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Temperature and deformation rate dependence of the work of fracture in polycarbonate (PC) film

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Single edge notched polycarbonate (PC) specimens of thickness 0.175 mm were pulled to complete fracture at temperatures between 25°C and 100°C and at loading rate values of 2, 5 and 50 mm/min. A duckbill-shaped yielded zone was formed ahead of the crack tip in all the specimen tested. Propagation of the crack within the yielded zone was always stable. The method of essential work of fracture (EWF) was used to study the effects of temperature and loading rate on fracture toughness. The specific essential work of fracture, w_e, was found to be independent of both temperature and loading rate. The non-essential work of fracture, βw_p, increased with increasing temperature but showed no systematic variation with respect to loading rate. Moreover, plastic constraint factor, m, also increased with increasing temperature. A linear temperature dependence was obtained for both βw_p and m giving the extrapolated values of $\beta w_p = 0$ and $m = 0.5$ at -23°C. © *2000 Kluwer Academic Publishers*

1. Introduction

The theory of Linear Elastic Fracture Mechanics (LEFM) deals with fracture occurring at nominal stresses well below the uniaxial yield stress of the material. Under this condition, the plastic flow at the tip of the crack is intimately associated with the fracture process that is brittle in nature. However, in characterising the failure of ductile materials, the LEFM approach becomes redundant mainly due to development of a large plastic zone at the crack tip.

Recently, many investigators [1–12] have adopted the concept of the Essential Work of Fracture (EWF) in determining the fracture toughness of polymeric materials under plane-stress conditions. According to EWF, total work of fracture can be divided into two components, one referred to as the essential work of fracture (W_e) and the other as the non-essential works of fracture (βW_p). The W_e represents the energy required to fracture the material in its process zone whereas βW_p represents the energy consumed by various deformation mechanisms in the surrounding outer plastic deformation zone. It has been shown that EWF [1–12] is a useful method of characterising fracture toughness of polymeric systems under plane-stress conditions and that the value of W_e per unit ligament area (w_e) is a material constant for a given thickness. Thus far, little work has be done investigating the effect of temperature on w_e. The main aim of this work is to study temperature dependence of EWF using polycarbonate film as a reference material. The effect of loading rate on EWF is also investigated.

2. Essential work of fracture concept

The EWF concept was first developed by Cottrell and Reddel [13] following an idea by Broberg [14] who proposed that the non-elastic region at the tip of a crack may be divided into two regions as shown in Fig. 1 - An inner fracture process zone (IFPZ) and an outer plastic deformation zone (OPDZ). The total work of fracture, W_f, of a cracked specimen is then partitioned into two terms: (i) the work that is expended in the inner fracture process zone, W_e and (ii) the work that is dissipated in the plastic zone outside the inner fracture process zone, W_p. The total work of fracture is therefore written as:

$$W_f = W_e + W_p \tag{1}$$

The work W_e is referred to as the *Essential Work of Fracture (EWF)* and it is the work that is required to form a neck, which subsequently initiates tearing of the neck. The work W_p is the work that is expended to plastically deform the material outside the inner fracture process zone (i.e. OPDZ). This work is referred to as the *Non-Essential Work of Fracture* which in the case of polymers involves both shear and microvoiding. If it is assumed that W_e is proportional to the ligament area and W_p is proportional to the volume of the outer plastic deformation zone, then the total work of fracture per unit ligament area (refered to as the *Specific Total Work of Fracture*) can be written as

$$w_f = \frac{W_f}{LB} = w_e + \beta w_p L \tag{2}$$

where w_e is the *Specific Essential Work of Fracture* and w_p is the *Specific Non-Essential Work of Fracture*. β is a proportionality constant or shape factor associated with the volume of the plastic deformation zone.

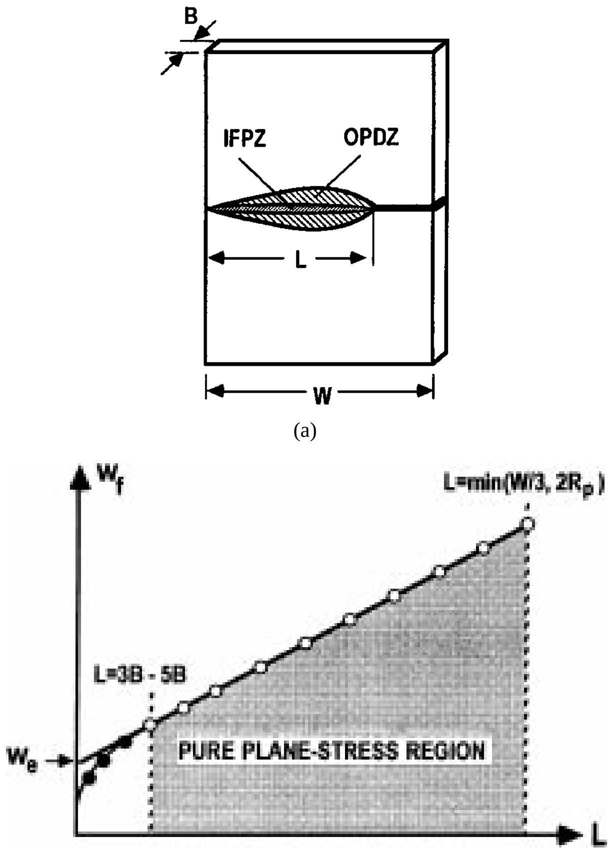

Figure 1 (a) Schematic representation of the inner fracture process zone (IFPZ) and the outer plastic deformation zone (OPDZ) in a double edge notched specimen. (b) Schematic representation of the specific total work of fracture versus ligament length, L.

For a given thickness, the term w_e is regarded as a material constant and provided βw_p term remains independent of the ligament length, a linear relationship should then be obtained between w_f and L as suggested by Equation 2. As depicted in Fig. 1b, the positive intercept of the line w_f versus L at $L = 0$ gives w_e and the slope of the line gives βw_p.

3. Experimental details

Polycarbonate films of thickness 0.175 mm were supplied by BAYER UK in the form of A4 size sheets of dimensions 300 mm × 210 mm. Eight rectangular coupons having width of 35 mm and length of 105 mm were prepared from each sheet. These were razor notched to produce series of single edge notched specimens as shown in Fig. 2 with ligament lengths (L) ranging from 1 mm to 15 mm. Minimum of thirty specimens were tested for determination of a single w_e value. The majority of the tests were carried out in duplicate by two independent co-workers. To distinguish between the two sets of data, open and filled circles have been used in all figures presented in this paper. All the tests were performed on an Instron testing machine using pneumatic clamps with initial clamp separation (Z) of 70 mm.

To study the effect of temperature on EWF, tests were carried out at temperatures ranging from 25°C to 100°C using a constant crosshead displacement rate of 5 mm/min. Further tests at 25°C were also performed at crosshead displacement rate values of 2 mm/min and 50 mm/min in order to study the effect of deformation rate on EWF.

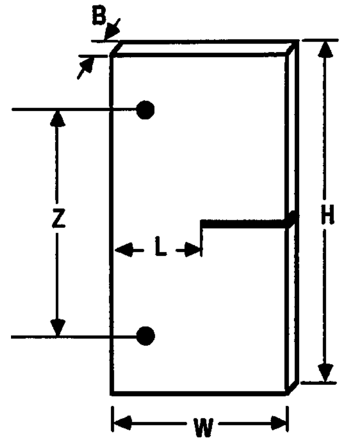

Figure 2 Single edge notched tension (SENT) specimen.

Additionally, series of tensile tests were also conducted on unnotched dumbbell-shaped specimens for the determination of the nominal tensile yield stress and modulus as a function of test temperature and loading rate. Values of the tensile yield stress and modulus were calculated from the maximum load and the initial slope of the load-displacement (P-δ) curve.

All the data obtained in this study was recorded using a computer data logger.

4. Results and discussion

4.1. Effect of temperature

The load-displacement (P-δ) curves in Fig. 3 show that dumbbell-shaped tensile specimens of polycarbonate film fail in a ductile manner after exhibiting a clear yield point and a drop in load after yield of about 10–15% due to strain-softening. Results obtained for tensile yield stress, σ_y, and modulus, E, are plotted in Fig. 4 as a function of test temperature where it can be seen that they decrease with increasing temperature due to viscoelastic processes.

The EWF tests on SENT specimens produced load-displacement (P-δ) curves at various ligament lengths and temperatures of the type shown in Fig. 5. The

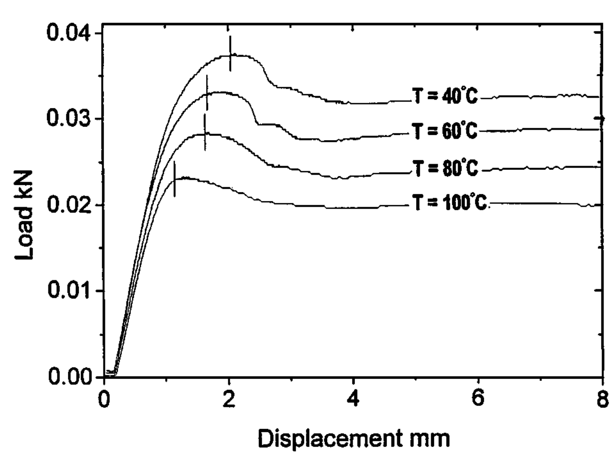

Figure 3 Typical tensile load-displacement curves as a function of test temperature.

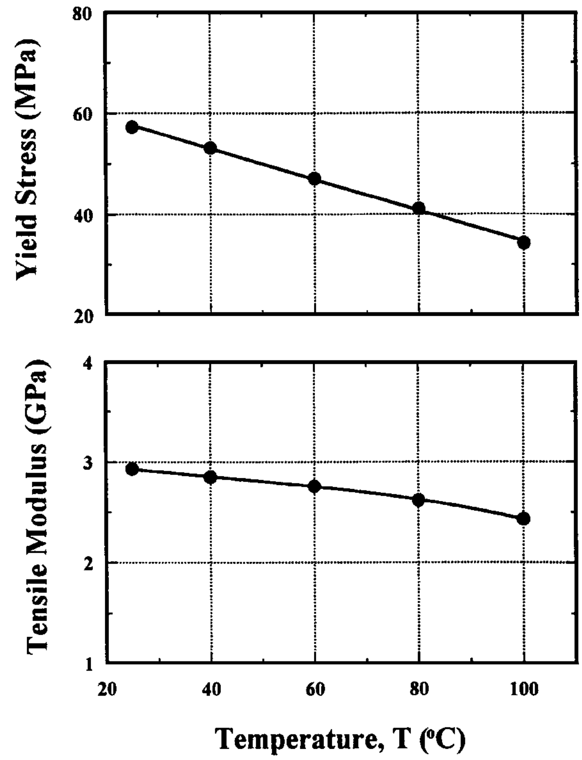

Figure 4 Tensile yield stress and modulus versus temperature.

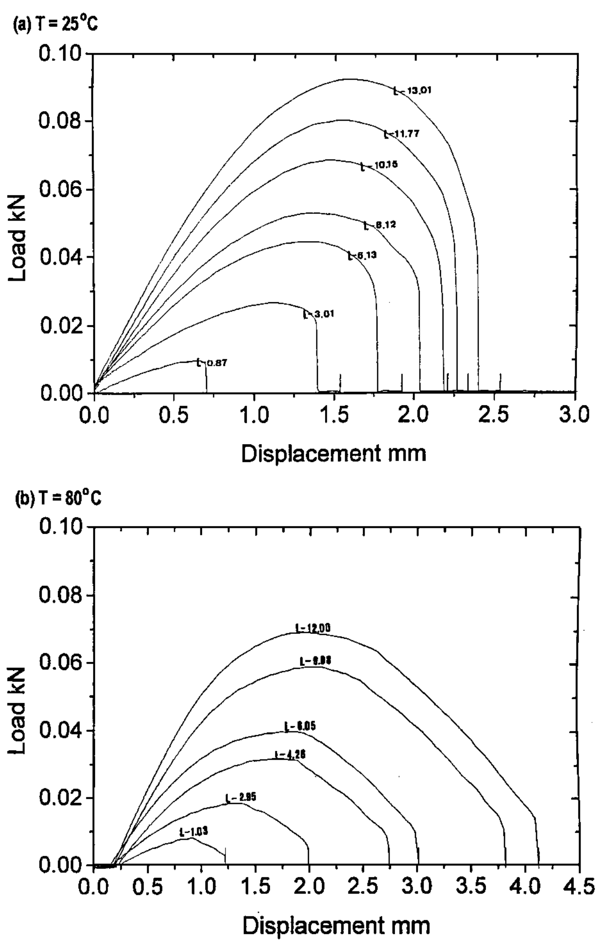

Figure 5 Typical SENT load-displacement curves at various ligament lengths; (a) $T = 25°C$, (b) $T = 80°C$.

notable feature of the curves is their geometrical similarity which is an essential requirement for determining w_e. Curves further demonstrate that the failure of the specimens is by ductile tearing of the ligament region and that a rise in temperature reduces the rate at which load after maximum diminishes to zero. All the specimens tested in this study underwent full ligament yielding prior to final fracture. However, visual observation of the specimens during the test clearly revealed that the load at which ligament yielded fully did not always coincide with the maximum load on the P-δ curves. Although the extent to which ligament length yielded at maximum load increased with increasing temperature, full yielding at maximum load only occured at the test temperature of 100°C. It was further observed that the onset of crack growth in most specimens occurred prior to full yielding of the ligament region.

Figure 6 shows plots of the specific total work of fracture, w_f, (as calculated from the total area under the P-δ curves and related to the ligament area), versus ligament length, L, at all temperatures considered here. Also included in these figures are plots of net-section stress, σ_n, at maximum load normalised with respect to σ_y (tensile yield stress). The ratio $\sigma_n : \sigma_y$ is known as the plastic constraint factor, m, whose value according to analysis by Hill [15] is 1.0 for SENT specimen under pure plane-stress conditions.

It is evident from the plots in Fig. 6 that the variation of w_f with L is essentially linear for all values of L greater than 4 mm (denoted as L_t). Below this value, w_f tends to deviate somewhat from the linear trend indicating presence of a mixed mode stress state in the ligament region. This deviation in w_f versus L plots coincides reasonably well with a sharp increase which is evident in the value of m. Indeed, it may observed that for $L > L_t$, m remains almost independent of the ligament length and thus reaching a steady state value that is always lower than the proposed value of 1.0. Further more, as depicted in Fig. 7, the steady value of m increases linearly with increasing temperature giving an extrapolated value of 0.5 at $-23°C$. It is worth pointing out, that m values of less than 1.0 for single edge notched tension specimens and less than 1.15 for double edge notched tension (DENT) specimens, as the case may be, are frequently reported in the literature [5, 7, 8, 11, 12]. Indeed, the work by Wu & Mai [10] on double edge notched LLDPE specimens has shown that m value greater than 1.15 is also possible under plane-stress conditions. Based upon the body of information available to-date, it is perhaps reasonable to assume that the requirement $\sigma_n = \sigma_y$ (i.e. $m = 1$) for SENT or $\sigma_n = 1.15\sigma_y$ (i.e. $m = 1.15$) for DENT may not be a necessary pre-requisite for EWF testing as long as failure of the specimen is after the ligament length had been fully yielded.

Another feature of the data in Fig. 6 is the value of the ligament length at the transition point, i.e. L_t. It has been suggested, that if ligament length is not large compared to the thickness of the specimen, B, then the state of stress in the ligament region becomes one of mixed mode at short ligament lengths, rather than the desired state of pure plane-stress. As a consequence, w_e and w_p both become dependent upon L giving rise to a nonlinear relationship between w_f and L at short ligament lengths (see Fig. 1b). To avoid this nonlinearity, the ligament length restriction of $L \geq$ 3B–5B is recommended which for the specimen thickness of 0.175 μm used

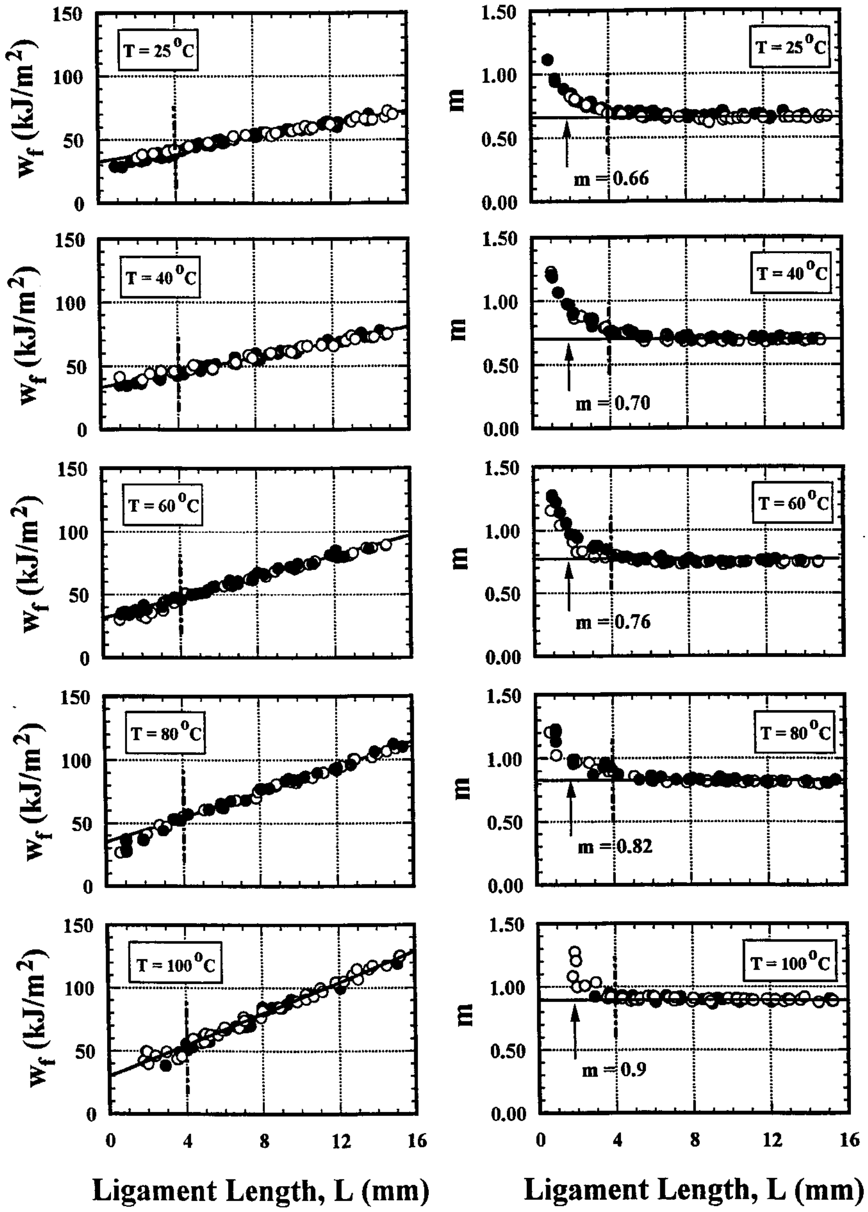

Figure 6 Typical plots of specific total work fracture, w_f, and net-section stress, σ_n, versus ligament length, L.

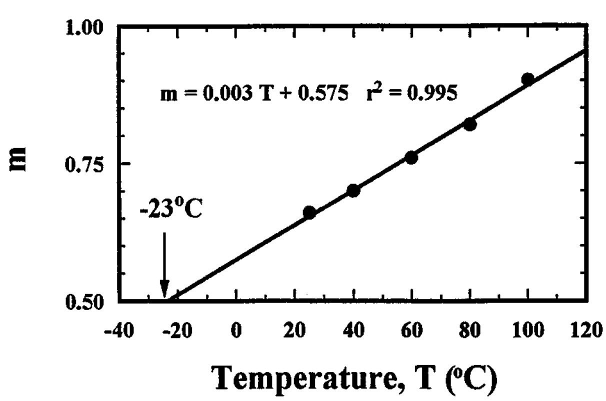

Figure 7 Plastic constraint factor, m, versus temperature, T.

here would correspond to a L_t value in the range of 0.53 mm to 0.88 mm. mm. However, according to Fig. 7, for the specimens tested here, L_t is 4 mm giving a transition ratio (L_t/B) of approximately 23. It is worth pointing out, that transition ratios higher than 3 to 5 can also be found in literature [1, 2, 5, 6, 10–12]. These findings tend to support the view expressed by WU & Mai [10] suggesting that the ratio L_t/B may depend on the material and in particular its sensitivity to the plastic constraint to which it is subjected.

Finally, before determining w_e, two further prerequisites need to be considered, both of which are related to the size of the OPDZ (i.e. $2R_P$) surrounding the IFPZ. Firstly, it is recommended that L should be less than or equal to $2R_P$, to ensure that final fracture occurs after full yielding of the ligament region thereby the size of the plastic zone is controlled by the ligament length. Secondly, the ligament length should be less than sample width, $W/3$, so that the size of the OPDZ is not disturbed by the lateral boundaries of the test specimen. The lower of the two values determines the upper limit for the valid ligament length range. In the present study $W = 35$ mm and therefore $W/3 = 11.7$ mm. The length $2R_P$ of a duckbill-shaped plastic zone can be estimated from

$$2R_p = \frac{\pi}{8}\left(\frac{E w_e}{\sigma_y^2}\right) \quad (3)$$

TABLE I Summary of test results for PC at loading rate value of 5 mm/min

	$T = 25$ (°C)	$T = 40$ (°C)	$T = 60$ (°C)	$T = 80$ (°C)	$T = 100$ (°C)
w_e, kJ/m^2	32.81	33.35	32.02	34.44	30.29
βw_p, MJ/m^3	2.52	2.97	4.06	4.99	6.17
$2R_P$, mm	11.54	13.23	15.49	21.08	24.60

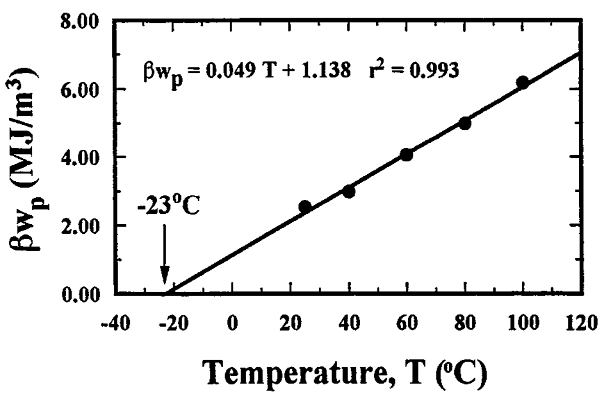

Figure 8 Specific non-essential work of fracture, βw_p, versus temperature, T.

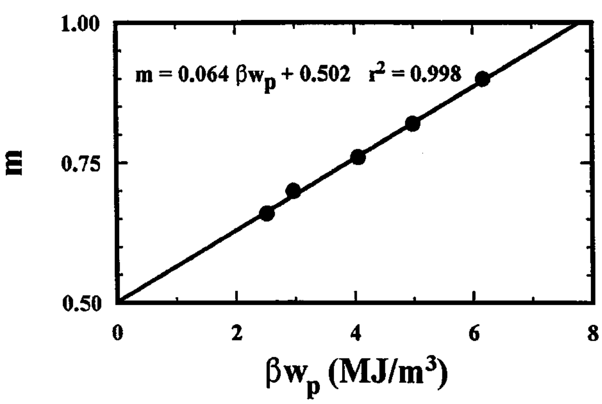

Figure 9 Plastic constraint factor, m, versus specific non-essential work of fracture, βw_p.

Obviously, in order to evaluate $2R_P$ one first need to have a prior knowledge of w_e which is an unsatisfactory situation given that the whole purpose of the investigation is to determine w_e. To determine w_e, values of w_f for which $L \geq 4$ mm were linearly extrapolated to $L = 0$. The w_e values obtained in this way are given in Table I as a function of temperature. As can be seen, for the polycarbonate film under consideration, w_e is more or less independent of temperature. The computed values of $2R_p$ are also given in Table I indicating that for the range of temperatures studied here we have $2R_p \geq W/3$. The upper limit for the valid ligament length is therefore defined by the length $W/3$ which is the smaller of the two lengths. However, given that the plots of w_f versus L showed no evidence of non-linearity for ligament lengths exceeding $W/3$, one may conclude that the pre-requisite $L \leq W/3$ is too restrictive for the material studied here. This is mainly due to the tendency of the yielded zone to remain localised because of the strain softening in PC during yielding process.

The slope of the line w_f versus L gives the specific non-essential work of fracture, βw_p. The values obtained from the slope of the lines are plotted in Fig. 8 as a function of test temperature. It appears that βw_p increases linearly with increasing temperature. Extrapolation of line in Fig. 8 to βw_p value of zero suggests a brittle fracture at a test temperature of −23°C. Interestingly, this is the same temperature at which steady state value of m extrapolates to 0.5. Given that net-section stress equals half the tensile yield stress of the material at −23°C, small amount of yielding if any at the crack tip is expected meaning that fracture at this temperature should be one of brittle nature. It is worth noting, that when values of m and βw_p are plotted against each other as in Fig. 9, the trend is also one of linearity. At present, the author can offer no explanation as to why the variations of m and βw_p with respect to temperature or indeed that of m versus βw_p should be linear.

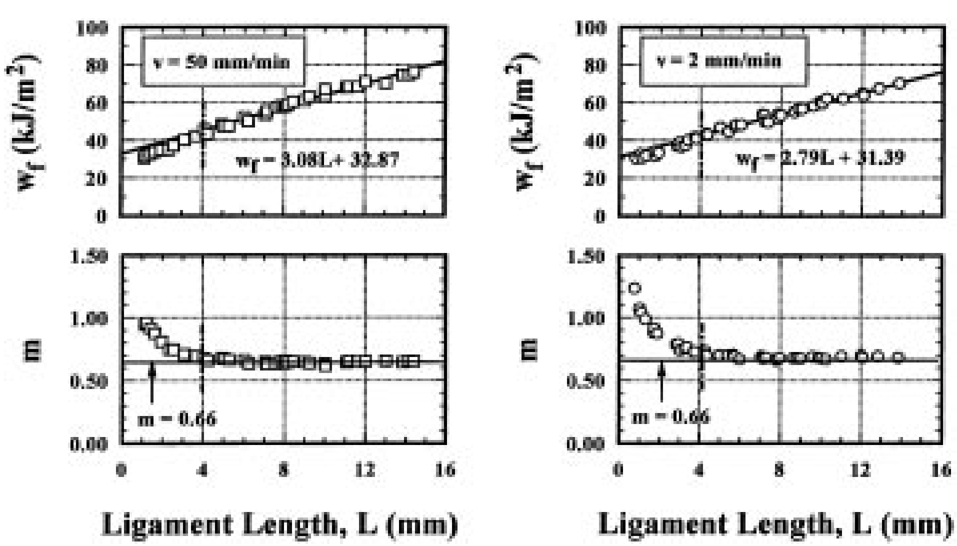

Figure 10 Typical plots of specific total work fracture, w_f, and plastic constraint factor, m, versus of ligament length, L at loading rate values of 2 and 50 mm/min.

4.2. Effect of loading rate

Variation in loading rate did not affect the behaviour of the P-δ curves nor did it change the way in which crack propagated in the specimens, i.e. crack propagation was always stable at all three rates studied here. Plots of w_f versus L and m versus L at loading rate values of 2 mm/min and 50 mm/min are shown in Fig. 10 (respective plots at loading rate value of 5 mm/min are given in Fig. 6) where it can be seen that they are effectively similar to the plots shown in Fig. 6. As before, w_e and βw_p values were determined using only the data points for which $L \geq 4$ mm. It is seen that for loading rate values in the range of 2 to 50 mm/min, w_e is rate insensitive. Indeed previous studies [6, 8, 9] albeit on different polymer systems, have also indicated that w_e is more or less independent of loading rate, at least within the range studied here.

As for the effect of loading rate on βw_p, it was found that this parameter shows no systematic variation with loading rate. Although this observation is similar to that of Chan & Williams [9], it differs to those of Karger-Kocsis *et al.* [8], Hashemi [3, 12] and Arkhireyeva *et al.* [6], where a significant change in βw_p with loading rate was noted.

5. Conclusions

Results obtained from this study indicated that the specific essential work of fracture of polycarbonate film is more or less independent of both temperature and loading rate. On the other hand, the specific non-essential work of fracture, βw_p, while being significantly affected by the temperature showed no systematic variation with loading rate. The βw_p value increased linearly with temperature giving an extrapolated value of zero at -23°C. A linear temperature dependence was also found for m giving an extrapolated value of 0.5 at -23°C.

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