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Observations and predictions of fracture in asbestos–cement composites

S. A. S. AKERS
Amiantus Centre, CH-8867 Niederurnen, Switzerland

G. G. GARRETT
Department of Metallurgy, University of the Witwatersrand, Johannesburg, Republic of South Africa

Direct observation by *in situ* scanning electron microscopy of the failure process in asbestos–cement composites indicates that multiple microcracking and extensive fibre pull-out are dominant in this material under load. From this experimental base, suitably modified analytical treatments are shown to give good predictions of mechanical strength.

1. Introduction

The fracture behaviour and properties of fibre composite materials are obviously of significant importance as far as their engineering applications are concerned. While analytical models of mechanical behaviour, recently extensively reviewed by Cooper and Piggott [1], have been relatively well considered in the literature, experimental treatments have, understandably, tended to avoid the more complex systems. However, in developing new composite materials significant advantage can be gained through careful evaluation and reliable prediction of mechanical properties from theoretical models. Such is the case with asbestos–cement, widely used in the construction industry for its excellent combination of properties but increasingly subject to scrutiny, particularly from the health and safety standpoints, making an investigation of suitable alternatives an important task. The objective of this paper, therefore, is to describe the micromechanisms of failure in asbestos–cement and hence select and test appropriate models of composite behaviour as applied to this system.

2. Experimental details

Direct observations of progressive failure in asbestos–cement were made through *in situ* testing in the scanning electron microscope (SEM) of specimens of dimensions 42 mm × 4 mm × 1.2 mm cut from both laboratory- and commercially-produced test sections. In order to detect initial microcracking, careful surface preparation was carried out using carbide grinding papers, and a suitable procedure was developed to provide a satisfactory surface finish. Control testing indicated that the multiple matrix microcracking induced by the four-point loading system was readily distinguishable from the fine craze-cracking induced by minor dehydration effects during surface preparation. After coating, the specimens were mounted in a standard bend-test stage modified for four-point loading, Fig. 1. Charging effects introduced due to freshly-exposed fracture surfaces were minimized by attaching small copper leads to either side of the cracked region, Fig. 1, to provide improved electrical contact. Mechanical loading of the specimens was carried out through a hand-operated attachment which provided the advantage of fine control during loading for critical fractographic examination.

Laboratory tensile tests (10% fibre volume fraction) were also carried out to evaluate whether cracking observed in the SEM was representative of more realistic testing geometries and environments. These test specimens were of dimensions 150 mm × 60 mm × 6 mm, centrally waisted to 30 mm immediately after manufacture. After curing, specimens were fitted to a conventional servo-hydraulic tensile testing facility by the use of end plates attached to the test pieces with contact adhesive.

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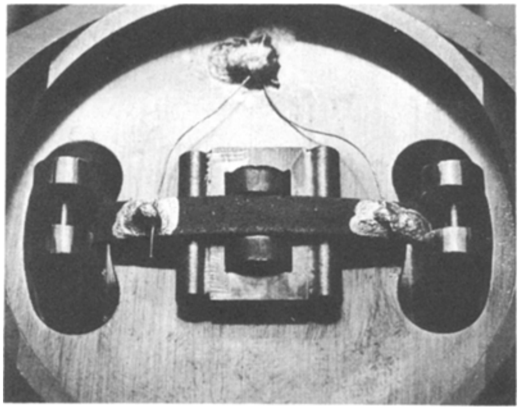

Figure 1 Four-point bend test rig used for *in situ* SEM studies (actual size).

3. Fractographic observations

Extensive multiple microcracking of the composite across the entire surface under stress occurs on loading, Fig. 2. These SEM observations are supported by typical stress/strain records, Fig. 3, for asbestos–cement tested in direct tension, where the deviation from linearity in the curve suggests the occurrence of multiple matrix cracking, as opposed to non-cumulative, single fracture. This is again confirmed by SEM of regions away from the fracture surface of tensile test specimens, Fig. 4.

The development of damage occurs progressively and is relatively easy to monitor. The multiple matrix cracking in form consists of a series of relatively large cracks, increasing to about 1 to 3 μm in width, parallel to each other and predominantly perpendicular to the major stress axis, together with finer cracks (less than 1 μm in width) randomly oriented throughout the surface under stress. As the cracks grow in dimensions, crack bridging by the fibres carrying load is uniformly in evidence. Thus Fig. 5 shows the simultaneous opening of three independent parallel cracks with the bridging fibre bundles clearly visible. Many of the finer, subsidiary cracks open simultaneously with the major cracks and contribute to the load-bearing capacity of the composite, Fig. 6a. On general failure, however, local stress relaxation can occur, after fibre pull-out has taken place, Fig. 6b.

Cracks which develop and propagate perpendicular to the direction of the major cracks, i.e. parallel to the direction of stressing, are generally known as delamination cracks [2]. It would appear that these types of cracks, an example of which is shown in Fig. 7, are initiated along the interface of, or within, individual fibre bundles which intersect the path of a major crack.

In general, the SEM observations indicate that fibre pull-out is a dominant mode of failure. For example, Fig. 8, as Figs. 5b and 6a, shows fibres bridging an opened crack where failure in the interfacial region has absorbed energy during the pull-out process as crack opening progresses. It is also interesting to note from Fig. 8 that there can be quite a wide variation in orientation of fibres bridging the crack, such that the efficiency of load transfer from the matrix to the fibres will obviously vary, and this must be taken into due consideration in any analytical treatment.

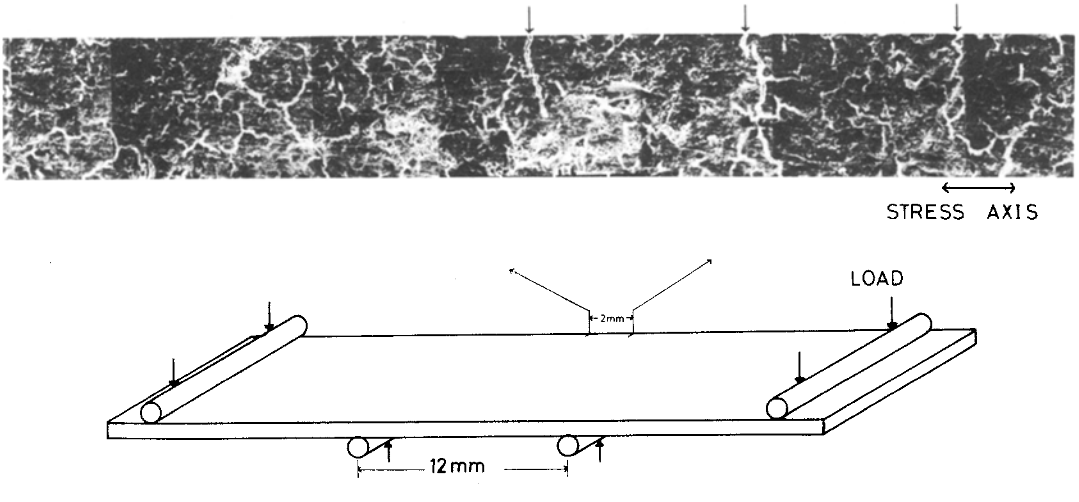

Figure 2 Montage of multiple matrix cracking, as observed in the SEM.

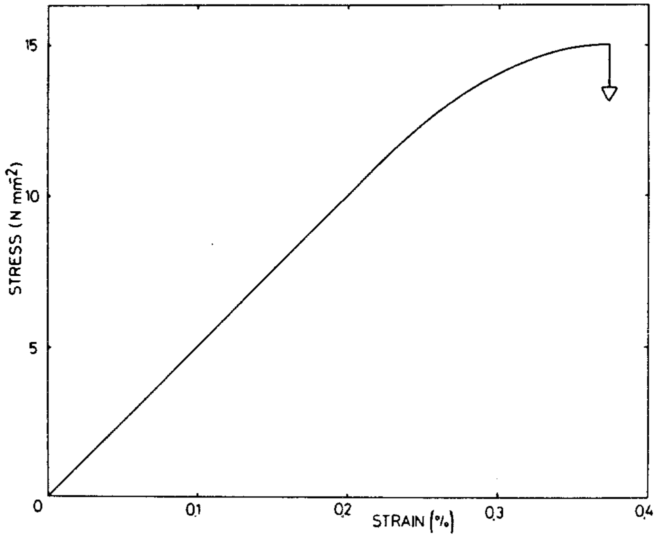

Figure 3 A typical stress–strain curve obtained in uniaxial tension.

It should also be mentioned that, whereas fibre pull-out is evidently the dominant mode of microdeformation, fibre failure can also take place, Fig. 9. Although it would be expected that smaller bundles, having larger l/d ratios, might fracture first, in contrast fibre failure is restricted to the larger fibre bundles. The reason for this appears to lie with the fact that in the larger bundles, where actual separation of the fibre strands during the fiberizing treatment has not taken place, the bonds between individual fibres within a bundle may still have been disrupted. Under these circumstances, fibre bundle separation may well occur during composite fracture, particularly if the initial disruption of the fibre-bond it too small to allow cement penetration into the bundle to take place.

4. Application of theoretical models

4.1. Uniaxial tension

When considering the case of "ductile" fibres in a brittle matrix, i.e. where the failure strain of the matrix is less than that of the fibres, so-called "single" fracture will take place if the fibres are unable to sustain the additional load imparted to them after initial failure in the matrix. "Multiple" matrix cracking will occur, however, if the fibres can withstand the additional transferred load. It can readily be shown (for example, see [3]) that there will generally be a minimum fibre volume fraction above which a transition will occur from single to multiple fracture, and that in the latter case the average crack separation will be directly proportional to the fibre diameter and inversely proportional to the volume fraction of the fibres.

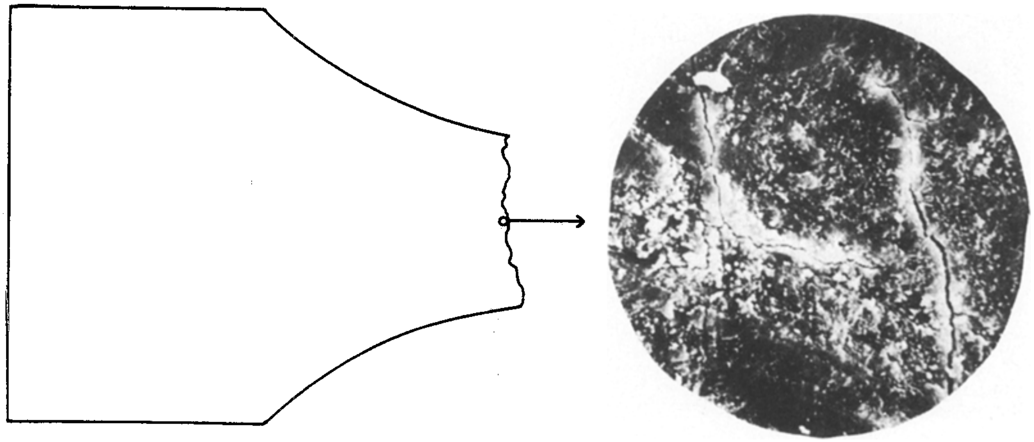

Figure 4 Microcracking observed close to the fracture surface of a tensile test specimen (×900).

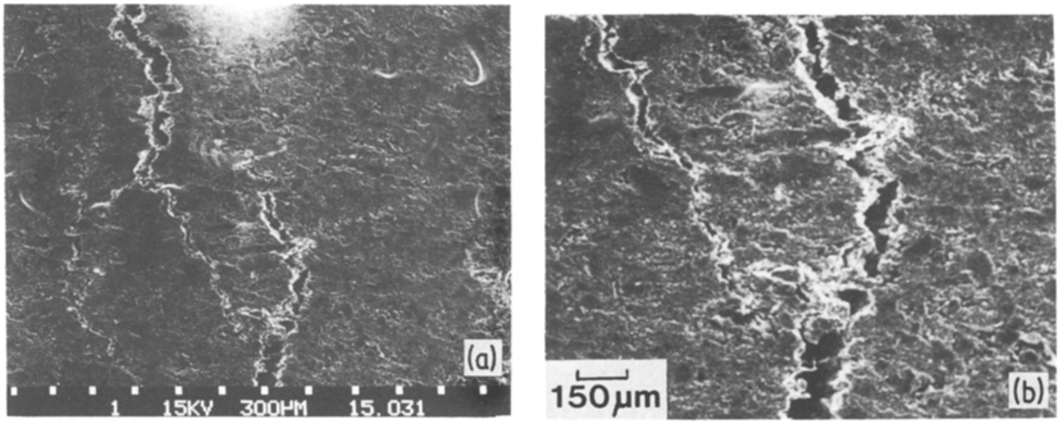

Figure 5 Simultaneous crack propagation of matrix microcracks, (a), showing fibres bridging cracks at higher magnification, (b).

As the load initially carried by the matrix and transferred to the fibres increases, whether the fibres break before they pull-out is again straightforward to calculate and will be a function of the so-called "critical aspect ratio" for the fibre composite, where

$$(l/d)_c = \frac{\sigma_{fu}}{2\tau} \tag{1}$$

in which l and d are the fibre length and diameter, respectively, σ_{fu} is the ultimate fracture stress of the fibres and τ is the frictional interfacial shear stress.

From general experimental observations, and as mentioned in the preceding discussion, it is reasonable to assume that fibre pull-out is the dominant failure mechanism, so that the strength of the composite should be equal to the total load per unit area required to extract N fibres of mean pull-out length, $l/4$, and diameter, d, bridging the crack [4]. Using a simple balance of forces the tensile strength of the composite, σ_u can be written as

$$\sigma_u = 2\pi r\tau Nl/4 \tag{2}$$

where τ is the interfacial shear stress and r the mean fibre radius. N can be estimated as

$$N = \frac{\eta V_f}{\pi r^2} \tag{3}$$

where V_f is the fibre volume fraction and η is the fibre orientation "efficiency factor", defined as that percentage of the total volume of fibres which contributes to strength in a given direction. Values for η for a two-dimensional random fibre composite have been variously given as 3/8 [5], 1/3 [6] and $2/\pi$ [4]. Hence, combining these two equations gives

$$\sigma_u = \eta V_f \tau (l/d). \tag{4}$$

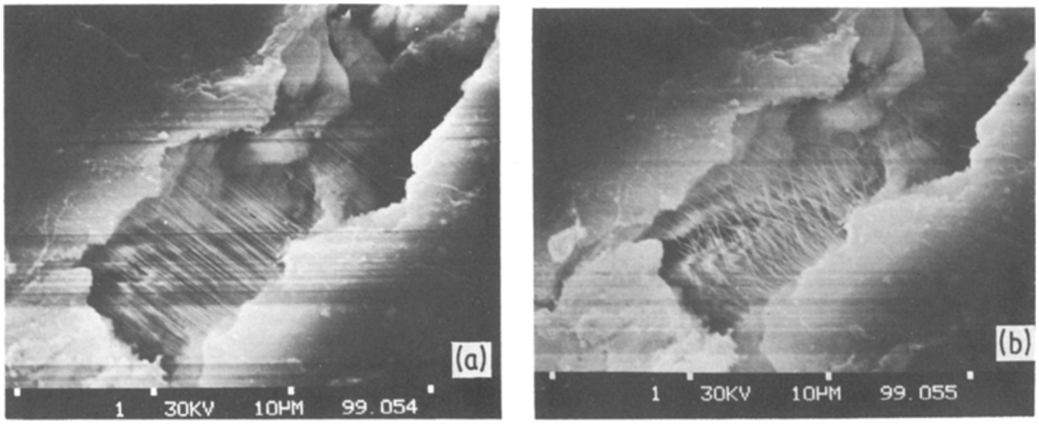

Figure 6 (a) Fibres under load and pulling out during microcrack opening, and (b) relaxation after composite failure.

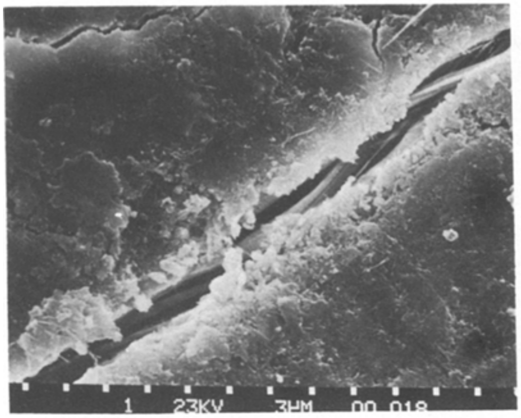

Figure 7 Delamination cracking associated with cross-oriented fibre bundles and inter-bundle separation.

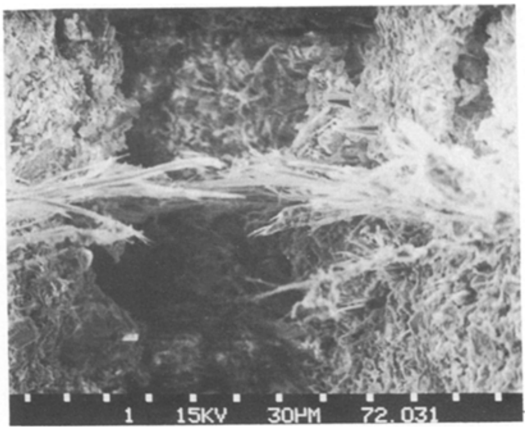

Figure 9 Fibre bundle fracture during composite failure.

In order to estimate τ, single fibre pull-out tests were carried out, as described elsewhere [7] and, for identical water/cement ratios and curing procedures to the tensile tests under consideration, an average value of $2.4\,\mathrm{N\,mm^{-2}}$ was obtained. Since it has been shown [8] that the interfacial shear stress will depend to a large extent on the strength of the cement matrix itself, this value is likely to be reasonably consistent throughout, and relatively independent of the fibre dimensions.

For the particular fibre processing treatment carried out, aspect ratios, l/d, were determined by measurement of lengths and diameters from SEM fractographs taken of the fracture surfaces of the tensile test specimens. For a number of fibres, pull-out was ill-defined since separation of the fibres within the larger bundles appeared to occur during the fracture process [8]. However, choosing fibre bundles which had not separated during failure, lengths and diameters were measured on approximately 40 fibre bundles and aspect ratios were determined using the assumption that the average pull-out length was $l/4$ [4]. A wide range of fibre diameters and lengths were found, varying from less than $1\,\mu\mathrm{m}$ to about $300\,\mu\mathrm{m}$ in diameter and from fractions of a millimetre to about 5 mm in length. This resulted in aspect ratios which ranged from 12 to 130, but with a statistical number average of approximately 100.

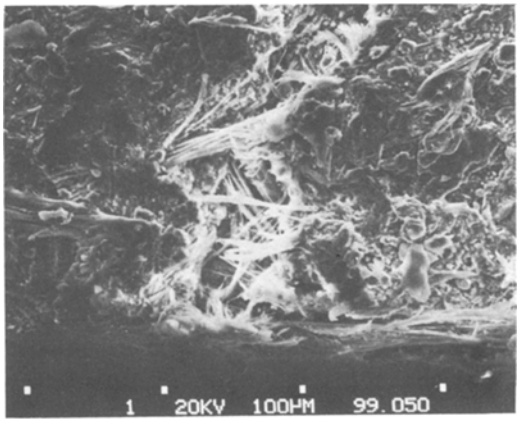

Figure 8 Extensive fibre pull-out, also showing complex orientation of the fibres and fibre bundles.

The critical aspect ratio, above which extensive fibre breakage, as opposed to pull-out, could be expected, can be calculated from Equation 1. The value of σ_{fu} has been quoted by Aveston [9] as 3000 to $4400\,\mathrm{N\,mm^{-2}}$ for asbestos fibres, but measurements by Majumdar *et al.* [10] show that more typically it will vary between 200 and 1800 $\mathrm{N\,mm^{-2}}$, giving corresponding critical aspect ratios in the range 40 to 375, with an average value around 200. These values, being in excess of the measured aspect ratios, are consistent with the observation that fibre pull-out is the dominant mode of separation.

Now for a fibre volume fraction of 0.1, and taking an average value of 100 for l/d, the three η values quoted above give values for the uniaxial tensile strength of, respectively, 9, 8 and 15.3 $\mathrm{N\,mm^{-2}}$. The latter value, utilizing the fibre orientation efficiency factor of $2/\pi$ quoted by Aveston *et al.* [4], certainly provides very good agreement with the experimentally observed value of $15.0 \pm 2.0\,\mathrm{N\,mm^{-2}}$ obtained from asbestos–cement with a 10% fibre content.

4.2. Flexure

Using an engineering approach of stress block analysis, Hannant [10] derived an expression relating tensile and flexural strength in fibre–cement composites. As he pointed out, however, the shape of the stress blocks in flexure used in the development of the theory represents a broad generalization since the flexural stress blocks in composites are governed by parameters such as: fibre type and dimensions, fibre content, water/cement ratio, curing conditions, age and crack width. However, since these parameters do not greatly affect the conclusions obtained, such a generalization is appropriate in the first instance.

Hannant therefore derived an expression for the modulus of rupture, σ_{mr} of the composite which, incorporating the efficiency factor of $2/\pi$, can be written as

$$\sigma_{\mathrm{mr}} = 1.55 V_{\mathrm{f}} \tau (l/d). \tag{5}$$

Substituting values of $V_{\mathrm{f}} = 0.1$, $\tau = 2.4\,\mathrm{N\,mm^{-2}}$ and $l/d = 100$, $\sigma_{\mathrm{mr}} = 37.2\,\mathrm{N\,mm^{-2}}$ which again compares very favourably with the value of $36 \pm 1\,\mathrm{N\,mm^{-2}}$ obtained from four-point bend tests.

In view of some significant experimental variations, for example across an order of magnitude in measured values of aspect ratio, the excellent agreement obtained between the theoretical and experimental values for both tensile and flexural strength in these asbestos–cement fibre composites not only gives confidence in the validity of the models themselves, but through this provides improved scope for the application of such models to property predictions in more practical, yet complex fibre composites.

5. Conclusions

(i) Direct experimental observation, primarily by *in situ* SEM studies, of the failure process in asbestos–cement indicates extensive multiple fracture, with a complex interaction of microcracks of varying dimension and random distribution.

(ii) Fibre pull-out evidently dominates as the failure mechanism, although interfibre separation and fracture is also observed.

(iii) Despite a wide variation in measured fibre aspect ratios, together with complex fibre orientation effects, good agreement has been obtained between experimentally measured and predicted strength levels in both tension and flexure.

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