PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Composite Materials Based on Cement Matrices [and Discussion]

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Composite materials based on cement matrices

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All materials produced from inorganic hydraulic cements are composites of one kind or another because of their multiphase nature. This paper briefly considers the relevance of composite principles in predicting the mechanical properties of hardened cement paste, mortar and concrete and then discusses recent developments towards enhancing these properties by the addition of polymers and more particularly fibres.

Fibres derived from glass, polypropylene and cellulose with metal wire are currently being used as cement reinforcements. Important properties of some of these practical fibre reinforced cement and concrete (F.R.C.) materials are discussed with particular reference to the replacement of asbestos products. Some examples of recent innovations in the manufacture of F.R.C. materials are given together with projections for their future use.

1. Introduction

Hydraulic cement paste, mortar and concrete can all be considered as composite materials because of their multiphase nature. Concrete, perhaps the most important construction material today, is most simply described as a two-phase system comprising aggregate particles embedded in hardened cement paste (H.C.P.) or alternatively coarse aggregates in mortar. To enhance the properties of cement mortar and concrete, various additions – polymers, fibres, special 'waste' materials and admixtures of different kinds – are now made and new industries have come into being to exploit these even more complex materials.

In this paper we discuss the composite nature of some of the cement products briefly before describing the current developments in one of the newer areas, that of fibre reinforced cement and concrete (F.R.C.). Unless otherwise stated the cement referred to in this paper is ordinary Portland cement (O.P.C.).

2. Hardened cement paste, mortar and concrete

Several investigations have shown (Hansen 1968) that the elastic constants of concrete can be predicted from the elastic constants and volume fractions of the constituents by using two-phase models and mixture rules, and that such an approach can be extended to H.C.P. and mortar. However, the agreement between predicted and observed values is not very close when simple models (Reuss or Voigt) are used. Several alternative models have been proposed and Hobbs (1973) has shown that the equation for elastic constants derived by Hashin & Shtrikman (1963) from variational principles gives very good agreement between theory and experiments. These models, however, rely on assumptions that are not strictly valid and an alternative approach has been suggested, namely fitting exponential and power law curves (see, for example, Kotsovos & Newman 1979).

Properties can be altered very substantially by the addition of polymers, and several different types of polymer modified H.C.P., mortar and concrete have been developed in the last two decades (Manson 1976). Of these polymer impregnated concrete (P.I.C.) is the most interesting and also the most difficult to manufacture on a large scale. The polymer greatly enhances the durability of the concrete and can improve its mechanical properties severalfold. In general a glassy polymer such as polymethyl methacrylate (PMMA) produces a solid that is linearly elastic almost up to the point of failure, but the stress–strain behaviour can be modified by introducing plasticizing co-polymers. Although the role of the polymer in P.I.C. is understood in a qualitative way, satisfactory analytical models have not been demonstrated yet. Current ideas about the nature of the polymer in the pore system of H.C.P., the extent of chemical reaction between the polymer and H.C.P., and interfacial effects remain largely speculative.

Molten sulphur is a far simpler impregnant and Feldman & Beaudoin (1977) have recently made a detailed study of the properties of H.C.P. and autoclaved cement/silica mixtures impregnated with sulphur. Uniform and nearly total impregnation was possible in some cases and the elastic constants of the composites could be predicted with reasonable accuracy from the mixture rule (Reuss) by using the properties of the constituents at zero porosity.

Constitutive relations have been derived for several other properties of concrete (Hansen 1968), for example shrinkage and thermal expansion, creep, thermal and electrical conductivity. However, it has not been possible to describe the strength of concrete (or of H.C.P.) in this way since it fails in a progressive manner, owing to its inherently complex structure, and failure criteria are not well established.

3. Fibre reinforced cement and concrete

(a) *Constitutive relations*

It is usual to regard F.R.C. as consisting of two phases, fibres and matrix, and relations have been derived to predict the tensile and bending properties of the composite in terms of the properties and volume fractions of the two components, and of their interactions in terms of the bond between them.

(i) *Elastic properties*. In the elastic region simple mixture rules have been developed but usually any improvement in elastic modulus is small. There is some evidence to suggest that fibres can modify the failure criterion and therefore the failure strain of the matrix, but the comparatively large increases predicted by the elastic theory of Romualdi & Batson (1963) are not seen in practice. Kelly (1974) attributes this to debonding and loss of elastic continuity at the interface. The non-elastic theory of Aveston *et al.* (1971) predicts a smaller increase in matrix failure strain. Experimentally, strict confirmation of the prediction is difficult to obtain. However, if the addition of fibres leads to a more reliable matrix-cracking strain, this in itself would have considerable practical significance.

(ii) *Stress–strain curve and composite strength in tension*. The effect of fibres that has received most attention is that applying after the matrix has failed, and has been defined by Aveston *et al.* (1971). The A.C.K. theory supposes that, after the first matrix crack has formed, there are sufficient fibres present to support the load. Predicted stress–strain curves in tension deduced by Aveston *et al.* (1974) are shown in figure 1 for cement reinforced with continuous aligned carbon fibres. The agreement between the two sets of curves (predicted and experimental) is good, and generally the A.C.K. theory appears to describe the stress–strain curves of F.R.C. materials containing more than the critical volume of fibres exceptionally well.

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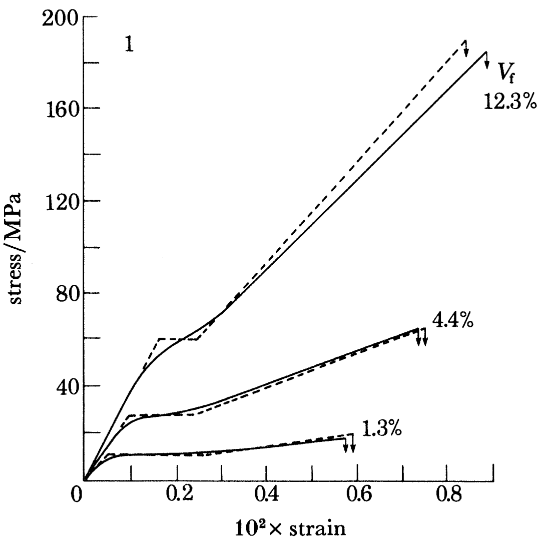
When the reinforcement is in the form of a two-dimensional random array of short fibres, one approach is to replace the response to stress of the continuous aligned fibres of the A.C.K. model by that of a mat of short fibres held across a crack (Laws *et al.* 1971). The response to stress of the fibrous mat defines the shape of the tensile stress–strain curve after cracking of the matrix has ended, the strength of the composite, and the curve after the composite has failed, as illustrated in figure 2. The response consists of two parts, namely the contributions of the fibres that 'hold', that is the elastic response, and that of the fibres that 'slip', the frictional response. After the maximum stress has been reached there is still a mainly frictional component (a post-failure stress capacity) as fibres that have slipped are pulled out of the matrix and one crack opens up. The strength of the composite, σ_c, is the maximum stress that the fibrous mat can support and is given by $\sigma_c = \eta\sigma_f V_f$, where σ_f and V_f are the ultimate tensile strength and volume fraction of the fibres and η is an efficiency factor that depends on the orientation of the fibres, their length, l, the strength of the bond opposing slipping, τ_s, and that of the frictional bond, τ_d, operating over the fibres that are slipping. The term ϵ_f is the fibre failure strain and c *il*s the critical fibre length.



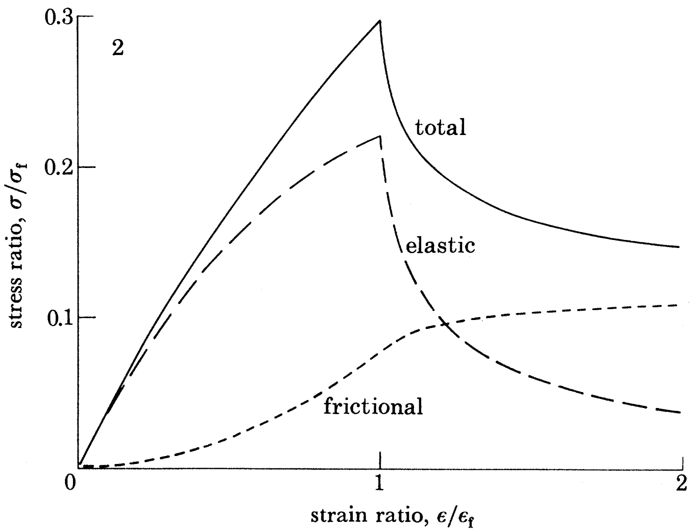


FIGURE 1. Tensile stress–strain diagrams for continuous carbon-fibre reinforced cement. Full lines are the experimental curves, broken lines are the curves predicted by the A.C.K. theory (Aveston *et al.* 1974).

FIGURE 2. The stress–strain response of a fibrous mat, for $l/l_c = 2$ and $\tau_d/\tau_s = 1$. The broken line refers to the proportion of fibres that hold (the elastic response); and the broken line with shorter strokes to those that slip (the frictional response). The full line is the total response.

(iii) *Bending properties and m.o.r./u.t.s. ratio.* Commonly, even linear materials are stronger in bending than in tension (the size effect) but the ratio of the modulus of rupture (m.o.r.) to the ultimate tensile strength (u.t.s.) is usually much lower than 2. F.R.C. materials are markedly non-linear in tension and this non-linearity alone leads to m.o.r./u.t.s. ratios up to a theoretical maximum of 3. Aveston *et al.* (1974) have developed constitutive relations for the m.o.r. and the ratio m.o.r./u.t.s., based on the A.C.K. model. In practice, prediction with these relations is problematical because of the uncertainty about the values of the variables involved, and bending curves are commonly computed directly from measured tensile and measured or assumed compressive stress–strain curves (Allen 1971). However, the computed values often fall short of those measured directly and in particular the apparent strain at failure in bending is often higher than that predicted. This discrepancy can be accounted for, at least in part, by the post-failure stress capacity in tension and the 'size effect' (Laws & Walton 1978).

The bending test is widely employed in materials testing to obtain an indirect measurement of the tensile strength; for fibre cement composites, correction factors (m.o.r./u.t.s. ratios) must be applied and this leads to uncertainties. There is also a problem in determining the limit of proportionality (l.o.p.) in bending. Experiments suggest that for F.R.C. materials the l.o.p. in bending is considerably higher than that in tension. Part of this increase may be attributed to a size effect; but part might also be the result of the increased uncertainty in locating the first deviation from linearity on the bending curve.

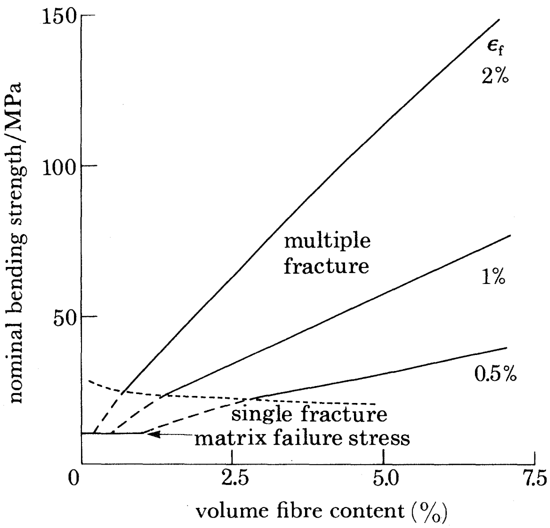


FIGURE 3. Predicted bending strength as a function of fibre content, for Young moduli E_f 76 GPa and E_m 25 GPa, ϵ_m 0.04 %, and increasing values of ϵ_f. The full lines refer to the A.C.K. model composites (V_f above critical V_f for reinforcement in tension); the broken lines refer to composites with V_f below critical V_f in tension and above critical V_f in bending. The broken line with shorter strokes separates the multiple fracture and the single fracture conditions.

There is a further effect of the bending–tensile relation that appears to have been overlooked. It is generally agreed that for F.R.C. materials that fail after multiple cracking, the u.t.s. is given by $\eta\sigma_f V_f$ and there is no contribution from the matrix. But experimental results, for example on carbon fibre cement (Briggs *et al.* 1974) suggest that a mixture rule might apply for the bending strength. The relation between the m.o.r. and the u.t.s. for F.R.C. offers an explanation. At low fibre volume fractions the tensile stress–strain curve after matrix failure is flat and the m.o.r./u.t.s. ratio is high; at high fibre volumes the tensile curve approaches linearity and the m.o.r./u.t.s. ratio is low. When these factors are applied to a linear u.t.s. against V_f relation, the resulting m.o.r. against V_f relation is biased upwards at the low fibre volume end. It then has the appearance of a two-phase mixture rule. Figure 3 shows the apparent bending strength against V_f relation computed from the A.C.K. model. Extrapolation of these solid lines to zero fibre content suggests a positive intercept, i.e. a matrix contribution. The figure also shows the implied effect in the single fracture region between critical fibre volume fraction for reinforcement in tension and the critical fibre volume fraction for reinforcement in bending. In this region the composite fails in tension at the matrix failure strain ϵ_m; a mixture rule should apply although the effect of V_f would be small. The work of Swamy & Mangat (1974), however, suggests a much bigger effect and one that depends on the fibre–matrix bond strength and the fibre aspect ratio. It is difficult to visualize, as implied in the theory of Swamy & Mangat, how the fibres can all slip at the matrix failure strain and it is much more attractive to suppose that the post-failure 'tail' during fibre pull-out, which leads to a critical V_f for reinforcement in bending (Hannant 1978), might be responsible for the observed results.

(iv) *Work to break*. The energy required to extend and to break the composite follows directly from the tensile stress–strain curve. The energy to break an aligned continuous fibre composite described by the A.C.K. model is the area under the load–extension curve up to fibre failure. A large part of this energy is the elastic strain energy of the fibres.

When the fibres are short, by using the fibrous mat model (figure 2) and neglecting the constraint of the matrix in reducing the average fibre strain at failure, it can be shown that for $l \geqslant l_C$ the contribution W of the fibres to the composite strain energy per unit area up to fibre failure strain is

$$W = \frac{3}{16}\left\{\left(1-\frac{5}{9}\frac{l_C}{l}\right)+\frac{5}{18}\frac{l_C}{l}\frac{\tau_d}{\tau_s}\right\}\sigma_f\epsilon_f V_f L, \tag{1}$$

where the first term is the elastic contribution and the second is that arising from frictional slip. The term L is the length of the specimen. The relative size of the two terms follows from equation (1); for example if $\tau_d = \tau_s$, the ratio of frictional to elastic energy is $\frac{5}{26}$ when $l = 2l_C$ and increases to $\frac{5}{8}$ for $l = l_C$.

The total energy per unit area, W', needed to pull out the fibres that do not break is, for $l \geqslant l_C$,

$$W' = \frac{2}{\pi}\left(\frac{1}{12}\frac{\tau_d}{\tau_s}\frac{l_C^2}{l}\sigma_f V_f\right) = \frac{1}{6\pi}\frac{\tau_d r^2}{l}\left(\frac{\sigma_f}{\tau_s}\right)^3 V_f. \tag{2}$$

For a model composite containing 5% (by volume) of fibres of strength 1200 MPa, length 30 mm and critical fibre length 15 mm, the energy to break calculated from equation (2) is approximately 24 kJ m^{-2} when $\tau_d = \tau_s$. The strain energy to maximum stress ratio calculated from equation (1) is 0.17 kJ m^{-2} per mm of sample strained, or 10 kJ m^{-2} if a specimen of length 50 mm is uniformly strained. Of this, less than 2 kJ m^{-2} is the frictional component.

The contribution of the fibres to the total energy to break a specimen and pull out the fibres is (approximately) the sum of the irrecoverable part of the strain energy W and the pull-out energy W'. If the elastic strain energy is largely recovered as one crack opens and the others close, the total energy to break for the model above is approximately 25 kJ m^{-2}, which is within the range of measured impact strengths of young glass reinforced cement (G.R.C.) samples.

There has been some discussion of the relative importance of the bond strength and the fibre tensile strength in determining the energy needed to break a fibrous composite. The ratio σ_f/τ_s is directly related to the critical fibre length l_C and determines the proportions of fibres that slip and that hold. From equation (1) it follows that a high elastic energy contribution from the fibre requires a low l_C together with a high fibre strength, hence a strong bond; and the maximum possible value of this is $\frac{3}{16}\sigma_f\epsilon_f V_f L$. The maximum work to pull-out, however, requires that all the fibres slip and that τ_d is as high as possible, i.e. that $\tau_d = \tau_s$ since $\tau_d \leqslant \tau_s$. The relation between pull-out energy, fibre strength and bond strengths τ_s and τ_d is illustrated in figure 4. The discontinuities in the curves mark the conditions where all fibres slip, further increase in σ_f then has no effect on pull-out energy; but an improvement in τ_d has a marked effect.

(b) *Asbestos cement replacement*

The properties of different types of F.R.C. materials have been reviewed recently by the ACI Committee 544 (1982). There is much general interest in the performance of the relatively cheap melt-extracted stainless steel fibres that have been introduced successfully in the refractory-castable industry. Some experiments have been done at B.R.E. recently with different types of melt-extracted stainless fibres. Sheets of reinforced O.P.C. mortar, 10 mm thick and

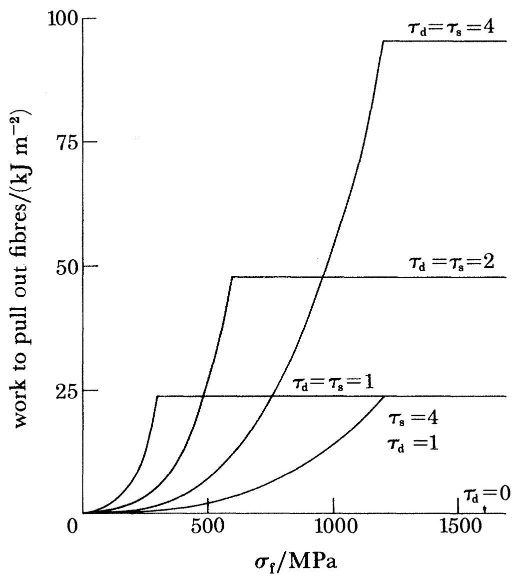


FIGURE 4. Work to pull-out fibres, calculated from equation (2), as a function of fibre strength σ_f and bond strengths τ_d and τ_s (for V_f 0.05; l 30 mm and fibre radius 0.1 mm). Values for τ_d and τ_s are quoted in MPa.

incorporating up to 6% (by volume) of fibre, were made by the spray-up method. Strength values, m.o.r. of 15–20 MPa and u.t.s. of 6–8 MPa are not particularly impressive although impact resistance (Izod) values 11–15 kJ m^{-2} are good. No significant changes in the properties of these materials have been observed up to 2 years under natural weathering conditions. The composite boards were, however, difficult to manufacture and handle, and were very hard to cut and saw.

Many of the new fibre cement composites are serious contenders for replacing different types of asbestos products traditionally used in the construction industry. In the development of asbestos-free fibre cement composites, in roofing applications for example, two distinct trends are discernible. Traditional asbestos cement manufacturers are choosing the alternative fibre mainly in terms of the ease with which it can be handled by the existing manufacturing techniques within the industry, particularly the Hatschek process. Developers outside the asbestos cement industry have more freedom in this respect and entirely new production methods are being attempted, for instance, to incorporate polyolefin-film fibre nets (Bijen & Geurts 1980). The cost of the fibre and the properties of the new composite, including its durability, are other major considerations in fibre selection.

Wells (1982) has recently described the properties of some of the asbestos cement alternatives produced on the Hatschek machine (table 1). The mechanical properties of the composites, for example carbon fibre cement, can be improved considerably by increasing the fibre volume fraction, but present fibre costs (Harper 1982) are such that the alternatives may then be less attractive than other materials, say PVC-coated steel. From the point of view of costs, cellulose fibres (for example, wood pulp) have obvious advantages and asbestos-free insulation boards containing large amounts of cellulose are already in use (Harper 1982). These autoclaved cellulose reinforced alternatives are dimensionally stable as the matrix is not H.C.P., but consists mainly of crystalline calcium silicate hydrates with very little, if any, free lime. In the cement matrix, the long term viability of wood pulp or other vegetable fibres (Cook 1980) remains questionable.

TABLE 1. PROPERTIES OF ASBESTOS CEMENT SUBSTITUTES MANUFACTURED ON THE HATSCHEK MACHINE (AFTER WELLS 1982)

product	fibre content (% by mass)	dry Charpy impact strength kJ m^{-2}	modulus of rupture/MPa dry	wet	wet aged at 50 °C	combustibility (BS 476, Part 4)
asbestos cement	10	2–4	30	25	—	pass
alternative fibre composite based on a.r. † glass (CemFIL)	3.5	4.6	16	11.5–12.3	9–10 (200 days)	pass
a.r. mineral wool	5	3.5–4.5	18	17.2	8.2 (84 days)	pass
polypropylene monofilament	0.5–2	6	16–17.5	16–17.5	—	fail, 70 °C temperature rise, 600 s flaming
carbon	1.0–2.0	2.5–4.5	18–22	17–19	16.0 (122 days)	pass
refined cellulose	3.5	1.5–2.5	15–18	13–15	11.0 (84 days)	pass
cellulose‡	9	3.9	19.5	12.2	—	fail, 65 °C temperature rise, Class 1 surface spread of flame

† Alkali-resistant. ‡ Autoclaved calcium silicate matrix.

Several other fibres not included in table 1 are currently receiving attention in industrial laboratories as asbestos substitutes and judging from the patent literature it would appear that fibres derived from polyvinyl alcohol are of particular interest. Much research has also been done on glass reinforced cement (G.R.C.) made by the spray-up process, and on cement composites containing continuous nets of very fine fibrillated polyolefin film fibre. The latter material produced by a lay-up technique (Hannant & Zonsfeld 1980) is very tough and claimed to be strong enough to satisfy the requirements for corrugated roofing. But as with other alternatives containing organic fibres the combustibility test of BS 476 may pose a particular problem (Wells 1982).

Alkali-resistant glass fibre CemFIL (trade mark of Fibreglass (U.K.) Ltd) has been the cornerstone of the G.R.C. industry during the last decade. By using a high throughput spray-up method G.R.C. sheets can now be manufactured on a nearly continuous basis with speeds of 10 m/min or more, which is comparable to the production rate of asbestos cement by the Hatschek process. The properties of spray-dewatered G.R.C. of this type containing *ca.* 4% (by volume) of CemFIL fibre in different environments for up to 10 years have been the subject of detailed studies (B.R.E. 1979; Proctor 1980), and very long-term (more than 100 years) projections of some of these properties have been made from the results of accelerated ageing tests and natural weathering in various parts of the world (Proctor 1982). These studies have shown that under wet and natural weathering conditions the strength and impact resistance of

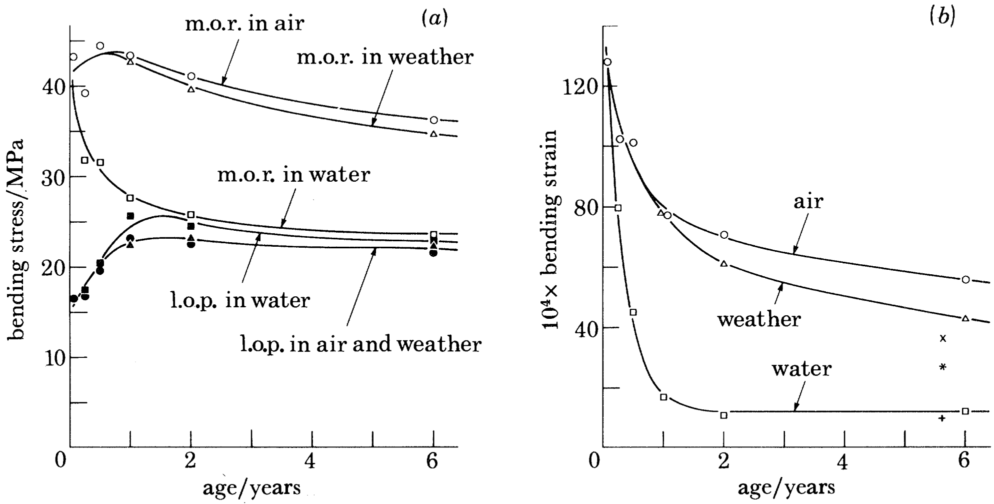


FIGURE 5. Bending properties of polymer modified G.R.C. in different environments as a function of age. (*a*) Modulus of rupture and limit of proportionality: ○●, in air; □■, in water; △▲, in weather, (*b*) Average strain in the outermost fibres at maximum load; ○, in air; □, in water; △, in weather. Other symbols: x, G.R.C. control in air; +, G.R.C. control in water; *, G.R.C. control in weather.

CemFIL G.R.C. made from O.P.C. are significantly reduced with time and this factor must be taken into account in designing with G.R.C. In relatively dry air, however, G.R.C. properties remain more or less stable with time and lightweight G.R.CS (West *et al.* 1980) incorporating, for instance, pulverised fuel ash cenospheres have considerable potential as substitutes for asbestos-containing materials in internal applications such as insulation and fire protection.

The long-term properties of CemFIL G.R.C. in wet environments are improved when non-Portland cements such as high alumina and supersulphated cements or modified O.P.C. such as pozzament are used (Majumdar 1980; Majumdar & Singh 1982). In natural weather the addition of certain types of polymer dispersions may also be beneficial. This option has been exploited in the development of a type of G.R.C. (Forton), where the reinforcement is provided by borosilicate E – glass fibres and 15% (by volume) of an acrylic polymer emulsion is added to the O.P.C. mortar matrix (Jacobs 1982). The flexural properties of a G.R.C. sheet (10 mm thick) produced by the spray-dewatering method at B.R.E., incorporating 4% (by volume) of CemFIL fibres, an O.P.C. matrix, and containing 11.5% (by volume) styrene-acrylic co-polymer solids, kept in three different environments up to 6 years are shown in figure 5*a*, *b*. It is interesting to note that in natural weather (B.R.E. site) the polymer modified G.R.C. has retained a significant proportion of its initial strength after six years although its strain capacity has been reduced. The reasons for the much improved performance of the polymer modified materials in natural weather, in comparison with that under water, are not clear.

The emergence of CemFIL 2 fibre, which is more alkali-resistant than CemFIL (Proctor 1982), may lead to the use of G.R.C. as a replacement for asbestos cement. Smith (1982) has recently reported that asbestos cement products such as corrugated roofing, pipes, guttering etc. can be made in CemFIL 2 G.R.C. by using standard asbestos cement production methods. He claims that by using 3% (by mass) fibre and a modified O.P.C. matrix, a corrugated roofing sheet in G.R.C. can be manufactured that will pass the existing British Standard for the corresponding asbestos cement product and will incur only a small cost penalty. The properties of two composite boards, made at B.R.E., each containing *ca.* 5% (by mass) CemFIL 2 fibres, but very different matrices, are given in table 2. For both boards weathering results up to 2 years are highly encouraging, particularly in respect of ultimate failure strain and impact resistance. Accelerated ageing test results indicate that for the granulated slag–cement composite, the properties should not change very much with time unless factors such as carbonation become important. For CemFIL 2–O.P.C. mortar composites some reduction in properties with time would be expected.

TABLE 2. PROPERTIES OF CEMENT COMPOSITES CONTAINING *ca.* 5% CemFIL 2 GLASS FIBRES

	70% O.P.C. 30% sand (by mass)			70% granulated slag 30% O.P.C. (by mass)		
property	28 days	natural weathering at B.R.E. for 2 years	wet aged at 50 °C for 180 days	28 days	natural weathering at B.R.E. for 2 years	wet aged at 50 °C for 50 days
modulus of rupture/MPa	38	36	24	35	36	37
limit of proportionality in bending/MPa	12	11	12	11	15	11
ultimate tensile strength/MPa	15	13	9	13	15	13
ultimate tensile failure strain in microstrain	11000	8000	870	9800	9000	9500
tensile Young modulus/GPa	30	33	33	22	23	33
Izod impact strength/(kJ m^{-2})	21	20	8	21	19	20

While seeking replacements for asbestos cement it should be borne in mind that the replacement must meet the performance specifications for particular applications. National and International Standards on asbestos cement products may require important amendments or additions, or both, if they are to be used as the basis for specifying similar products in other F.R.C. materials.

(*c*) *Future prospects*

The past decade has seen numerous applications of F.R.C. materials in construction (Hannant 1978; ACI 1982). Many of the current uses of steel fibre reinforced concrete, for example in pavements and overlays, hydraulic structures and refractory concrete, will no doubt continue but in future more use is likely to be made of fibre reinforcement in selected zones of the component or structure. In precast components, fibre concentrations could be increased greatly by prepacking the moulds with fibres first (Lankard & Lease 1982). More research will be done to improve the effectiveness of fibres by placing them in a favourable disposition. The glass fibre reinforced spun concrete pipe (Farahar 1978) in which continuous strands of glass fibres in large concentrations are positioned in the inner and outer layers only, provides a very good example. Magnetic alignment of short steel wires in concrete components has also been achieved (Skarendahl 1980). For economic reasons, general use of fibres in reinforced concrete structures may be limited to special cases such as concrete reactor vessels and blast or seismic resistant buildings. A recent use of steel fibre reinforced concrete in the construction of hemispherical domes by using an inflated membrane process may also be a pointer for the future.

Fibre reinforced cement sheets are energy efficient in comparison with similar products in metal or plastics and their predominant constituent, i.e. cement, is non-combustible. The advantages of F.R.C. materials have been exploited with great enthusiasm by the G.R.C. industry in uses such as cladding, permanent formwork and repair of old buildings and structures. The reduction of strength of the first generation alkali-resistant glass fibres in cement has limited the range of G.R.C. applications (B.R.E. 1978), but with the emergence of CemFIL 2 and the promise of an even more alkali-resistant fibre (Proctor 1982), the future prospect of G.R.C. as a material has improved considerably. One may see more widespread use of the material in low-cost housing or as encasements for steel reinforced concrete beams and columns.

In many of these thin sheet applications several other fibres are suitable also. Carbon and aramid fibres produce excellent cement composites, and if their cost can be reduced such composites could be developed further for structural use. Composites reinforced with nets of fibrillated polyolefin film fibre may become commercially available in the near future and their usefulness may be extended further by the introduction of the high-modulus fibre varieties (Ward 1980). In future we may see more widespread use of mixtures of fibres in cement reinforcement.

Much more attention will be paid in future to matrix formulations. The addition of pozzo-anas, fillers, admixtures, polymers etc. to an O.P.C. matrix will probably increase, and so might the use of non-Portland cements. It would be interesting to see if fine fibres can be introduced in strong low-porosity cements, such as the recently developed 'macro-defect-free' (MDF) cement (Birchall *et al.* 1981), to provide extra toughness. The principles behind fibre reinforcement of cement and concrete are reasonably well understood now but there are still uncertainties in some areas such as the importance of the fibre–matrix bond and the best method to measure bond strength or the efficiency factors that designers might need to use to predict composite properties. Further work should be aimed at resolving these issues.

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Discussion

J. E. Bailey (*Department of Metallurgy and Materials Technology, University of Surrey, Guildford, U.K.*). In view of the need for research on the durability of glass fibre reinforced cement building products, is it true to say that sufficient attention has been paid to the effect of the environment on pipes made out of these materials for the sewerage and drainage applications briefly touched upon in this paper?

A. J. Majumdar. The pipe described by Farahar (1978) has undergone a rigorous testing programme that has included accelerated ageing, and the acceptance of the pipe in various countries is based on the favourable results obtained. Existing information on the long-term properties of g.r.c. flat sheets is not strictly applicable to the g.r.c. layers in the pipe because the latter are constructed in a very different way and have large concentrations of highly oriented continuous glass-fibre rovings.

The long-term performance of the pipe in drains and sewers may depend primarily on the type of cement and the quality of concrete in these pipes.

D. B. Downey (*ARC Concrete Ltd., U.K.*). It is only fair to respond to Professor Bailey's question and to put his mind to rest in respect of sewer failures. For glass reinforced concrete pipe there has been a programme of accelerated testing underway for the past ten years, which clearly demonstrates strength retention. This evidence is supported by successful performance under service conditions for over seven years, and currently more than 100 km of Slimelinepipe is functioning effectively within the nation's sewer asset. Similar test work in South Africa and Japan is also supportive. The available data have been studied by a specialist group brought together by the British Standards Institution, whose conclusion is published in DD76 stating that it is reasonable to conclude that no strength loss will be experienced with these pipes in service.

In regard to acid attack, it is well known that H_2S generated in conditions of low flow, shallow gradient and hot climate can attack concrete. Glass reinforced concrete pipes are only used in circumstances where other more traditional concrete pipes are acceptable. It is therefore reasonable to conclude that sewer failures are unlikely in the short, medium or long term.

C. D. Pomeroy (*Cement and Concrete Association, Slough, U.K.*). ARC pipes have been thoroughly studied and the method of manufacture is not a randomly reinforced fibre mat, but the pipes are a true sandwich composite. There is no need to worry about their use in sewers. The inner skin is a very dense and impermeable layer and this will provide extra protection against chemical attack.

J. Bensted (*Blue Circle Industries p.l.c., Research Division, Greenhithe, U.K.*). Has Dr Majumdar investigated the influence of cement alkali content upon the long term behaviour of G.R.C. composites?

A. J. Majumdar. We have not studied the effect of the alkali content (Na_2O+K_2O) of cement on the long-term properties of G.R.C. in a systematic manner. However, over the years several different batches of O.P.C. having different alkali contents have been used in our work. G.R.C. composites made from these cements have shown very similar trends in long-term durability.

I may mention in this connection that Proctor *et al.* (1982) have recently published results that indicate that the range and type of alkali content commonly encountered in rapid hardening Portland cements in the U.K. has little effect on the degree of strength reduction suffered by CemFIL fibres when they are placed in the cement matrix.

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