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Influence of weldlines on tensile properties of hybrid acrylonitrile butadiene styrene (ABS) composites filled with short glass fibres (GF) and glass beads (GB)

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Abstract The present study investigated the effect of weldlines on tensile strength and modulus of injection moulded ABS polymer reinforced with both short fibres (GF) and spherical glass beads (GB). It was observed that tensile strength and modulus of ABS/GF/GB hybrids increased with increasing the concentration total of glass in the hybrid as well as the concentration of glass fibres in the hybrid (χ_{GF}). Results indicated that tensile strength and modulus of ABS/GF/GB hybrids obey the rule-of-mixtures. The presence of weldlines had a negative effect on tensile properties of ABS/GF/GB hybrids. Although tensile strength and modulus of ABS/GF/GB hybrids were reduced in the presence of weldlines, nonetheless both increased with increasing the total concentration of the glass particles and χ_{GF}. The observed linearity of weldline strength and modulus with χ_{GF} indicated that these properties like their unweld counterparts can be expressed by simple rule-of-mixtures. It was noted also that weldline integrity factor for tensile modulus and strength decreased with increasing χ_{GF} and the total concentration of the glass particles in the hybrids. Weldline integrity values indicated that hybrid tensile strength was more affected by the weldlines than hybrid modulus.

Introduction

It is well recognised that the mechanical properties of polymer composites such as strength and modulus are derived from a combination of the filler and matrix properties and the ability to transfer stresses across the interface between the two constituents. These properties, however, are affected by a number of parameters, such as the concentration of the filler, geometrical shape and the aspect ratio of filler and the degree of interfacial adhesion between the filler and the matrix [e.g. 1–12]. For example, whist addition of short fibres to polymers matrices enhances strength, addition of spherical shaped particles (e.g. glass beads) cause deterioration. On the other hand, spherical particles with aspect ratio of unity provide isotropic mouldings, whereas short fibres having aspect ratio much greater than unity provide mouldings which although are strong and stiff when loaded longitudinally (along the length of the fibres) they are quite weak and less stiff when loaded transversely (normal to the fibres). Dimensional stability and non-uniform shrinkage is also a problem with thick mouldings containing short fibres.

Hybridisation with more than one type of filler (e.g. glass fibres and spherical glass beads) provides other dimensions to the potential versatility of composite materials. For example, by incorporating glass fibres and glass beads in the same matrix, one may obtain a moulding which may not be as stiff as the fibre reinforced system but stronger than the glass bead system [13, 14].

The study by Philips [15] raised the issue surrounding the possible synergistic hybrid effects, in which the properties of the hybrid composite might not follow from a direct consideration of the independent properties of the individual components. A positive or negative hybrid effect was then defined as a positive or negative deviation of a certain mechanical property such as tensile strength from the rule-of-mixtures behaviour. In general, tensile and flexural strengths and moduli of hybrid systems do conform to rule-of-mixtures [e.g. 13, 14]. However, as polymer

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composites are often fabricated by an injection-moulding process, the presence of weldlines is a major design concern as weldlines could lead to a considerable reduction in mechanical properties and designers often need to accommodate liberal safety factors in design analysis to compensate for this weakness. Weldlines are often observed in injection-moulded components due to multi-gate moulding, existence of pins, inserts, variable wall thickness and jetting and are classified as either being cold or hot. The cold weldlines are formed when two melt fronts meet head on and this type of weld provides the worst-case scenario as far as mechanical properties are concerned. A serious reduction in strength has been reported for many polymers and their composites in the presence of cold weldlines [e.g. 1–10]. In general, the presence of a weldline reduces tensile strength by up to 60% and tensile modulus by up to 40% depending on the polymer, the characteristic features of the reinforcing filler and the processing conditions being used. For example, whilst addition of spherical shaped fillers (e.g. glass spheres) has shown to have little effect upon tensile strength of injection-moulded thermoplastics with weldlines, addition of cylindrical shaped fillers (e.g. short fibres) has led to a considerable reduction in weldline strength due to the alignment of the fibres parallel to the weldline. The processing conditions such as melt temperature, injection speed and mould temperature could also play an important role in determining the integrity of the welded components and many studies have addressed this issue for both amorphous and semi-crystalline polymers [e.g. 16–20].

The majority of hybrid studies have been conducted in the absence of weldline. Indeed, little is known about the way in which weldline influence mechanical properties. In this article, we first analyse tensile properties of ABS/GF and ABS/GB composites with and without weldlines. We then study the effect of hybridisation on tensile properties and the influence of weldlines on tensile strength and modulus of ABS/GF/GB hybrids. Comparisons are made between the experimentally observed values and predictions based on the rule-of-mixtures.

Experimental details

Materials

Owens Corning chopped E-glass fibres (GF) of approximately 6.0 mm in length and 10 μm in diameter and Potters Ballatoni spherical glass beads (GB) of approximately 12–26 μm in diameter were used as reinforcing fillers for Acrylonitrile Butadiene Styrene (ABS) copolymer received by Bayer. The ABS and the reinforcing fillers were used to produce a series of ABS/GB, ABS/GF and ABS/GB/GF compounds with nominal glass contents of 10, 20 and 30% w/w.

Compounding

The formulations listed in Table 1 were at first dry blended to the desired glass content and then dried in an oven at 80 °C for 4 h. After drying, each formulation was passed through a Leistritz twin-screw extruder at an average screw speed of 60 rpm to produce a homogeneous dispersion of bead and or fibre throughout the matrix. The extruder temperature profile was 203/232/232/235 (°C) and the die diameter was 4 mm. The extrudates emerging from the die exit was continuously cooled in a water bath and fed through a granulator to produce pellets for injection moulding process. Pellets were dried in an oven at 80 °C for 4 h before being injection-moulded into test specimens.

Specimen preparation

Dumbbell shaped tensile bars were produced using a Negri Bossi NB60 injection-moulding machine at the processing conditions listed in Table 2. The mould used consisted of a single-and a double-feed cavity each of dimensions 1.7 mm × 12.5 mm × 125 mm (thickness, width, length). In the latter, the two opposing melt fronts met to form a weldline approximately mid-way along the gauge length of the specimen as shown in Fig. 1.

Table 1 Formulation for composites and hybrids. (χ_{GF} = concentration of glass fibres divided by the concentration of total glass)

Formulation	Hybrid ratio, χ_{GF}
ABS/GB Composites	
ABS + 10 wt% glass beads	0
ABS + 20 wt% glass beads	0
ABS + 30 wt% glass beads	0
ABS/GF Composites	
ABS + 10 wt% glass fibres	1.0
ABS + 20 wt% glass fibres	1.0
ABS + 30 wt% glass fibres	1.0
Hybrids	
ABS + 5 wt% glass fibres + 5 wt% glass beads	0.50
ABS + 5 wt% glass fibres + 15 wt% glass beads	0.25
ABS + 10 wt% glass fibres + 10 wt% glass beads	0.50
ABS + 15 wt% glass fibres + 5 wt% glass beads	0.75
ABS + 10 wt% glass fibres + 20 wt% glass beads	0.33
ABS + 15 wt% glass fibres + 15 wt% glass beads	0.50
ABS + 20 wt% glass fibres + 10 wt% glass beads	0.67

Table 2 Injection moulding processing conditions

Processing condition	100% ABS matrix	Composites & Hybrids with 10% total filler	Composites & Hybrids with 20% total filler	Composites & Hybrids with 30% total filler
Barrel temperature (°*C*)				
Zone 1	230	230	230	230
Zone 2	230	230	232	232
Zone 3	232	232	235	235
Mould temperature (°C)	80.00	80.00	80.00	80.00
Injection pressure (MPa)	8.50	8.50	9.00	9.00
Holding pressure (MPa)	3.00	3.00	3.00	3.00
Cooling time (s)	30.00	30.00	30.00	30.00
Cycle time (s)	33.00	33.00	33.00	33.00
Shot weight (g)	27.00	27.00	28.00	29.00

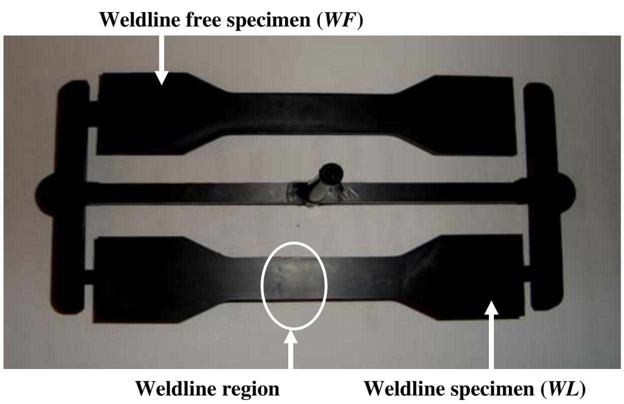

Fig. 1 Weld and unweld tensile specimens (all dimensions are in mm)

Mechanical testing

At least six dumbbell specimens with weldline (WL) and six without weldline (WF) were tested for each compound in tension using a Tinius Olsen H10KS testing machine. Tests were carried out at 25 °C at constant crosshead speed of 50 mm/min (i.e. strain rate of 1.11×10^{-2} s^{-1}) using an extensometer. From the recorded load-extension curves, tensile strength and modulus values were determined. Tensile strength was evaluated from the maximum load and modulus from the initial slope of the load-extension curve.

Filler concentration measurements

The concentration of total glass in each material was determined from the glass residue remained by ashing at 550 °C weighed samples that were cut from the gauge length of the moulded specimens. After cooling, the ash of glass residue was weighed and the exact weight fraction of glass (w_G) was determined. The w_G values were subsequently converted into glass volume fractions ϕ_G using the following equation:

$$\phi_G = \left[1 + \frac{\rho_G}{\rho_{ABS}}\left(\frac{1}{w_G} - 1\right)\right]^{-1} \quad (1)$$

Taking density of pure ABS matrix (ρ_{ABS}) as 1.12 kgm^{-3} and that of glass (ρ_G) as 2.54 kgm^{-3} gives ϕ_{GF} values of 4.4, 9.5 and 15.5% for ABS/GF composites and ϕ_{GB} values of 4.2, 9.1 and 14% for ABS/GB composites. The volume fraction of glass fibres in each hybrid was calculated from ϕ_G sand the hybrid ratio.

Fibre length measurements

The ash of fibrous material was subsequently spread on a glass slide and placed on the observation stage of a microscope. Magnified fibre images were transmitted to a large screen, and the fibre images were then automatically digitised. Fibre length distributions curves gave average fibre length ($\bar{L}_f$) values of 550, 430 and 360 μm for ϕ_{GF} values 4.4, 9.5 and 15.5%, respectively. Clearly, $\bar{L}_f$ has decreased from an initial unprocessed value of 6 mm. The increased damage to fibre length with increasing ϕ_{GF} is attributed to a greater degree of fibre–fibre interaction as well as increased in the melt viscosity at higher fibre loadings. The latter give rise to higher bending forces on the fibres during compounding and moulding processes causing further fibres breakage.

Results and discussion

Tensile modulus

The load-extension curves for pure ABS, ABS/GF, ABS/GB and ABS/GF/GB indicated linear elastic type deformation during the early stage of loading.

Figure 2 shows the effect of fibre concentration, ϕ_{GF}, and weldline on tensile modulus of ABS/GF composites. It

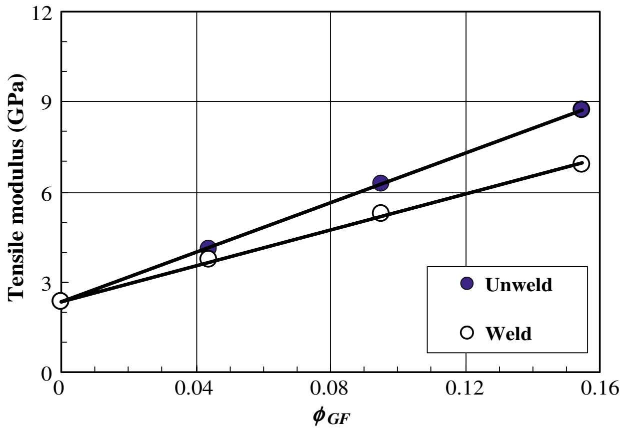

Fig. 2 Effect of glass fibre volume fraction, ϕ_{GF}, on weld and unweld tensile modulus of ABS/GF composites

can be seen that modulus of ABS/GF system is reduced significantly in presence of weldlines. As shown in Fig. 2, tensile modulus of ABS/GF system with and without weldlines is linearly dependent upon the volume fraction of the glass fibres, ϕ_{GF}. The influence of weldline on tensile modulus of ABS/GF composites is quantitatively expressed here in terms weldline integrity factors defines as;

$$F^{E} = \frac{\textit{Tensile modulus in the presence of weldline}}{\textit{Tensile modulus in the absence of weldline}} \quad (2)$$

The effect of ϕ_{GF} on weldline integrity factor for modulus of ABS/GF composites, $F^{E}_{ABS/GF}\left(=\frac{E^{w}_{ABS/GF}}{E_{ABS/GF}}\right)$ is shown in Fig. 3 where it can be seen that $F^{E}_{ABS/GF}$ decreases in a linear manner with increasing ϕ_{GF} (Note that $E_{ABS/GF}$ is the unweld tensile modulus and $E^{w}_{ABS/GF}$ is the weldline counterpart). The linear dependence between $F^{E}_{ABS/GF}$ and ϕ_{GF} can be reasonably expressed as;

$$F^{E}_{ABS/GF} = 1 - 1.352\phi_{GF} \quad (3)$$

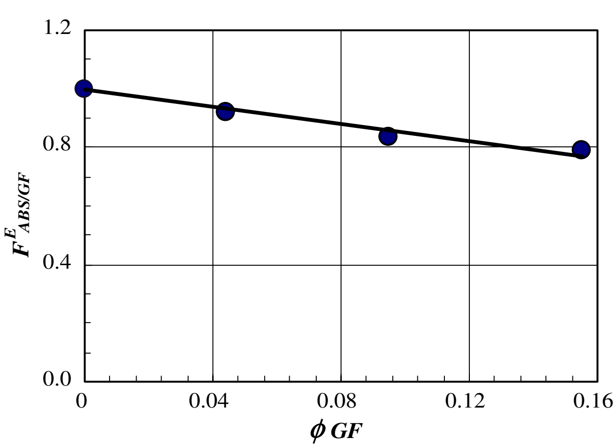

Fig. 3 Effect of glass fibre volume fraction, ϕ_{GF}, on the weldline integrity factor for tensile modulus, $F^{E}_{ABS/GF}$, of ABS/GF composites

The linearity observed between unweld tensile modulus, $E_{ABS/GF}$, and ϕ_{GF} as depicted in Fig. 2 is consistent with "rule-of-mixtures" which for composites containing short fibres i.e.:

$$E_{ABS/GF} = E_{ABS} + (\lambda_E E_{GF} - E_{ABS})\phi_{GF} \quad (4)$$

where E_{ABS} is modulus of the ABS matrix and E_{GF} is modulus of the glass fibres (assumed 75 GPa in this study). The term λ_E in Eq. 4 is often termed fibre efficiency parameter for composite modulus whose value depends on the length and the orientation of short fibres in the moulded specimen. The best linear regression line fitted through the data in Fig. 2 gives the following relationship for $E_{ABS/GF}$;

$$E_{ABS/GF} = E_{ABS}(1 + 17.86\phi_{GF}) \quad (5)$$

According to Eq. 5, λ_E is 0.583 for the ABS/GF composites and this agrees quite well with the range of values reported for several other injection-moulded short-glass fibre-polymer composites [2–7].

Similarly, the observed linearity between $E^{w}_{ABS/GF}$ and ϕ_{GF} implies also that rule-of-mixtures is equally applicable to $E^{w}_{ABS/GF}$ i.e.

$$E^{w}_{ABS/GF} = E^{w}_{ABS} + \left(\lambda^{w}_{E} E_{GF} - E^{w}_{ABS}\right)\phi_{GF} \quad (6)$$

where E^{w}_{ABS} and λ^{w}_{E} are values of E_{ABS} and λ_E in the presence of weldlines. The best linear regression line through the weldline data in Fig. 2 suggests the following relationship between $E^{w}_{ABS/GF}$ and ϕ_{GF};

$$E^{w}_{ABS/GF} = E^{w}_{ABS}(1 + 12.95\phi_{GF}) \quad (7)$$

According to Eq. 7, $\lambda^{w}_{E} \approx 0.432$ which is lower than λ_E value of 0.584 obtained for unweld specimens. This observation implies that efficiency of the short fibres as reinforcing filler is reduced in the presence of weldlines.

The efficiency parameter λ_E is often expressed as product of two other efficiency parameters, one to account for the shortness of fibres (λ_L) and the other for the orientation of the fibres (λ_o), in the moulded specimens i.e.

$$\lambda_E = \lambda_L \lambda_o \quad (8)$$

Efficiency parameter, λ_L, can be evaluated from the Cox shear lag model [21] as;

$$\lambda_L = 1 - \frac{\tanh \beta}{\beta} \quad (9)$$

The term β is defined as

$$\beta = \frac{\bar{L}_f}{2}\left(\frac{4E_{ABS}}{E_{GF} d^2 \ln p}\right) \quad (10)$$

where $\bar{L}_f$ and d are average length and the diameter of the fibres, respectively and p is the packing arrangement of the fibres in the composite whose value for square packing arrangement is defined as;

$$p = \sqrt{\frac{\pi}{4\phi_{GF}}} \quad (11)$$

Using Eq. 9 with d of 10 μm, E_{GF} of 75 GPa and the average fibre lengths, one obtains an average λ_L value of 0.843. Substituting this value and λ_E of 0.584 into Eq. 8 gives an average λ_o value of 0.692. Similarly, from the weldline modulus data in Fig. 3 we obtain average values of 0.852 and 0.507 for λ_L^w and λ_o^w, respectively. Using the Krenchel definition of λ_o [22], we obtain an average fibre orientation angles $(\bar{\theta})$ of 32 and 24° (with respect to loading direction) for weld and unweld specimens, respectively. Efficiency parameters indicate that λ_E^w is than λ_E mainly because fibre angle, $\bar{\theta}$ for the unweld specimens is greater.

The effect of glass bead concentration, ϕ_{GB}, and weldline on tensile modulus of ABS/GB composites is shown in Fig. 4. As can be seen, weldline has no significant effect upon tensile modulus of ABS/GB composites. However, as Fig. 4 shows, tensile modulus increases with increasing ϕ_{GB} in a linear manner. The linear dependence between $E_{ABS/GB}$ and ϕ_{GB} as illustrated can be expressed as;

$$E_{ABS/GB} = E_{ABS}(1 + 3.61\phi_{GB}) \quad (12)$$

There are several models for predicting the modulus of spherical filled systems. The simplest one is that of Einstein [23] which is given by Eq. 13. This equation underestimates $E_{ABS/GB}$ by 3–8%.

$$E_{ABS/GB} = E_{ABS}(1 + 2.50\phi_{GB}) \quad (13)$$

Another model which has been used extensively in predicting modulus of filled composite systems is that of extended Kerner [24]. This model proposes the following relationship between $E_{ABS/GB}$ and ϕ_{GB}:

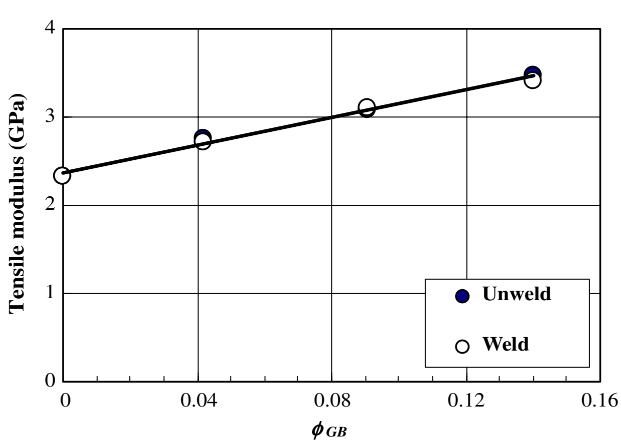

Fig. 4 Effect of glass beads volume fraction, ϕ_{GB}, on weld and unweld tensile modulus of ABS/GB composites

$$E_{ABS/GB} = E_{ABS}\left(\frac{1 + K_1K_2\phi_{GB}}{1 - K_2\psi\phi_{GB}}\right) \quad (14)$$

where constants K_1 and K_2 are defined as:

$$K_1 = \frac{7 - 5\upsilon_{ABS}}{8 - 10\upsilon_{ABS}} \quad K_2 = \frac{E_{GB} - E_{ABS}}{E_{GB} + AE_{ABS}} \quad (15)$$

In the above equations E_{GB} is modulus of the glass beads taken here as 75 GPa and υ_{ABS} is the Poisson's ratio of the ABS matrix taken as 0.35. The parameter Ψ takes into account the maximum packing fraction of the glass beads ϕ_{max} defined as:

$$\psi = 1 + \left(\frac{1 - \phi_{max}}{\phi_{max}^2}\right)\phi_{GB} \quad (16)$$

where for random packing of single-size spheres ϕ_{max} = 0.64. Kerner equation like Einstein underestimates $E_{ABS/GB}$ by 3–8%. Both models assume weak interfacial adhesion which may not be the case here.

The data for ABS/GF/GB hybrids is expressed here in terms of hybrid ratio λ_{GF} defined as;

$$\chi_{GF} = \frac{\phi_{GF}}{\phi_G} \quad (17)$$

where ϕ_{GF} is the volume fraction of the fibres in the hybrid and ϕ_G is the total volume fraction of glass in the hybrid. Figure 5a–c shows tensile modulus of ABS/GF/GB hybrids for both weld and unweld specimens versus λ_{GF} for total glass concentration values of 10, 20 and 30% w/w. It is evident that tensile modulus is reduced in the presence of weldline and that the effect of weldline becomes more significant with increasing λ_{GF} (i.e. the concentration of glass fibres) and the total concentration of the glass in the hybrid, ϕ_G. As depicted in the figures, unweld tensile modulus, E_H, and its weld counterpart, E_H^w, both increase with increasing λ_{GF} in a linear manner. This observation implies that E_H and E_H^w can be expressed by an additive rule-of-mixtures i.e.

$$E_H = E_{ABS/GF}\chi_{GF} + E_{ABS/GB}(1 - \chi_{GF}) \quad (18)$$

$$E_H^w = E_{ABS/GF}^w\chi_{GF} + E_{ABS/GB}^w(1 - \chi_{GF}) \quad (19)$$

By substituting Eqs. 5 and 12 into Eq. 18 and Eqs. 7 and 12 into Eq. 19 one obtains the following relationships for E_H and E_H^w, respectively.

$$E_H = E_{ABS}[1 + (3.61 + 14.25\chi_{GF})\phi_G] \quad (20)$$

$$E_H^w = E_{ABS}^w[1 + (3.61 + 9.34\chi_{GF})\phi_G] \quad (21)$$

The solid lines drawn in Fig. 5a–c represent the fit according to Eqs. 20 and 21.

The effect of weldline on hybrid tensile modulus was quantitatively expressed in terms of weldline integrity factor for modulus, $F_H^E(=\frac{E_H^w}{E_H})$. Figure 6 shows the effect of

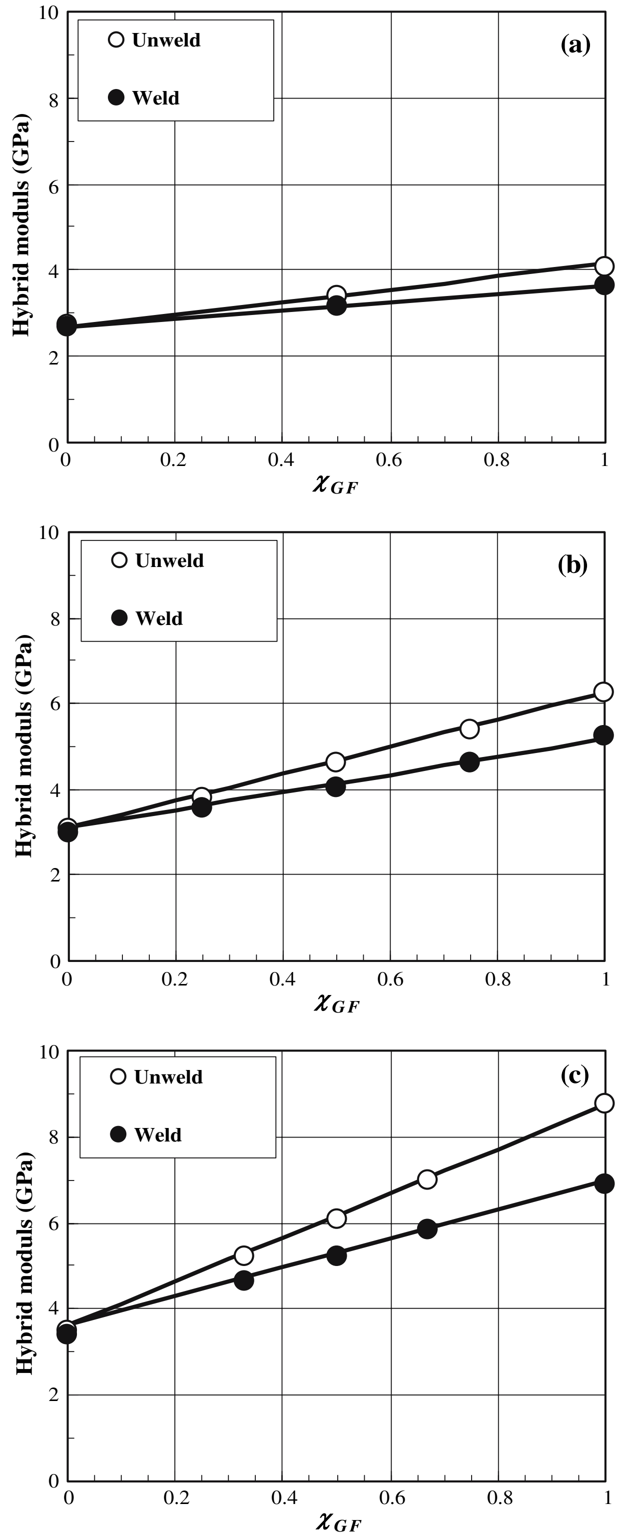

Fig. 5 Hybrid unweld tensile modulus, E_H, and weld modulus, E_H^w, versus hybrid ratio, χ_{GF}, for total glass contents of (**a**) 10%, (**b**) 20% and (**c**) 30% w/w

λ_{GF} on F_H^E for total glass contents of 10, 20 and 30% w/w. It can be seen that F_H^E decreases with increasing λ_{GF} and with increasing the total concentration of the glass in the hybrid, ϕ_G. Using Eqs. 20 and 21 one obtains the following expression for F_H^E;

$$F_H^E = \frac{1 + (3.61 + 9.34\chi_{GF})\phi_G}{1 + (3.61 + 14.25\chi_{GF})\phi_G} \qquad (22)$$

Lines in Fig. 6 show that fit according to Eq. 22.

Tensile strength

It was evident from the load-extension curves that whilst pure ABS failed in a ductile manner after extensive yielding, ABS/GF composites failed in a brittle manner. ABS and ABS/GF composites all failed in a brittle manner in the presence of weldlines. Failure of the weldline specimens occurred at the weldline region as illustrated in Fig. 7.

The effect of ϕ_{GF} and weldline on tensile strength of ABS/GF composites is shown in Fig. 8. It can be seen that tensile strength of weldline free specimens, $\sigma_{ABS/GF}$, and tensile strength of weldline specimens, $\sigma^w_{ABS/GF}$, vary with ϕ_{GF} in a nonlinear manner. Evidently, whilst unweld tensile strength, $\sigma_{ABS/GF}$, increases with increasing ϕ_{GF}, weldline strength, $\sigma^w_{ABS/GF}$, increases initially before decreasing with increasing ϕ_{GF}, showing a maximum in the process. The nonlinearity of the strength data implies that the weld and unweld strengths of ABS/GF composites do not conform to rule-of-mixtures, at least over the entire fibre concentration range. The strength data for ABS/GF composites can be expressed by the following second order polynomial function;

$$\sigma_{ABS/GF} = \sigma_{ABS}(1 + 9.27\phi_{GF} - 29.69\phi_{GF}^2) \qquad (23)$$

$$\sigma^w_{ABS/GF} = \sigma^w_{ABS}(1 + 2.01\phi_{GF} - 13.41\phi_{GF}^2) \qquad (24)$$

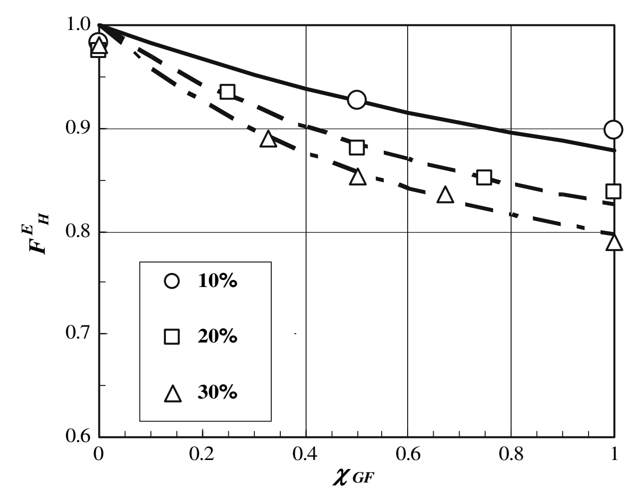

Fig. 6 Weldline integrity factor for hybrid tensile modulus, F_H^E versus hybrid ratio, χ_{GF}, for total glass contents of 10, 20 and 30% w/w

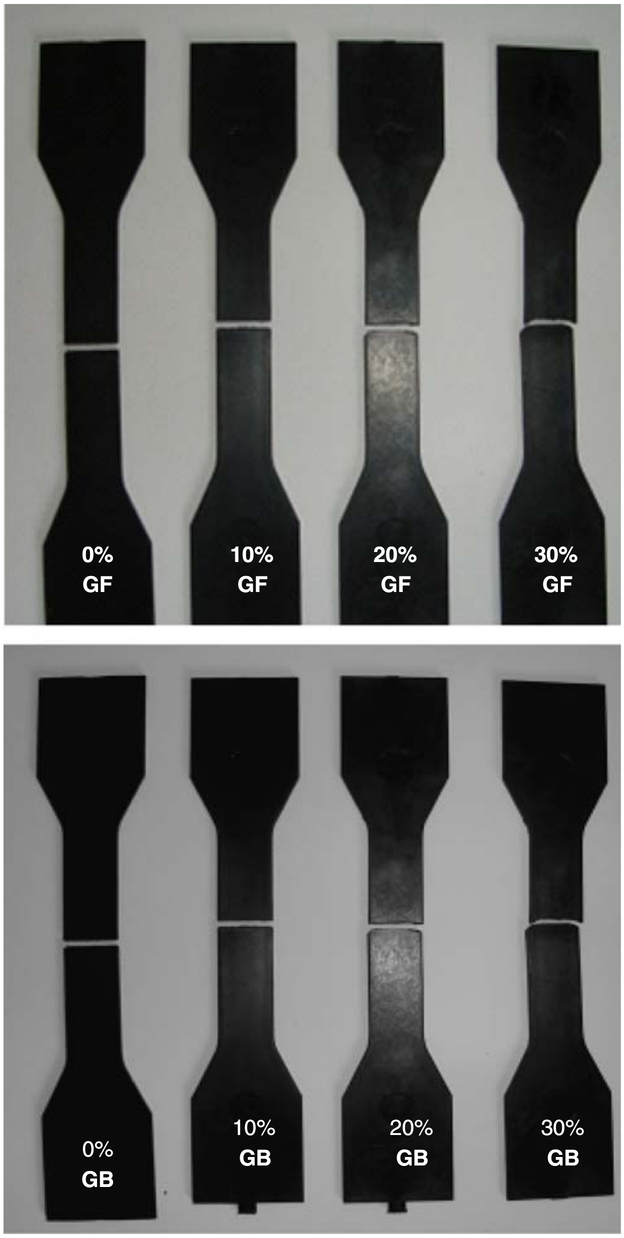

Fig. 7 Tested ABS/GF and ABS/GB composite tensile specimens with weldlines

It is worth stating, that for ϕ_{GF} values in the range 0–10% v/v, variation of $\sigma_{ABS/GF}$ with ϕ_{GF} is linear (with regression coefficient of 0.989) and therefore consistent with role-of-mixtures for composite strength. Thus, for ϕ_{GF} of less than 10% v/v, unweld tensile strength can be expressed as;

$$\sigma_{ABS/GF} = \sigma_{ABS} + (\lambda_\sigma \sigma_{GF} - \sigma_{ABS})\phi_{GF} \tag{25}$$

where σ_{ABS} is tensile strength of ABS matrix and σ_{GF} is strength of the fibre and λ_σ is the fibre efficiency parameter for composite strength whose value according to the slope of the linear part of $\sigma_{ABS/GF}$ versus ϕ_{GF} (shown as a broken

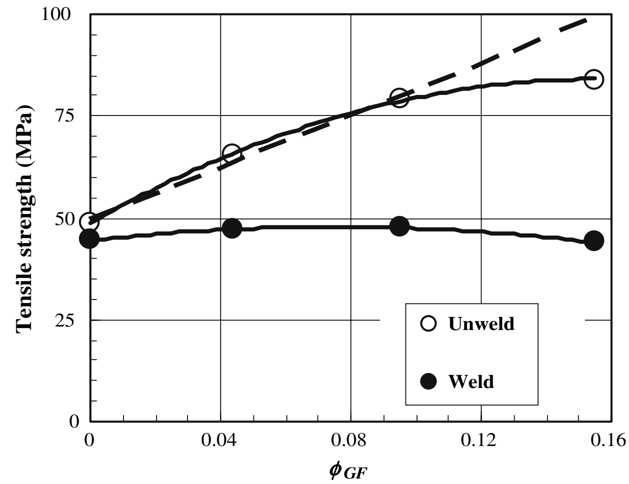

Fig. 8 Weld and unweld tensile strengths of ABS/GF composites versus volume fraction of glass fibres, ϕ_{GF}

line in Fig. 8) is 0.148 (assuming tensile strength of the fibre, σ_{GF}, is 2,470 MPa).

The influence of weldline on tensile strength like tensile modulus is quantitatively expressed in terms weldline integrity factor defines as;

$$F^\sigma = \frac{\textit{Tensile strength in the presence of weldline}}{\textit{Tensile strength in the absence of weldline}} \tag{26}$$

Figure 9 shows weldline integrity factor for tensile strength of ABS/GF composites, $F^\sigma_{ABS/GF}$ decreases with increasing ϕ_{GF}. Substituting Eq. 23 and Eq. 24 into Eq. 26 gives the following expression for $F^\sigma_{ABS/GF}$;

$$F^\sigma_{ABS/GF} = F^\sigma_{ABS}\left(\frac{1 + 2.01\phi_{GF} - 13.41\phi^2_{GF}}{1 + 9.27\phi_{GF} - 29.69\phi^2_{GF}}\right) \tag{27}$$

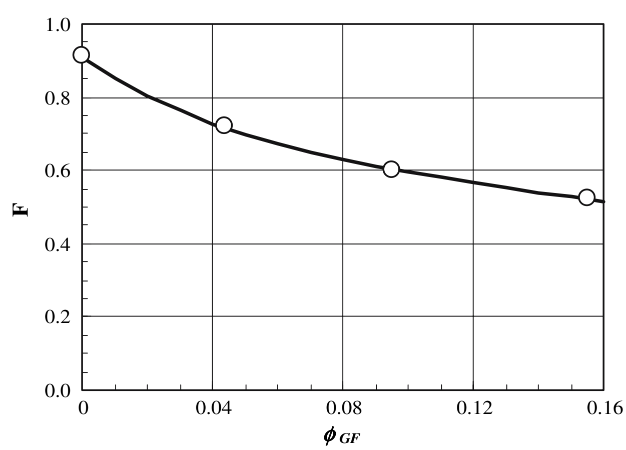

Fig. 9 Weldline integrity factor for tensile strength of ABS/GF composites, $F^\sigma_{ABS/GF}$, versus volume fraction of glass fibres, ϕ_{GF}

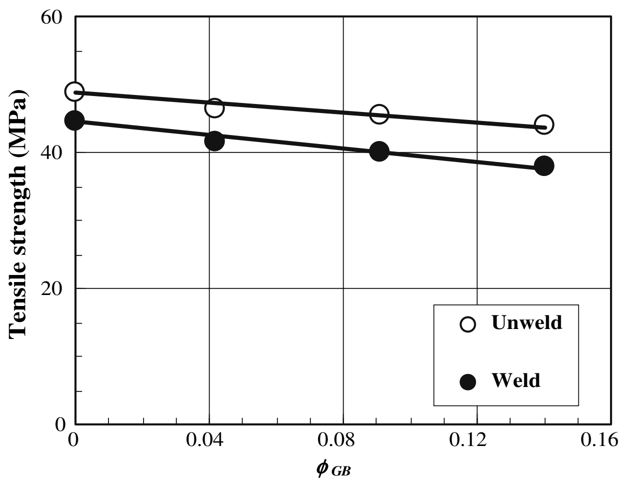

Fig. 10 Weld and unweld tensile strengths of ABS/GB composites versus volume fraction of glass beads, ϕ_{GB}

where F^{σ}_{ABS} is weldline integrity factor for tensile strength of pure ABS. Lines in Fig. 9 show the fit according to Eq.27.

As for tensile strength of ABS/GB composites, it can be seen from Fig. 10 that both weld and unweld tensile strength decreases with increasing ϕ_{GB} in a linear manner. It is also evident that tensile strength of ABS/GB composites is reduced in the presence of weldlines. The linearity observed for both weld and unweld strengths with ϕ_{GB} follows the model proposed by Piggott and Leidner [25] i.e.

$$\sigma_{ABS/GB} = \sigma_{ABS}(1 - 0.735\phi_{GB}) \tag{28}$$

$$\sigma^{w}_{ABS/GB} = \sigma^{w}_{ABS}(1 - 1.085\phi_{GB}) \tag{29}$$

Figure 11 shows weldline integrity factor for tensile strength of ABS/GB composites, $F^{\sigma}_{ABS/GB}$, decreases with increasing ϕ_{GB}. Using Eqs. 28 and 29 we obtain the following expression for $F^{\sigma}_{ABS/GB}$;

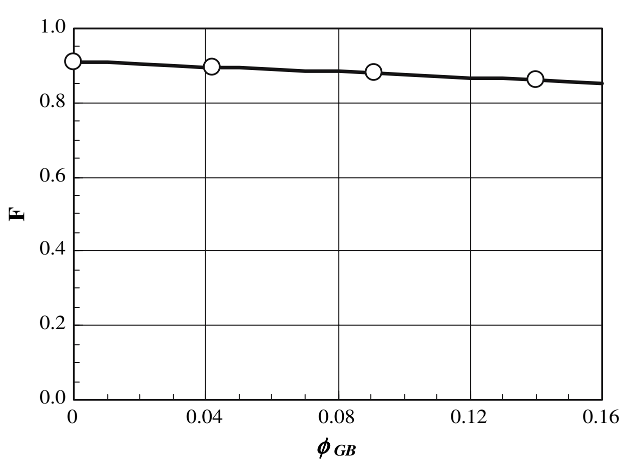

Fig. 11 Weldline integrity factor for tensile strength of ABS/GB composites, $F^{\sigma}_{ABS/GB}$, versus volume fraction of glass beads, ϕ_{GB}

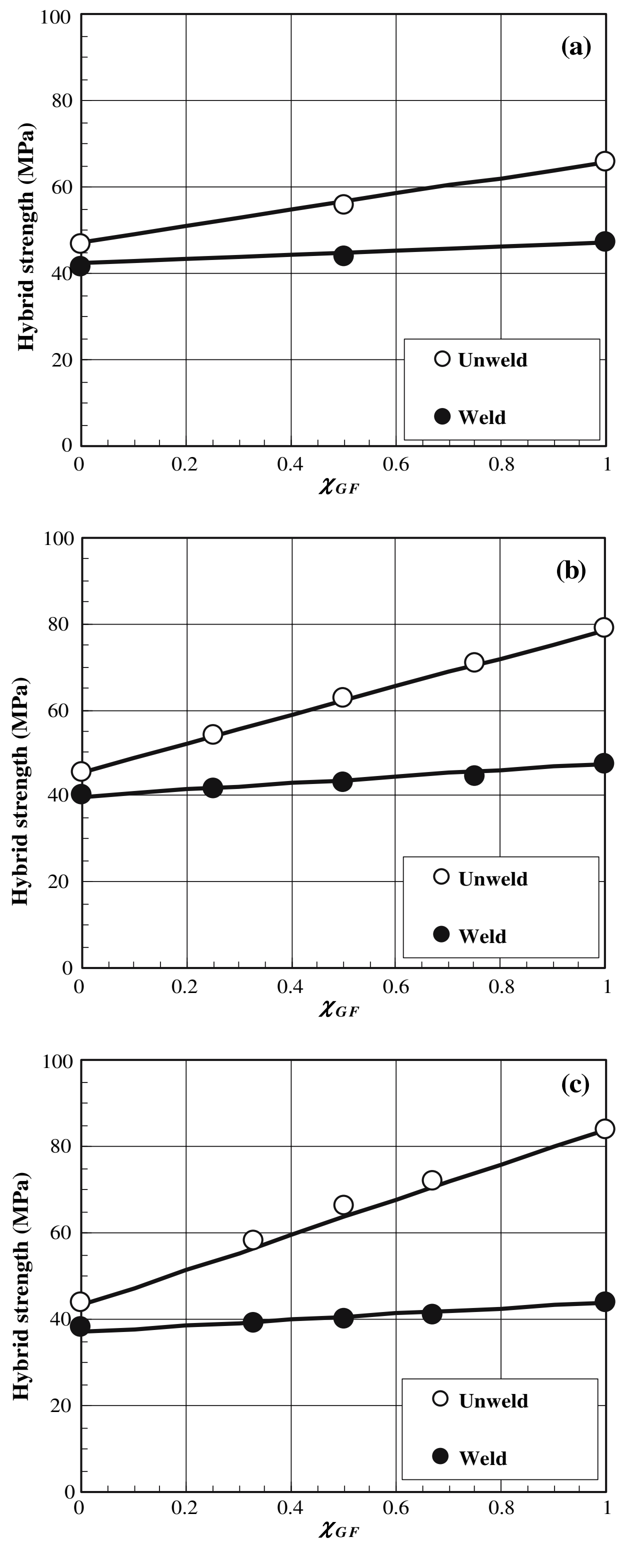

Fig. 12 Hybrid unweld tensile strength, σ_H, and weld strength, σ^{w}_{H}, versus hybrid ratio, χ_{GF}, for total glass contents of **(a)** 10%, **(b)** 20% and **(c)** 30% w/w

$$F^{\sigma}_{ABS/GB} = F^{\sigma}_{ABS}\left(\frac{1 - 1.085\phi_{GB}}{1 - 0.735\phi_{GB}}\right) \tag{30}$$

F^{σ}_{ABS} is weldline integrity factor for tensile strength of pure ABS. The line drawn in Fig. 11 represents Eq. 30 and as can be seen it fits the data very well.

Figure 12a–c shows tensile strength of ABS/GF/GB hybrids for both weld and unweld specimens versus λ_{GF} for total glass concentration values of 10, 20 and 30%w/w. It is evident that tensile strength is reduced in the presence of weldline and that the effect of weldline becomes more significant with increasing λ_{GF} (i.e. the concentration of glass fibres) and the total concentration of the glass in the hybrid, ϕ_G. It can be seen from the figures, that unweld tensile strength, σ_H, and its weld counterpart, σ^w_H, both increase with increasing λ_{GF} in a linear manner. This observation implies that hybrid tensile strength values σ_H and σ^w_H like tensile modulus E_H and E^w_H can be expressed by the following rule-of-mixtures i.e.

$$\sigma_H = \sigma_{ABS/GF}\chi_{GF} + \sigma_{ABS/GB}(1 - \chi_{GF}) \quad (31)$$

$$\sigma^w_H = \sigma^w_{ABS/GF}\chi_{GF} + \sigma^w_{ABS/GB}(1 - \chi_{GF}) \quad (32)$$

By Substituting Eq. 23 and Eq. 28 into Eq. 31 and Eq. 24 and Eq. 29 into Eq. 32 one obtains the following expressions for σ_H and σ^w_H, respectively

$$\sigma_H = \sigma_{ABS}[1 + (10\chi_{GF} - 29.69\chi_{GF}\phi_T - 0.735)\phi_G] \quad (33)$$

$$\sigma^w_H = \sigma^w_{ABS}[1 + (3.10\chi_{GF} - 13.41\chi_{GF}\phi_T - 1.085)\phi_G] \quad (34)$$

Lines in Fig. 12a–c show the fit according to Eq. 33 and Eq. 34.

The effect of weldline on tensile strength of ABS/GF/GB hybrids can be quantitatively expressed in terms of weldline integrity factor, $F^{\sigma}_H = \frac{\sigma^w_H}{\sigma_H}$. Figure 13 shows the effect of λ_{GF} on F^{σ}_H for total glass contents of 10, 20 and 30% w/w. It can be seen that F^{σ}_H decreases with increasing λ_{GF} and with increasing the total concentration of the glass in the hybrid, ϕ_G. Using Eqs. 33 and 34 one obtains Eq. 35, from which weldline integrity factor for the hybrid tensile modulus can be estimated. Lines drawn in Fig. 13 represent Eq. 35 and as can be data for F^{σ}_H is described very well by this equation.

$$F^{\sigma}_H = \frac{1 + (10\chi_{GF} - 29.69\chi_{GF}\phi_T - 0.735)\phi_G}{1 + (3.10\chi_{GF} - 13.41\chi_{GF}\phi_T - 1.085)\phi_G} \quad (35)$$

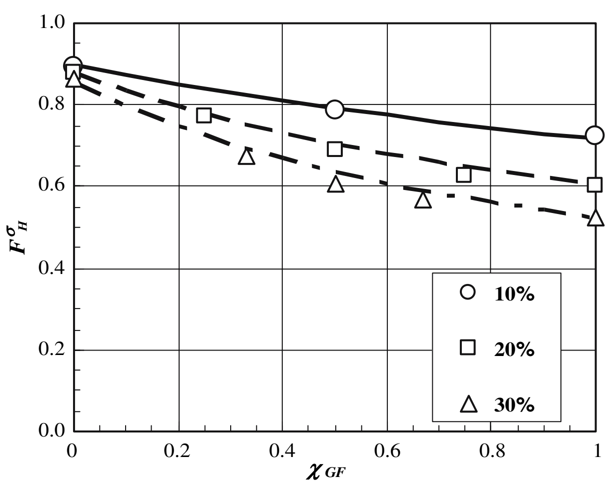

Fig. 13 Weldline integrity factor for hybrid tensile strength, F^{σ}_H versus hybrid ratio, χ_{GF}, for total glass contents of 10%, 20% and 30% w/w

Conclusions

A positive and negative hybrid effect in hybrid composites is defined as positive or negative deviation of a certain mechanical property from the rule-of-mixtures. The question of hybrid effect was examined here on several injection moulded ABS hybrids containing both short glass fibres (GF) and spherical glass beads (GB). Results obtained from this study led to the following conclusions;

(i) Tensile modulus (E_H) and strength (σ_H) of ABS/GF/GB hybrid increases with the total concentration of the glass in the hybrid, ϕ_G, and the hybrid ratio, χ_{GF} (= ϕ_{GF}/ϕ_G). The variation of E_H and σ_H with χ_{GF} obeys rule-of-mixtures.

(ii) The presence of weldline affects E_H and σ_H. Although values of E_H and σ_H were reduced in the presence of weldline, both increased with increasing χ_{GF} in a linear manner; thus indicating that weldline properties like their unweld counterparts obey rule-of-mixtures.

(iii) The weldline integrity for tensile modulus and tensile strength decreases with increasing λ_{GF} and with increasing the total concentration of the glass in the hybrid.

References

1. Hashemi S, Gilbride MT, Hodgkinson JM (1996) J Mater Sci 32:5017
2. Din KJ, Hashemi S (1997) J Mater Sci 32:375
3. Chrysostomou A, Hashemi S (1998) J Mater Sci 33:1165
4. Chrysostomou A, Hashemi S (1998) J Mater Sci 33:4491
5. Nabi ZU, Hashemi S (1998) J Mater Sci 33:2985
6. Hashemi S (2002) Plast Rubber Compos 31:1
7. Hashemi S, Lepessova Y (2007) J Mater Sci 42:2652
8. Necar M, Irfan-ul-Haq, Khan Z (2003) J Mater Process Technol 142:247
9. Fu SY, Lauke B, Mader E, Yue CY, Hu X (2000) Compos Part A 31:1117
10. Fisa B (1985) Polym Composite 6:232
11. Thomason JL (2002) Compos Sci Technol 62:1455
12. Thomason JL (2001) Compos Sci Technol 61:2007
13. Yilmazar U (1992) Compos Sci Technol 44:119
14. Hashemi S, Elmes P, Sandford S (1997) Polym Eng Sci 37:45

15. Phillips LN (1976) Composites 7:7
16. Debondue E, Foumier J-E, Lacrampe MF, Krawczak (2004) J Polym Polym Compos 12:373
17. Sanschagrin B, Gauvin R, Fisa B,Vu-Khanh T (1990) J Reinf Plast Comp 8:194
18. Meddad A, Fisa B (1995) Polym Eng Sci 35:893
19. Akay M, Barkley D (1993) Plast Rubber Compos 20:137
20. Nadkarni VM, Ayodhya SR (1993) Polym Eng Sci 33:358
21. Cox H L (1952) Br Appl Phys 3:72
22. Krenchel H (1964) Akademisk. Forlag, Copenhagen
23. Einstein A (1906) Ann der Phys 19:289
24. Kerner EH (1956) Proc Phys Soc 69B:908
25. Leidner J, Woodhams RT (1974) J Appl Polym Sci 18:1639