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DURABILITY OF POLYPROPYLENE FIBERS IN PORTLAND CEMENT-BASED COMPOSITES: EIGHTEEN YEARS OF DATA

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ABSTRACT

Portland cement-based composites containing two formulations of fibrillated networks of polypropylene film have been subjected to natural weathering, storage in laboratory air, and storage under water for periods of up to 18 years. The durability of the polypropylene fibers in these conditions has been evaluated by tensile tests on the composite, which has enabled the change in strength of the polymer with time to be determined. Excellent strength retention has been found, which gives increased confidence in the long-term stability of polypropylene as a cement reinforcement whether used inside buildings or in structures exposed to the weather. © *1998 Elsevier Science Ltd*

Introduction

Polypropylene fibers are widely used in Portland cement-based products, both in fine grained mortars and in mass concrete. The fibers, which range in diameter or thickness from 15 to 80 μm, may be monofilament or fibrillated film, chopped or continuous, and may improve the properties of the composite in both the fresh and hardened states. Durability of the fiber is of no consequence for improvement of the properties of fresh concrete, but may be of crucial importance to the maintenance of hardened properties where the expected lifespan of the structures may well be in excess of 30 years.

The mechanisms of degradation of polypropylene by oxidation are well established, as are commercial chemical stabilizers that retard or prevent oxidation. The effectiveness of such stabilizers in cement products has been examined (1) using the standard Arrhenius equation at temperatures up to 140°C. It was shown that 0.25% of commercial antioxidants by weight of film should give lifetimes well in excess of 30 years at normal temperatures. However, Gysling (2) found that this procedure predicted longer lifetimes than were actually obtained, and there are a number of additional complicating factors in the prediction of in-service lifetime when the fibers are contained in a cracked cement matrix subjected to natural weathering. In this case, the composite may be saturated with water for a significant time, which, although reducing the amount of oxygen reaching the polymer, could have an adverse effect if the stabilizers used are able to be leached out. Also, the cracks may allow ready access of oxygen to the fiber, with the additional possibility of irradiation by ultraviolet (UV) light near the crack surface. Another significant factor found with other fiber-reinforced cements (3) is the growth over many years of large $Ca(OH)_2$ crystals adjacent to the fiber cement interfaces, which can cause fiber fracture either due to local fiber damage or to matrix densification preventing fiber pullout at cracks.

Due to the complexity of the reactions involved and other potential mechanical factors that may affect the strength of these thin fibers in cement and concrete, it was considered that the assumption of an Arrhenius plot may not be generally accepted as valid for predictive purposes in civil engineering applications. Therefore, a real-time test program was initiated in 1979/1980 to examine the change with time of tensile strength and strain to failure of the polymer in cement mortar under three exposure conditions and in the cracked and uncracked states.

Test Program

Polypropylene films

Two types of stretched and oriented polypropylene films were used supplied in 1978 by Bridon Fibers & Plastics Ltd. Film type A (code named 1952/R1/7) contained only thermal stabilizers for processing purposes, whereas film type B (code named 1952/R1/9) contained thermal stabilizers plus a high UV stabilizer to protect against possible attack by UV light and improve the resistance to oxidation. The films were fibrillated (Fig. 1) to enable easy penetration of cement mortar and had a hairy texture to promote bond with the cement paste.

Some characteristics of the film fibers are shown in Table 1, the specific surface areas having been determined by Montedison S.p.a. by the absorption of krypton gas at 77 K. In Table 1, the quoted film strengths were determined from tests on the composite at 28 days. The elastic moduli were determined from the films alone over the strain range expected in the composite, the lower moduli being measured at higher strains.

Manufacture and testing of specimens

Full details were described previously (4); hence, only a brief summary is presented in this paper.

The mortar matrix consisted of ordinary Portland cement, pulverised fuel ash, and sand in the proportions 1.0:0.25:0.19, respectively, with a total water-to-cement ratio of 0.34 and 2.4% by weight of cement of Melment L10, a sulfonated melamine superplasticizer.

About 350 specimens, 300 mm long by 25 mm wide and nominally 6 mm thick, were cut from 30 separate sheets. The sheets, which were laid up by hand, contained 51 layers of film networks, 34 layers being in the test direction and 17 layers at right angles to this, giving a film volume of about 6% in the test direction and 3% in the orthogonal direction. The actual film volume was determined for each specimen by acid dissolution in diluted hydrochloric acid after testing to failure.

All tests were carried out in uniaxial tension using an Instron 1122 testing machine, the strains being measured by a clip-on strain measuring device outputing to X-Y-Y recorders. The rate of loading was controlled by the strain rate, which was about 4% per minute. All specimens that reached 5% strain were unloaded to check whether strain recovery varied with time and exposure conditions. The crack spacing was determined after failure, using a

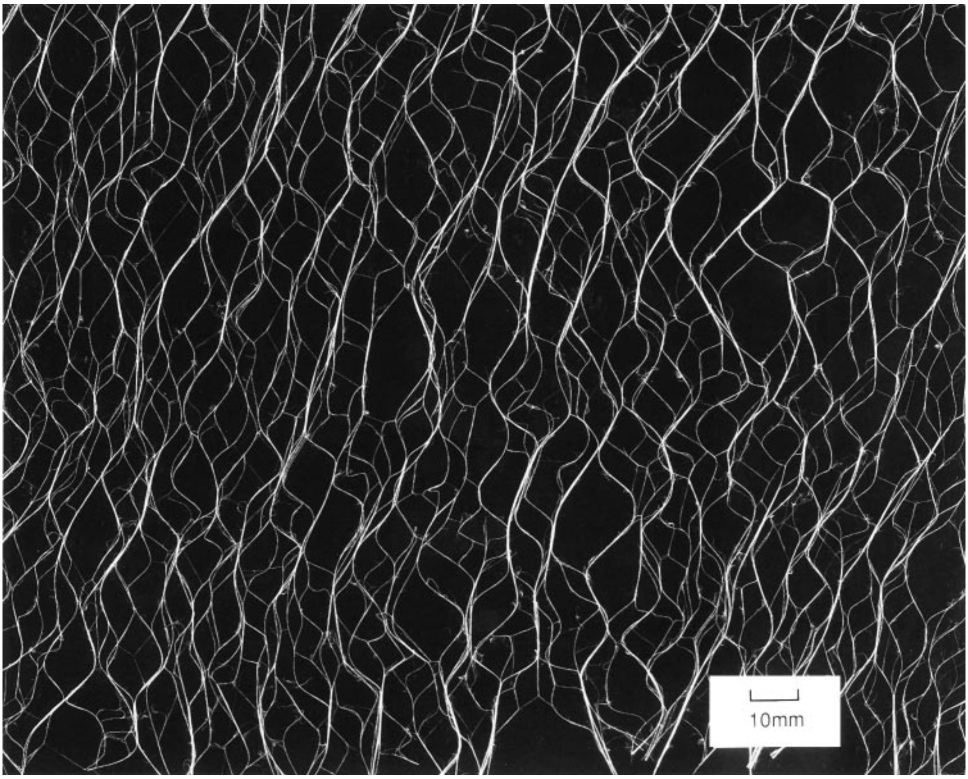

FIG. 1.
Fibrillation pattern of film type A.

microscope, and the values for crack spacing were used to calculate the fiber–matrix bond strength.

Half of the specimens were precracked. The cracking procedure involved the application of a tensile strain of 0.5%, which resulted in 22 cracks in the 100-mm strain measuring length, with an average crack width of 7 μm after unloading to a residual strain of about 0.16%.

TABLE 1
Film classification.

Film type	Elastic Mod.E (GPa)	Unopened film width (mm)	Nominal thickness (μm)	Slit frequency (slits/mm)	Specific surface (mm^2 per mm^3)	Strength (MPa)
1952/RI/7 Type A	5.8 to 2.9	95	43	4.10	482	276
1952/RI/9 Type B	5.2 to 2.8	90	47	4.26	564	279

Three exposure conditions were selected, one in natural weathering conditions at the Building Research Establishment exposure site at Garston, Hertfordshire, one in laboratory air at the University of Surrey, and the third consisting of a smaller number of samples stored under water at 20°C.

Test ages were 1, 7, and 13 months, 2, 3, 5, 9, or 10 years, and 17 or 18 years depending on the exposure condition. Eight specimens were tested for each fiber type and exposure condition at each age, with half of the specimens being precracked except for the under water storage condition.

Basis of Fiber Strength Determination

Although the tensile strength of oriented polymer films may be determined by cutting strips from the unfibrillated film and loading to failure, the strength of the same film after it has been fibrillated is much more difficult to assess accurately. There are many hairs or fibers (Fig. 1) that are partly detached from the main elements and, therefore, it is not possible to produce an equal stress in all of the elements when loading in a tensile machine.

However, if the polymer is bound into a cement matrix, the loose ends are well bonded mechanically into the matrix (4), which then can be used as the load transfer device. After cracking, the stress in the composite at a crack is completely sustained by the fibers; therefore, the film strengths can be determined provided the fiber cross-sectional area is known. This procedure has the advantage that the fibers are tested in their naturally aged state within the matrix, as they would be at failure in a practical application.

This approach can only be used when the critical fiber volume is exceeded, where "critical fiber volume" is defined as that volume of fiber that, after matrix cracking, will support the load that the composite sustained before cracking.

In this investigation, the critical fiber volume at all ages was generally exceeded at the first few cracks, but in some cases for film B under natural weathering, matrix cracking at higher stresses produced film fracture before multiple cracking was complete. Where the strain at failure of the composite exceeded 5%, matrix cracking was complete for all exposure conditions and the maximum load could be directly converted into the ultimate strength of the film.

A typical tensile stress–strain curve for a composite with well in excess of the critical fiber volume after 18 years of natural weathering at the Building Research Station is shown in Figure 2. The initially almost vertical portion represents the stiffness of the uncracked matrix. This is followed by a region up to about 4% strain where the matrix is cracking, with each sudden reduction in stress representing a matrix crack with local fiber extension across the crack at a greater rate than the cross-head movement of the testing machine. The excellent resilience of the fiber after this long period of time is demonstrated by the unloading curve from 5% strain and subsequent reloading to failure. The ultimate composite failure strain in this case was about 6.4%, and the fiber maximum stress was determined from the maximum load.

In contrast, Figure 3 shows the tensile stress–strain curve for a composite containing film type B, which contains only marginally above the critical fiber volume and fails at about 1.2% strain. This does not necessarily imply that the failure strain of the polypropylene has decreased, because the composite failure strain cannot be used to determine fiber failure strain until well after multiple cracking of the matrix is completed.

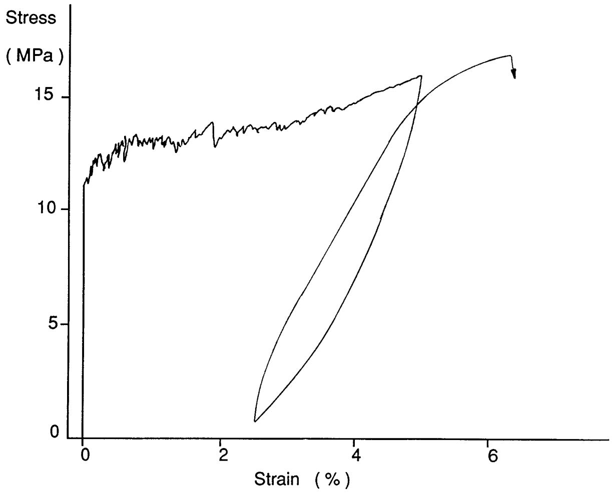

FIG. 2.

Typical tensile stress–strain curve for a composite containing more than the critical fiber volume after 18 years of natural weathering. Film type A. Fiber volume in the stress direction is 6.32%.

Results and Discussion

Film strength

The variation in film strength with time under various exposure conditions is shown in Figures 4 and 5. For external exposure (Fig. 4) there was apparently about a 10% reduction

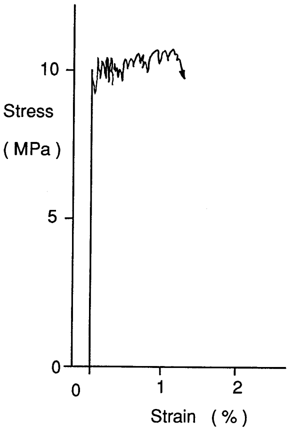

FIG. 3.

Typical tensile stress–strain curve for a composite containing about the critical fiber volume after 18 years of natural weathering. Film type B. Fiber volume in the stress direction is 5.21%.

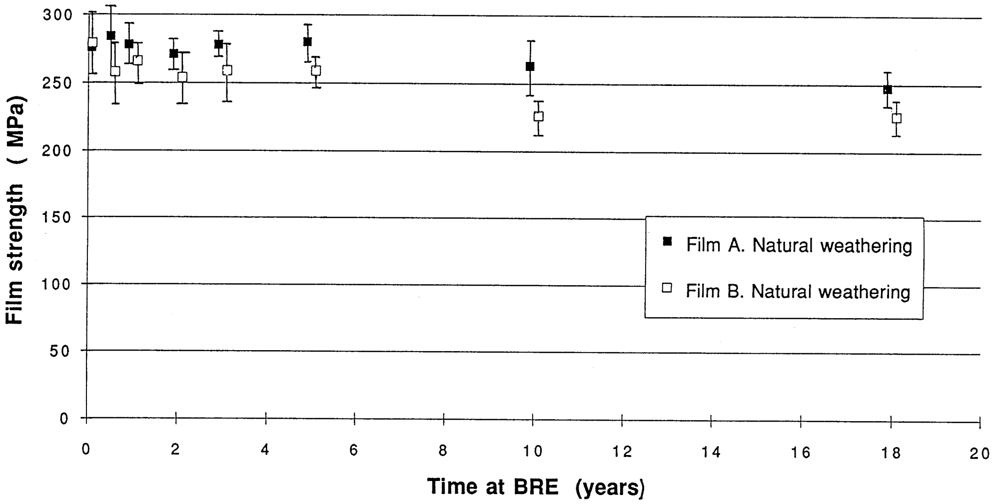

FIG. 4.
The effect of natural weather for up to 18 years on the strength of the polypropylene film. Error bars denote 95% confidence limits.

in film strength at 18 years for film A and about 19% reduction in strength for film B, although the latter had shown no change between 10 and 18 years. These differences are significant at the 95% confidence level. In the case of these externally weathered samples, the top surface of the cement paste in some samples had dissolved away locally (Fig. 6), exposing the top one or two layers of film to UV attack and chain scission (Fig. 7). Although severe, this was only a local effect that had not occurred in the bulk composite where the films were completely surrounded by cement paste, but nevertheless would have had a small effect on the strength results.

The strengths for film A stored under water (Fig. 5) showed little strength change over 18 years, whereas there was about a 10% change in strength for film B. The results for both films in laboratory air storage (Fig. 5) were very similar to those stored under water.

No other data have been found in the literature for measurements of the strength of polypropylene fibers in a cement matrix over such long time scales. The performance of film A without UV stabilizers has proved marginally better than film B with UV stabilizers so that the shielding effect of the cement matrix, even at cracks, has been more than sufficient to enable the cheaper film (A) to be used. The factors affecting the long-term film strength in cement subjected to different exposure conditions are so complex that it is not possible to state with any confidence an explanation for the differences in performance between the two fibers.

Bond strength

Polypropylene has virtually no physicochemical bonding with cement paste, but nevertheless excellent mechanical bond has been achieved by penetration of the cement hydration

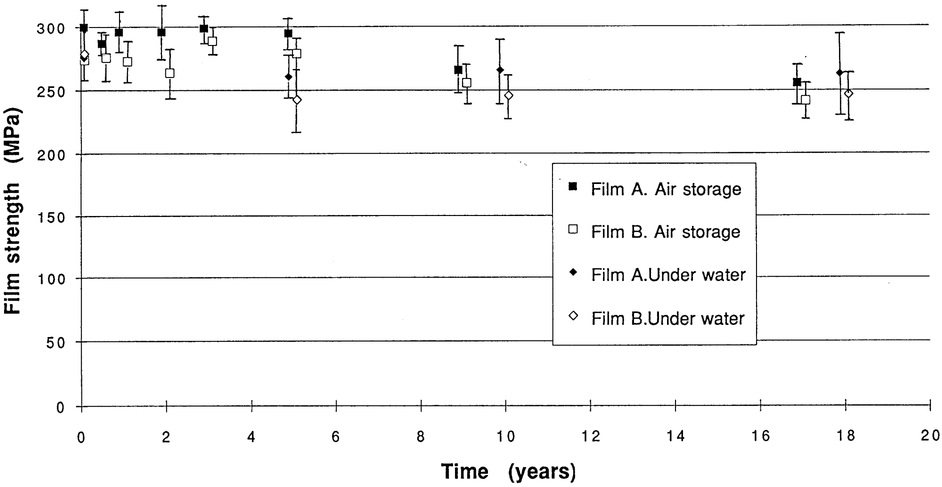

FIG. 5.

The effect of inside storage for up to 17 years or under water storage for 18 years on the strength of the polypropylene film. Error bars denote 95% confidence limits.

products through the macro- and microslits in the film, which give high specific surface area, and around the hairy, partly detached elements. It might be expected that these bonds would increase with time as the cement hydration products densify at the interfacial region. Surprisingly, however, bond strength determined from crack spacing (5) was found to remain constant at about 0.4MPa regardless of time or exposure condition. This implies that fiber slip

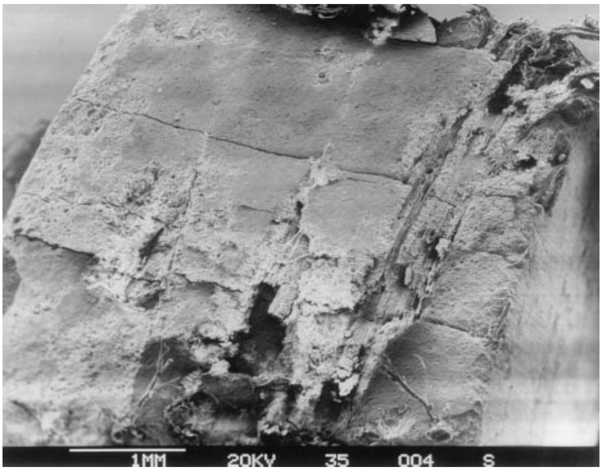

FIG. 6.

Composite sample after testing showing local dissolving of the cement surface exposing the reinforcing fibers.

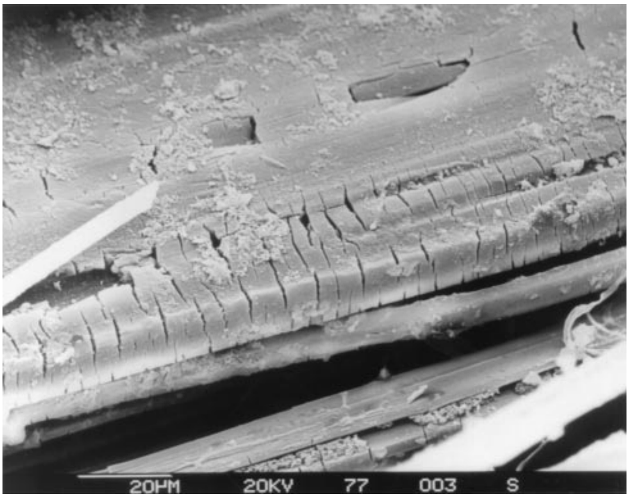

FIG. 7.
Local damage to fibers exposed to UV light and oxidation.

may be controlled mostly by shearing within the film elements themselves, which would be unaffected by changes in the matrix. Photographic evidence to support this hypothesis has been obtained by Ohno and Hannant (6) so that the measured bond strengths may depend on the intermolecular shear strengths of the aligned polymer chains, which are naturally time stable and do not depend on the matrix microstructure.

Toughness of the composite

Toughness depends on the area under the tensile stress–strain curve (7), and because failure strains have remained in excess of 5% for both films at all ages and weathering conditions except for film B in natural weathering, the long-term toughness has been very time stable. Values for toughness in excess of 700 kJ/m^3 are typical in comparison with about 5.5 kJ/m^3 for asbestos-cement, which has been another widely used fiber-reinforced cement product. The long-term toughness provided by polypropylene networks has been validated in practical applications by 10 years of use of corrugated sheeting (8).

Conclusions

1. In the cement composite,the strength of polypropylene film type A, which had no additives apart from processing additives, had decreased by about 10% over 18 years of natural weathering. There was virtually no change in the strength of this film after 18 years under water and about a 15% reduction in strength after 17 years in dry air. Film type B, which contained a high UV stabilizer, was generally slightly weaker than type A with a strength reduction in natural weathering of 19% between 1 month and 10 years, but no further reduction between 10 and 18 years. After 17 years in laboratory air, the

strength reduction was 12%, whereas under water there was a 13% reduction at 5 years and no further change between 5 years and 18 years.

2. Bond strength between polypropylene and cement was relatively unaffected by exposure condition or time for periods up to 18 years.
3. The use of polypropylene as a reinforcement to cement products has been shown to give excellent toughness and strength to the composite over many years, thus giving increased confidence in the long-term stability of polypropylene in a cementitious environment.

Acknowledgments

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