The relevance of single fibre models to the industrial behaviour of asbestos cement composites

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SYNOPSIS
To evaluate appropriate screening procedures for optimisation and substitution programmes for asbestos fibres in cement-based composites, interfacial debonding tests have been carried out on individual asbestos fibre bundles embedded in a cement matrix. It is shown that experimental manipulation of the mechanical strength of the fibre-matrix interface, through variations in the processing parameters of water/cement ratio, cement particle size and curing procedure, can provide a reasonable indicator of the corresponding changes in the mechanical performance of production composites. Alternative fibres must, however, be investigated individually because of the effect of differing inter-fibre properties and the relative response to production processing treatments.

KEYWORDS
Composite materials, natural fibres, asbestos cement products, product development, production models, pull-out tests, shear stress, bonding strength, composite fabrication, production control, bond stress, fibre reinforced cement, strength of materials.

INTRODUCTION

Asbestos cement is undoubtedly still one of the most popular cement-based fibre composites in use in the construction industry, despite the increasing non-engineering pressures concerning the extent of its application. Limited global reserves of asbestos fibres have, additionally, led to the necessity to optimise the use of these fibres in the composite, as well as to efforts aimed at finding suitable replacements.

Since the mechanical behaviour of any fibre composite is, to a considerable extent, directly influenced by the nature and properties of the fibre-matrix interface, considerations of the behaviour of this region under stress are obviously central to any programme of optimisation or substitution. Furthermore, it is widely held that the measurement of bond strength will in itself provide a specific indication of bulk composite properties. Experimental manipulation of the mechanical strength of the fibre-matrix interface should, therefore, provide a convenient method for modifying composite behaviour. However, such a correlation is by no means universal, and in steel-fibre reinforced cement-based materials, for example, various treatments designed to improve the bond strength have produced only marginal improvements in bulk strength [1,2]. Thus, the validity of any guidelines for the production-scale composite indicated by way of laboratory scale, model tests (for example, on the strength of an individual fibre-matrix bond) should generally be investigated and one of the objects of this paper is to provide an assessment of such screening procedures for asbestos cement.

In asbestos cement, the strength of the interfacial bond is likely to be affected by the properties of the matrix, as governed by the water/cement ratio, cement particle size and conditions of curing, as well as by the type of fibre used. The influence of these factors is therefore described in this paper. In addition, in view of

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the nature of the hydration process during which the strength of the composite is developed, it seems reasonable to consider that the electrical surface properties of fibres in solution at the curing stage could have a substantial influence on the interfacial bond. Thus, when asbestos fibres are submerged in a liquid suspension, an electrokinetic interaction exists between the fibres and the solution adjacent to the fibres. It is well established [3–5] that chrysotile asbestos fibres possess a surface layer of magnesium atoms, and it has been suggested [3] that these hydroxyl sites exert a strong influence on activity in solution, which could cause interaction with the surrounding cement particles in an asbestos cement slurry, with a corresponding effect on the interfacial bond. Since the zeta potential of chrysotile fibres has been shown to vary from +100 mV to −100 mV over the pH range 8 to 13 [6], a change in pH of the water used to make asbestos cement could, in this way, have an effect on the resultant mechanical properties of the composite. For this reason, the influence of pH on the interfacial bond strength has also been examined.

EXPERIMENTAL PROGRAMME

Single fibre pull-out tests Bundles of chrysotile ('white') and crocidolite ('blue') fibres, in the size range 60–140 μm in diameter and ~25 mm in length, were cut from parent silicate rock and subsequently cast into two separate pellets of cement, as shown schematically in Figure 1. Cement of varying specific surface area (SSA) was obtained using a series of vibrating screens which separated ordinary portland cement into three groups, viz: 5050, 2200 and 1300 cm²/g. These average values

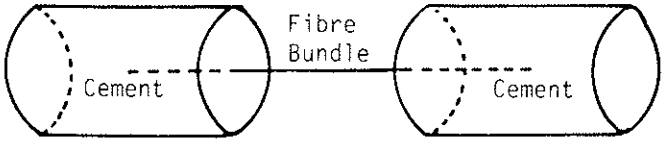


Figure 1 Schematic illustration of the model test system, consisting of a fibre bundle cast into two separate cement cylinders.

were obtained by sampling from the cement accumulated on the various screens, and measured using conventional Blaine testing equipment. Chemical analysis was carried out on each of the three groups, but negligible variation in composition was found. Specimens were either 'wet-cured' (under water) or 'dry cured' (in laboratory air with variable humidity), and for the range of SSA values examined the different corresponding rates of strength development were shown to have little effect on the as-tested strengths.

A range of w/c ratios were studied, as well as the influence of pH values of the water, at a constant w/c ratio of 0.4, used in making, and curing, specimens. Each individual fibre bundle was cast in a capsule of cement paste and vibrated for 60 seconds in order to release air bubbles which may have developed at the interface during casting. After curing, tensile testing was carried out using a model 1122 Instron, with appropriate chart recording facilities.

The fibre-matrix contact area was calculated according to the method used successfully by Aveston [7], by accurate weighing of the individual bundles coupled with a knowledge of the specific gravity, making the assumption that the fibre bundle is cylindrical.

Laboratory and production-scale testing Multiple fibre, mould cast specimens were prepared in the laboratory by mixing a suspension of prepared fibres and water with the required amount of cement and pressing into mould boxes of dimensions 20 × 20 × 180 mm. After an initial setting period of one day, specimens were removed for curing.

Under these conditions, the fibre distribution approximates to 3-D random. This is, however, very different from the production process which produces a laminated, essentially 2-dimensional composite, with approximately 70% of the fibres aligned preferentially in the 'rolling' direction. For this reason, comparative tests were also carried out on specimens manufactured through the production route, primarily utilising an industrial pilot-scale version of the commonly used wet transfer roller, or Hatschek process. Suitably prepared fibres, first mixed in suspension with cement in lime saturated water, are then picked up as a thin film on the surface of a rotating drum of wire mesh, and are transferred from this to an endless conveyer belt of permeable felt. This then passes over a vacuum box to remove excess water from the fibes before the slurry is transferred to a steel accumulation drum, on which it is compacted and further dewatered and formed to the required thickness. Finally, the sheet is stripped from the drum, pressed, cut into test sections and cured.

The experimental variables studied in both the laboratory mould-cast and production line specimens were essentially those defined above for the single fibre pull-out tests, in order to assess the interrelationship between these testing procedures.

RESULTS AND DISCUSSION

The form of load-extension curve obtained from the single fibre pull-out tests is illustrated in Figure 2.[1] Debonding takes place at B and after the initial load drop a stick-slip pull-out process occurs, with a corresponding diminishing load (C to D).

By increasing the water/cement ratio a decrease in the strength of the interfacial bond is observed (Figure 3a). This might readily be expected since on increasing the w/c ratio, the number of cement particles surrounding the embedded fibre bundles is reduced, with a corresponding decrease in effective interfacial contact area and a drop in debonding load.

An analogous argument may be applied to the effect of variations of cement particle size on bond strength (Figure 4a). Thus for a fixed w/c ratio, a decrease in the specific surface area of the cement obviously results in an increase in cement particle size. In an ideal situation, i.e. for all particles packed uniformly along the surface of a fibre bundle, as illustrated schematically in Figure 4d,

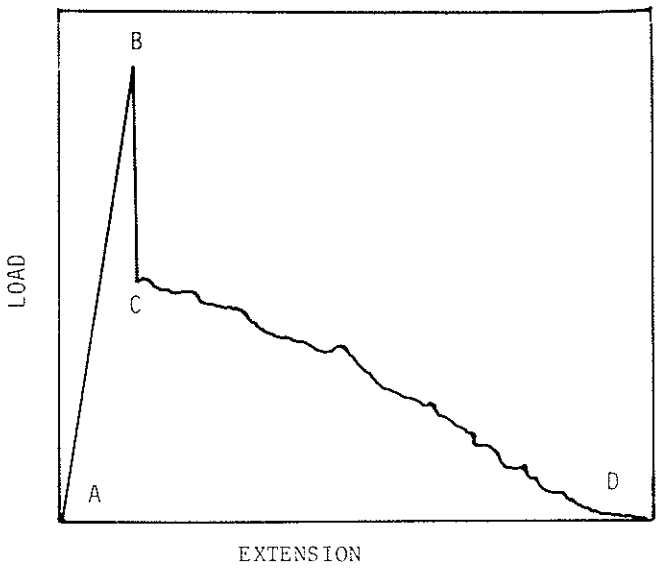


Figure 2 Typical load-extension curve obtained during fibre pull-out.

the larger cement particle size will always result in less interfacial contact and a correspondingly lower debonding load, as observed (Figure 4a).

Similar trends are observed with the mould cast specimens and with the production line tests, for both variations in w/c ratio (Figures 3b and 3c), and in specific surface area (Figures 4b and 4c). With regard to variations in w/c ratio, there does, however, appear to be an optimum value for maximum strength. The influence of w/c ratio on the compressive behaviour of cement-based materials is in fact fairly well documented, and the decreasing strength observed with increasing w/c ratio has generally been associated with corresponding increases in porosity [8,9]. However, the relationship between mechanical behaviour and porosity is not altogether a simple one, and is beyond the scope of this discussion. It should be noted, though, that increases in strength and toughness, interestingly enough, can occur in conjunction with an increase in porosity [10].

For a w/c ratio of 0.4 it was found with single fibre bundle pull-out tests that larger loads were required to

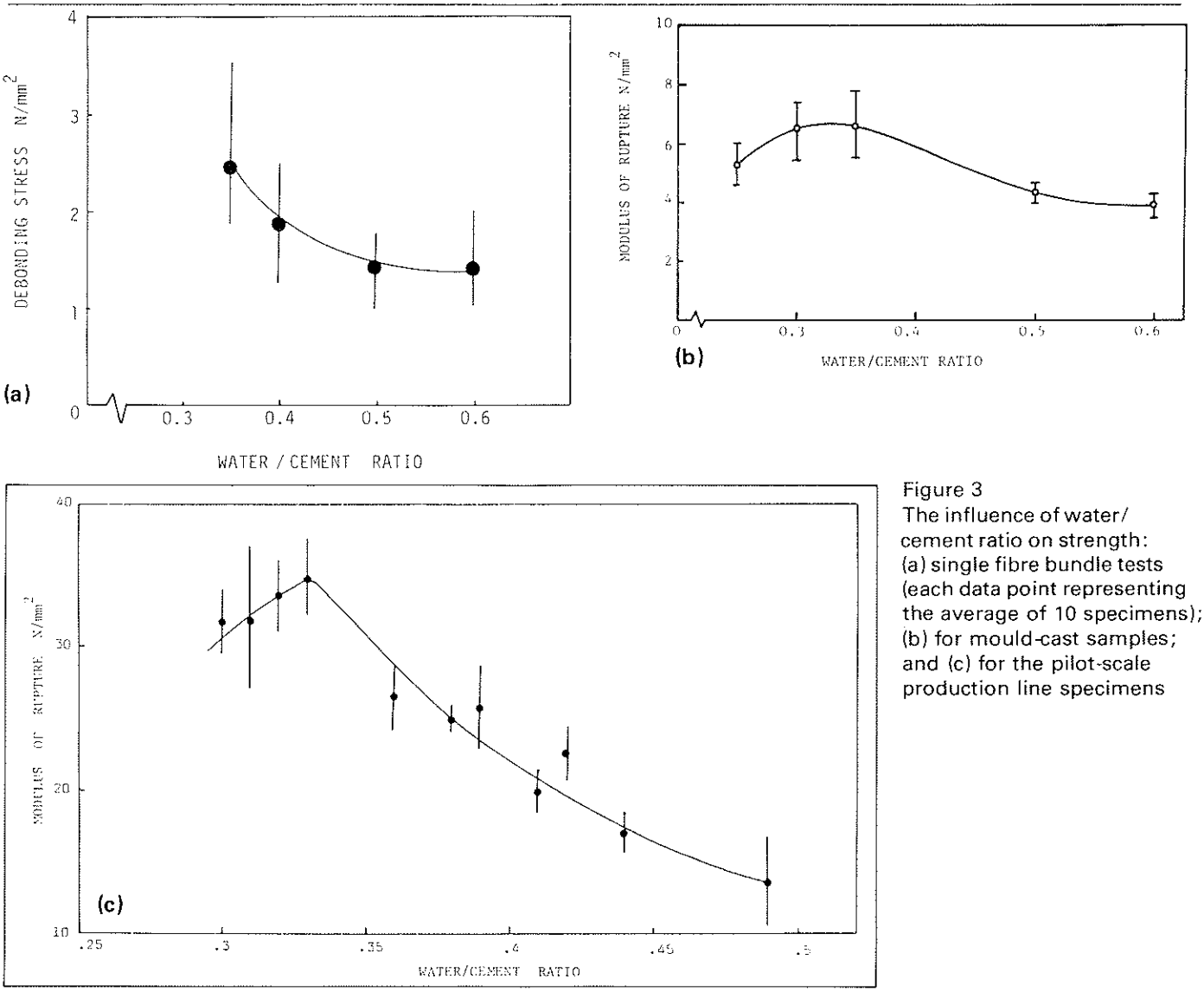
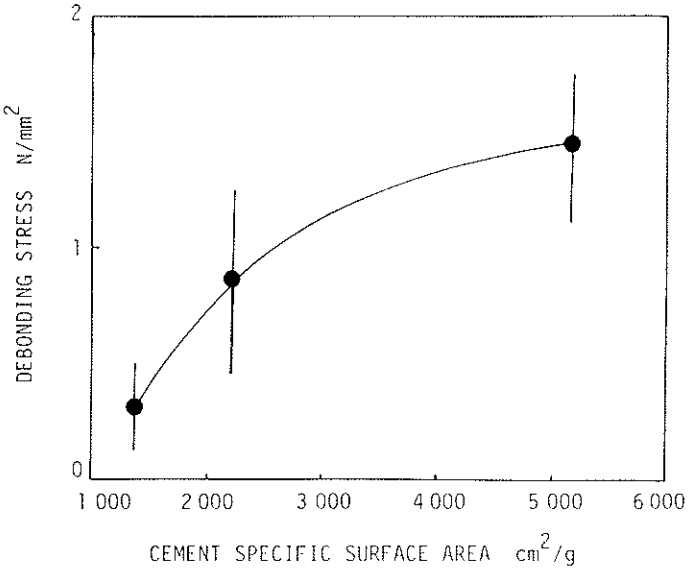
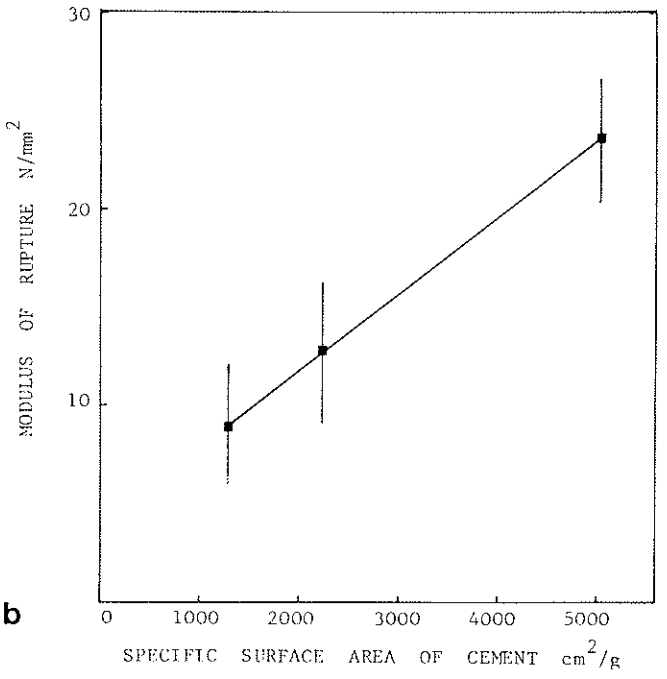


Figure 3
The influence of water/cement ratio on strength: (a) single fibre bundle tests (each data point representing the average of 10 specimens); (b) for mould-cast samples; and (c) for the pilot-scale production line specimens



a



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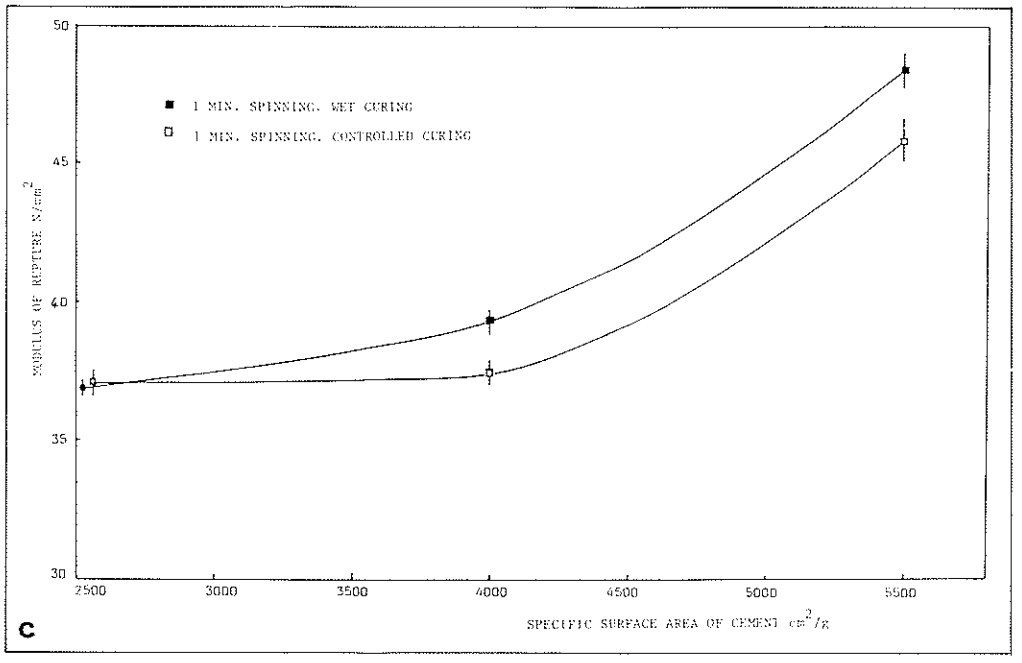

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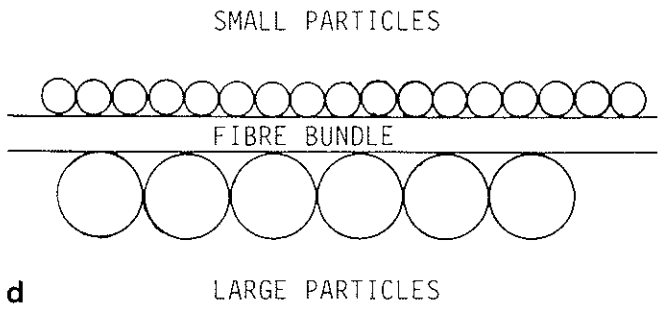

d

Figure 4 Increase in strength associated with decreasing the cement average particle size, (a) pull-out tests; (b) mould cast samples; (c) pilot-scale production line specimens; (d) schematic representation of the influence of a smaller cement particle size on strength, via increased interfacial contact area

extract chrysotile fibres from wet cured specimens when compared with dry curing, Table 1, which can be related to the additional hydration, and therefore greater bonding area, which occurs under water curing conditions. Such improvements are confirmed with tests on both the pilot-scale and full-scale production process, Table 1, from which it can readily be seen that the direction and order of magnitude of the effect observed on the industrial scale is reasonably predicted from the single fibre bundle pull-out tests.

Table 1 The influence of curing procedure on bond strength and composite strength (fiberised chrysotile, prepared with RHPC). All measurements in N/mm², average of 10 specimens

		Shear stress ± s.d.	% change
single fibre bundle pull-out	wet cured	2.4 ± 0.65	+ 33%
	air cured	1.8 ± 0.5	
		Modulus of rupture	
pilot-scale production	wet cured	48.5 ± 1.3	+ 18%
	air cured	41.0 ± 1.2	
full-scale production	wet cured	51.1 ± 1.8	+ 27%
	air cured	40.2 ± 1.6	

It was also found that crocidolite ('blue') fibres in general required larger debonding loads than the chrysotile fibres. No results could be obtained under water curing conditions, for reasons which will be subsequently discussed, but for air curing an average value of 3.1 N/mm² was obtained, which gives a 72% increase over the value of 1.8 N/mm² obtained for chrysotile fibres, as given in Table 1. The value for crocidolite is close to that of 3.19 N/mm² obtained by Hodgson [3], although his value for chrysotile of 0.82 N/mm² is on the low side in comparison with the values obtained in this study. (It must be noted, however, that Hodgson makes no mention of curing procedures or the w/c ratio he used.)

Chrysotile fibres are generally found in the form of flexible, hollow tubes whereas crocidolite fibres are relatively rigid, solid cylindrical 'bars'. For this reason one might expect the flexibility of the chrysotile fibres to provide an advantage, bending around the cement particles to form a good mechanical bond, as shown in Figure 5a, in comparison with the more rigid crocidolite fibres, Figure 5b. However, experimental results imply precisely the opposite effect, so it is evident that the debonding process may be governed by some other mechanisms, or even chemical interaction.

Hodgson [3] has in fact suggested that a chemical bond could exist between asbestos fibres and cement, and that a chrysotile fibre could react in such a manner that the bond strength is reduced due to a stripping of the Mg-OH layer from the fibre during processing. Conversely, he has proposed that crocidolite fibres do not react chemically with the cement and that their surfaces could act as nucleating points for the growth of cement hydrate, producing the stronger bond strength observed.

However, the precise basis for such proposals is somewhat unclear and an alternative answer would appear to lie with the complex interfacial separation characteristics of the chrysotile fibres. Thus, it has recently been shown that a chrysotile fibre bundle can fail in pull-out by the separation of the main core from an outer sheath [11], which remains embedded in the matrix, as shown in Figure 6, and the magnitude of the inter-fibre separation stress is likely to depend on the mechanical treatment the fibre bundles have received prior to adding to the cement matrix, as well as on the fibre type. Thus, by carefully cutting small rectangular blocks of fibre bundles from the parent silicate rock,

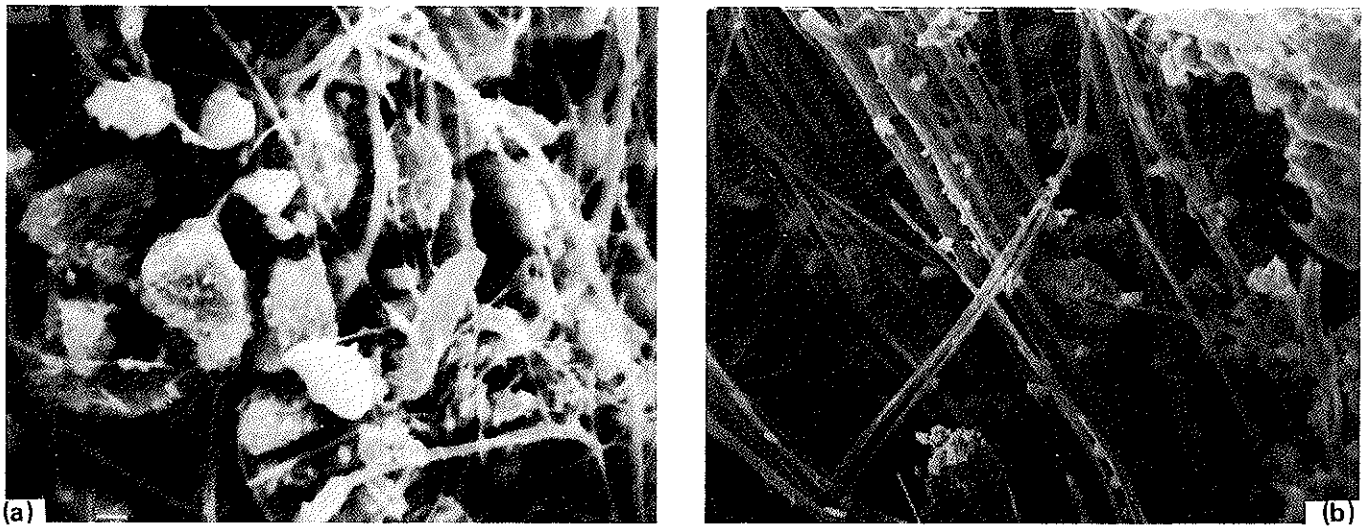

Figure 5 (a) Chrysotile fibres which are flexible are able to bend around cement particles (×7K). (b) By comparison, rigid crocidolite fibres (×1K)

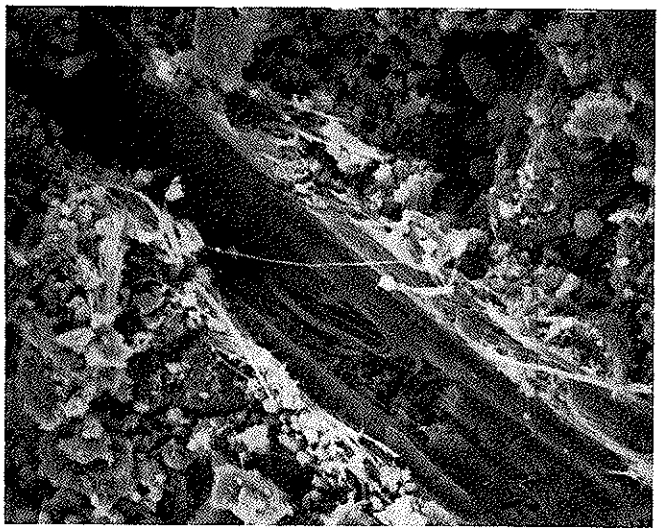

Figure 6 The outer sheath of chrysotile fibrils from a bundle remaining in a cement trough after separation and pull-out of the inner core (×1K)

attaching to small end plates and pulling in shear, it was possible to determine a value for the inter-fibre bond strength. The value for crocidolite was three times that for chrysotile (1.5 and 0.5 N/mm², respectively) thus confirming that this effect is indeed likely to be important in explaining the improvements in pull-out bond strength observed with crocidolite fibres.

Under conditions of water curing it might be anticipated that crocidolite fibres would give even larger values for pull-out bond strength. However, the fibres are exceedingly brittle and very susceptible to damage during specimen preparation, and after water curing fibre breakage consistently occurred in the range 3.5–4.0 N/mm² prior to any interfacial debonding. However, on the basis of these results it would seem reasonable to conclude that, consistent with the effects of curing procedure observed with chrysotile fibres, the interfacial failure stress for undamaged crocidolite fibres obtained by more sophisticated tests would be well in excess of the average value of 3.1 N/mm² obtained for air-cured specimens.

Under production line conditions, however, such substantial improvements as were observed with single fibre bundle tests were this time not carried over to the production line results, as was the case with studies of the effects of w/c ratio, cement particle size and curing procedure. Thus, replacement of a 12% volume fraction chrysotile fibre composite with entirely crocidolite fibres produced just under a 10% increase in strength. Undoubtedly the reasons for this are complex, but are likely to be associated with the typical fibre processing treatments and the susceptibility of the crocidolite fibres to mechanical damage, reducing their inherent strengthening characteristics in production composites.

Turning finally to the effect of water chemistry on the mechanical properties of the fibre-matrix interface, the results summarised in Table 2 show that the influence of pH (over a range designed to vary zeta potential from +100 mV to −100 mV) is negligible. These specimens, it

Table 2 Interfacial shear stresses calculated for chrysotile fibres which were extracted from cement pastes (0.4 water/cement ratio) prepared with water of varied pH's

pH of water used	Shear stress N/mm²	Standard deviation	No. of specimens
8	2.2	0.5	5
9	2.2	0.5	5
11	2.1	0.4	5
13	2.0	0.8	5

should be recalled, were cured under water with pH levels the same as that used in their preparation. Even taking account of changes in pH due to the calcium hydroxide released as a by-product of the hydration process, it must be concluded that changes in zeta potential induced by pH variations which might be expected to modify the asbestos fibre-cement particle interactions (and indeed may well do so to some limited extent), in fact have no significant corresponding influence on the fibre cement interfacial bond strength. In view of the confidence developed in single fibre tests from the preceding programme, as far as experimental trends are concerned (for a given fibre type), the negative, or rather non-positive, effect anticipated for these variations in water pH led to the conclusion that production trials could not be justified.

CONCLUSIONS

1. Laboratory measurements of the interfacial debonding stress of individual (chrysotile) asbestos fibre bundles embedded in a cement matrix generally provide a good indication of the direction and magnitude of strength changes to be expected in production composites associated with variations in processing parameters.

2. Wet-curing, decreasing water/cement ratio and decreasing cement particle size all result in improved interfacial bond strengths, but water pH has no effect.

3. Chrysotile fibres debond at lower stresses than do crocidolite fibres, which can be associated with a difference in inter-fibre bond strength within individual bundles.

4. The effects on production composite properties of substitution (of chrysotile fibres) with crocidolite fibres are not accurately predicted from single fibre tests. This is probably a result of production processing treatments on the more brittle (crocidolite) fibre.

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