

Thin-Section Fiber Reinforced Concrete and Ferrocement

J.I. Daniel
S.P. Shah
Editors

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Printed in the United States of America

Editorial production Patricia Kost

Library of Congress catalog card number 90-82842

PREFACE

Thin-section fiber reinforced concrete is portland cement concrete or mortar reinforced with dispersed, randomly oriented discrete fibers. Fibers can be metal (low carbon or stainless), mineral (glass or asbestos), synthetic organic (carbon, cellulose, or polymeric), or natural organic (sisal). Fiber lengths can range from 1/8 inch to 2 1/2 inches. Furthermore, many existing thin fiber-cement composites on the market today comprise a blend of different fiber types.

By ACI's definition, ferrocement is portland cement mortar reinforced by a number of very closely spaced layers of continuous fiber networks or meshes. Ferrocement can be manufactured with any of the fiber types mentioned above, even though its name might imply steel wire meshes.

Therefore, to address all of the many thin-section fiber-cement building products available around the world today or under development, ACI committees 544 on Fiber Reinforced Concrete and 549 on Ferrocement organized and cosponsored an international symposium. The original papers for this symposium were presented at the ACI conventions in Atlanta, February 1989 and in San Diego, November 1989. The papers were reviewed by members of both committees as well as members of the international community of experts on this subject. These original, reviewed, and revised papers constitute this ACI special publication.

The papers are divided into four parts: (Part 1) Synthetic Fibers, (Part 2) Glass Fibers, (Part 3) Steel Fibers, and (Part 4) Ferrocement and Other Thin-Section Composites.

The editors gratefully acknowledge ACI Committees 544 and 549, the reviewers, the authors, Dr. Gordon B. Batson (symposium cochairman and Chairman of ACI Committee 549), and the staff of ACI who have made this volume a timely contribution to the state-of-the-art of thin-section fiber reinforced concrete and ferrocement.

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Specialty Cellulose Fibers for Cement Reinforcement

by K.D. Vinson and J.I. Daniel

Synopsis: This paper describes the investigation of a new range of cellulose fibers suited to the reinforcement of a Portland Cement matrix.

This investigation indicated that fibers selectively derived from high density summerwood are better suited for reinforcement than is the unmodified pulp which contains a large measure of fibers derived from springwood as well as summerwood.

Another cellulose fiber material, termed expanded fiber because of its finely fibrillated microstructure, was indicated to have potential as a processing aid. Expanded fiber displayed excellent suspending and retention properties and imparted relatively high uncracked strength to finished composites.

Overall, substantial performance differences were observed comparing tests on wet versus dry specimens and the long term durability was not evaluated. Despite these limitations, flexural stress/strain performance of the cellulose reinforced composites compared quite well to asbestos and glass fiber reinforced composites. The cellulose composites had substantially more ductility than asbestos cement; in this regard the load-deflection curve was similar to glass reinforced cement.

Keywords: asbestos; cellulose fibers; ductility; fiberboard; fibers; flexural strength; load-deflection curve; performance tests; portland cements; reinforcing materials

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INTRODUCTION

Background

Asbestos for cement reinforcement consumed 1.5 million metric tons of fiber by early in this decade. Usage was principally for factory-made cement cladding panels and pipes produced in some 800-900 manufacturing units operating in virtually every country of the world. Consequently, the asbestos replacement activity during recent years has resulted in vast world-wide research into alternative cement reinforcement fibers.

Cellulose is widely regarded as offering one of the best cost/performance positions among the potential replacement fibers which include glass, carbon, aramid, acrylic, poly (vinyl alcohol), polypropylene, and others(1). Cellulose has been used for many years to some extent as an additive in the conventional asbestos cement industry; some of the asbestos cement replacement products utilize cellulose fibers as well(1). Cellulose fiber in these cases is sometimes used in small amounts, 1% or less by weight, in combination with the other fibers; in this role the cellulose contributes mainly processing benefits rather than reinforcement(1).

It is the purpose of this paper to report on an investigation designed to quantify the potential for cellulose fibers in general and, in particular, a new range of modified cellulose fibers to act as the sole reinforcement of a Portland Cement matrix.

Cellulose Fiber Preparation

It was a purpose of this investigation to focus on the effect of novel forms of cellulose fibers achievable by making modifications to the physical form of the fibers.

One of the modified fibers used in this study was made by a separation process by which a fraction composed predominantly of fibers of the summerwood type is created. Annual growth rings of coniferous (softwood) trees are comprised of low density, springwood, rings and high density, summerwood, rings. For illustration, the SEM micrographs in Figure 1 are two magnifications of a typical cross section of spruce, a Northern softwood. The thinner cell wall material of the springwood fibers compared to the summerwood fibers is clearly evident.

After the kraft pulping process, the fibers collapse into flat ribbons, with the springwood fibers being wider, but thinner than the summerwood fibers. Figure 2 is a photomicrograph of slash pine fibers after the pulping process. Slash pine is a Southern U.S. species and is the sole starting material for the cellulose fibers used in this investigation. Quantitatively, slash pine springwood fibers average 61 microns width at 12 microns cell wall thickness, while summerwood fibers average 37 microns width at 4 microns cell wall thickness.

Since there is little difference in the fiber length or in the density of the cell wall substance, a given mass of the summerwood fibers will contain about one-half as many fibers as a given mass of springwood fibers. However, the summerwood fibers have much higher fiber strength due directly to the greater mass of cell wall substance and indirectly to differences in the S_2 cell wall structure(2), in particular the average fibril angle(5).

The naturally occurring unweighted percentage of summerwood fibers in the slash pine pulp, designated SSK in the present investigation, is 55%. For the purposes of this study, a fractionated laboratory sample which contained 86% summerwood fibers was prepared (SSK-SUWD).

A second modified fiber type was prepared by reducing SSK fibers to a finely divided fibrillar material to examine the effect of extreme fine particle diameter on the reinforcement potential. Fibrillation is readily accomplished with naturally occurring cellulose fibers which are built-up of fibrils which can be separated and further sub-divided into smaller and smaller diameters owing to the high levels of molecular orientation. Indeed, a level of fibrillation is introduced by the action of beaters and refiners in common use by the paper industry to alter the drainage and bonding characteristics of paper pulps. A much higher level of fibrillation was used to prepare the modified fiber referred to as Expanded Fiber (EF) in this paper. In EF the fibrillation process was carried to extreme to render the constituent fibrils virtually completely separated.

The EF used in this investigation was prepared using SSK in a 1.5 liter horizontal media mill(3). A comparison of EF to SSK fiber prior to the fiber expansion process is illustrated by the micrographs in Figure 3, which display the fiber before and after the fibrillation process. The degree of fibrillation is best quantified by the tendency of an aqueous dispersion of EF to resist separating and settling from the aqueous medium. Specifically, the EF specimen in this investigation was fibrillated until a 0.1% dispersion of EF solids in water would settle to only 50% of its original volume upon quiescent standing for one hour.

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Composites Preparation

Since fiber cement production technology based on the Hatschek process is widely available, it is highly desirable for a fiber to be compatible with this slurry dewatering method of composites formation(1). Consequently, we selected a laboratory, slurry dewatering process to investigate the potential of these fibers for reinforcement, essentially described as follows:

1. The cellulose fiber materials were dispersed with high speed mixing in an appropriate quantity of water for good dispersion. The solids content at this point varied from 1.75% to 4.6%.
2. Type 1 Portland Cement was added, with high speed agitation, to the fiber slurry in an amount necessary to give the desired final fiber content based on the weight of the dry ingredients.
3. The slurry was flocculated by adding an anionic polyacrylamide with gentle agitation, then poured into a mold fitted with an assembly of permeable screens, the finest being 100 mesh, to form the 15 inch (0.37 meter) square composite panels.
4. Excess water was removed through the screen using a vacuum dewatering device at 5 in (127 mm) mercury. Cement fines in varying amounts were visible in the drain water; this water was retrieved and the fines loss determined.
5. The moist cakes, which varied from 0.5 to 0.75 inch (13 to 19 mm) thick after dewatering, were pressed at 1200 psi (8300 kPa) for 3 minutes. Pressing was carried out in a hydraulic press designed to permit the excess water squeezed from the wet cake to be removed.
6. The procedures of steps 4 and 5 were adequate for all mixes except those containing EF only. In this case, the slurry would not dewater by vacuum and it was necessary to use the hydraulic press to remove all of the water. While dewatering in this way was a slow process, the maximum pressure of 1200 psi (8300 kPa) was maintained for only the 3 minute standard.
7. The composite boards after removing from the press were allowed to harden for four hours, then stored on edge and moist cured at 23°C and 100% relative humidity for seven days.
8. After moist cure, the boards were wet sawed into flexural test specimens of 2 X 12 X 0.5 inch (51 X 305 X 12.7 mm). These were stored at 23°C and 50% relative humidity until tested.

9. For each composite type, six specimens were tested dry and six specimens were tested wet. The dry specimens were tested as conditioned. The wet specimens were further prepared by soaking in water at 23°C for 24 hours prior to testing.
10. All specimens were tested in third-point bending using a 0.09 in/min (2.3 mm/min) cross-head speed and a 10 inch (254 mm) free span. The resultant load versus deflection curve was used to compute the proportional elastic limit (PEL), the modulus of rupture (MOR), and the total flexural toughness. The PEL is calculated using the load value at the end of linearity of the load-deflection diagram and the MOR is calculated using the maximum load; these points on a typical load-deflection diagram are illustrated in Figure 7. The total toughness is the total area underneath the load-deflection diagram.

RESULTS

Fiber evaluations were normally completed in a series of three levels of addition, 4%, 8%, and 12% based on the weight of dry ingredients. A series of this type was prepared from each of the following types of fiber:

1. SSK fiber refined in a laboratory beater to 500 ml Canadian Standard Freeness (termed SSK-R)(4).
2. SSK-SUWD, unrefined.
3. SSK-SUWD, refined in a laboratory beater to a Canadian Standard Freeness of 500 ml (termed SSK-SUWD-R).
4. Expanded Fiber (termed EF).

During the course of the study, a dispersion benefit for composites prepared with the Expanded Fiber was recognized. To further investigate this finding a single composite was prepared at the level of 1.5% by weight EF, combined with 8% by weight of SSK-SUWD (termed SSK-SUWD/EF).

Hence, a total of thirteen sample types were prepared.

Figure 4 is a graphical representation of the flexural test results for PEL, Figure 5 for MOR, and Figure 6 for total toughness.

It should be pointed out that the specimens containing fiber types SSK-SUWD-R and SSK-SUWD/EF were tested at 49 days after preparation rather than the 28 day period common for the other specimens. Although all samples had the same 7 day moist cure period, the additional conditioning time could have affected the extent of cure of the matrix to a degree, although the effect should be negligible.

In addition to the flexural test results, some quantitative and qualitative observations were made relative to the processability of the fibers. For example, the fines retention varied considerably among the fiber types. Mixes containing SSK-R fibers had a 1.0%-1.5% loss of cement fines. With the SSK-SUWD fibers the loss increased markedly to 17%-18.5%. This system also had visibly poor distribution of fiber within the composites, especially when comparing one surface of the composite with the other surface. The loss of cement fines for the summerwood decreased markedly with refining to 1.8%-2.6%. The EF fiber mixes had a negligible fines loss. Finally, the mixed fiber system where the EF was blended with the unrefined summerwood (SSK-SUWD/EF) had a 3.8% fines loss.

Table 1 lists the water-cement ratios, the densities of the wet specimens, and the densities of the dry specimens.

CONCLUSIONS

1. The overall best performing fiber was the summerwood fiber type.

Although the unrefined version of the summerwood fiber is unacceptable from a processing standpoint, as illustrated from the poor fines retention and visibly poor dispersion in the composites, these processing difficulties with the unrefined summerwood were completely addressed by either the moderate refining to 500 ml CSF, or by blending the fiber with a small amount of the Expanded Fiber.

In both PEL and MOR, the refined summerwood version, and the summerwood/EF blend were the best performing fibers. In toughness, the refined summerwood fiber and the summerwood/EF blend were unsurpassed, and the unrefined version was clearly superior in this case.

In view of the lower surface area to volume ratio present in the summerwood fiber, this perhaps indicates that the specific bonding strength of cellulose to the cement matrix might be sufficient to approach the intrinsic fiber strength.

2. Expanded Fiber has potential use as a processing aid.

Composites containing Expanded Fiber possessed outstanding fines retention; as previously noted, the composites containing EF only had negligible fines loss. Although composites reinforced with EF lacked significant toughness, they did have excellent PEL. EF can thus be viewed as a matrix modifier which has a beneficial effect in suspending and retaining the solids materials in the slurry process.

3. While the relative performance among the various fiber types tested was essentially the same whether judged from wet testing or from dry testing, the absolute test values were quite different depending on the test condition.

Specifically, the PEL and MOR strengths were generally reduced by one-half in wet testing versus dry. Despite this reduction in load bearing ability, the total toughness values were actually observed to be about 40% greater when taken from the wet specimens compared to the dry specimens. Figure 7 is particularly illustrative of this point; it is a typical load deflection curve for the SSK-SUWD-R at 8% for both the dry and the wet condition. There are two possible explanations for this difference in behavior, wet compared to dry. First, the elastic modulus of cellulose is known to be reduced under wet condition compared to dry(5). Second, it is possible that hydrogen bonding between fiber and matrix is disrupted by the water directly resulting in more fiber pull-out.

4. The optimum fiber addition level depends upon the desired balance of properties; higher fiber levels yielding lower densities and higher toughness levels, but reduced PEL.

Generally, toughness goes up with addition of fiber. The only exception to this was the unrefined summerwood fiber which likely suffered from dispersion problems at the high, 12%, fiber level.

The PEL and MOR values were less predictable by fiber content. Wet PEL generally declined with higher fiber levels; dry PEL generally remained constant from 4-8% and declined at 12%. No uniform trends were evident with regard to MOR.

Water cement ratios increased and densities decreased with higher levels of fiber. These parameters depended more upon the fiber level of addition than upon the type of fiber.

5. Refining was shown to be highly beneficial, at least for the best performing fiber type, the summerwood fiber.

Refining improves the processability as illustrated by the summerwood fiber fines retention before and after refining; the 17%-18.5% fines loss decreased to 1.8%-2.6%. Further, refining greatly improved both PEL and MOR at some expense to toughness. This is probably a result of some fiber shortening and increasing in the fiber-to-matrix bonding with the mechanical surface modification caused by refining.

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6. The best cellulose containing composite, compared to representative composites using the asbestos and glass fibers, were shown to have higher toughness than the asbestos cement at somewhat reduced load bearing ability; the load deflection diagram was similar to GFRC rather than asbestos cement.

Figure 8 is an assortment of load deflection curves intended to compare the best of the fibers tested in this investigation (SSK-SUWD-R) with asbestos cement(6) and with alkali resistant glass reinforced cement(7). Compared to asbestos cement, the cellulose cement composite panel possesses much greater energy absorbing quality at sharply reduced load bearing ability. In this regard, the characteristic curve for cellulose cement is more similar to that of GFRC.

RECOMMENDATIONS

The desirable properties of cellulose cement in view of the low cost of cellulose and its proven compatibility with the Hatschek process would indicate that there might be many applications for panel products based on cellulose fibers in general, with specific forms of cellulose capable of substantially improving composite properties.

No attempt was made in this investigation to evaluate the durability of the cellulose cement composites. A durability investigation should be completed.

The vast differences in properties of dry versus wet test specimens need to be taken into account by designers using the composites. A further modified fiber or system which would overcome these differences would be desirable.

ACKNOWLEDGMENTS

The cement reinforcement study was carried out in the laboratories of Construction Technology Laboratories in Skokie, Illinois; Mr. Eric D. Anderson of CTL assisted as a co-investigator on this project. Mr. Donald M. Schultz and Mr. Henry G. Russell of CTL, and Dr. Richard G. Fisher and Dr. B. Jerry L. Huff of Procter & Gamble Cellulose provided valuable input as members of the project steering committee. Dr. Arthur Tallentire of Vitrocem Consultancy Services, Manchester, assisted in the preparation of this paper.

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TABLE 1--Summary of Specimen Properties After Pressing

FIBER TYPE	FIBER CONTENT (% BY WEIGHT)	WATER-CEMENT RATIO	WET DENSITY (lb/ft ³)	DRY DENSITY (lb/ft ³)
SSK-R	4	0.33	126	118
	8	0.34	120	108
	12	0.43	113	98
SSK-SUWD	4	0.34	124	119
	8	0.39	117	109
	12	0.57	109	96
SSK-SUWD-R	4	0.33	129	123
	8	0.36	122	112
	12	0.40	112	104
EF	4	0.30	132	123
	8	0.35	123	108
	12	0.42	117	101
SSK-SUWD/EF	8	0.36	117	109

SI equivalent: $1 \text{ lb/ft}^3 = 16.05 \text{ kg/m}^3$

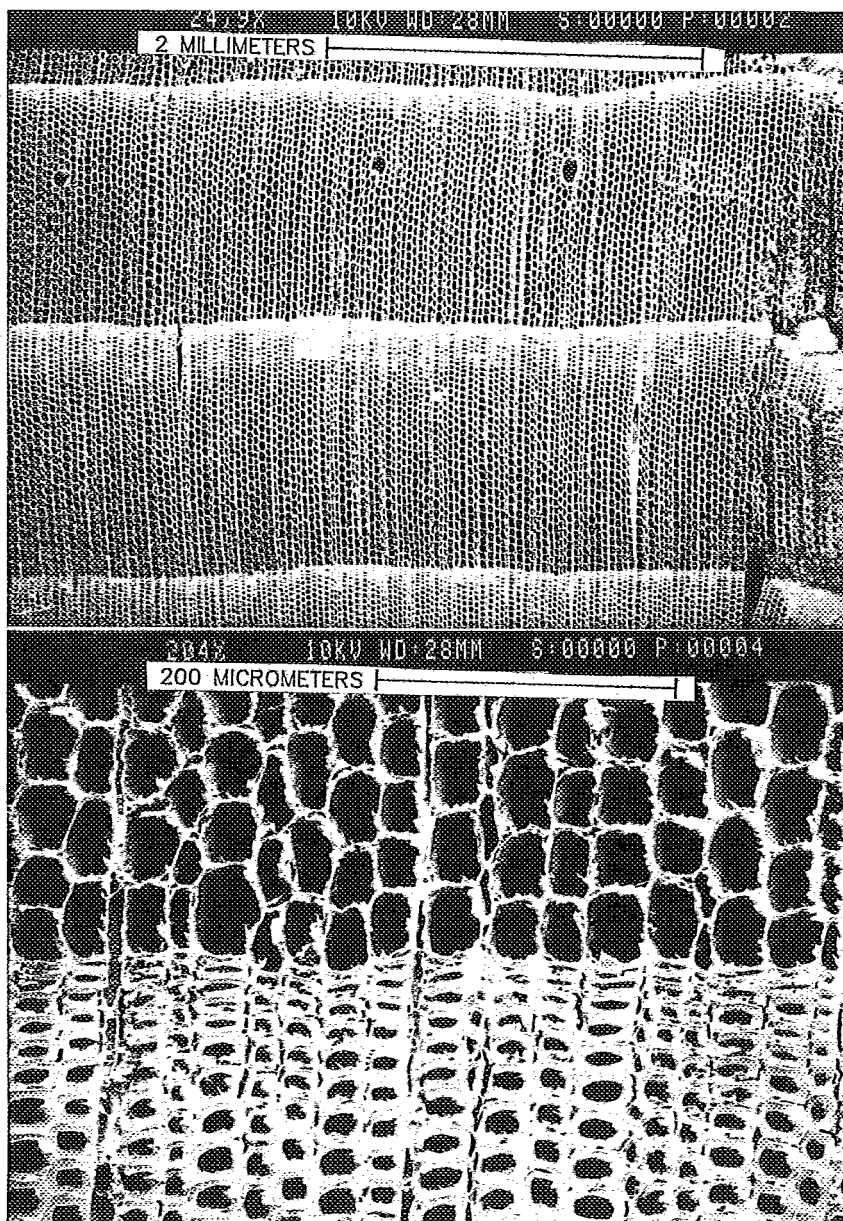


Fig. 1--Scanning electron micrographs of cross section of Spruce Wood at two magnifications; illustrating the cell wall differences between Springwood and Summerwood Tracheids

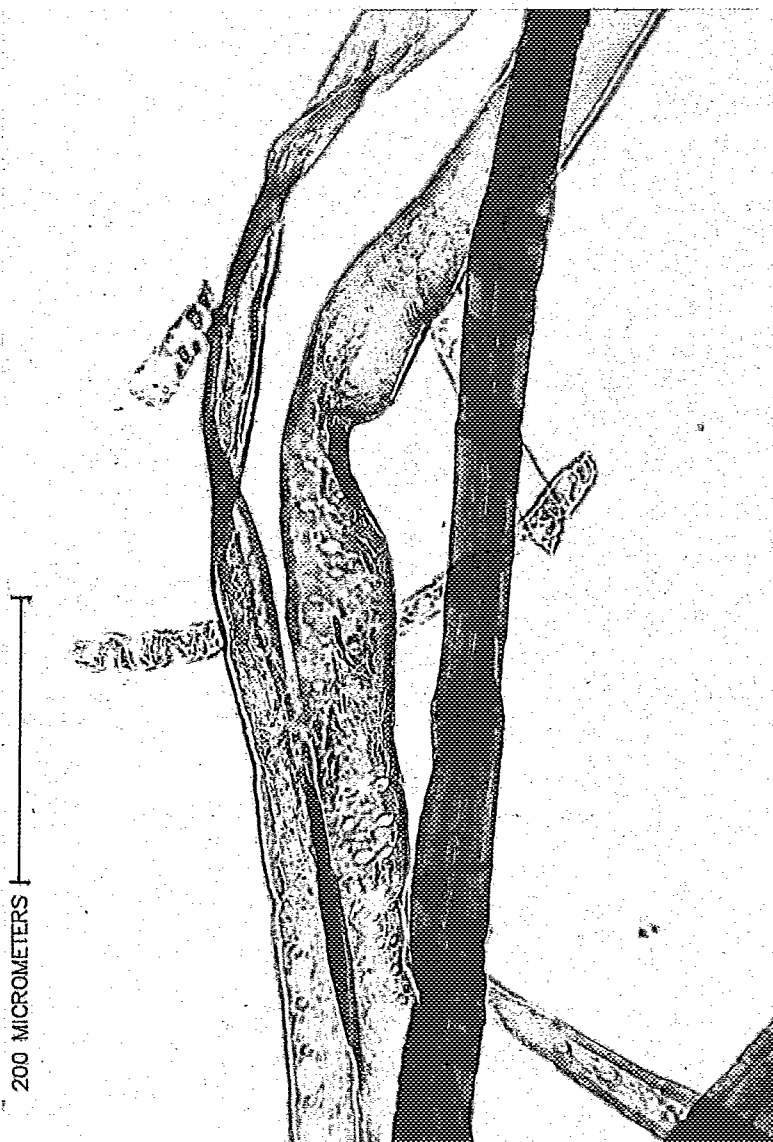


Fig. 2--Light micrograph illustrating Summerwood (dark lower fiber) and Springwood Fibers (two lighter upper fibers) after Kraft Pulping

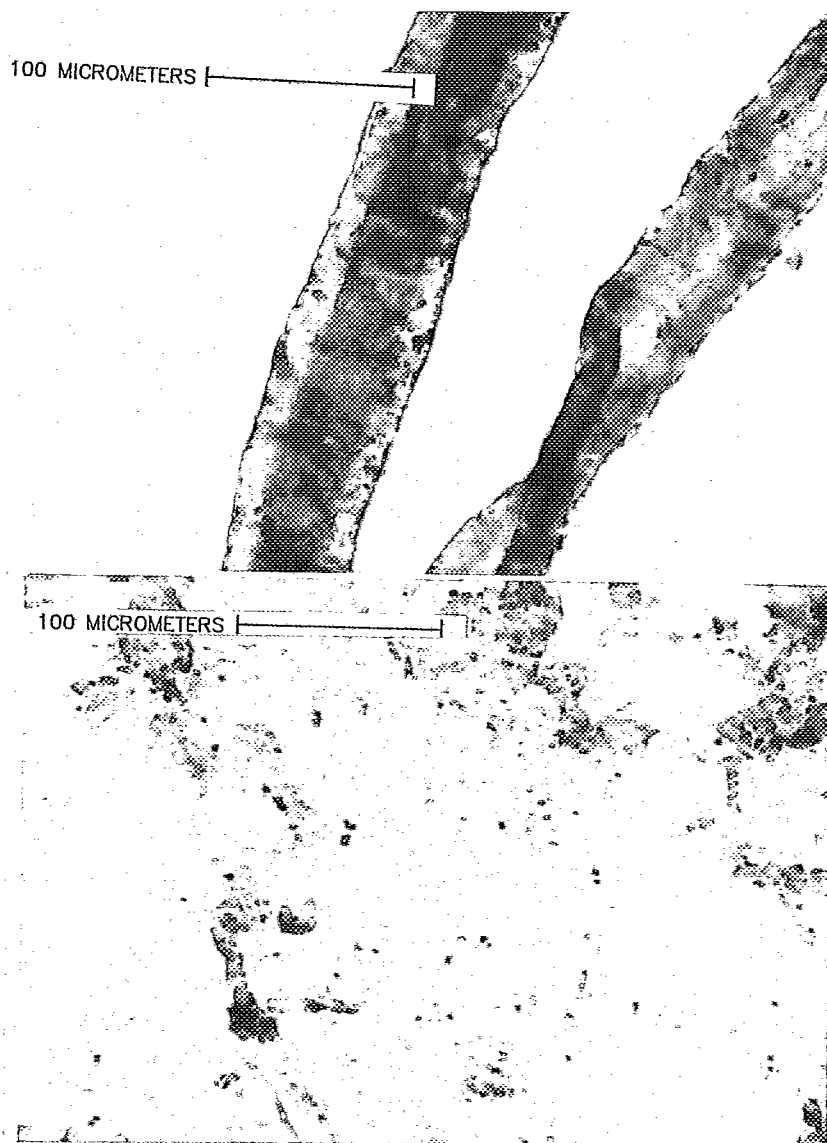
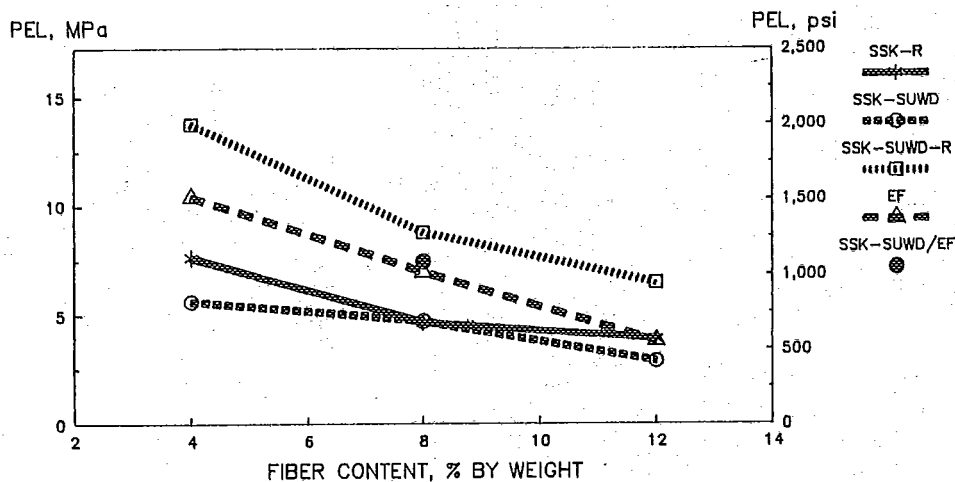


Fig. 3--Light micrographs of SSK fiber before expansion (above) and after expansion (below) illustrate the effect of the expanded fiber process

WET TESTS



DRY TESTS

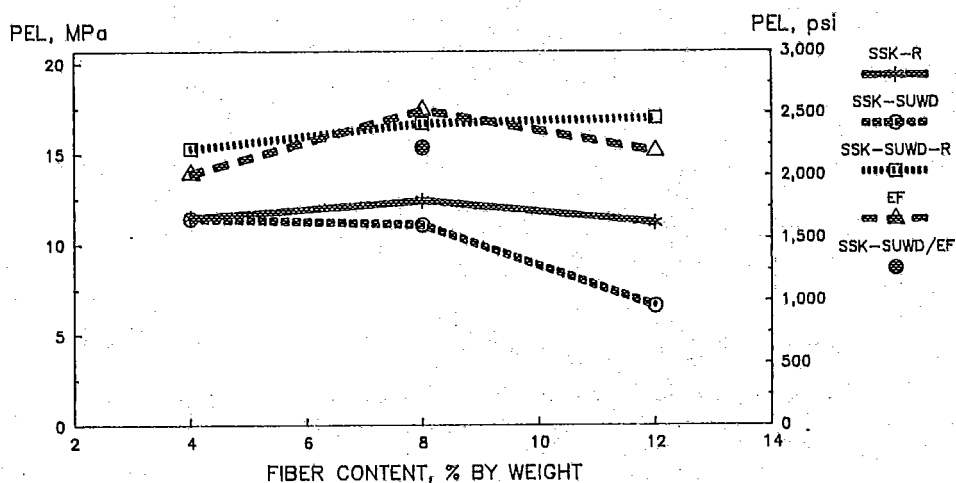
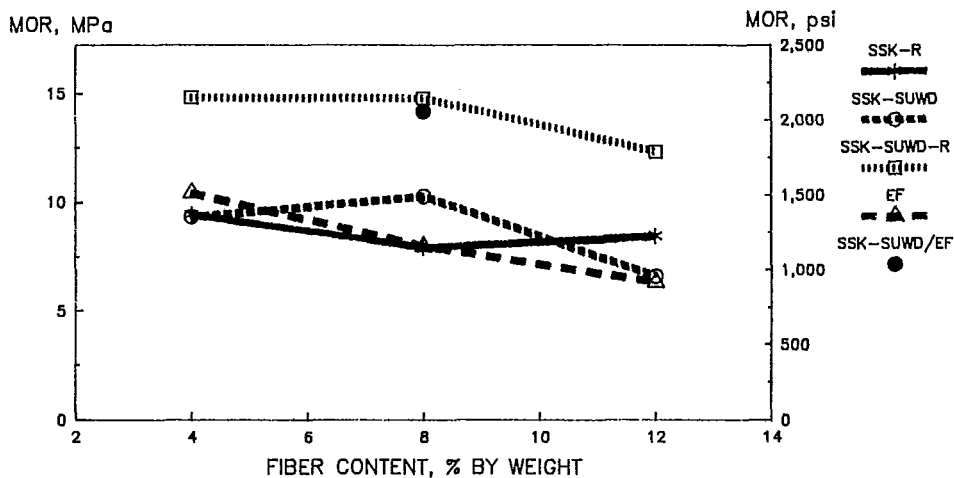


Fig. 4--Comparison of proportional elastic limit values of the several fiber types as a function of fiber loading by weight

WET TESTS



DRY TESTS

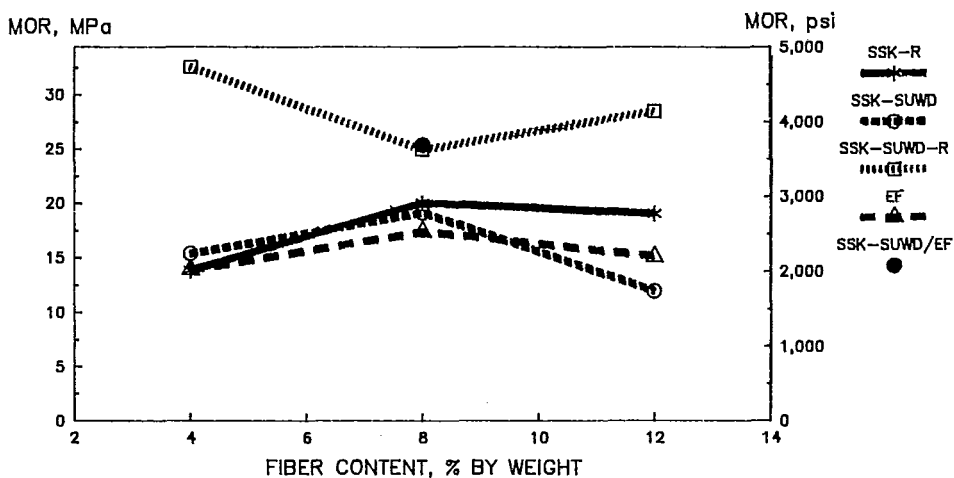
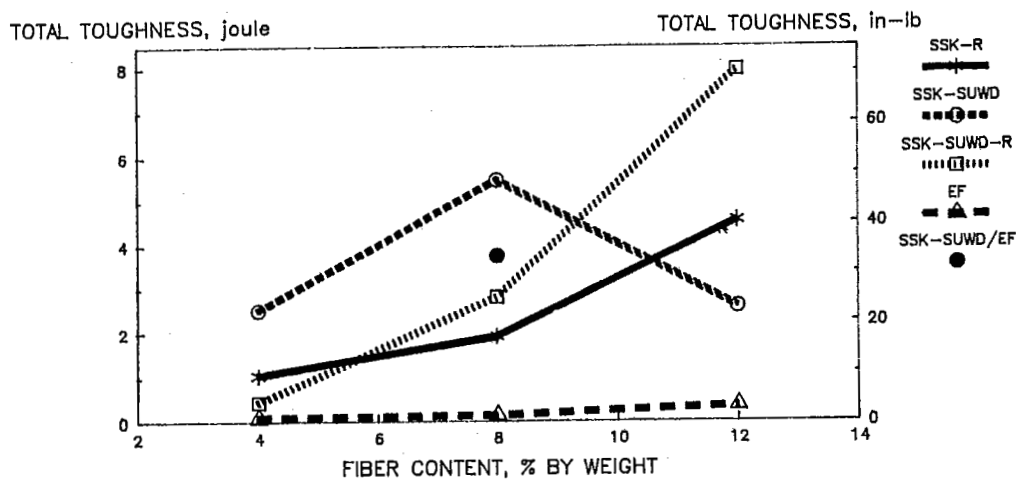


Fig. 5--Comparison of modulus of rupture values of the several fiber types as a function of fiber loading by weight

WET TESTS



DRY TESTS

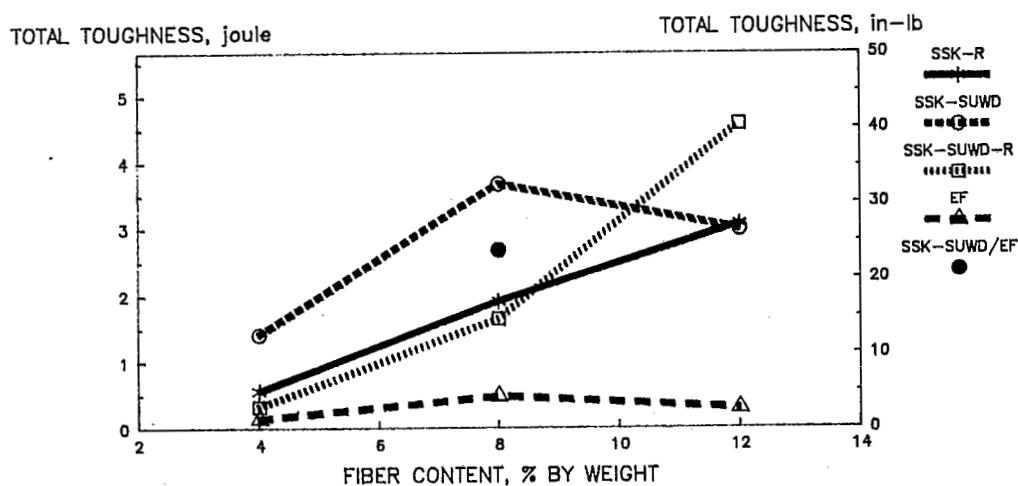


Fig. 6--Comparison of total toughness values of the several fiber types as a function of fiber loading by weight

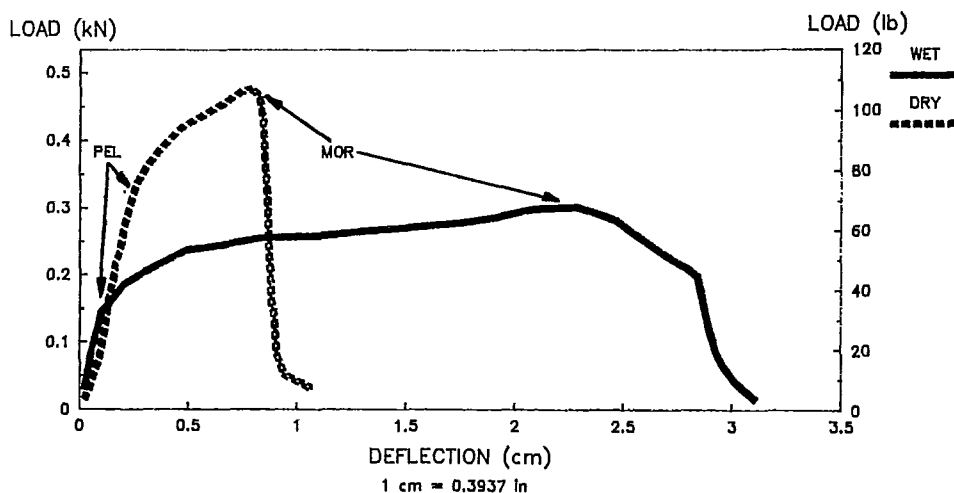


Fig. 7--Comparison of load/deflection behavior of specimens containing 8% SSK-SUWD-R, tested wet and dry

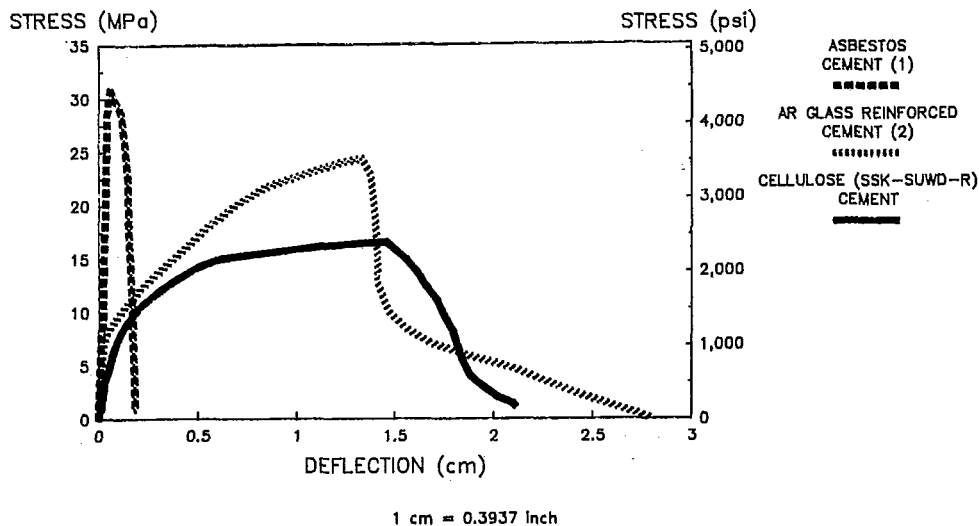


Fig. 8--Comparison of stress/deflection behavior of Asbestos Cement (1) and Alkali Resistant Glass Reinforced Cement (2) to the Refined Summerwood Cellulose Reinforced Cement (All tests apply to wet specimens.)

Performance of Non-Asbestos Fiber Cement Sheeting

by J.G. Keer

Synopsis

The production of a polypropylene-reinforced cement material marketed as an alternative to asbestos-cement is outlined. Typical tensile stress-strain curves of a number of alternative materials are compared with asbestos-cement. The load-deflection characteristics of corrugated sheets made from non-asbestos materials are also presented and discussed. The non-asbestos materials are generally much less brittle than asbestos-cement although they have a lower first-cracking strength. The pseudo-ductile behaviour exhibited, with multiple cracking before the ultimate load is reached, means that permissible loads in service must not be based solely on ultimate loads, but on cracking and possibly deflection criteria. Less well-defined stresses arising during installation and from restrained moisture movements, which may crack the non-asbestos materials, are likely to be critical for the effective performance of new sheeting materials.

Keywords: asbestos; cladding; cracking (fracturing); fiberboard; fiber reinforced concretes; performance; polypropylene fibers; polyvinyl alcohol; production methods; standards

Autobiographical Note

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INTRODUCTION

As sales of asbestos-cement have declined in Europe and North America in recent years, an extensive research and development effort has been devoted to producing alternative fibre cements to maintain the cement share of the roofing and cladding market. A number of alternative fibre cement materials are now marketed in Europe, although other cladding types have made severe in-roads into the asbestos-cement market. In the U.K. for example, in 1975 about 40% of roof cladding for industrial buildings was asbestos-cement with less than 10% being steel sheeting. In 1986 the comparable figures were about 10% asbestos or fibre cement and about 65% steel (1).

Asbestos is appreciated as a remarkably good reinforcing fibre. The strength, stiffness, fineness and affinity for cement of the fibres contribute to the enhancement of the apparent tensile cracking strain of the cement matrix to values well in excess of $1,000 \times 10^{-6}$. Furthermore, the reinforcing effect is maintained over long periods of natural exposure. The manufacturing method ensures two-directional strength in sheets although there is some preferential (and beneficial) alignment in the direction of machine flow. More importantly in the manufacturing process, the asbestos fibres control slurry drainage ensuring that the water content is reduced without loss of cement. However, asbestos-cement is not a perfect fibre-cement cladding material; it is a brittle material and its lack of impact strength has been dangerous.

Since there were 208 major asbestos-cement sheet machine installations in Western Europe alone in 1979 (2), it is not surprising that many developments sought alternative reinforcement that would allow existing machinery to be used. This has resulted in composites in which the primary reinforcing polymer fibres (such as polyvinyl alcohol (PVA) fibres) must be combined with cellulose fibres or even with some asbestos (as in Japan) in order to provide the same control of slurry drainage during processing. Furthermore, the fibres must be short with the attendant problem of ensuring adequate bond so that reinforcement occurs.

A different approach has resulted from the development of the fibre cement, initially at the University of Surrey by Hannant et al, (3, 4) in which the reinforcing fibres are continuous opened networks of fibrillated polypropylene. The novel production technique required is outlined in this paper. The performance under load of this material and other alternatives to asbestos-cement are compared with asbestos cement. Possible problems associated with the performance and specification of the alternative materials are discussed.

PRODUCTION OF SHEETING CONTAINING CONTINUOUS POLYPROPYLENE NETWORKS

Fibrillated polypropylene film is normally produced in spools in the unopened form. In initial laboratory production, the film had to be held open to prevent springback and to allow the matrix to penetrate between fibrils. For commercial production a dimensionally stable, opened form is required, which can be fed from reels directly to the impregnation stage. This stable form is achieved by transversely stretching layers of fibrillated film and stabilising the network by thermal treatment at a temperature below that of the softening of the polymer (5). A pack of several layers of film can then be welded at the edges for subsequent use. Two-dimensional reinforcement of packs is obtained by a process which intersperses orthogonal networks between longitudinal networks (6). A typical network pack which results may be 1.2m wide, (48 in) containing eight layers longitudinally, four layers transversely and weighing 100g/m^2 (0.18 lb/yd^2) (Fig 1). Stable opened one and two-directional networks are available commercially under the trade-name Retiflex (a registered trade name of Moplefan SpA). The film has a modulus of elasticity of about 16 GN/m^2 ($2.3 \times 10^6\text{ psi}$) and an ultimate tensile strength of about 550 MPa (80000 psi).

Two methods of production of flat or corrugated sheet are under development. The essential difference in the processes lies in the manner in which the two-dimensional polypropylene networks are impregnated by the cement matrix. In one process (Fig 2) (7), the cement matrix is deposited in an accurately controlled thin layer onto a porous, continuous belt by means of matrix laying boxes. The networks are fed and laid onto the matrix by means of special feeding and laying devices. The networks are impregnated by the cement paste by compacting and dewatering devices. A new layer of cement paste is then deposited onto the previously impregnated network and the cycle of operation repeated until the desired sheet thickness is obtained. For 6-6.5mm (0.25 in) thick sheet three or four layers are required depending on the type of network chosen. Additional dewatering follows, and the surface of the flat green sheet is pressed and finished with an upper porous

belt. The flat sheet is cut, corrugated if required and cured in a similar manner to asbestos-cement sheeting. The objective is to achieve production rates similar to those of asbestos-cement machinery.

In the second method (Fig 3) (8), the network pack is guided onto a moving felt band (which may be flat or corrugated in profile) and then impregnated by spraying the cement matrix onto it. A suction system enables excess water to be extracted from the sheet. Figure 3 shows three mesh impregnation stations. As in the previous process, the number can vary depending on the networks used and the thickness of sheet required. A compression device compacts the sheet, reducing its porosity and smoothing the surface. The sheet is then further processed as before. Sheets produced by Fibronit (8) have been on the market in Italy for more than one year.

The published range of cement matrices for both processes are similar in composition:

cement	100
water	35 - 45
fillers (fine silica sand, ground marble, pfa)	25 - 40
workability aid	0.5 - 0.7

COMPARATIVE TESTS ON NON-ASBESTOS FIBRE CEMENTS

A test programme has been undertaken on alternative materials to asbestos-cement to establish material characteristics and performance under load of corrugated sheets. The materials tested were:

- A: a compressed and autoclaved calcium silicate/cement product reinforced mainly with cellulose fibres and bought ex-stock.
- B: a cement product reinforced by PVA and cellulose fibres, produced on modified Hatschek machinery and bought ex-stock.
- C: a product similar to B but fully compressed for use as slates.
- D: another cement product reinforced by cellulose and PVA fibres, made on modified Hatschek machinery and bought ex-stock.
- E: the cement product reinforced by continuous polypropylene networks. The results presented here are from tests on hand-made laboratory sheet, not commercially produced sheet, although the behaviour is broadly similar. The

composite tested contained 5% by volume of polypropylene in the longitudinal direction parallel to the corrugations and about 3% by volume transversely. The matrix composition was similar to that given above.

F: for comparison, a typical asbestos-cement bought ex-stock.

The precise compositions of the commercially obtained materials A-D and F is unknown.

Tensile stress-strain characteristics

Tensile stress-strain curves are the most appropriate characteristics to assess the reinforcing effect, pseudo-ductility and energy absorption capability of the various products. It is known that products containing cellulose can be sensitive to the moisture condition at test, so products A to D were tested in wet and dry states. Specimens were 300mm long by 25mm wide by 5-8mm (12 in x 1 in x 0.25 in) thick strips and were tested in an Instron 1122 machine with strain recorded via a clip-on extensometer.

Typical tensile stress-strain curves for the various materials are shown in Figure 4. Table 1 summarises important properties, including density, water absorption and the volume of pores accessible to water. It can be seen from Figure 4 and Table 1 that the compressed materials A and C have a higher dry strength, a much lower strain to failure than the other alternative materials and a shape of curve similar to asbestos-cement. The effect of cellulose fibres is to reduce the wet strength of products A, B and C, but not of D. The unpressed, non-autoclaved materials B and D have a relatively low tensile strength but, as the next section indicates, give adequate performance in flexure as corrugated sheeting due to the increased ductility in comparison to asbestos-cement. Multiple cracking could only be seen in materials B, D and E and was very closely spaced for B and D, giving the impression of general disintegration of the matrix, possibly due to the angled fibres, although some discrete individual cracks could be seen under the microscope. Material E has a very high strain to failure compared to the other materials and was the only material to exhibit the stage following multiple cracking, when the continuous fibres alone are stretched as they slip through the matrix.

Performance of corrugated sheets

The load-deflection relationships of the corrugated sheets manufactured from the various materials are shown in Figures 5 and 6. Sheets of materials A, B and D were tested wet to simulate the worst conditions for these materials. The sheets in Figure 5 were

standard corrugated profiles (overall depth about 55mm (2.2 in)) tested over a span of 1.38m (54 in), the common span for general roofing in the U.K. The section moduli of the sheets are given on the Figure, together with the apparent flexural tensile stress, σ_{fl} , at maximum load. The load is expressed as a uniformly distributed (u.d.) load per unit area of sheet between supports, and the deflection is the average value at midspan. The test procedure has been detailed elsewhere (4).

In Fig 5, the alternative materials are markedly more ductile than asbestos-cement (a-c). The a-c and material A sheets were the only sheets which actually broke into two pieces by a single crack propagating in a brittle fashion across the sheet with no multiple cracking apparent. The other sheets were unloaded at rather arbitrary deflections as the testing was carried out over a period of years as sheets were obtained. Certainly the material E sheets could have sustained much higher deformations without breaking in two. The load at the limit of proportionality (L.O.P.) can be determined in accordance with a standard procedure, such as that in Danish recommendations (9), for the sheets exhibiting pseudo-ductile behaviour. This load is in excess of 2.8 kN/m^2 (41.8 lb/ft^2) for all sheets, a load which corresponds to a flexural tensile stress in the sheets of about 8 MPa (1160 psi), which is approximately the load at which the materials crack in direct tension (Fig 4). Note that at the L.O.P. deflections are small and should not present a serviceability problem. The values of σ_{fl} at failure or maximum load reached in the test are close to the value of 15.7 MPa (2280 psi), which has been a recommended value for asbestos-cement. These stresses, obtained by dividing the bending moment by the section modulus, do not, of course, represent real stresses because the position of the neutral axis changes in the post-cracking stage. All sheets withstood a load of 4 kN/m^2 (83.6 lb/ft^2).

Fig 6 shows the performance of two sheet materials, B and D, with a deeper sheet profile (about 90mm (3.5 in)) designed to span over 1.8m (71 in), and tested over this span. The maximum load of the sheet material B is considerably greater than that of material D, although the apparent flexural tensile stress is lower. The higher load is the result of the more efficient profile shape of sheet B, which has a section modulus 60% greater than sheet D, although the cross-sectional area is only 5% greater.

Sheets of materials B, D and E, which multiply cracked but did not break, were soaked on the top surface after loading. Although cracks were very fine, lines of dampness quickly became visible on the underside of the sheets.

STANDARDS FOR NON-ASBESTOS FIBRE CEMENT SHEETING

Loading

A problem which has not yet been fully resolved is the specification of performance under load of the new fibre cements. Some recent proposals still refer to the measurement of a breaking strength or load only (10, 11). Since the alternative materials exhibit pseudo-ductile behaviour with the matrix possibly undergoing multiple cracking before the ultimate load is reached, permissible loads in service must not be based solely on ultimate values from tests (as with asbestos-cement) but on cracking and possibly deflection criteria. An obvious approach is to define the permissible uniformly distributed load P_p at a particular span as:

$$P_p = \frac{\text{Load at L.O.P.}}{\gamma_1} \quad \text{or} \quad \frac{\text{Load at ultimate (max. load)}}{\gamma_2}$$

whichever is less, where γ_1 and γ_2 are safety factors and the load at L.O.P. could be assessed as in the Danish Standard (9). In fact there is a British Standard in existence, BS 5427 (12), for sheeting which already adopts this approach but which is not widely used in the fibre cement sheet industry. It suggests a γ_2 factor of 2 for sheets which fail by fracture and 5.0 for glass reinforced polyester sheets. Appropriate values for fibre cement sheets might be 2.5 for γ_2 and 1.25 for γ_1 .

It is also important that concentrated loads are resisted without damaging sheets by matrix cracking. It is ironic that the high impact resistance of the alternative materials encourages the abandonment of traditional practice, such as the use of crawling boards, and more abuse of sheets during installation, although most sheet manufacturers will still recommend use of crawling boards for access. Concentrated loads can be a more demanding load criterion than u.d. loads. Fig 7 shows that the measured longitudinal strain distribution across an a-c sheet under an edge concentrated load of 0.9kN (200 lb), the usual concentrated load requirement (12), is more critical than that under a u.d. load of 2 kN/m² (42 lb/ft²) or a total load of about 3kN (670 lb). While any cracks formed during installation do not allow water to drop through sheets and may heal autogenously (13), nonetheless they can be unsightly and undesirable on the underside, particularly when highlighted by absorbed moisture.

Moisture movements

One aspect of sheet performance which new standards are addressing (and a-c standards did not) are the significant stresses which may be induced in sheets due to wetting and differential

moisture movements. Draft ISO proposals for short corrugated sheets and flat sheets require sheets, fixed to a frame in standard fashion, to be subjected to a rain/heat cycling regime without showing signs of cracking or delamination (10, 11).

Fig 8 shows the deflection at the centre of corrugated sheets over a period of time during which the top surface of the initially dry sheets has been wetted with a saturated cloth. The sheets are free to deflect upwards, simply resting on supports under each corrugation at the sheet ends. Fig 8 shows results from two materials, B and E. The sheets deformed into the shape of an arch in the transverse direction, with little relative deflection along the line of any corrugation. The maximum deflections, for a wetting period of six hours, were 26mm (1 in) for the sheet B and about 16mm (0.6 in) for the sheet E. The wetting cycle in the draft ISO standard is 2 hours 55 minutes so that free, unrestrained deflection over this period would also be large. In Fig 8 deflections reduce as the sheet dries out and would also reduce eventually if the saturated cloth had remained in place, since the moisture gradients will reduce. The restraint of fixings on these free deformations induce significant stresses in sheets, of similar magnitude to those induced by service loads (14). Asbestos-cement behaves similarly and is known to crack in thunderstorms after long spells of dry weather. At the end of four wetting cycles of sheet B, microcracks had begun to appear even without external restraint of sheet deformation. Bearing in mind the higher cracking strength of asbestos-cement compared to the alternative materials, there is more work required in this area to relate laboratory assessments of moisture effects to satisfactory field performance.

One approach which has been considered to improve the performance of sheeting in some environments is the application of a waterproofing silane treatment to the surface of sheeting. This has three potential advantages:

- (i) reduction in water absorption and hence, induced stresses due to restrained deformation. Fig 8 shows that for both materials, pretreatment with an alkylalkoxysilane product considerably reduces free deflection (in the sheet of material E to a negligible amount).
- (ii) freeze-thaw durability can be enhanced (15).
- (iii) treatments may be successful in preventing moisture penetration through very fine cracks, although work at Surrey indicates that this may not be a fruitful approach when cracks have formed post-treatment (16). The development of decorative coatings which are capable of crack-bridging and which limit moisture absorption into sheets is another area where improved sheeting performance in certain environments can be obtained.

Durability of new fibre cements

Appropriate methods of test for the durability of fibre reinforced cement products are currently being considered by ISO (TG 77) and RILEM (102 AFC) international committees. The problem is a complex one, because of the range of fibres involved and the variety of potentially degrading mechanisms. Also, with the introduction of new products, there is the need to have confidence in accelerated testing procedures whilst long-term results from natural exposures are being collected. One possible degradation mechanism of new fibre cements containing polymer fibres is oxidation of the polymer, which can lead to loss of performance, although antioxidants can be incorporated into the fibres. For the material containing polypropylene networks, accelerated tests on composite specimens at temperatures of 140°C, 120°C, 100°C and 80°C in air-circulating ovens have been carried out and specimens tested in tension after various exposure times. An Arrhenius plot is used to predict the lifetime at ambient temperatures, which has been estimated as well in excess of thirty years (17).

Real time tests, currently approaching ten year results, have also been carried out on polypropylene network reinforced specimens exposed to natural weathering, indoor exposure in laboratory air and underwater storage. The type of exposure had virtually no effect on composite strength and failure strain for times up to five years, and the cracking strength increases with age (Fig9)(17). At the present time, there is little published detailed data on the ageing of the other fibre cements referred to in this paper, although trade literature indicates design lives in excess of thirty years.

CONCLUDING REMARKS

1. Alternative fibre cements to asbestos-cement are more ductile than asbestos-cement, with different tensile stress-strain and load-deflection characteristics.
2. New international standards need to base permissible loads on loads at the limit of proportionality as well as on ultimate loads, because of the quasi-ductile nature of some alternative materials.
3. The alternative materials have lower cracking strengths than asbestos-cement and careful attention must be paid to the avoidance of cracking due to installation stresses and stresses due to restrained moisture movements. These stresses are less well-defined than those induced by normal design loading.

ACKNOWLEDGEMENTS

The author would like to thank John Keating, Rachel Scott, Dr David Hughes, Dr Armen Baroonian and Dr David Hannant for their contributions to this paper.

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TABLE 1. PROPERTIES OF FIBRE CEMENTS

MATERIAL		Elastic Modulus GPa	Tensile strength MPa	Failure strain $\times 10^{-6}$	Relative density (saturated)	Water absorption % dry weight	Volume of pores %
A. Cellulose fibres calcium silicate matrix	Wet	11.7	7.6	730	1.85	21.3	32.6
	Dry	15.5	17.2	1,170			
B. PVA & cellulose fibres	Wet	15.0	6.4	20,000	1.94	20.4	32.7
	Dry	14.6	8.0	21,000			
C. as B but Fully compressed	Wet	33.6	11.8	360	2.17	11.5	22.4
	Dry	37.0	16.6	490			
D. PVA & cellulose fibres	Wet	15.3	7.1	8,000	1.94	22.6	35.7
	Dry	15.3	5.6	<2,500			
E. Continuous polypropylene networks	Wet	28.0	17.0	70,000	2.11	9.5	18.3
F. Asbestos-cement	Dry	21.0	23.0	2,000	2.06	16.9	29.9

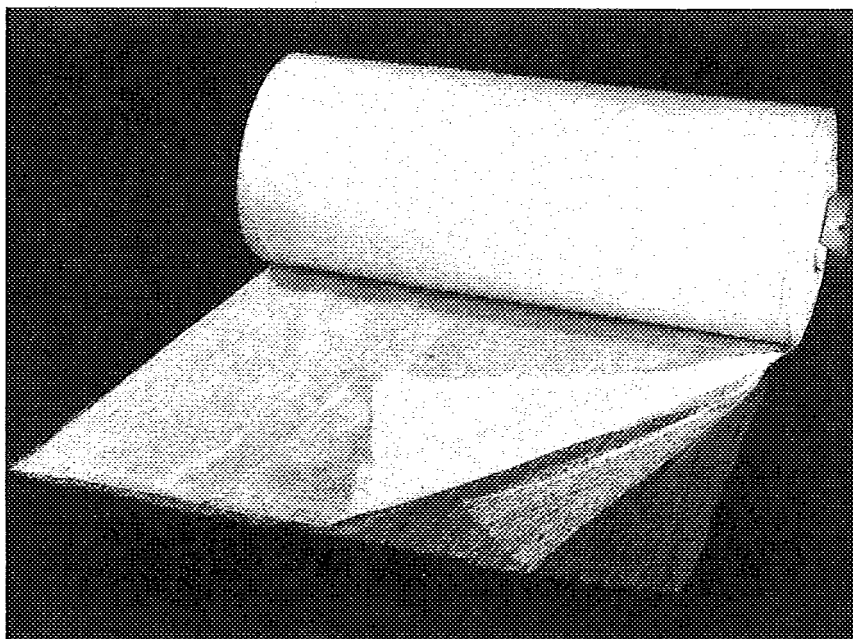
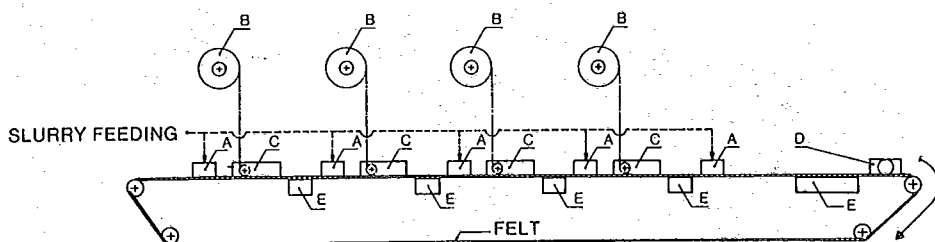


Fig. 1--Retiflex two-dimensional polypropylene networks



- A Matrix laying boxes
- B Network uncoilers
- C Network embedding into matrix and compacting
- D Final pressing
- E Vacuum boxes

Fig. 2--Production process using continuous polypropylene networks laid onto matrix (7)

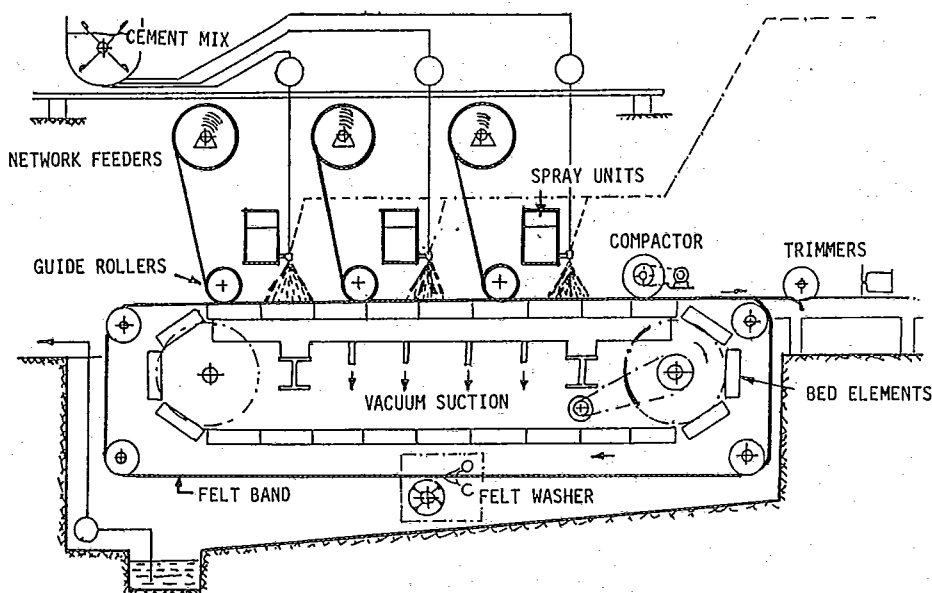


Fig. 3--Production process in which the matrix is sprayed onto continuous polypropylene networks (8)

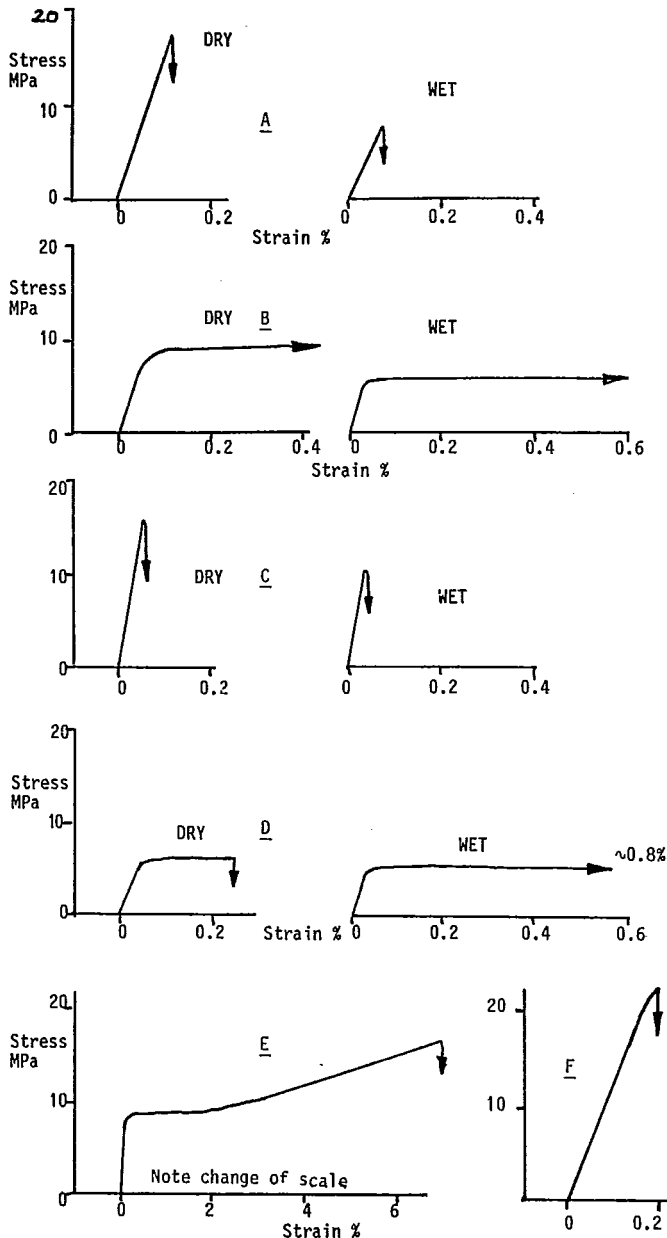


Fig. 4--Comparative tensile stress-strain curves
 A. calcium silicate matrix reinforced mainly with cellulose
 B. PVA + cellulose reinforced cement
 C. as B but fully compressed
 D. another PVA and cellulose reinforced cement product
 E. polypropylene-reinforced cement
 F. asbestos-cement

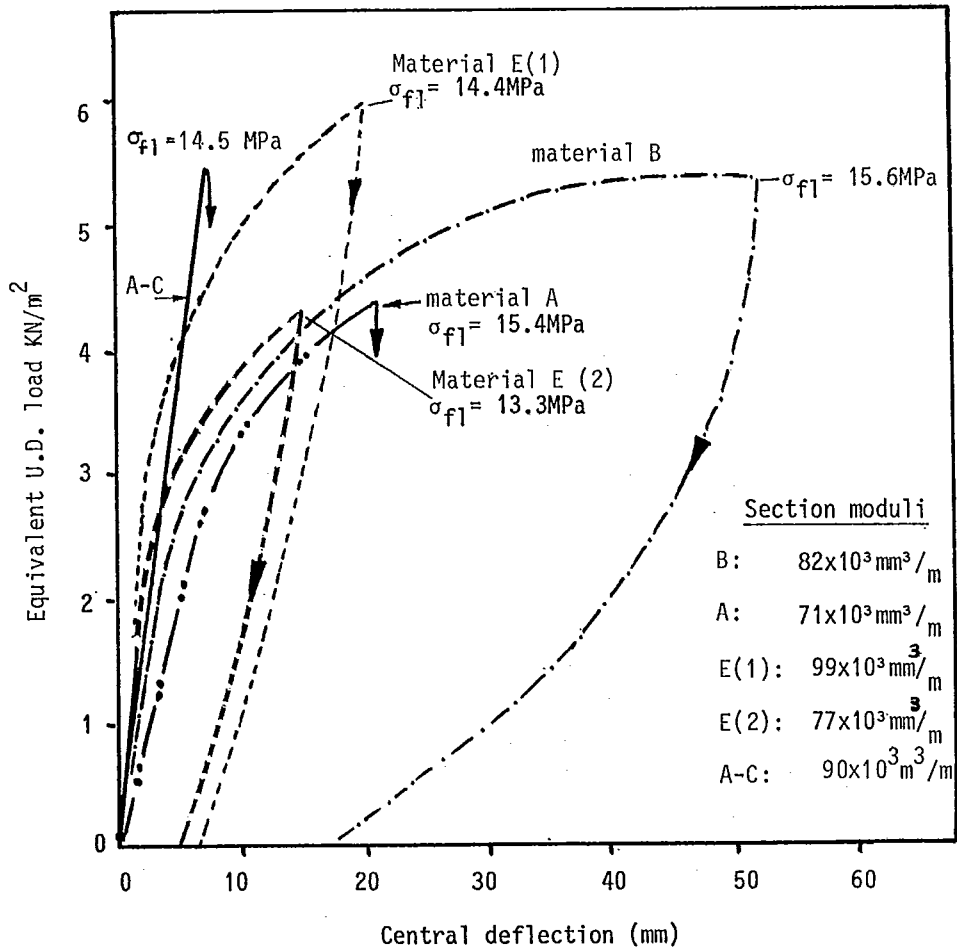


Fig. 5--Load-deflection curves of various corrugated fibre-cement sheet materials, span 1.38m

- A. calcium silicate matrix reinforced mainly with cellulose fibre
- B. PVA + cellulose reinforced cement
- E. polypropylene-reinforced cement
- A-C. asbestos-cement

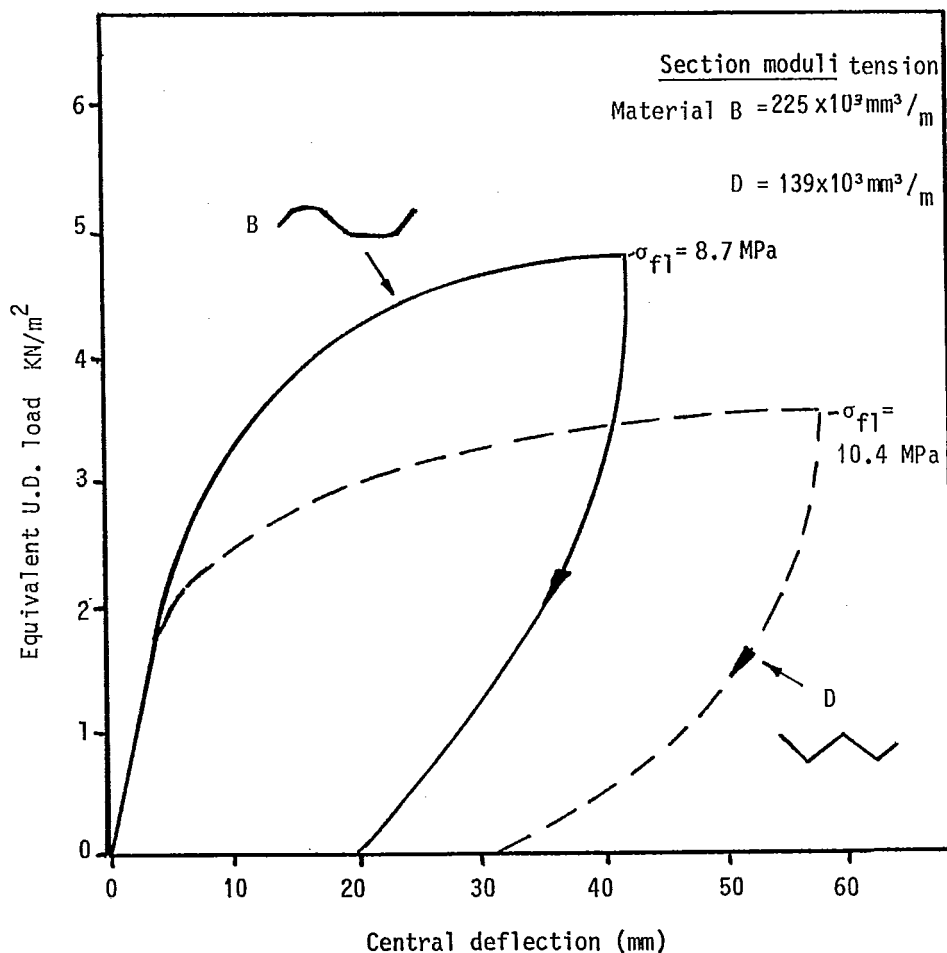


Fig. 6--Load-deflection curves of two deep profile corrugated fibre cement sheet materials, span 1.8m

B. PVA + cellulose reinforced cement type 1

D. PVA + cellulose reinforced cement type 2

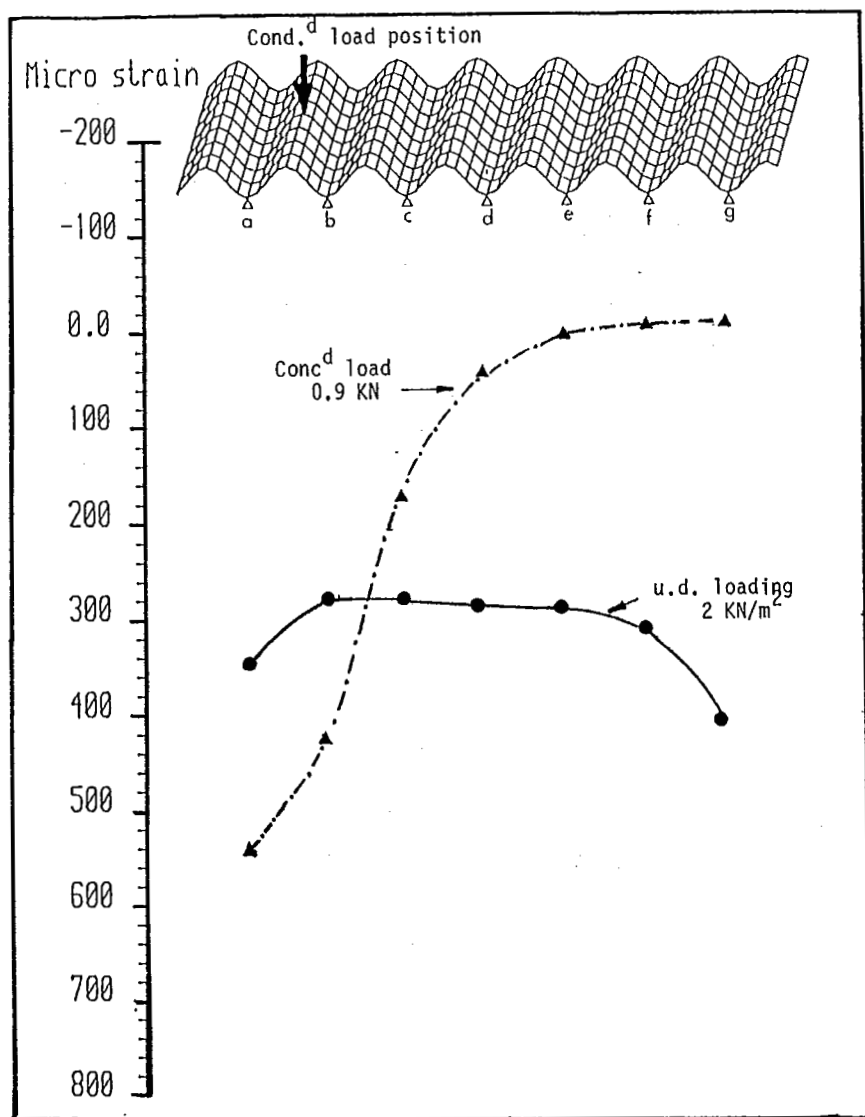


Fig. 7--Comparison of strains induced in corrugated sheet by uniformly distributed load of 2 kN/m^2 and concentrated load of 0.9 kN on edge corrugation, span 1.38 m

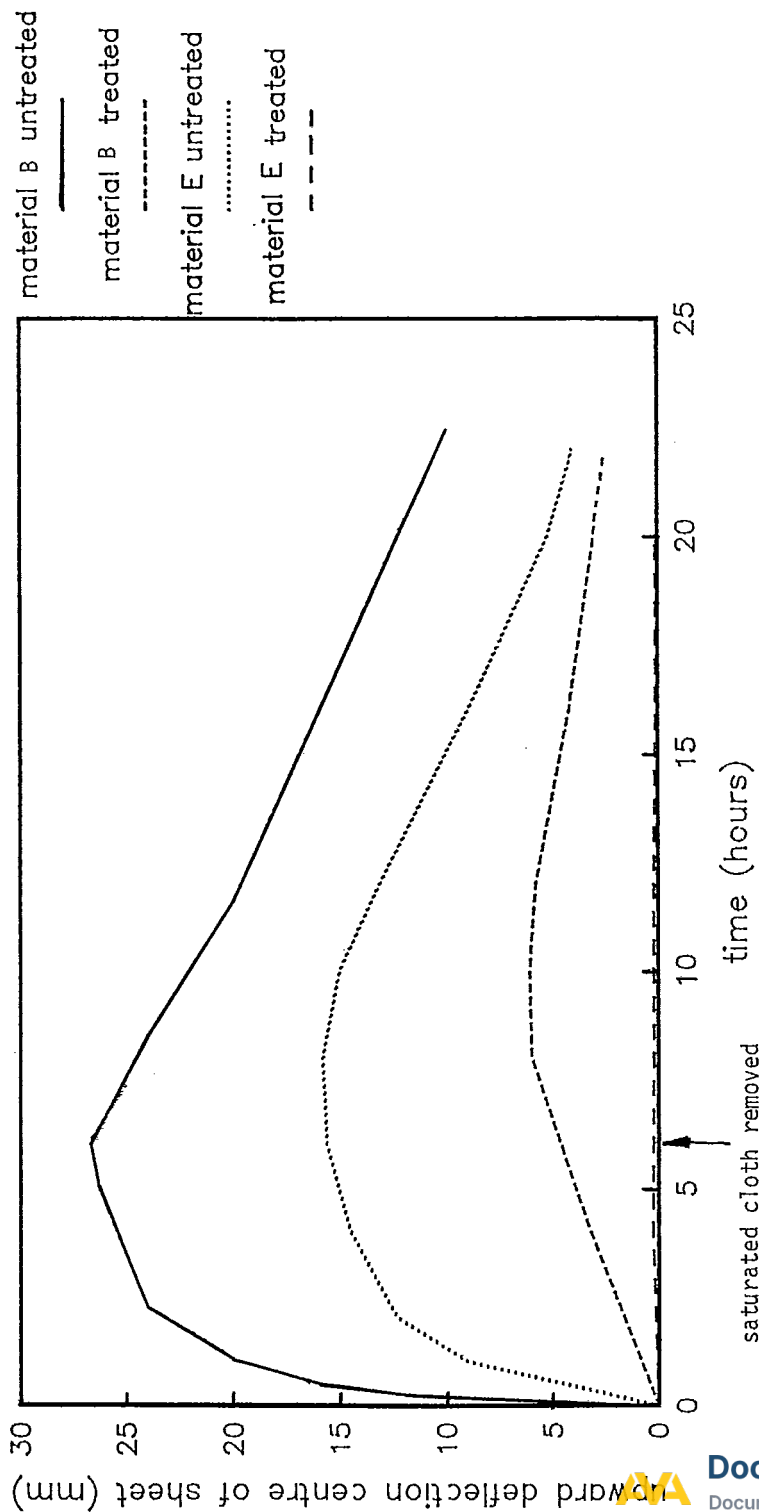


Fig. 8--Deflections of corrugated sheets due to wetting of top surface

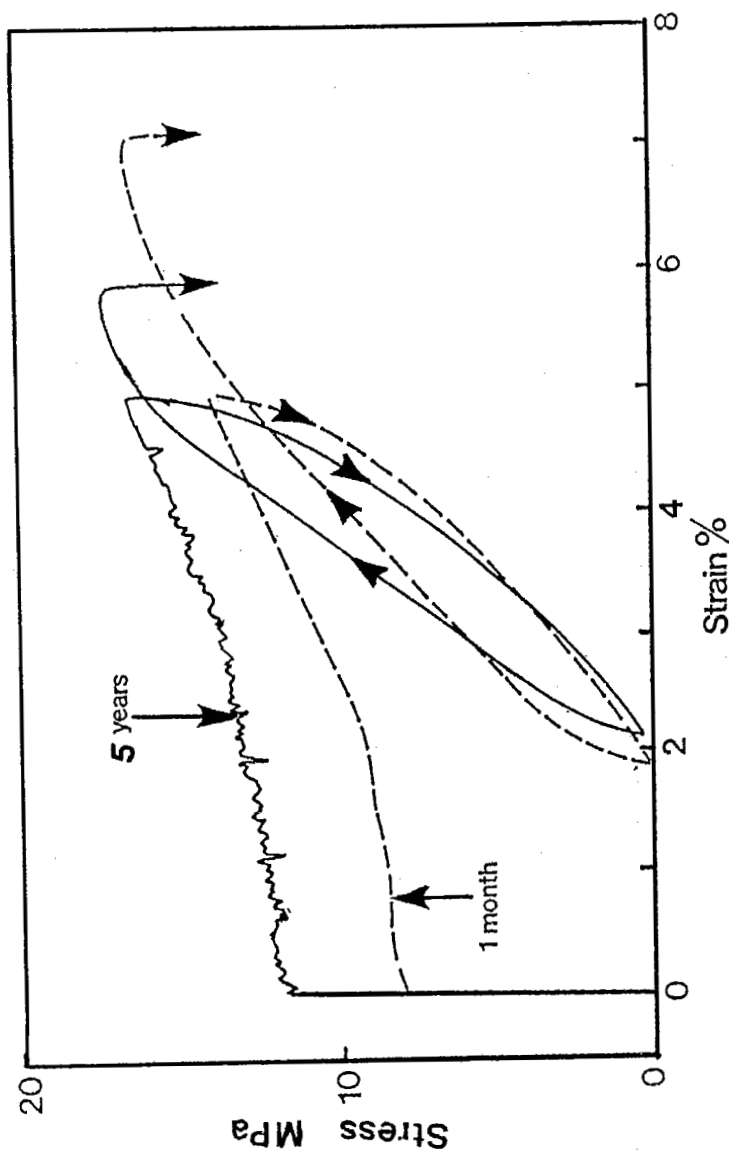


Fig. 9--Tensile stress-strain curves of specimens containing continuous polypropylene networks after five years natural weathering compared with one month under water

Fabrication and Properties for a New Carbon Fiber Reinforced Cement Product

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Synopsis: The fabrication, properties and application of carbon fiber reinforced cement (CFRC) product made of coaltar pitch-based high-performance carbon fiber are presented. The experiments were conducted by mixing the chopped carbon fiber strands with cement and sand to obtain CFRC. The mixing test results revealed that this type of carbon fiber disperses quickly and uniformly in ordinary mortar. No special type of mixer is required. In order to optimize the characteristics of CFRC, experimental analysis was conducted on batches made in a mortar mixer regarding the fiber properties and mix proportion. The relationships of these parameters to the mechanical properties were examined. It was revealed that the parameters determining the apparent viscosity F (flow index) of CFRC slurries are fiber diameter ϕ , filament number n , specific surface area S and fiber volume fraction V_f . It was also revealed that the parameters determining the strength of the hardened body were fiber tensile strength TS and V_f . The flexural strength of the 20mm thick CFRC is about 3~4 times greater than that of plain mortar. This CFRC is also stronger and durable than other FRC under the same conditions. High productivity, lightweight and weatherability characterize this new CFRC. These characteristics being appreciated, precast CFRC products have been increasingly used in construction in Japan. Some detailed descriptions of the practical applications are also made.

Keywords: carbon fibers; cladding; durability; fiberboard; fiber reinforced concretes; flexural strength; mixers; mixing; production methods; tensile strength; tests; workability

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INTRODUCTION

This paper describes the carbon fiber optimization, properties and application of the new CFRC fabricated in an ordinary mortar mixer. Steel fiber (SF) and glass fiber (GF) have been used to reinforce cement matrices. The problems associated with steel fiber are that they are difficult to disperse and hard to trowel when finishing. In addition, rust staining of the concrete surface prevents extensive outdoor application. Glass fibers, on the other hand, have been known to lose tensile strength and ductility with aging(1). In this respect, carbon fiber offers more favorable properties especially in terms of thermal resistance, weatherability as well as mechanical properties. Attempts have been made to use carbon fiber for building and construction purposes in Japan. In 1987 lightweight CFRC curtain walls, 32,000 m² in all, were installed to a 37-story office building in Tokyo(2).

So-called "general-purpose pitch-based carbon fiber" (GP-CF) with low tensile strength and modulus had solely been used. These materials tend to form fiber balls on being mixed with cement matrix. Without a special type of mixer (Omni mixer), it has been impossible to uniformly disperse this type of fiber. "High-performance pitch-based carbon fiber" (HP-CF) developed recently can solve this problem. The authors recently succeeded for the first time in dispersing the chopped carbon fiber uniformly in cement matrices with an ordinary mortar mixer with less amount of dispersant(3,4). This has dramatically facilitated the production efficiency of CFRC products. Based on the experiments, the results of carbon fiber parameter analysis are also presented.

EXPERIMENTS

Materials and Mix Proportion

Two types of carbon fiber were used and they were both pitch-based. The general-purpose carbon fiber (GP-CF) was about 15μ in diameter and 6mm in length. The average monofilament tensile strength and modulus are 60kg/mm^2 and 3 ton/mm^2 respectively. The high-performance carbon fiber was 17μ in diameter and 18mm in length. The average monofilament tensile strength and modulus are 200kg/mm^2 and 20ton/mm^2 respectively. The cement, sand, water and additives are listed in Table 1. Early strength Portland cement was used. The sand was silicate sand finer than 0.5mm in diameter. The three types of additives used were air-entraining water-reducing agent, dispersant and defoamer. In Method A, the amount of dispersant used was 1.0% by weight, while it was 0.25% in Method B.

Batch Preparation

Fig.1. shows two types of mixing methods and time required in the experiments. In both cases, carbon fiber, cement and sand were dry-mixed at first. Water and admixtures were then added and mixed again. In Method A, 1/2 of sand was provided at the dry-mixing stage, another 1/2 being added at the wet-mixing stage. In Method B, on the other hand, the sand was added all at the same time. The mix proportion of the Method B using a 70 liter mixer was reproduced in a larger mortar mixer (750 liter). The flow index of CFRC slurry was determined by flow table test according to the current JIS-R 5201 "Test Method for Physical Properties of Cement."

Specimen Size and Preparation

CFRC slurry was cast into a wooden mold and was taken out of the mold 24 hours later. The specimens were 20mm thick, 40mm wide and 320mm long. These were subjected to 3 point flexural test. The specimens were cured in air at 20°C , 60%RH for 7 days. The span length for flexural testing was 260mm.

Test Results

The test results are shown in Table 2. The fiber dispersion is equally uniform in both methods. No fiber balls are observed as shown in Fig.2. In Method A, however, 4 times greater amount of dispersant (carboxyl methyl cellulose) than in Method B was needed to achieve uniform fiber dispersion. Excessive addition of the dispersant hindered trowel finishability. In Method B, on the other hand, the trowel finishability was significantly improved by the lowered viscosity. Higher flow index (workability) was obtained by Method B. Moreover, it required shorter mixing time. These facts indicate the advantages of Method B in terms of production.

In order to examine the reproducibility of the test results, mixing was conducted by a larger mortar mixer with the capacity of 750 liter. It is considered that the result in Table 3. essentially reproduces the results in Table 2. in terms of workability and flexural strength, although a little longer mixing time was required. The difference in mixing time is mainly due to the difference of rotation rate: 46 rpm with the 70 liter mixer and 27 rpm with the 750 liter mixer. It is concluded that the difference in mixer capacity does not cause any special problems in reproducibility.

Significant findings can be summarized as follows:

1. Method B is superior to Method A in terms of trowel finishability and mixing time.
2. Though no conspicuous difference is observed in the fiber dispersion between the two mixing methods, the CFRC obtained by Method B is superior to Method A in the flexural strength by 57%. The difference is considered to be mainly due to the difference in the tensile strength of fibers.
3. No trouble was encountered to produce the CFRC by Method B with a larger mixer. Industrialized CFRC production has therefore become possible by Method B.

DATA ANALYSIS

The CFRC slurries made by the premix method should be workable enough to be shaped into various products. So far, the addition of various admixtures like superplasticizers, air-entraining agents, etc. have been attempted, as well as the adjustment of water cement ratio. However, the alternative approach optimizing the carbon fiber properties has not yet been given sufficient attention. The influence of carbon fiber properties on the workability and flexural strength is investigated by means of the regression analysis in order to optimize the carbon fiber and CFRC.