MEASUREMENT OF THE FRACTURE TOUGHNESS OF POLYMER CONCRETE

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ABSTRACT

Current uses for polymer concrete generally exploit only the compressive properties of the material. For potential applications, such as casings, it becomes necessary to understand the behaviour of these materials under tensile loading. This paper examines the fracture behaviour of polymer concretes containing two different sand size ranges, in comparison with the filled polyester matrix. The relevance of fracture toughness measurements and the effects of notch root diameter in combination with the statistical strength variability are considered.

KEYWORDS

Polymer concrete, fracture toughness, stress concentration, notch root radius, Weibull modulus.

INTRODUCTION

The fracture toughness of conventional metallic materials is generally measured by testing specimens containing sharp cracks, usually introduced by fatigue. For composite materials, such as polymer concrete, this method is generally inappropriate, both because of the difficulties in introducing fatigue cracks into brittle materials and the uncertainty as to the interaction between a sharp crack and the relatively large particles and voids found in these materials.

The term, polymer concrete, usually refers to a mixture of a polymer resin with a sand-based aggregate, as examined in the present paper. (The term is also used to describe various combinations of cement based concrete with polymer additives.) Polymer concretes do not fit easily into any of the common groups of composite materials which include continuous fibre polymer composites, metal matrix composites, cement concretes, and short fibre and particulate composites. Instead, they show some individual features in common with such groups, whilst in other respects they are very different.

Perhaps the most obvious material for initial comparison is cement concrete since the nature of the filler is very similar, i.e. sand or larger aggregate. Many of the present uses for polymer concrete are also very similar to those for cement concrete, e.g. road carriageway repairs, floor tiles, sewage pipe linings, etc. (Fowler, 1987; Goudev, 1975; Bares, 1978). Such uses mainly exploit the compressive strength of the material which is strongly influenced by the quantity of aggregate present. In this type of application the inclusion of large quantities of aggregate is therefore desirable, aggregate/aggregate contact is not necessarily detrimental and may even be advantageous. However, care must be taken when comparing polymer and cement concretes as the matrix behaviour of the materials is somewhat different.

Interest is currently growing in the use of polymer concretes in applications where tensile loading will be experienced. Designing with polymer concrete in tension requires information on the appropriate parameters to characterise strength when stress concentrating features are present. For this reason, an investigation of the notch sensitivity of polymer concretes, as a function of notch root diameter, has been conducted. It is also important to study the strength variability inherent in these materials and the way in which it interacts with the effect of notches. This variability is quantified in terms of the Weibull modulus.

In this investigation polymer concretes containing two different sand filler sizes are examined and compared with the matrix material, a microsilica filled polyester. Consideration is given to three areas: whether fracture toughness is a useful design parameter for polymer concrete; the effect of the size of the filler in relation to the stress concentrator by means of a study of the effects of notch diameter and filler size; whether notch strength can be predicted using a Weibull modulus/specimen volume approach.

MATERIALS

The materials used were a polyester resin filled with a fine microsilica powder and sand, in the following proportions (by weight).
MS (microsilica): 1 part polyester resin : 0.15 parts microsilica : 0 parts sand.
SF (sand, fine): 1 part polyester resin : 0.15 parts microsilica : 3 parts sand (size range 0.3-0.7mm).
SC (sand, coarse): 1 part polyester resin : 0.15 parts microsilica : 3 parts sand (size range 0.7-1.4mm).
Material MS was the matrix material used for the two polymer concretes. All specimens were heat-cured at 80°C for four hours prior to testing. Fractographs of the three materials are shown in figure 1, in which voids and particle size and distributions can be seen.

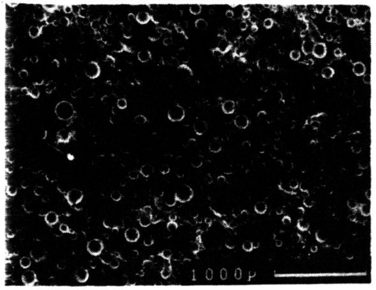

Fig. 1a: MS material.

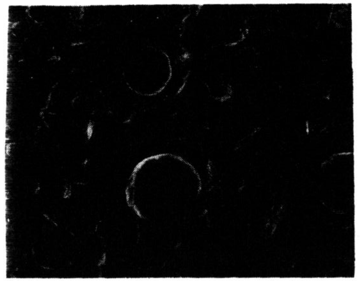

Fig. 1b: SF material.

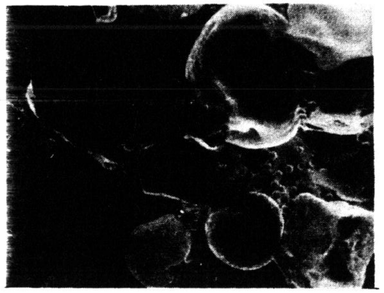

Fig. 1c: SC material.

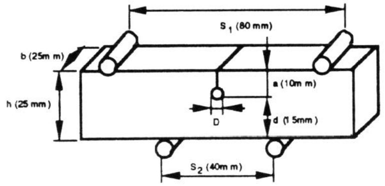

Fig. 2 Schematic view of loading arrangement.

EXPERIMENTAL TECHNIQUES

Notch Radius Effects. Specimens 25mm x 25mm x 100mm, with notch diameters of 0.4mm, 0.8mm, 1.1mm, 2.0mm, 2.5mm, 3.0mm, 4.0mm, 6.0mm, 8.0mm were used for each material, with the addition of 0.15mm, 0.25mm and 1.5mm notches for the MS material. The notches were machined into the specimen using drills and slitting wheels and were nominally 10mm deep. Un-notched specimens of each material were also tested for comparison.

Procedure. The specimens were tested in symmetrical four point bend loading, with a major span, S_1, of 80mm and a minor span, S_2, of 40mm. A schematic view of the loading arrangement is shown in figure 2. Tests were performed on a 100kN servo hydraulic Mayes testing machine at a constant cross-head speed of 0.1mm per minute and the load at failure was recorded for each specimen. A clip gauge was mounted across the notch for the fracture toughness tests, and a plot of clip gauge opening against load made during each test.

Young's Modulus. This was measured using 30mm long strain gauges attached to un-notched four-point bend test specimens of the dimensions specified above. Strain was read from a digital strain gauge amplifier for particular loads and the Young's modulus calculated assuming that the behaviour at low strains was described by simple beam theory.

RESULTS

Un-Notched Strength. Average un-notched strength values measured for the materials in four point bending are as follows:
MS: 21MPa (4 specimen average with a range of 15 - 27MPa)
SF: 18MPa (6 specimen average with a range of 15 - 22MPa)
SC: 17MPa (4 specimen average with a range of 16 - 19MPa)

Young's Modulus. The Young's modulus values used in calculations are: MS: E=3GPa; SF and SC: E=13GPa. Measured values of Young's modulus appeared fell as the applied load was increased. This may be due to a small amount of debonding between matrix and sand, occurring within the specimen prior to failure. Measured values of modulus ranged from 2.4 to 3.2 GPa (MS material), and from 11.5 to 13.9GPa (SF and SC materials). These values are similar to those found in the literature, typically E≈3.2GPa, at room temperature, for polyester resin (Vipulanandan et al., 1987; Vipulanandan et al., 1988), and E≈13-18GPa for sand filled polyester (Ahmed and Jones, 1988).

Weibull Modulus. For all three materials an approximate Weibull modulus of 10 has been used. This value was determined for a polymer concrete, containing sand and gravel, from a series of tests on 100 bend specimens (Tarafder and King, 1990; Pemberton and King, 1991). The limited data for the three materials in this paper and for other polymer concretes of similar types suggest that a similar value of m is appropriate.

Fracture Toughness Measurement. The apparent fracture toughness of the specimens, K_{app}, was calculated on the assumption that all notches could be treated as a sharp cracks, using the equation:

$$K_{app}=\{YP(S_1-S_2)\}/[6bh^{3/2}] \qquad (1)$$

where K_{app} is the apparent fracture toughness, Y is the compliance function given by:

$$Y=9\{1.99(a/h)^{1/2}-2.47(a/h)^{3/2}+12.97(a/h)^{5/2}-23.17(a/h)^{7/2}+24.80(a/h)^{9/2}\} \qquad (2)$$

(Walker and May, 1967) and other parameters are defined in figure 2.

Apparent fracture toughness (averaged from a minimum of three tests for SC and SC, and data from single tests for MS) is plotted against notch diameter in figure 3. For the microsilica material, MS, the data show a degree of scatter, however the apparent fracture toughness is approximately constant at notch diameters below 2mm, and then rises to a higher constant value at larger diameters. For the fine sand material, SF, apparent fracture toughness initially rises with increasing notch diameter and then becomes approximately constant. The toughness of the coarse sand material, SC, is almost independent of notch diameter, but shows a slight drop off towards the largest diameters. Apparent toughness values at smallest and largest notch diameters are listed in table 1.

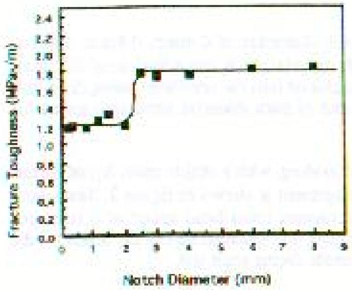

Fig. 3a: Apparent fracture toughness: MS material.

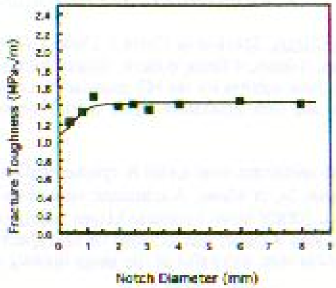

Fig. 3b: Apparent fracture toughness: SF material.

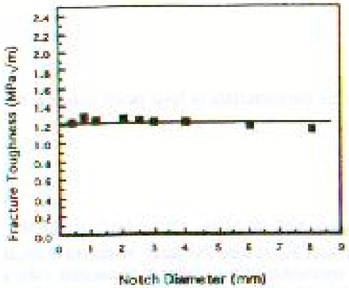

Fig. 3c: Apparent fracture toughness: SC material.

The apparent energy release rates, G_{app}, have also been calculated using the equation:

$$G_{app}=\{(1-\nu^2)K_{app}{}^2\}/E \qquad (3)$$

where ν is Poisson's ratio and has been taken as 0.3 (Kimura et al., 1987). G_{app} values at smallest and largest notch diameters are also given in table 1.

Table 1: Apparent toughness values at smallest notch diameters and largest notch diameters

Material	K_{app} at smallest notch diameter (MPa√m)	K_{app} at largest notch diameter (MPa√m)	G_{app} at smallest notch diameter (Jm^{-2})	G_{app} at largest notch diameter (Jm^{-2})
MS	1.2	1.8	543	1239
SF	1.2	1.4	106	140
SC	1.2	1.1	106	92

Microstructure and Crack Path. Fracture surfaces from notched MS, SF and SC specimens are shown in figure 1. In the two sand filled materials, SF and SC, there is no obvious effect on the fracture surface due to the notch geometry, nor between the notched and un-notched specimens. In both of these materials failure involves debonding of the sand from the matrix and there is no sign of sand particle failure in the bulk material. In the matrix material, MS, the fracture surface in the region of failure to becomes rougher as the notch diameter increases with the effect being most pronounced in the un-notched specimens. There is some evidence in all three materials, that failure may initiate at or near to flaws in the material near the base of the notch, e.g. voids and broken or poorly bonded sand particles. In all three materials numerous voids are visible on the fracture surfaces.

Nett Section Stress Analysis. In order to determine whether the notches were having any significant effect on the strength of the bars, other than simply a reduction in the cross section, nett section stress values at failure, σ_{NSS}, were calculated, using the expression:

$$\sigma_{NSS}=\{3P(S_1-S_2)\}/2bd^2 \qquad (5)$$

where P is the applied load at failure and the other parameters are defined in figure 2. The results are plotted as nett section stress versus notch diameter, figure 4, and show similar trends to the K_{app} data.

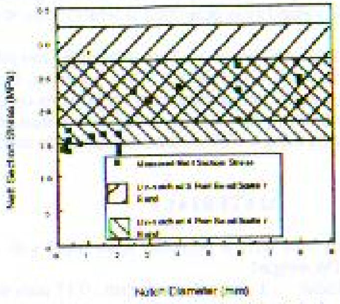

Fig. 4a: Nett section stress: MS material.

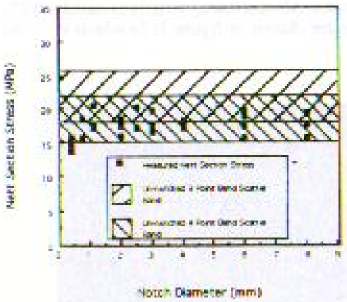

Fig. 4b: Nett section stress: SF material.

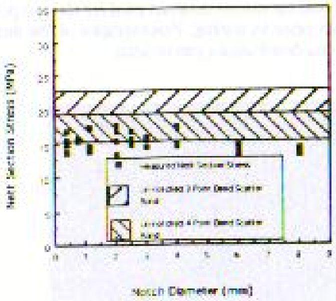

Fig. 4c: Nett section stress: SC material.

DISCUSSION

Microsilica Filled Resin - MS. For the matrix material, the microsilica filled resin, an approximately constant value of fracture toughness is produced for notch diameters less than 2mm. The value of K_{IC}, approximately 1.2MPa√m, is similar to values reported in the literature for un-reinforced polyesters (Price and Hull, 1987). For larger notch diameters the apparent toughness initially increases and then levels off, i.e. the use of large notch diameters in tests results in misleadingly large values of fracture toughness.

The nett section stress data in figure 4(a) also include two scatter bands for fracture strengths of un-notched bars in four and three point bend. The three point bend data have been predicted from the values measured in pure bend, assuming that the strength of the material can be described using the approach developed by Weibull (Weibull, 1951). Weibull proposed that the failure probability, P_f, of a specimen of volume, V, with an applied stress, σ, was given by:

$$P_f(V)=1-\exp[-\int_V (\sigma/\sigma_o)^m dV] \qquad (5)$$

where σ is the applied stress, σ_o is a material constant, m is the Weibull modulus of the material. Because applied stress varies through the specimen volume in bend bars, it can be shown that the failure stress in 3 point bend, σ_{3PB}, is related to the failure stress at equal failure probability in four point bend, σ_{4PB}, by the equation:

$$\sigma_{3PB}/\sigma_{4PB} = \{(m+2)/2\}^{1/m} \qquad (6)$$

In notched specimens, the highest stresses are experienced only below the notch, so, although the samples were tested in pure bend, it is more appropriate to compare them with the scatter band predicted for three point bend. This comparison suggests that the material is only notch sensitive for notch root diameters below 2mm. For blunter notches, failure appears to be described by the criterion of the nett section stress reaching the failure stress. This can be understood in terms of the defects within the material which initiate fracture. In un-notched material. This would suggest that for notches with small diameters, i.e. less than about 0.5mm, the notch would be the main stress concentrator and the failure would be notch dominated. For larger notch diameters, the voids, inherent in the material, would be more effective than the notch and would therefore become the primary stress concentrators, leading to void dominated failure similar to that seen in the un-notched specimens.

The distance over which significant stress elevation occurs at the notch root is also relevant here. With a fracture toughness value of approximately 1MPa$\sqrt{m}$ and a fracture strength of around 15MPa (these values have been used as they apply, approximately, to all three materials) the radius of the region at the crack-tip, over which the stress would exceed the fracture strength of the material is only around 0.2mm, calculated from the conventional equation for plastic zone size in metals (Knott, 1973), in plane strain. Furthermore, if it is assumed that the spherical voids concentrate stress locally to 3 times the maximum applied stress at fracture, the presence of a notch only raises the stress above this level for approximately 20μm.

It is notable, in figure 4, that when failure is notch dominated, at small notch diameters, the scatter is small, whereas at large notch diameters similar scatter to that observed in un-notched tests is seen. Figure 5a shows local crack initiation from a large void below the largest diameter notch (8mm).

Polymer Concrete – SF. The toughness value of the SF material, 1.2MPa$\sqrt{m}$ is similar to those reported in the literature for epoxy/marble mortar (Sachan and Kameswara Rao, 1988) where fracture toughness is in the range 0.75-1.1MPa$\sqrt{m}$, marble (1.2MPa$\sqrt{m}$), cement/sand mortar (0.7MPa$\sqrt{m}$) and cement concrete (0.67-0.8MPa$\sqrt{m}$) (Carpinteri, 1982). This value is similar to that for the matrix material alone, see table 1. In many particulate reinforced materials, the fracture toughness of the material containing the reinforcement is higher than that for the matrix material alone. Such observations are generally put down to crack deflection and crack pinning in coarse particle reinforced materials (Newaz, 1987; Mall et al., 1987). However, when the critical energy release rate, G_{IC}, values are compared the fracture energy for MS is in fact highest. This may be due to the fact that the sand particles debond relatively easily from the matrix when the material fails, leading to weak regions within the material and a relatively low energy fracture path. There is also a suggestion (Newaz, 1987) that although, crack pinning is seen in sand filled plain resins, this is not an active mechanism in resin materials containing both sand and very fine particles, such as clay. The apparent fracture toughness of the SF material is independent of notch diameter for diameters greater than around 1mm. With sand sizes in the range 0.3 to 0.7mm, once the notch diameter exceeds the sand diameter, the sand particles themselves become the dominant local stress concentrators. This causes the notch to behave simply as though it were reducing the nett section.

Polymer Concrete – SC. In contrast to the two previous materials the coarse sand polymer concrete shows no drop in toughness or nett section stress for small notch diameters. Given that the distance over which the stress at a crack-tip would exceed the fracture stress is calculated to be significantly less than the smallest sand particle size, it is not surprising that the very high local stresses at the tip of a sharp crack have no more effect on fracture behaviour than those around a relatively blunt notch of the same depth.

Scatter in toughness in metallic materials has been related to the need for a critical stress to act over a critical microstructural distance, to activate an initiation site (Ritchie et al., 1976). This has in turn, been related to the distribution of defects in the form of initiation sites. In this case it appears that the distance over which the critical stress acts is too small to be of any significance.

It can be seen (figure 4c) that for this material the nett section stress falls with increasing notch diameter for notch diameters larger than about 2mm. This reduction in strength at larger notch diameters may be explained in terms of Weibull modulus and the volume sampled by the highest stress levels. Larger volumes of material are statistically more likely to contain more and larger defects than smaller volumes. This approach has been used to predict the values of failure stress for smaller diameter notches from that measured from the 8mm diameter notch.

By assuming equal failure probabilities in equation 6 for different volumes of material it should be possible to predict the failure stress of one volume of material if the failure stress of the other is known. It can be shown that:

$$\sigma_1{}^m V_1 = \sigma_2{}^m V_2 \qquad (7)$$

where σ_i is the failure stress of a specimen with a volume, V_i, experiencing maximum stress, and m is the Weibull modulus. If all notches and specimens are assumed to be of the same dimensions, except for notch diameter, D_i, then equation 8 reduces to:

$$\sigma_1{}^m D_1 = \sigma_2{}^m D_2 \qquad (8)$$

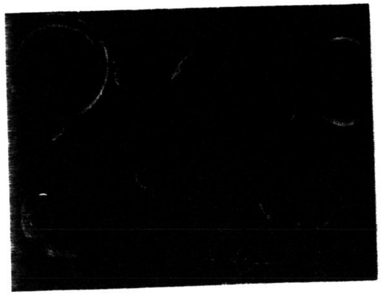

Fig. 5a: MS material, showing crack initiation at a void.

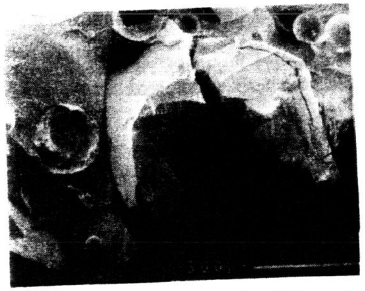

Fig. 5b: SC material, showing broken sand particle near base of notch.

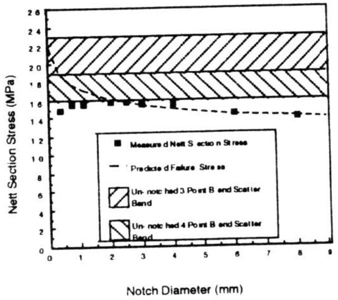

Fig. 6: Plot of predicted and measured failure stress for SC material.

The results of this are plotted in figure 6 which shows that there is a good match between the predicted and measured values of failure stress for notch diameters of 2mm and above. In contrast to the MS results, the nett section stress at failure for all the slit and drilled notches for the SC material is significantly lower than the three and four point bend predictions. This appears to be associated with the damage introduced by the notching operation. Figure 5b shows a fractured sand particle immediately below a machined notch in an SC specimen. Damage of this type was not observed for MS of SF specimens, and would be expected to result in lower strengths than for the un-notched material.

CONCLUSION

MS Material. The measured fracture toughness of this material is similar to those, quoted in the literature, for un-reinforced polyester resins and can be measured reasonably by using notches with diameters less than about 2mm. Use of larger diameter notches results in misleadingly high values of fracture toughness. For small notch diameters the failure is dominated by the stress concentration effect due to the presence of the notch, whereas, for larger diameter notches the failure tends to initiate at flaws inherent in the material and the only effect of notching is to reduce the specimen cross section.

SF Material. The fracture toughness value measured is similar to those in the literature for comparable materials and is slightly higher than that for the matrix alone. This leads to the conclusion that the addition of sand does result in a composite with enhanced fracture properties. However, fracture energy is lower than for the un-reinforced material.

SC Material. The fracture toughness, of this material, is apparently constant over the range of notch diameters used. Examination of the nett section stress data suggests that failure tends to result, not from the stress concentration around the notch, but from flaws inherent in the material itself. For this material, the nett section stress decreases with increasing notch diameter for notch diameters greater than 2mm. This could be explained by the use of a Weibull type, statistical flaw distribution approach. It is suspected that drilling of this material, to form notches, places excessive stress on the sand particles, causing damage to the material near to the notch, and, thus reducing the apparent strength of the notched specimens as compared to the un-notched specimens.

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