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Mechanical Properties of Unsaturated Polyester Resin

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Abstract: Mechanical behaviour of unsaturated polyester resin used for the composite materials has been studied to determine various important parameters, such as tensile and compressive, single edge-notch tensile fracture toughness, flexural properties and fracture energy. Fracture toughness, K_{IC}, and fracture energy, G_{IC}, obtained for the polyester resin lie between the typical values for epoxy resins and polystyrene.
Keywords: Polyester Resin, Flexural Test, Hand Lay-up Moulding.

Introduction

The matrix forms a significant volume fraction of a polymer composite and it has a number of critical functions; it binds the reinforcements together, maintains the shape of a component and transfers the applied load to the reinforcing fibres. it protects the reinforcing fibres from degradation, due to abrasion or environmental attack. It contributes significantly to the mechanical properties of structural polymer composites, acting to resist delamination between plies of reinforcements and to inhibit fibre buckling during compression. Thermoplastics are used in certain applications but constitute a relatively small sector of the structural composites market. Matrices used for structural composites are mainly thermosetting plastics, such as polyester resins, epoxy resins, phenolic resins and vinyl-ester resins. Polyester resins are the most widely used resin systems, particularly in the marine industry. By far the majority of dinghies, yachts and work-boats built in composites make use of this resin system. Thermosetting plastic systems generally consist of liquid mixtures of relatively low molar mass reactants, such as monomers and/or prepolymers, which polymerise upon heating to form highly-crosslinked, network polymers [1-9]. This paper reports on the mechanical properties of polyester resin used as matrix for the polymer composites to determine parameters, such as tensile and compressive responses, fracture toughness, fracture energy and flexural properties.

Experimental

Materials. The resin used for moulding sheets of resin was based on a low-viscosity unsaturated polyester resin of the orthophthalic type (UP-973 ST V, Reefiran Polimer Khodrang, Iran). It is especially suitable for hand lay-up (HLU) and resin transfer moulding (RTM) due to its low viscosity and non-thixotropic nature.

Curing System. The curing agent used was a cobalt octoate accelerator (Unidry Co 12, Pamukkale Company of Turkey)/methyl-ethyl-ketone peroxide (MEKP) (EPerox-P, Pamukkale Company of Turkey) initiator system of 0.03/2.0 weight ratio, respectively. The cobalt accelerator was a solution of cobalt salts diluted in styrene and white spirit of 12% (w/w) cobalt content, which was mixed into the resin first, before the MEKP initiator. The initiator was a solution of MEKP diluted in dibutyl phthalate of 50% (w/w) MEKP content. This cure system was chosen to allow cure to occur in a reasonable time, in order to allow sheets of resin to be moulded before gelation occurs. To determine reactivity a pre-mixed resin (0.03 g accelerator/2 g MEKP and 100 g resin) was poured into a thermoset cup and allowed to react from an initial mould temperature of 25 ^{0}C. Chemical activity of the resin system during its transition from liquid to a solid was monitored to determine the gelation time ≈ 27 minutes.

Moulding. A hand lay-up (HLU) technique was used to mould sheets of various thicknesses.

Mechanical Testing. Tensile data for the polymer resin were obtained at 25±2 ^{0}C using a Santam, universal tensometer (15T). Tests were conducted on at least five specimens (dumb-bell specimens), according to ASTM D 3039, at a cross-head rate of 2 mm min^{-1}. The fracture properties of the matrix were measured in a single edge-notch tensile (SENT) geometry using rectangular specimens of length (L) 150 mm, width (w) 25 mm and thickness (b) 6 mm. Tests were conducted at 25±2 ^{0}C, using a Santam, universal tensometer (15T) at a cross-head rate of 2 mm min^{-1}. At least ten specimens were tested and the nominal notch depth of the specimens, a, was varied to give a/b ratios in the range 0.30 ≤ a/b ≤ 1.50. The actual notch depths, a, were measured, after fracture, to within 0.03 mm using a travelling microscope. A linear-elastic fracture mechanics analysis was used to determine fracture toughness, K_{IC}, according to equation 1;

$$K^2_{Ic} = \sigma^2_f Y^2 a \qquad (1)$$

where σ_f is the stress at fracture and Y is a calibration factor that depends on the crack length and specimen dimensions[11]. From the plots of $\sigma^2_f Y^2$ versus 1/a which is linear with slope equal to K^2_{Ic}. Fracture energy, G_{Ic} was determined according to equation 2;

$$G_{Ic} = K^2_{Ic}/E \qquad (2)$$

where E is the elastic modulus of the polymer matrix. However, this expression is only valid if the thickness, b, of the specimen satisfies the criterion;

$$b \geq 2.5\ (K^2_{Ic}/\sigma_y)^2 \qquad (3)$$

where σ_y is the yield stress of the polymer resin (as specimens under tensile testing showed yielding, therefore, the yield stress of this brittle resin was used in order to determine whether the above expression is valid for specimen thickness), using at least five specimens of 20 mm x 20 mm and thickness 6 mm. The tests were conducted at 25±2 ^{0}C, using a Santam, universal tensometer (15T) at a cross-head rate of 2 mm min^{-1}.

Flexural Testing of Polymer Resin. The flexural properties were determined in 3-point bending. At least five rectangular beam specimens were tested at a support span-to-depth ratio of 16:1 according to ASTM, D790M [12]. Tests were conducted at 25±2 ^{0}C, using a Santam, universal tensometer (15T). Specimens were centre loaded in 3-point bending as a simply supported beam, using 3 mm diameter supports and loading bar.

Results and Discussion

Tensile data for the polyester resin were obtained according to ASTM D 3039 [10]. A typical stress-strain plot for the resin is shown in Figure 1. The curve shows linear deformation behaviour with the stress rising to a maximum value which shows sign of yielding (σ_y) before fracture occurred (σ_f). The Young's modulus, E, of the polyester resin was calculated from the slope of the curve. Fracture toughness is a measure of a material's resistance to crack propagation, but in a composite this can be hard to measure accurately. However, the stress-strain curve of the resin system on its own provides some indication of the material's toughness. Generally the more deformation the resin will accept before failure the tougher and more crack-resistance the resin will be. The fracture properties of the polyester resin were measured in a single edge-notch tensile (SENT) geometry using rectangular specimens (length 150 mm, width 25 mm and thickness 6 mm). Figure 2 shows a plot of $(\sigma_f Y)^2$ versus 1/a data obtained from SENT tests, from which the fracture toughness K_{Ic} can be calculated according to equations 1 [11]. The plot of $(\sigma_f Y)^2$ versus 1/a is linear with a slope equal to K^2_{Ic}. A linear regression fit to this data through the origin gave a value of fracture toughness, K_{Ic} of 0.30 MPa m$^{1/2}$ with a correlation coefficient of R=0.94. The fracture energy, $G_{Ic,}$ was determined according to equation 2 [11]. However, plane strain fracture parameters are only obtained if the thickness, b, of the specimen satisfies the criterion in equation 3 [11]. In tension fracture occurred at 63±2.0 (MPa) and there was sign of yielding at σ_y=65 MPa before fracture (Figure 1). Thus, the critical value of b calculated using equation (3) was 0.053 mm and the specimens (b = 6 mm) easily satisfy the criterion.

The flexural properties of the polymer matrix were determined according to ASTM D790M [12]. The tensile, flexural and fracture parameters obtained for the polyester resin are shown in Table 1, Table 2 and Table 3, respectively.

Table 1. Tensile properties of the polyester resin (± 95% confidence limits)

Tensile Parameters		
Stress at failure σ_f (MPa)	Modulus E (GPa)	Strain at failure ε_f (%)
63±2.0	1.0±0.40	4.7±0.20

Table 2. Flexural properties of the polyester resin (± 95% confidence limits)

Flexural Parameters		
Stress at failure σ_f (MPa)	Modulus E (GPa)	Strain at failure ε_f (%)
78±1.4	4.0±0.5	1.8±0.30

Table 3. Fracture properties of the polyester resin (± 95% confidence limits)

Fracture Toughness	Fracture Energy
K_{Ic} (MPa $m^{0.5}$)	G_{Ic} (J m^{-2})
0.30	90

In three-point flexure, the specimen is subjected to a combination of tensile and compressive stresses. As the compressive moduli of polymers are relatively high, flexural testing resulted in higher values of modulus and ultimate stress but lower values of ultimate strain compared to tensile tests. Polyester resins, without reinforcement, are relatively brittle polymers and the fracture toughness, $K_{Ic,}$ and fracture energy, G_{Ic}, obtained for the polyester resin lie between the typical values of K_{Ic} and G_{IC} reported [11] for epoxy resins (0.5 MPa $m^{1/2}$, 100 J m^{-2}) and polystyrene (1.1 MPa $m^{1/2}$, 400 J m^{-2}). The matrix toughness plays an important role in the fracture behaviour of composites. It is reported [13,14} that decreasing the yield strength of the matrix increases delamination fracture energy by increasing the size of the plastic deformation or non-linear viscoelastic zone ahead of the crack tip, resulting in greater load redistribution away from the crack tip and hence more crack-tip blunting. However, there is a relatively low efficiency of translation of a high matrix G^m_{Ic} value into the delamination fracture energy of a composite, due mainly to constraint provided by the fibres in the confined spaces between the reinforcing plies which restricts the size of the plastic deformation zone. Therefore, a decrease in fibre V_f can result in a smaller degree of crack tip constraint, giving larger deformation/damage zone sizes and, consequently, higher composite G_{Ic} and G_{IIc} values[13-16].

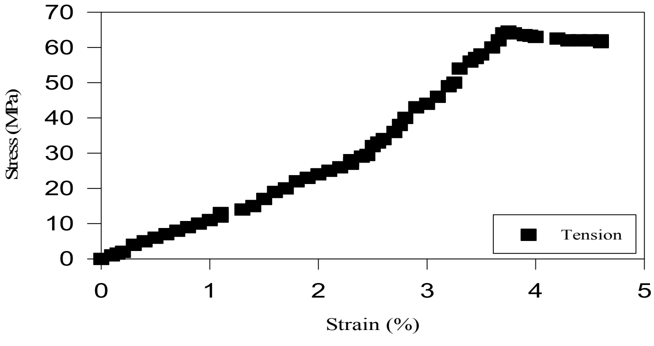

Figure 1. Typical stress versus strain curves in tension and compression for the polyester resin.

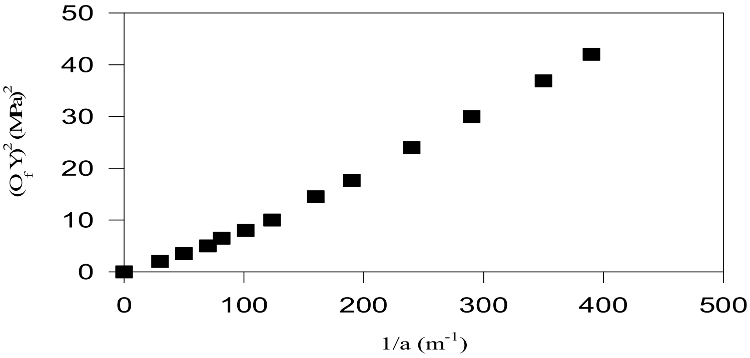

Figure 2. A plot of $(\sigma_f Y)^2$ versus 1/a curve for the polyester resin.

Conclusions

1. Tensile stress and strain at failure of the neat resin was found 63 MPa and 4.7% respectively.
2. Fracture toughness, K_{Ic}, and fracture energy, G_{Ic}, obtained for the polyester resin lie between the typical values for epoxy resins and polystyrene, which was found 0.30 MPa $m^{0.5}$ and 90 J/m^2 respectively.
3. Flexural stress and flexural strain at failure of the neat resin was found 78 MPa and 1.8% respectively.

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