Mechanical properties of poly(ether-ether-ketone) for engineering applications

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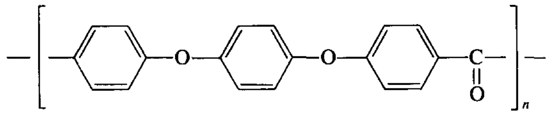
An outline of the characteristics of PEEK and the versatility of its compositional forms (micro and macro composites) are given to illustrate its wide potential for success in engineering applications. Although it is necessary to have particular tabulations of mechanical properties for engineering design, these are seldom available and consequently it is argued that an understanding of stiffness, toughness and strength properties are required to fully exploit available manufacturer's data and thus develop the full potential of PEEK and its composites. Stiffness characteristics are considered in terms of a modulus function which is dependent on time under load and temperature. In its composite forms, whether reinforced with short or continuous fibres, stiffness anistropy can be both considerable and complex, but some empirical ground-rules are apparent. For continuous fibre composites even in the form of complex lay-ups, it is also possible to attempt some stiffness prediction from certain pseudo-elastic constants. Toughness of PEEK and its composites is described in terms of both comparative and intrinsic properties. Instrumented falling weight impact data, particularly as a function of temperature enable some insight into ductile–brittle transitions for the unreinforced material, but crack initiation and crack propagation processes for the various fibre reinforced forms. Intrinsic toughness is described in terms of linear elastic fracture mechanics theory. Strength properties are described for static and dynamic loading configurations. In particular, PEEK and its composites are evaluated for increasing test severities for strength characteristics; stress concentration, loading form and test temperature are considered.

(Keywords: poly(ether-ether-ketone); mechanical properties; composites; engineering applications)

INTRODUCTION

Poly(ether-ether-ketone) is a relatively new aromatic polymer. It has a glass transition temperature of 143°C and a melting point of 334°C[1]. This implies a high temperature performance but also high temperature melt processing, typically in the range (370°–400°C). The maximum achievable crystallinity of PEEK is $\approx 48\%$ although more typical values are $< 30\%$. It has a specific gravity of 1.265 in the amorphous state and 1.320 with maximum achievable crystallinity. The chemical structure of PEEK is:



PEEK is a thermoplastic material and as such it can be converted into a range of component shapes and sizes by the full spectrum of fabrication technologies (extrusion, injection moulding, etc.). It is also possible to compound formulations based on PEEK and the incorporation of short glass and carbon fibres is now a well-established method for preparing injection moulding materials. These compounds are generally referred to as micro-composites. Fibre concentrations up to at least 40% w/w are being evaluated.

A further area of technology where PEEK is used relates to its pioneering role in continuous fibre reinforced thermoplastic composites. It is a polyaromatic matrix and therefore these materials have become known as aromatic polymer composites (APC) being based on continuous carbon fibres in a PEEK matrix. These are referred to as macro-composites. Impregnation technology is applied from which lay-ups of the tapes are then moulded to produce sheet[2,3,4].

PEEK, as a thermoplastic, undergoes the widest conceivable range of processing methods to produce engineering components. PEEK, as a composite material, provides the widest mechanical property spectrum so far achieved by a thermoplastic:

1. modulus in the range (3 to 150) GN m^{-2} at 23°C
2. strength in the range (100 to 2,000) MN m^{-2} at 23°C

It is not surprising therefore that PEEK has considerable potential in engineering applications, which is only just beginning to be realized. These applications can be in various areas of engineering including aerospace, automotive, bearings and electrical. Each area will impose requirements on properties which in turn will dictate the compositional form for PEEK, e.g. unreinforced, biaxial film, short fibre reinforced micro-composite or continuous fibre reinforced APC. Naturally, this also imposes a character on the type of fabrication method to be used, as well as a price for the component.

The mechanical properties for this range of engineering applications need to be specified in some detail. They will comprise considerations of stiffness, toughness and strength and there are many possibilities in terms of which properties are relevant to a particular application. Raw material suppliers provide reference documents of specific properties for specific grades, but before these can be compiled, it is necessary to gain some understanding of mechanical performance. This understanding embraces the various parameters that influence properties (e.g. time,

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temperature, level of deformation) and also how processing might influence these properties. There is also a need to establish which properties depend on geometry or dimensions in their experimental derivation and which are invariant of these factors. This paper is concerned with such an understanding; it is not a catalogue of properties.

The remainder of the paper divides mechanical properties into three categories: stiffness, toughness and strength. It is inevitable, in specific engineering applications, that such simple demarcations are totally false; indeed, balances often have to be made between at least two of these categories. Nevertheless, it is hoped that some insight into these properties can help when selecting and sifting through the tabulated mechanical properties for the PEEK family of materials.

STIFFNESS

Creep

Engineering design based on a stiffness criterion will require an insight into a modulus-time-temperature function. The general deformation behaviour of thermoplastics is known to be non-linear viscoelastic[5]. Consequently, there can be no unique value of a modulus at any specific time under load or at a specific temperature; instead a modulus will be dependent on the magnitude of applied stress (or strain). The degree of non-linear viscoelasticity varies between different thermoolastics, but with PEEK the relationship between stress and strain appears to follow a simple pattern.

Figure 1 illustrates 100s isochronous stress-strain[6] plots for PEEK at temperatures in the range 20°–180°C. The curves are virtually parallel lines on these double logarithmic plots and are straight up to strain levels of $\approx 1\%$. This simple behaviour suggests an ease in predicting intermediate temperature behaviour. The 'glass transition' temperature for PEEK is 143°C[1] (although it depends on test rate) consequently there is a large shift in deformational characteristics between 80° and 150°C.

The time dependence of modulus is investigated in tensile creep tests[6], where experimental results have been collected in the temperature range 20°–180°C and for long times under load (≈ 1 year). Detailed families of creep curves for specific conditions are presented in the manufacturer's booklet[7]. The purpose here is to consider the interacting effects of stress (strain), time and temperature on modulus to examine overall trends.

A tensile modulus can be defined at a specific constant stress or at a specified constant strain. For both definitions of modulus the influence of time and temperature dependence can then be explored. Experimental creep data are generated at a specific test temperature, and usually at several levels of applied stress. The data can be stored in a computer data-bank which then enables detailed interpolations and crossplots[8] to be conducted.

Consequently, it is possible to express several creep functions at various test temperatures as if the short-term stiffness of the material was similar. These functions are illustrated in *Figure 2* where a common 10s strain of 0.5% is used to explore the effect of temperature on the creep characteristic. For the creep curves at higher temperature the applied stresses are smaller because stiffness falls with temperature. With reference to *Figure 2*, it is then apparent that the modulus dependence on time increases with increasing temperature. It is surprising, however, to observe such a small change in time dependence of creep in the large temperature range 20°–180°C, i.e. even at temperatures above the 'glass-transition' temperature.

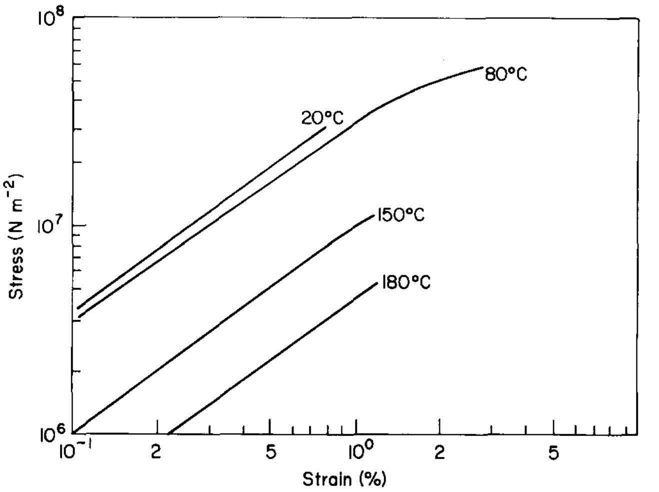

Figure 1 100s isochronous data for PEEK

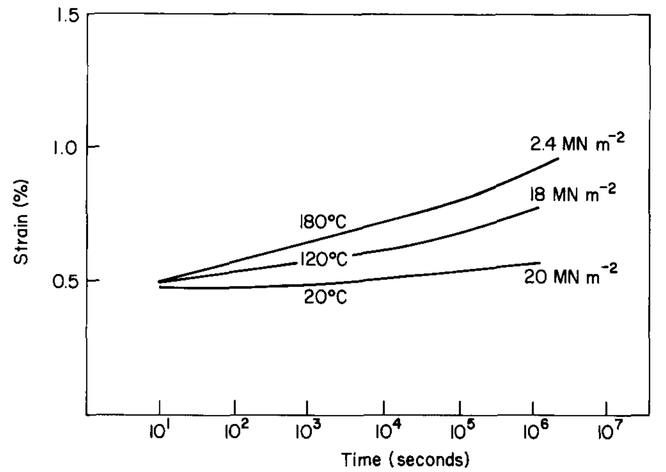

Figure 2 Tensile creep curves for PEEK (subsequent to interpolation of experimental curves)

There are other ways of presenting these deformational characteristics. The creep function involves a changing level of strain; but interpolation and cross-plotting of the creep data enables modulus to be plotted against time, at common and constant deformational levels. *Figure 3* illustrates these isometric plots at a strain of 0.5% and for temperatures in the range 20°–180°C. A simple pattern of behaviour is observed at this level of deformation. Again, the gap between 120° and 150°C reflects the 'glass-transition'.

The simple pattern of deformation characteristics, particularly at small levels of strain (<0.5%), enables a stiffness–time–temperature function to be displayed. This is achieved by a combination of stiffness–time and stiffness–temperature functions[9]. A resultant three dimensional plot is illustrated in *Figure 4*. This plot enables the 'glass-transition' of PEEK to be interpreted at different times under load. This type of information then provides a safe guideline for long-term predictions of stiffness, which can be made up to the 'precipice' presented by the

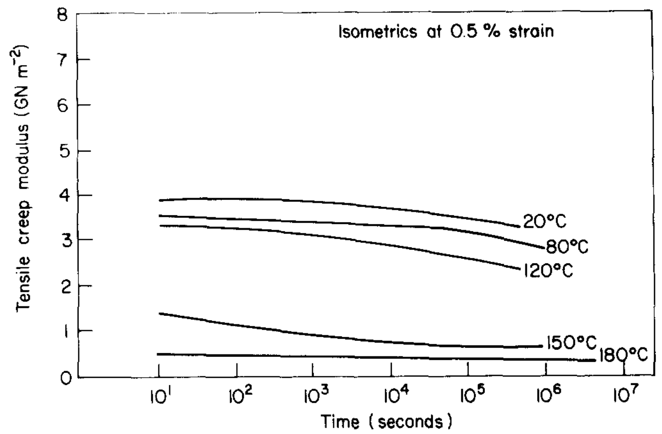

Figure 3 Isometric curves for PEEK (subsequent to interpolation of creep data)

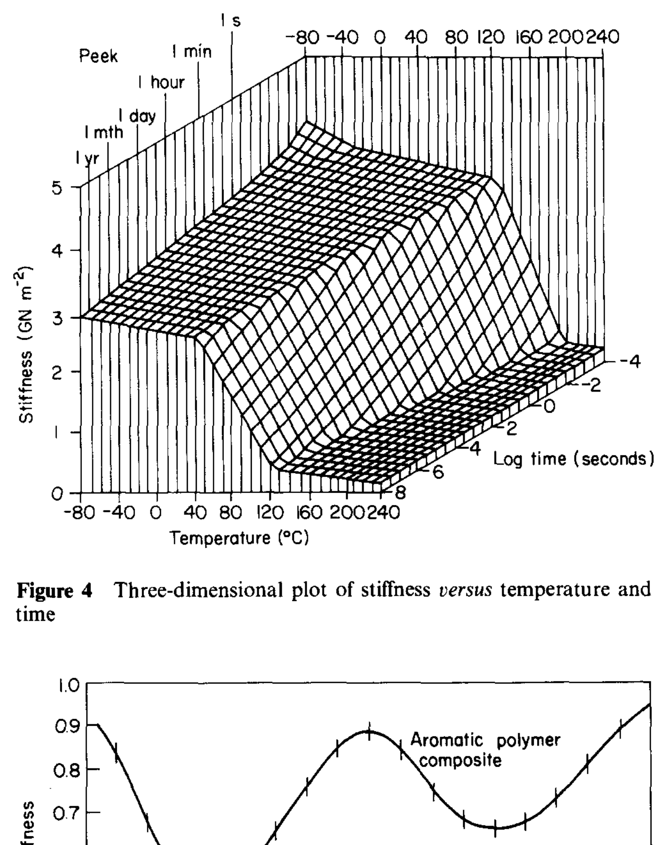

Figure 4 Three-dimensional plot of stiffness *versus* temperature and time

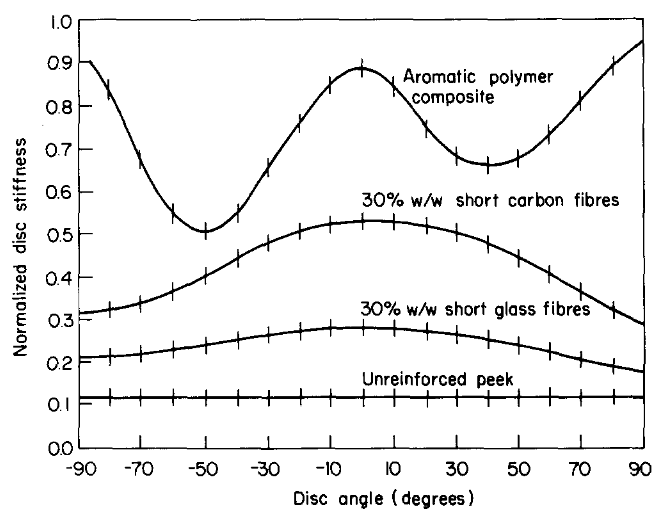

Figure 5 Disc stiffness test at 23°C for various PEEK samples. Maximum disc stiffness = 32.9 GN m^{-2}. Value at any angle = normalized value × maximum value

transition. These predictions of deformational behaviour are also restricted to relatively low levels of strain; at higher strain levels it becomes necessary to consider non-linear viscoelastic effects together with failure and fracture behaviour.

Anisotropy

It is encouraging to identify some simplifying trends in the deformational characteristics of PEEK. Introduction of fibre reinforcement, whether long or short, carbon or glass, adds a further complication; namely, that of anisotropy. Perhaps the clearest and simplest manifestation of anisotropy is illustrated in a disc test[10]. A 115 mm diam. disc is subjected to small strain three line bending and its stiffness is measured at 10° intervals relative to the direction of principal flow or some other reference direction. *Figure 5* illustrates a normalized disc stiffness *versus* direction for four different materials. Normalized disc stiffness is expressed as the ratio of a specific stiffness for any of the four specimens relative to the maximum observed stiffness (32.9 GN m^{-2}) for the APC material reinforced with continuous carbon fibre in a cross plied lay-up ('mat').

The injection moulded single edge-gated PEEK discs show different levels of anisotropy. Virtually no anisotropy is exhibited for the unreinforced PEEK, such that the anisotropy factor would be 1 (anisotropy factor is the ratio of maximum to minimum stiffness). The 30% w/w short carbon fibre reinforced PEEK compound has an anisotropy factor of 1.7, whilst the 30% short glass fibre reinforced PEEK compound has an anisotropy factor of 1.4. The higher stiffness and anisotropy of the short carbon-fibre reinforced PEEK will be partly due to higher fibre volume fraction. Other factors such as the fibre orientation in the skin and core of the moulding as a result of processing may also be important.

The anisotropy of the APC material is naturally governed by the characteristics of the carbon fibre orientation. As can be seen from *Figure 5*, the deformational characteristics for this type of material are more involved. APC materials can be prepared in various ways the most common being the laying-up of the impregnated tapes. Prediction of stiffness performance for these materials can be complex and although outside the scope of this paper, it is nevertheless possible to comment on approach.

The stiffness of different lay-ups of continuous carbon fibre composites can be predicted from the pseudo-elastic* constants of simple consolidated uniaxial sheet or tape. This is the building block of the more complicated structures. When fibre symmetry is assumed (i.e. isotropy in the plane normal to the fibres), five independent pseudo-elastic constants are required for the sheet[11]. Tensile testing of thin sheets along and normal to the fibre direction enables three of these to be determined, torsion about the fibre axis gives a fourth[12]. *Figure 6* illustrates five pseudo-elastic constants:

E_{11}—modulus in the fibre direction
E_{22}—modulus normal to the fibre direction
ν_{12} and ν_{21}—lateral contraction ratios
G_{12}—shear modulus in the plane

These are not independent but are linked by the relation:

* 'Pseudo-elastic' is used to describe modulus, etc., obtained under one particular test rate or duration. This distinguishes it from truly elastic behaviour, although the time dependence is only slight

Typical elastic properties for APC (23°C) (60% v/v carbon fibre)	
E_{11} (GN m^{-2})	124
E_{22} (GN m^{-2})	8.9
ν_{12}	0.38
ν_{21}	0.04
G_{12} (GN m^{-2})	4.0

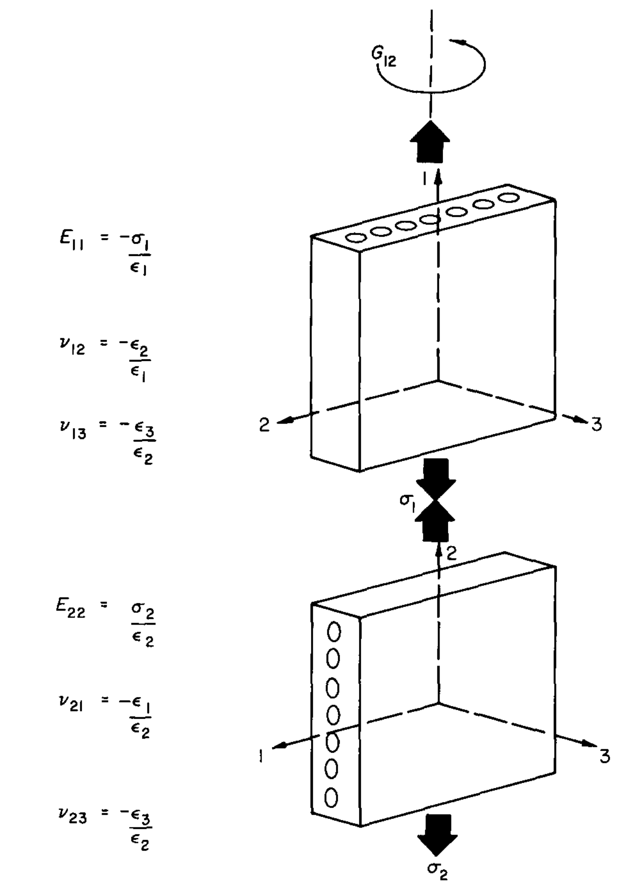

Figure 6 Typical elastic properties and constants for APC

$$\frac{E_{11}}{E_{22}} = \frac{\nu_{12}}{\nu_{21}}$$

They can be determined on a universal testing machine equipped with axial and lateral extensometry. The experimental technique is described elsewhere[13]. *Figure 6* shows typical results for APC material. The above relation is not precisely obeyed, probably reflecting the difficulty in obtaining a precise value for ν_{21}. Alternatively, the assumption of fibre symmetry may be inappropriate.

These pseudo-elastic constants allow a tensile modulus as a function of test direction to be determined using laminate theory[14]. With a second shear modulus G_{23}, the set of pseudo-elastic constants is complete. From these (and their time and temperature dependence) the stiffness properties of different lay-ups can be predicted.

TOUGNESS

Preamble

An objective measure of toughness is difficult to obtain because of geometry dependence. Therefore, a simple expression of absorbed impact energy per unit ligament area from a Charpy or Izod test is very likely to mislead. Additional consideration should be given to the prospect of different types of failure and fracture, where ideally these should be similar for toughness comparisons.

In discussing toughness for PEEK and its composites, two approaches will be used. First, geometry-dependent types of test, but where resolution of failure and fracture modes is possible; this approach involves an instrumented falling weight impact (IFWI) technique[15]. Second, a geometry-independent fracture test where linear elastic fracture mechanics techniques are adopted to measure critical values for both stress field intensity factor (K_c) and strain energy release rate (G_c).

Instrumented falling weight impact

Toughness measurements from an IFWI technique involve monitoring a force-time plot during impact. This is conducted at a test speed of $5\,\mathrm{m\,s^{-1}}$ and in the temperature range $-70°$ to $+100°$C. Analysis of the force-time curve enables a number of parameters to be calculated. Two of these are of particular interest, namely, the total energy absorbed by the specimen for complete fracture and also the energy absorbed to initiate a specific failure (i.e. yielding, initiation of a crack). Details of the technique are more fully described elsewhere[15], but in these experiments on PEEK and its composites a specific set of test conditions is used. (A plaque specimen is supported on a ring of 50mm diam. and impacted with a cylinder whose hemispherical end has a diameter of 12.5mm). All injection-moulded samples were single edge-gated 115mm diameter discs of thickness 3mm, whilst the APC plaques were 2mm thick. In some separate experiments on APC material, the relationship between absorbed energy and plaque thickness has been established:

$$\text{Total energy} \propto \text{thickness}^{1.47}$$

$$\text{Initiation energy} \propto \text{thickness}^{1.42}$$

These empirical rules enabled the APC data to be normalized to a plaque thickness of 3mm to compare toughness with the injection-moulding materials of that thickness.

Figure 7 illustrates plots of absorbed energy *versus* test temperature for unreinforced PEEK. A transition from ductile to brittle fracture can be defined in temperature

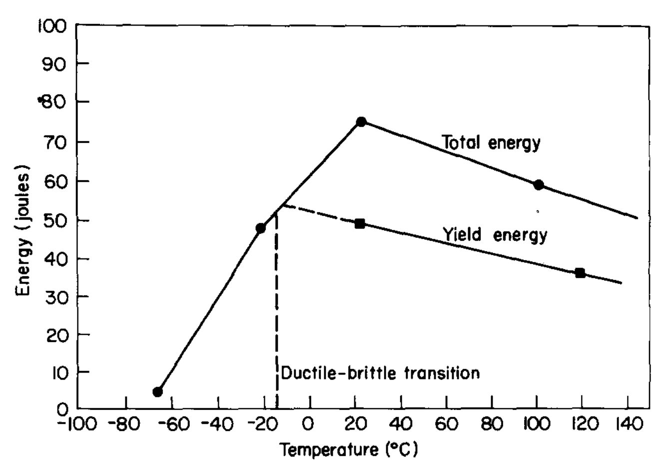

Figure 7 Energy absorbed *versus* temperature for unreinforced PEEK. Conditions: $5\,\mathrm{m\,s^{-1}}$, 50mm support diameter, 12.5mm impactor nose

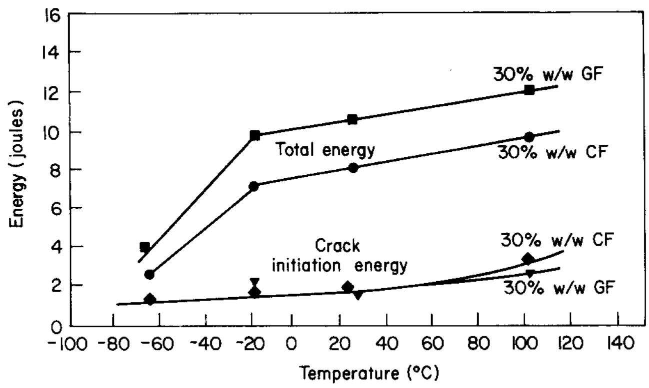

Figure 8 Instrument falling weight impact 30% w/w carbon and glass fibre reinforced disc mouldings. Conditions: $5\,m\,s^{-1}$, 50 mm support diameter, 12.5 mm impactor nose

terms as that temperature where the extrapolated yield energy curve intercepts the total energy curve. Consequently, a ductile–brittle transition temperature of about −15°C is recorded for PEEK (albeit a geometry dependent parameter).

Injection mouldings of short fibre compounds of PEEK were also prepared in the same mould tool. But microcomposites do not usually exhibit ductile–brittle transitions in their impact performance, because other failure processes dominate. *Figure 8* illustrates impact energy *versus* temperature plots for compounds based on 30% w/w short carbon and glass fibres. Fracture occurs by crack initiation[16] and is followed by crack propagation. Consequently, total energy comprises initiation and propagation components (both dependent on geometry). There appears to be little difference in crack initiation between carbon and glass fibre reinforced materials over the experimental test temperature range, whilst total energy to fracture is larger for glass-fibre-reinforced PEEK. This implies that the energy to propagate a crack is lower for carbon-fibre-reinforced PEEK compared with that for the glass fibre system. This may be an effect of the fibre volume fraction because it is higher for the carbon composite, but might also be related to the flow anisotropy.

The component of energy required to initiate a crack is small compared with the total fracture energy, particularly at temperatures above −20°C, for both compounds. Consequently, crack propagation would be expected to be the dominant energy absorbing process. At temperatures below −20°C, crack propagation energy decreases relative to the energy required to initiate a crack. With reference to *Figure 7* for the unreinforced material, this is co-incident with the PEEK becoming brittle. Therefore, it is implicit for the fibre-reinforced PEEK that the crack initiation process is fibre dominated, whilst propagation is matrix dominated. Consequently, when the matrix is tough, crack propagation is the energy absorbing process; but when the matrix is brittle, then crack initiation becomes the energy absorbing process.

The impact behaviour for the continuous carbon fibre PEEK composites exhibit different failure/fracture characteristics. *Figure 9* illustrates impact energy *versus* temperature plots for quasi-isotropic lay-ups which are 2 mm thick. (Data normalized to 3 mm thickness are also included for comparison with the injection moulded discs.) Again, initial failure is through cracking followed by subsequent propagation. But observation of the fractured specimens shows that the overall area of impact damage is restricted to that in and around the impact area, i.e. long crack propagation is restricted by the lay-up. The energy absorbed in initiating and propagating failure is greater for APC than for the microcomposites. This results in a considerable increase in the total energy absorbed. By contrast to the microcomposites, the total energy absorbed by APC does not fall markedly between −20° and −50°C. This suggests that the fibres dominate the propagation process for APC as well as initiation.

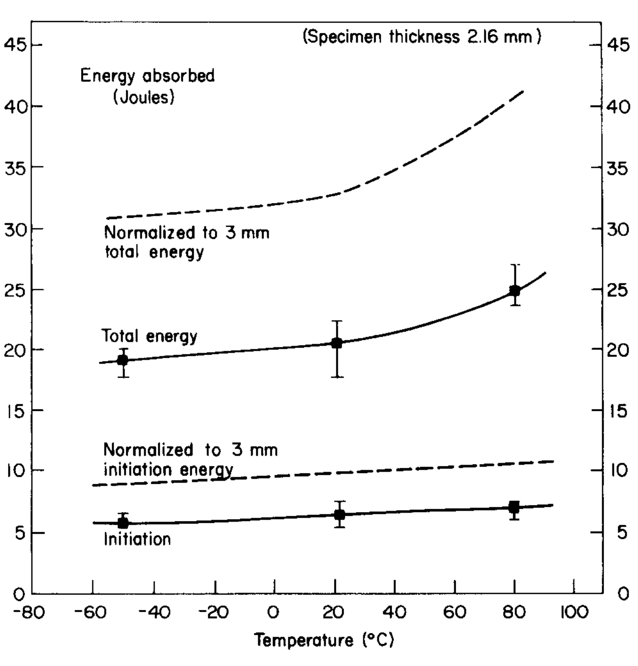

Figure 9 Impact data for an aromatic polymer composite. Conditions: 60 vol% carbon fibres $-[+45/0/-45/90]_{2S}$ lay-up; specimens 75 × 75 mm, $5\,m\,s^{-1}$, impactor nose 12.5 mm

Intrinsic toughness

Instrumented falling weight and other impact techniques enable comparative toughness to be measured. However results from these techniques are all geometry dependent and this limits their usefulness in both providing understanding and enabling design for toughness. Consequently it is helpful to use linear elastic fracture mechanics methods to measure intrinsic toughness[17]. Two toughness parameters are usually of interest:

K_{CI}—a plane strain value for the critical stress field intensity factor.

G_{CI}—a plane strain value for the critical strain energy release rate.

A relevant value of yield strength is necessary to complete the toughness picture, and the merits of these three parameters are discussed elsewhere[18]. It is not our intention to present a comprehensive fracture toughness picture for PEEK, but rather to present a set of intrinsic toughness values and to comment on the importance of establishing experimental conditions that lead to interpretable data.

While it is relatively easy to obtain 'fracture toughness parameters' these will only be of use if they are indeed intrinsic properties. To ensure that this is the case, certain criteria must be imposed to ensure that the measured values are independent of geometry. These problems have already been considered and a set of recommended experimental constraints have emerged[19,20]. To ensure that the ductility at the crack tip is small (i.e. plane strain conditions) it is suggested that[20]:

$$\frac{b}{b_{\min}} > 1 \qquad (1)$$

where b is the beam width (see *Figure 10*) and:

$$b_{\min} = 2.5\left(\frac{K_{\mathrm{CI}}}{\sigma_y}\right)^2$$

To achieve geometry independence they suggest the following condition:

$$\frac{w}{w_{\min}} > 1 \qquad (2)$$

where w is the specimen depth and

$$w_{\min} = 5\left(\frac{K_{\mathrm{CI}}}{\sigma_y}\right)^2$$

Usually if condition (1) is not met then the measured K_c (or G_c) will be larger than the plane strain value. However if condition (2) is not met then the measured value will be too small. Hence if neither condition is met the fracture toughness results will be difficult to interpret.

The fracture toughness measurements were made on notched beam specimens tested in three line flexure, the experimental techniques being described elsewhere[21]. The specimen dimensions were 70 × 11 × 3 mm, and they were supported on a 50 mm span, with notches of nominal 10 μm tip radius machined into their surface. A range of notch depths were used.

Fracture toughness results for unreinforced PEEK are shown in *Figure 10*, using two test conditions, namely 23°C with a test speed of 100 mm min^{-1} and −40°C with test speed of 1 m s^{-1}. Taking the yield stress temperature behaviour discussed in the next section then the values at 23°C and −40°C are 100 MN m^{-2} and 145 MN m^{-2}, respectively. Putting the experimental data into the two requirements of expressions 1 and 2, it can be seen that the 23°C data met neither the specimen thickness criteria (since $b/b_{\min} = 1$) nor the depth criteria (since $w/w_{\min} = 0.3$). As discussed earlier these data cannot therefore be readily interpreted and certainly cannot be used as intrinsic toughness data. The results at −40°C do meet both criteria as $b/b_{\min} = 10$ and $w/W_{\min} = 1.1$. Therefore these fracture toughness results are plane strain, geometry independent values, and a complete set of fracture toughness parameters would then be (σ_y vs. temperature: see *Figure 11*):

$$K_{\mathrm{CI}}(-40°\mathrm{C}) = 3.3\ \mathrm{MN\,m^{-3/2}}$$

$$G_{\mathrm{CI}}(-40°\mathrm{C}) = 4.8\ \mathrm{kJ\,m^{-2}}$$

Introducing intrinsic fracture toughness techniques, it is shown how such measurements lead to an understanding of toughness, but that they must involve geometry independence, and that proper consideration must be given to the test conditions. It is also shown that unless due care is taken, then even in apparently straightforward situations, the introduction of a fracture mechanics approach can lead to confusion rather than clarity.

STRENGTH

Static strength

Strength is considered in terms of its magnitude and the mode of failure; time under load and environmental temperature are also prime factors. In general terms, unreinforced PEEK exhibits a yielding or shear banding process whilst fibre-reinforced composites are dominated by the fibre and show crack-like fractures.

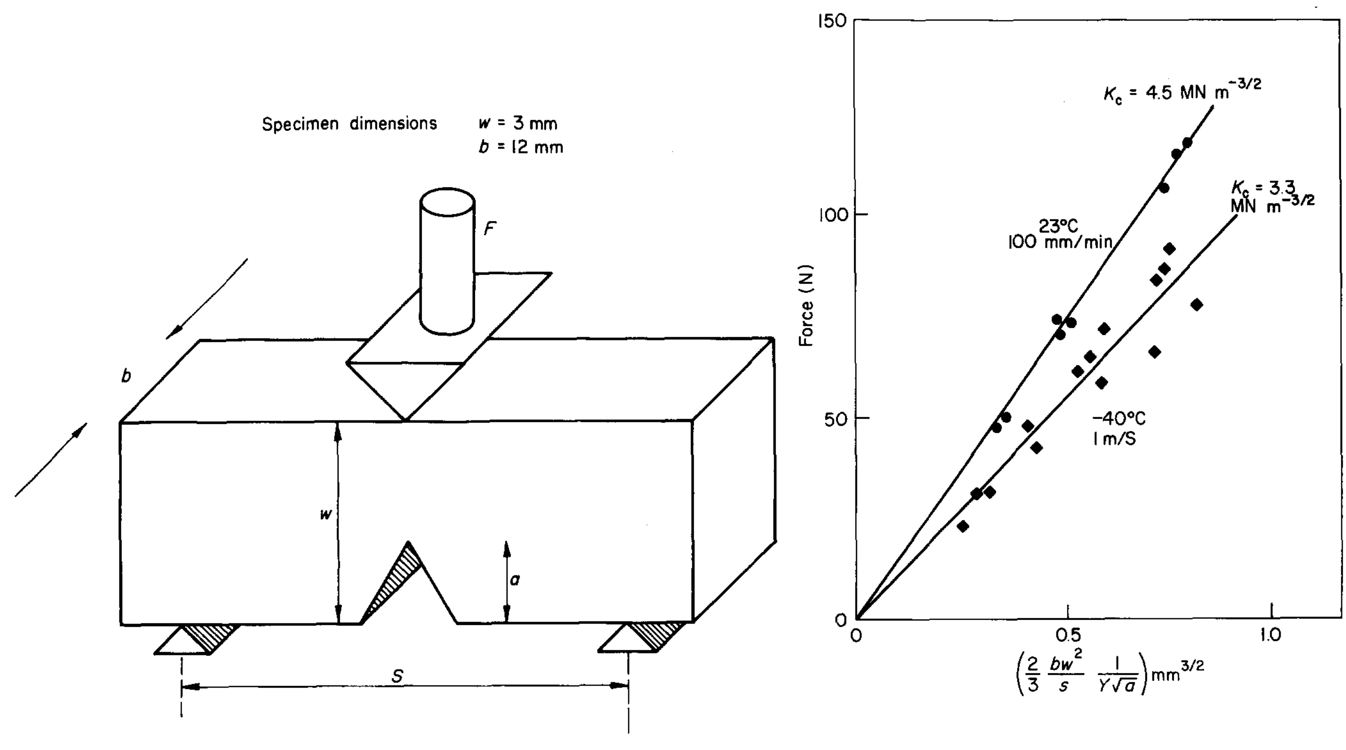

Figure 10 Fracture mechanics plots for a grade of unreinforced PEEK

A full picture of the time and temperature dependence of yield stress can be generated from short-term strength and some creep rupture functions. *Figure 11* illustrates yield stress *versus* temperature obtained at a test speed of 5 mm min^{-1} (elapsed time under load of $\approx$20 s) on waisted tensile bars. *Figure 12* illustrates yield stress *versus* elapsed time under load (observed as necking in the creep rupture test) for similar specimens tested at 23 and 150°C. It is noticeable that the influence of temperature is greater than that of time under load.

The influence of short fibre reinforcement for injection moulded samples can be expected to enhance static strength. *Figure 13* illustrates creep rupture curves at 150°C (fibre reinforcement is introduced to improve high temperature performance) for unreinforced PEEK, 30% w/w short glass fibre and 30% w/w short carbon fibre PEEK compounds. Data are included for specimens cut from 115 mm single edge gated disc mouldings, 3 mm thickness, where specimens are either cut along the principal melt flow direction (0° specimens) or at right angles to it (90° specimens), as illustrated. It is apparent that the strength of the 30% w/w carbon fibre reinforced PEEK is greater than that for the 30% w/w glass fibre reinforced PEEK, which in turn is superior to that for the unreinforced material, considerations of anisotropy apart. This relative strength position is maintained for all elapsed times under load.

Strength anisotropy for these injection moulded compounds is not so straight forward. For the unreinforced PEEK, the directional dependence of strength is minimal (if detectable), but the fibre reinforced PEEK compounds exhibit significant anisotropy. The glass fibre reinforced material shows higher strength for 0° specimens, whilst the carbon fibre reinforced material exhibits higher strength for 90° tensile specimens. This observation together with the degree of anisotropy (ratio of 0° to 90° properties) indicates a fundamental difference between stiffness and strength properties. An explanation can be given in terms of the fibre orientation produced in the diverging flow field during injection moulding[22,23]. It is known that fibres in the 'skin' regions are predominantly aligned along the principal flow direction whilst in the 'core' fibres are mostly transversely aligned. A tensile stress applied to 0° and 90° specimens will produce different response from a flexural stress applied at 0° or 90°. The tensile (or compressive) strain is constant through the thickness of the specimen in the first case but is a maximum at the surface in bending. Therefore the properties in flexure will be dominated by the skin. This is

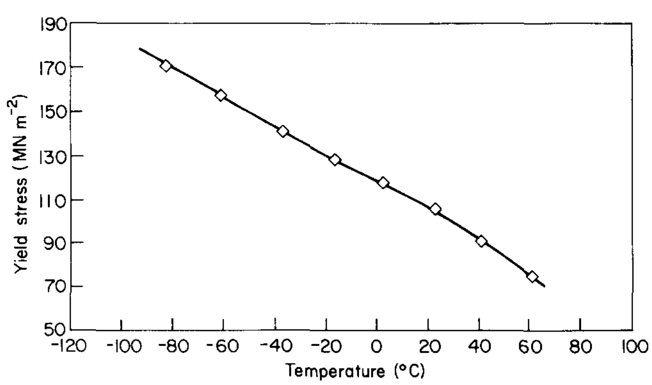

Figure 11 Yield stress *versus* temperature PEEK (5 mm min^{-1})

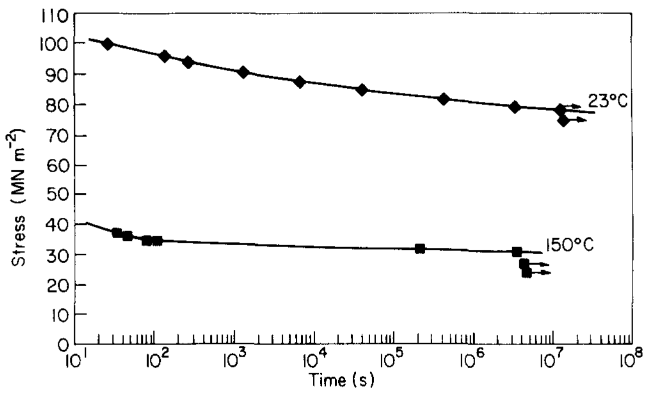

Figure 12 Tensile creep rupture for PEEK, specimens cut 90° to flow

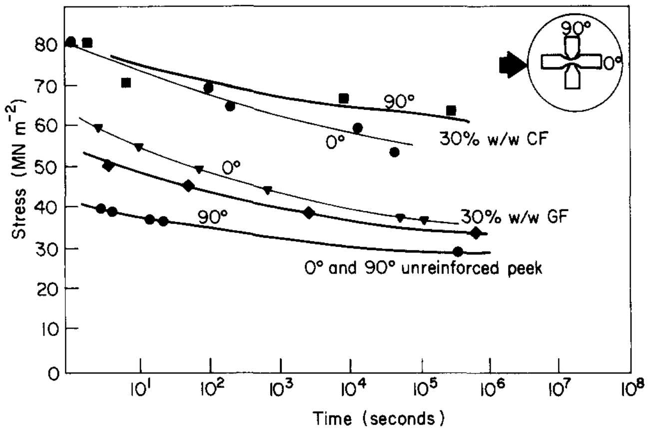

Figure 13 Creep ruptures curves at 150°C

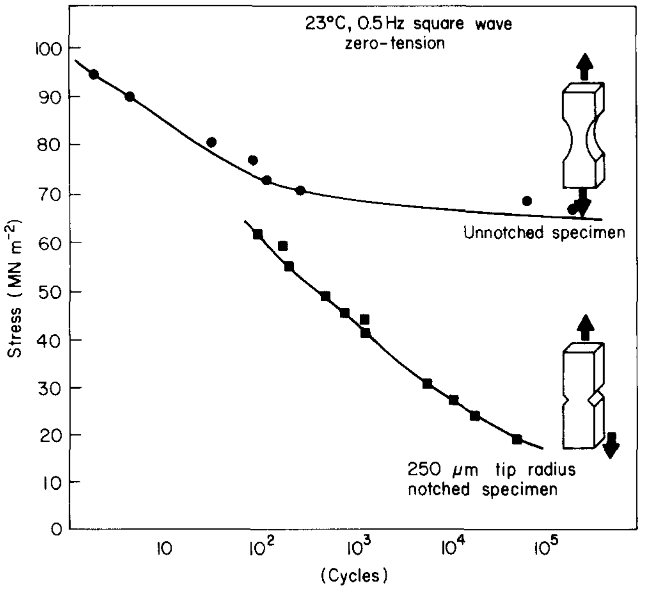

Figure 14 Stress *versus* log number of cycles to fracture for 90° specimens of unreinforced PEEK

shown by the flexural stiffness anisotropy of both materials (*Figure 5*). The strength results suggest that glass-fibre reinforced PEEK is dominated by fibres aligned at 0° in the skin whereas carbon-fibre-reinforced PEEK is dominated by fibres aligned at 90° in the core. In the latter case, the 90° strength is greater than that at 0°, a surprising result.

Because of these results, a unique property value for stiffness or strength will not exist. Moulding thickness and gate geometry will have an overriding influence. Generally, thinner mouldings will be more dominated by skin layers. The 3 mm thick mouldings used here are typical of component thickness but otherwise are as arbitrary choice.

These considerations do not arise in long carbon-fibre-reinforced PEEK because the lay-up design dictates properties. The time dependence of strength for APC is virtually non-existent, even when tensile specimens are cut from ±45° fibre lay-ups. For example, the reduction of creep rupture strength between times under load of 10 and 10^7 s is <13% at 23°C.

Dynamic strength

Increasing the test severity enables an even more critical view of the strength characteristics of PEEK and its composites. Dynamic loading and the introduction of stress concentrations are known to precipitate crack-like fractures in many plastics[24]. *Figure 14* illustrates zero-tension fatigue plots for unreinforced PEEK for notched (250 μm tip radius) and unnotched specimens. Neither curve relates to classical brittle fractures even though the presence of the notch reduces the strength. In the experiments conducted on unnotched specimens the degree of ductility extends up to gross yielding particularly at the higher stress levels; for the notched specimens, a much lower level of ductility is observed.

The relative fatigue performance of PEEK and its injection moulding compounds is shown in *Figure 15* for 90° specimens. Again, carbon-fibre-reinforced PEEK is stronger than the glass-fibre-reinforced PEEK. However, from the remarks about the fibre alignment and anisotropy it is apparent that the choice of 90° specimens cut from single edge-gated discs favours the carbon fibre material.

Perhaps of greater significance is the comparison of strength between static and dynamic loading. To this end, fatigue data can be presented in terms of cumulative time under load, when square waveform testing has been conducted. The total time under load being equal to the total number of cycles to fracture divided by twice the wave-form frequency. *Figure 16* illustrates stress *versus* log time plots for unreinforced PEEK where dynamic loading is seen to lower the strength. *Figure 17* illustrates similar plots for the 30% w/w short glass fibre reinforced PEEK. In both cases, the dynamic loading will minimize the plastic deformation, because the off-load period allows strain recovery. In both cases, this leads to reduced strength and reduced ductility.

Long carbon fibre PEEK (APC) is less dependent on time (or total number cycles) in fatigue than short carbon fibre PEEK. Such comparisons are less straight-forward because of the very different strengths of the two composites. APC can exhibit strengths up to 2000 MN m^{-2} whilst short carbon-fibre-reinforced PEEK will be an order of magnitude less strong. Consequently, fatigue data can be compared by plotting the ratio of fatigue strength to short term static strength against number of cycles to fracture. *Figure 18* illustrates such plots for two APC lay-ups (uniaxial carbon fibres and 0/90 lay-ups) against (the favourable) 90° specimens of short carbon-fibre-reinforced PEEK (30% w/w). The dominance of the fibre system is illustrated both in terms of orientation and concentration. It is apparent that time dependence of even fatigue strength is small when full alignment of the carbon fibres, and a high concentration of them is achieved.

CONCLUSIONS

Successful engineering application involves making certain choices correctly:

1. specifying the conditions for the application, particularly in terms of stress or strain, time under load, temperature, and geometry;
2. conducting an appropriate stress analysis so that a link can be made between loading conditions, geometry and material properties; and
3. knowing what mechanical properties are required, where to find such properties and how to interpret them in the light of the above stages.

These stages also incorporate decisions on material selection, fabrication method and costs.

This paper has provided a background for PEEK to assist successful engineering application. It has identified

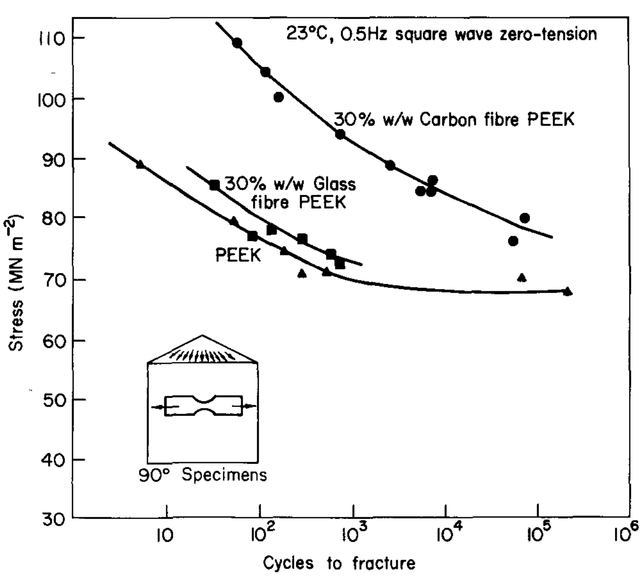

Figure 15 Stress *versus* log number of cycles to fracture for various PEEK samples, 90° specimens

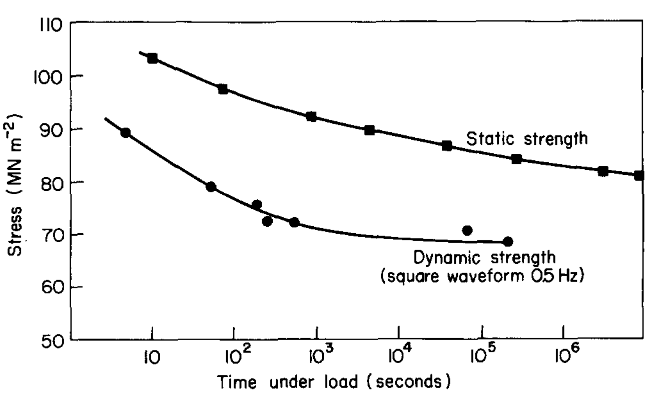

Figure 16 Comparison of static and dynamic strength for PEEK at 23°C, 90° specimens

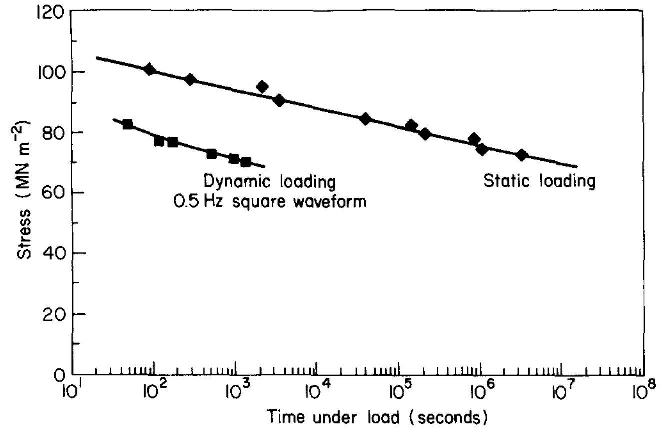

Figure 17 Comparison of static and dynamic strength 30% w/w glass fibre PEEK at 23°C, 90° specimens

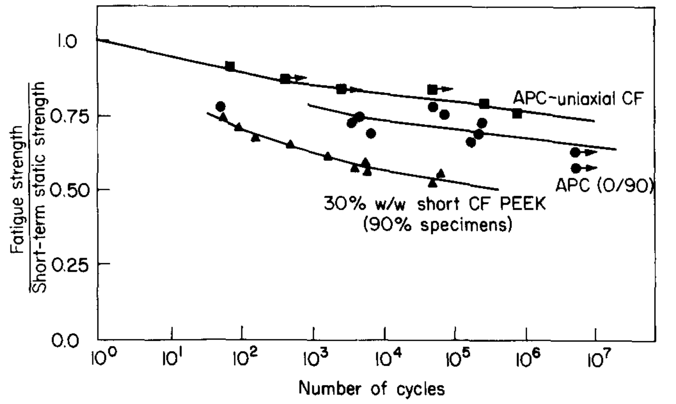

Figure 18 Comparative and normalized fatigue curves for short and long carbon fibre PEEK

the various forms of PEEK in terms of unreinforced material, micro-composite and macro-composite. It has described the various factors that influence their mechanical properties.

The raw material supplier will provide data sheets and catalogues of mechanical properties, but generally these will need interpretation and manipulation before application in design. For example, a specific application may need mechanical property data at other temperatures, times and stresses from those presented in the data sheets and the like. The foundation for some prediction or interpolation is presented here.

In terms of material and property selection, the two approaches to toughness complement each other. The instrumental falling weight impact technique is useful for material comparison whilst fracture toughness can establish intrinsic toughness. Underlining the importance of service conditions is illustrated by the influence of test severity on strength. It is shown that dynamic loading and high stress concentration reduce strength and again some empirical trends can be established.

It is our expectation that the future will see numerous successful engineering applications for PEEK and its composites. We hope that the contents of this paper will prempt the right choices that will be needed in the engineering design.

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