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Polyolefin fibrous networks in cement matrices for low cost sheeting

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The principles behind the use of continuous opened networks of fibrillated polypropylene film in a cement matrix are outlined. The excellent mechanical bonding between the film and the cement matrix enables closely spaced cracking to be achieved while the shape of the stress–strain curve demonstrates the ability of the composite to absorb transient overloads. It is shown that sheets of low materials cost can be produced which can comply with the British Standard loading requirements for asbestos cement sheeting.

1. Introduction

A solution to the problem of reinforcing a brittle cement matrix with fibres was obtained in the late nineteenth century by the inclusion of asbestos fibres, and large-scale production of flat and corrugated sheets was made possible by the invention of a manufacturing process which was patented at the beginning of the century (Hatschek 1901). The commercial success of this material is probably unparalleled in the entire field of fibre composites. An indication of the size of the market is that world production of asbestos-cement in recent years has been in excess of 20×10^6 t/a†, of which more than 0.4×10^6 t/a are used in the U.K. However, this market is likely to decline because it has been forecast that the supply of cheap asbestos fibres may be exhausted by the year 2000 (Krenchel & Hejgaard 1975) and the increasing awareness of the hazards to health of asbestos fibres has caused some European governments to consider banning the manufacture of asbestos-cement products. An economic alternative product is therefore being actively sought by the interested parties.

Adequate material characteristics for a substitute sheet have been achieved by the use of glass fibres in cement but the price of the glass fibres is unlikely to be low enough in the foreseeable future to allow direct competition with asbestos fibres. In contrast, polyolefins such as polypropylene can be comparable with asbestos in terms of cost per unit volume and at the 1978 price of about £900/m^3 for polypropylene film, the material costs of a 6 mm thick cement flat sheet containing 8% by volume of polypropylene would be about £0.65/m^2.

However, the potential of polypropylene as a direct substitute for asbestos fibre in a cement matrix has not been fully explored, partly because of the very significant differences in material characteristics. For instance, asbestos fibres have a high tensile strength, a high modulus of elasticity, and a peculiar affinity for cement particles which makes possible the inclusion of up to 10% by volume of fibre in a continuous production process. Polypropylene, on the other hand, has a low modulus of elasticity, virtually no physico-chemical bonding with cement paste and it has, until recently, been difficult to include fibre contents of 10% by volume in cement paste.

The relatively low modulus of polypropylene does not prevent the reinforcement of a brittle cement matrix in the post-crack zone, and the tensile strength of about 400 MN/m^2 is of the

† 1 a = 1 year.

same order as that of many asbestos fibre bundles (200–1000 MN/m^2), removed from asbestos-cement boards (Majumdar 1977).

The main problems therefore are those of achieving sufficient bond and of including an adequate fibre volume fraction in thin cement sheets and the solution of these problems forms the theme of this paper.

2. Polyolefin networks

(a) *Bond and fibre volume*

A method of bonding a fibrous polyolefin material into a cement matrix was discovered in the 1960s (Zonsveld 1970) after fibrillated film fibres had come on the market in the form of strings, ropes and baler twines. Pieces of twine cut to lengths of around 50 mm were simply added to fresh concrete in the mixer and the cement dispersion was found to penetrate between the elementary fibrils to effect a mechanical keying of polypropylene. Articles like piling units and cladding elements showed remarkable impact resistance with fibre volume percentages as low as 0.5. However, when attempts were made to incorporate higher fibre contents the mixes became progressively less workable. For the production of thin sheets, a different approach is necessary and the desirable feature of multiple cracking at less than 5 mm spacing necessitates the use of high percentages of strongly bonded fibres.

The solution to the incorporation of a high percentage of polyolefin fibre (5–15 %) required for the stronger composites, and also for complying with the complex bond requirements, is thought to lie in the concept of utilizing many layers of fibrillated film opened up to form networks which continuously span the length and width of the sheet material (Hannant *et al.* 1978). The complexity of the bond requirements is outlined below:

(i) Location of bond is important because films that are fully keyed by cement reaction products at, say, 10 mm intervals will not transfer stress back into the matrix as rapidly as films which are fully keyed at 1 mm or 1 μm intervals (Hannant *et al.* 1978). Both situations will entail film breakage before full composite fracture but the crack spacing will be closer for the closely keyed films.

(ii) The bond must be such that when densification of the matrix occurs at the film interface due to continuing hydration, sufficient slip or flexibility must be available to avoid local fracture of the film at the point where it bends across a crack.

Thus the ideal bond is one which will enable the full strength of the film to be utilized at composite failure, will produce very closely spaced cracks, yet will allow sufficient flexibility at a crack for failure strains in the composite of at least 1 % to be achieved throughout the life of the sheets under conditions of continuing cement hydration. The life envisaged might be perhaps 50 years.

It is thought that the use of continuous opened networks of fibrillated polyolefin film may provide a solution to these problems because the combined effect of mechanical bond due to the formation of keys or pegs through the macro- and micro-slits in the film and the high specific surface of the continuous filaments enables the full strength of the fibre to be utilized at composite failure and produces very closely spaced cracks. Also, localized de-bonding at cracks, due to lack of chemical affinity for cement paste, and the high Poisson contractions should allow for adequate ductility in the long term.

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(*b*) *Choice of polyolefin*

Polypropylene, a linear polyolefin obtained by stereospecific polymerization of propylene, is an obvious choice for this new process since it has high tensile strength derived from the high degree of crystallization and orientation of the macromolecules. The methyl groups along the polymer chain are systematically arranged and in the fibres discussed here are positioned in the so-called isotactic configuration. Processing the polymer into fibres by melt extrusion and by stretching induces the required molecular orientation and mechanical strength.

Fibrillated films are made by extrusion of the polymer from a die which produces a tubular or flat film which is then slit into tapes, and is monoaxially stretched to about eight times its original length. This leaves the film weak in the lateral direction. Fibrillation is the generation of longitudinal splits, and can be controlled to a regular pattern by the use of pin systems on rollers over which the stretched tapes are led.

The structure of drawn polypropylene film can be described (Spencer-Smith 1976) as a composite consisting of orientated small crystals (spherulites) in a matrix of amorphous polymer, in which the spherulites have been deformed into microfibrils during the stretching operation. This concept explains in a satisfactory way the mechanical properties of stretched films which can also be produced from polyamides and polyesters.

Polypropylene is produced in plants of the order of 100000 t/a and in Western Europe alone the production is over a million t/a so that existing production capacity is likely to be adequate for the new use. The fibrillated films currently find application as ropes and carpets. Compared with low modulus polyethylene, which is in the same class of economic importance, polypropylene has the advantage of a higher melting point (165 °C) and greater ease of fibrillation.

Other plastic materials made in the form of mesh or web might also be attractive technically and are commercially available. Examples are the co-extruded Netlon webs, or weaves made from flat strips of fibrillated polypropylene film such as Lenoweave, although their cost may make them commercially unattractive except for specialized uses. Recent research into methods of drawing polyolefin fibres with increased orientation and crystallization (Capaccio & Ward 1974; Capaccio *et al.* 1976; Zwijnenburg & Pennings 1976) may well lead to the commercial manufacture of polypropylene and polyethylene film with moduli of elasticity greater than the present market products and these could be beneficial in giving reduced deformations in the cracked composite.

(*c*) *Durability*

Compared with cement, polypropylene has such a high chemical resistance that the cementitious matrix will always be the first to deteriorate on contact with aggressive chemicals. The weakness of polypropylene regarding degradation under the influence of actinic rays can be overcome to a considerable extent by the addition of ultraviolet stabilizers, which enable the polymer to be used successfully in outdoor applications like mooring ropes for yachts. The degradation is also much retarded by pigmentation with carbon black. The danger of ultraviolet penetration into a cement matrix is slight, but long-term weathering tests have been arranged to study this possibility and to check whether it will be at all necessary to use ultraviolet stabilized polypropylene networks in the proposed composites.

3. Theoretical considerations

(a) Concepts

The theoretical principles of fibre reinforcement in brittle matrices are well known (Aveston *et al.* 1971; Aveston *et al.* 1974) and the major requirements for an effective thin sheet material for the construction industry can be summarized as follows:

(i) a high fibre content (in cementitious materials this could be between 5 and 10% by volume);

(ii) well bonded, but not too well bonded, fibres (there is a preference here for continuous fibres);

(iii) ductile fibres (to avoid fracture due to high local distortion across angular cracks);

(iv) uniform and closely spaced fibre distribution (this is particularly important near surfaces).

(b) Flexural theory

The main stresses to which thin sheet materials are subjected are bending stresses and the major contribution of the fibre reinforcement is made after cracking has been initiated in the matrix. Cementitious materials fail in tension at strains less than 0.05% and therefore the most relevant theoretical treatments are concerned with post-cracking flexural theory (Hannant 1975; Aveston *et al.* 1974; Laws & Ali 1977).

In these theories, the material in the compressive zone is generally considered to behave in a linear elastic manner with the elastic modulus equal to the initial modulus in tension. The tensile zone is considered to be quasi-plastic in the sense that, although strains increase linearly with distance from the neutral axis, the strain is no longer related to stress by the pre-cracking modulus in tension.

One of the most important requirements for the achievement of high flexural load bearing ability then becomes the tensile strain capacity of the composite, which controls the progressive movement of the neutral axis towards the compression surface of the beam. On the other hand if perfect bond is achieved, the neutral axis remains in the centre of the section and this leads to a brittle material with a flexural strength equal to the tensile strength instead of the value of up to three times the tensile strength, which is predicted if sufficient localized debonding occurs at cracks.

4. Experimental work

(a) Film lay-up

The fibrillated polypropylene films are laid up in a fine-grained matrix, and up to 12 vol. % may be included with no increase in air content if the film is used in the relatively unopened state. When widely opened films (for instance, greater than five times the original width) are used, the film layers may tend to buckle and bulk, thereby making it difficult to achieve more than 5–7% by volume without the use of pressure.

The degree of opening required for adequate two dimensional properties depends on a range of film parameters such as slit length and slit spacing. These have not yet been optimized and may well vary for different applications.

(*b*) *Stress–strain curves*

The material may be characterized by tensile stress–strain curves and flexural load–deflexion curves of the types shown in figure 1 for a composite containing 5.7% by volume in the direction of stress of 100 μm film opened to about three times its original width. The material was water-cured for 5 months before testing in this instance.

Typical features of the direct tensile stress–strain curve which are not all visible in figure 1 because of the small scale, are a linear, stiff uncracked portion up to stresses between 4 and 6 MN/m^2 followed by a flat portion to strains of about 1.5%. The slope then increases up to strains of about 7–10% at stress levels depending on the film volume. In order for complete composite failure to occur, all the fibres must fracture since pull-out is not possible. Thus,

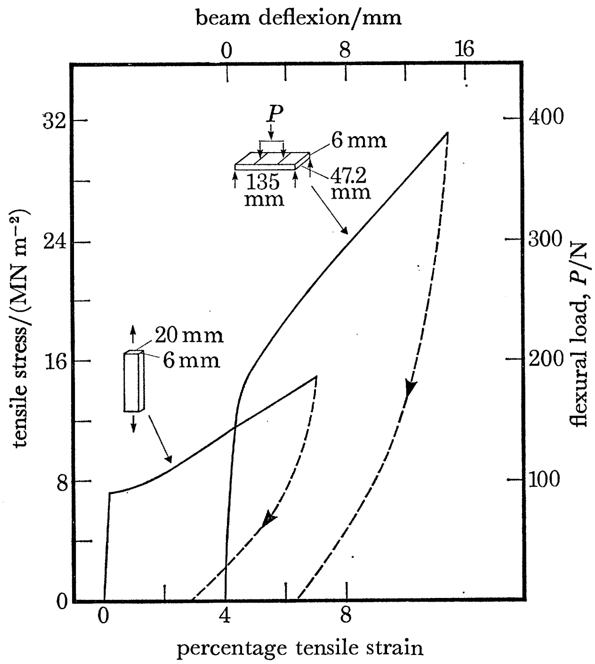

FIGURE 1. Tensile stress–strain curve and load–deflexion curve in flexure for a composite containing 5.7% by volume of fibrillated film networks parallel to direction of stress. 100 N (flexural load) ≡ 7.9 MN/m^2 (flexural stress).

provided that the ultimate load has not been reached, good strain recovery occurs on unloading even at the large strains shown on the figure. The load–deflexion curve in flexure is relatively stiff and linear up to a load equivalent to bending stresses (modulus of rupture) of about 10 MN/m^2 and bending stresses of over 30 MN/m^2 can be achieved at large deflexions. In tension, and in bending, crack spacings of less than 5 mm are normal. The very large areas under both tensile and flexure curves imply a high degree of toughness and impact resistance. Lacking realistic methods to characterize these properties, the common performance test of dropping a 2 kg steel ball from a height of 4 m onto a thin sheet demonstrates that this toughness is achieved in practice.

5. Stresses in corrugated sheeting in service

One of the major uses of thin cementitious sheets is as cladding for low cost, low rise industrial buildings in which stiffness is given to the thin sheeting by virtue of the corrugated shape of the cladding. The general requirement (B.S. 690, 1973) for symmetrical semi-compressed sheet of this type is that the minimum bending strength shall be 15.7 MN/m^2, and this can be easily achieved with between 5 and 8% by volume of fibrillated polypropylene film.

However, it is instructive to estimate the approximate stresses in the uncracked sheet and the stresses in the polypropylene film in cracked sheet when subjected to the loads to be expected under service conditions as defined in the relevant Code of Practice (B.S. 5247, 1975). For the purpose of these calculations, the neutral axis of the cracked corrugated sheet is assumed to be $\frac{3}{4}$ of the depth from the tensile face and the tensile stress block is assumed to be rectangular (Hannant 1975). The expected service stresses in flexure can then be compared with the bending load–deflexion curve shown in figure 1.

Substantial approximations have been made for the purpose of these calculations, particularly those associated with the distribution of concentrated loads throughout the sheet width, and the shape of the post-cracking stress block, but the results presented in table 1 should nevertheless give the order of stresses to be expected in the film under service conditions.

Typical physical parameters for symmetrically corrugated sheet

corrugation height	54 mm, nominal thickness = 6 mm,
section modulus	75×10^3 mm^3/m,
span (simply supported)	1.38 m,
sheet width	1 m,
polypropylene film volume	5.5% parallel to corrugation,
(total 8%)	2.5% at right angles to corrugation,
strength of polypropylene film	400 MN/m^2.

Table 1. Possible service loads based on B.S. 5247 part 14, 1975

loading requirements: type	loading requirements: applied load	approximate stresses in: uncracked sheet maximum tensile stress in bending in composite (MN m^{-2})	approximate stresses in: cracked sheet stress in polypropylene film (MN m^{-2})
roofs, slope 10–30°	0.75 kN/m^2	2.4	17.9
	0.9 kN on 300 mm square	3.7†	27.6†
		7.4‡	55.1‡
flat roofs up to 10° slope, with access	1.5 kN/m^2	4.8	35.8
	1.8 kN on 300 mm square	7.4†	55.1†
		14.8‡	110.3‡
wind	2.5 kN/m^2	7.9	58.8
self weight	0.15 kN/m^2	0.5	3.5

† Assumed that load is carried by 1 m width; section modulus = 75×10^3 mm^3.
‡ Assumed that load is carried by 0.5 m width; section modulus = 37.5×10^3 mm^3.

From table 1 it can be seen that the film stresses under working conditions are generally low compared with the film strength, except for the hypothetical condition in which 1.8 kN is carried entirely by a sheet width of 0.5 m. Wind loading is generally expected to cause the highest stresses in the sheet but, owing to the transient nature of these stresses and the excellent ductility and energy absorbing characteristics of the composite (figure 1), the material is likely to be very resilient under wind overload conditions and there remains a satisfactory margin between stress and strength.

It can also be seen that, in general, the working stresses in the composite are within the relatively straight, initially stiff portion of the load–deflexion curve in figure 1, i.e. up to loads equivalent to 10 MN/m² modulus of rupture, implying that excessive deflexions are unlikely to occur at working loads even when the material is partly cracked.

6. Conclusions

It is shown that it is possible to include an adequate volume of continuous opened networks of polypropylene film in thin cement-based sheets to comply with the relevant British Standard loading requirements for asbestos-cement sheeting. The composite is also a ductile building material with useful properties for additional end uses. Other important parameters such as durability and fire resistance are currently being investigated.

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