressive strength of E-glass fibre reinforced nylon 6/6 resin composites are dependent on the fibre volume fraction. The results are in line with Paul's results. The lower limit equation for tensile modulus can, however, be more useful for such composites due to hygroscopic properties.
2. The statistical approach seems to be more useful to calculate the tensile strength of nylon-based fibre composite especially Equation 2; gives closer results with experimental values.
3. The compressive strength on shear mode can be predicted from

$$\sigma_{CS} = (0.25\, G_m)/(1 - V_f)$$

with 15% error.

4. Bonding strength can be obtained by the lap shear test and interlaminar shear strength is dependent on the number of plies. The residual tensile strength can, however, be predicted from Equation 16 with 10% error for these composite materials.

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