Long term durability of PVA reinforcing fibres in a cement matrix

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Synopsis The long term durability of PVA (polyvinyl alcohol) fibres used as reinforcement in cement-based products has been assessed after exposure of the products to natural weathering and an accelerated ageing process. The PVA fibres were extracted, then characterised by X-ray diffraction techniques. The mechanical properties of the extracted fibres were compared with the mechanical properties of the composite. In general an increase in composite strength and stiffness was evident; this may in part be associated with carbonation of the matrix and increase in the PVA fibre-matrix interfacial bond.

X-ray diffraction studies on the extracted PVA fibres indicated in some cases a loss of crystalline order with age (natural weathering) related to a disordering of the hydrogen-bonded sheets. The possible changes are minor and have no influence on the tensile properties of the PVA fibres or the ageing properties of the composites.

It is suggested that PVA fibres which participate in the reinforcement of the cement matrix are durable over a period of at least 7 years, and there is every reason to believe that these fibres will continue to be durable for extended periods.

Keywords Fibre cement composites, durability, synthetic fibres, polyvinyl alcohol fibres, tensile strength, X-ray diffraction, ageing, weathering tests, accelerated tests, cement composites, flexural strength, elastic modulus.

INTRODUCTION

During the past decade, many innovative programmes have been established to find suitable replacements for asbestos fibres in asbestos cement products. The basic requirements for the mechanical properties of a reinforcing fibre for a brittle material such as cement are high elastic modulus, high tensile strength, and a low elongation to break. The fibres must also be stable in a highly alkaline environment, have good affinity for the cement matrix, and have good dispersion properties in an aqueous cement slurry.

The criteria used to judge the suitability of the alternative fibres can be complex, since they involve both short term and long term properties of the newly developed fibre cement composites. Concerning the assessment of the short term properties, the products are normally evaluated according to their function, and minimal standards are set to ensure adequate performance according to application. Of equal importance is the requirement that the product performs satisfactorily in service. The long term durability aspects of the product can be difficult to predict and require a complete understanding of the changes which take place in the various components with age. The composites studied here comprise: two fibre types, PVA (polyvinyl alcohol) and cellulose, a cement-based matrix, and some type of coating; the pores within the system must also be taken into consideration. The long term behaviour of each component must be investigated, both separately and together, as well as their interactive participation, in order to predict the service life of the product. This paper concerns the structural changes which could take place in the PVA fibres during natural and accelerated ageing, the development of mechanical properties in the composite and the changes in the properties of the PVA fibres. In a separate paper the cellulose component of this composite has been discussed [1].

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EXPERIMENTAL PROGRAMME

Products investigated

Various fibre cement composites were manufactured on a full scale production Hatschek machine. The composites all contained chopped PVA fibres and fibrous cellulose pulp with portland cement as the matrix material.

The specimens examined consisted of:

(a) A non-aged composite together with extracted fibres.
(b) Naturally weathered composites exposed for periods of 7, 6, 4 and 3 years respectively in Switzerland, depending on the year of manufacture; extracted fibres from these composites.
(c) Accelerated aged products exposed to a test programme for periods of 2, 4 and 6 months; extracted fibres from these composites. The accelerated ageing test method is described elsewhere [1].
(d) Virgin fibres non-aged and accelerated aged.

Extraction of PVA fibres from the composite

The PVA extraction procedure was developed specifically to prevent physical and chemical damage. Cement was removed by treatment with a 10% HCl solution for 6 minutes followed by washing in running water. The cellulose component was removed by treatment with cuprammonium hydroxide for 10–15 minutes followed by washing and drying. A feasibility study [2] using X-ray diffraction analysis showed that there was no significant structural change to PVA fibres after such a treatment.

Mechanical property tests on the composite and fibres

In order to monitor possible changes in mechanical properties of the composites, flexural strength, E-modulus and density data were determined using standard test methods. For single fibre tensile testing, single fibres were glued across 1 mm gaps cut with a special punch in graph paper strips. The fibres were then conditioned for 24 h at 20 °C and 65% RH. The instrument used to test the fibres was a Fafegraph T-Textechno. The rate of extension was set at 0.5 mm/min; the breaking loads were then calculated from traces for at least 100 individual fibres from each sample.

SEM examination of PVA fibres

Scanning Electron Microscope (SEM) examinations of gold-coated extracted fibres were carried out in a Cambridge 150B Stereoscan operated at an accelerating potential of 20 kV. In this way it was possible to identify morphological changes and the presence of contamination.

X-ray diffraction studies of PVA fibres

X-ray diffraction traces were recorded on a horizontal-circle diffractometer driven by a stepping motor under programme control from a local microprocessor. The fibres were mounted in a vertical circle device running continuously to randomise the X-ray scatter. Data was collected under software control and stored on a 10 Mbyte hard disk; it was later transferred to the Amdahl mainframe computer for normalisation and peak resolution following methods described previously [3].

The nature of the PVA diffraction pattern (see Figure 3a), with closely overlapping 101 and $10\bar{1}$ peaks, together with very weak 100 and 001 peaks, made profile resolution exceptionally difficult. When two peaks overlap closely it is not possible to suggest that a unique mathematical fit has been obtained in any resolution; consequently, only the 200 peak could be determined with accuracy, and this peak has been used throughout as a possible indicator of crystallographic change in the fibres.

Accelerated ageing tests on PVA fibres

A saturated cement slurry was prepared by stirring 0.2 kg of portland cement in 1 litre of water in a plastic bottle for 12 hours. The cement was filtered off and the liquid (pH 12.5) used for the ageing tests. Approximately 50 fibres each of 100 mm length were immersed in the cement liquid and the samples were kept in a sealed plastic bottle at 80 °C for 1 week. The samples were then transferred to an oven (dry air at 80 °C) for one week. The cycle was repeated for a period of 2 months. Before measuring the fibre properties the fibres were cleaned in 0.1 N HCl for 15 minutes at room temperature, rinsed with distilled water for 30 minutes, and stored for 3 days at 20 °C and 65% RH. The tensile properties were then measured.

CHARACTERISATION OF THE HIGH MODULUS PVA FIBRES

The PVA fibres used in the fibre cement composites described in this paper have unique properties such as non-fusibility at elevated temperatures, good affinity to water and high degree of crystallinity. These properties depend on the polymer structure and the presence of hydroxyl groups.

The hydroxyl groups of PVA, according to Bunn's crystallographic model [4] are randomly arranged in left- and right-hand positions along the polymer chains.

The dimensions of the unit cell of PVA were calculated by many authors from X-ray diffraction patterns. The dimensions proposed by Bunn are as follows:

Unit cell: monoclinic system, $a = 0.781$ nm, $b = 0.252$ nm, $c = 0.551$ nm, $\beta = 91°42$

The unit cells proposed by other authors are all monoclinic, and the dimensions are approximately the same. The b axis projection of the molecular chains on the (ac) plane in Bunn's model is represented in Figure 1.

As the intermolecular attraction is strengthened because of the hydrogen bond formation between two hydroxyl groups of neighbouring chains, crystallisation occurs easily during manufacture and crystallites are oriented in the direction of the fibre axis. The PVA fibres

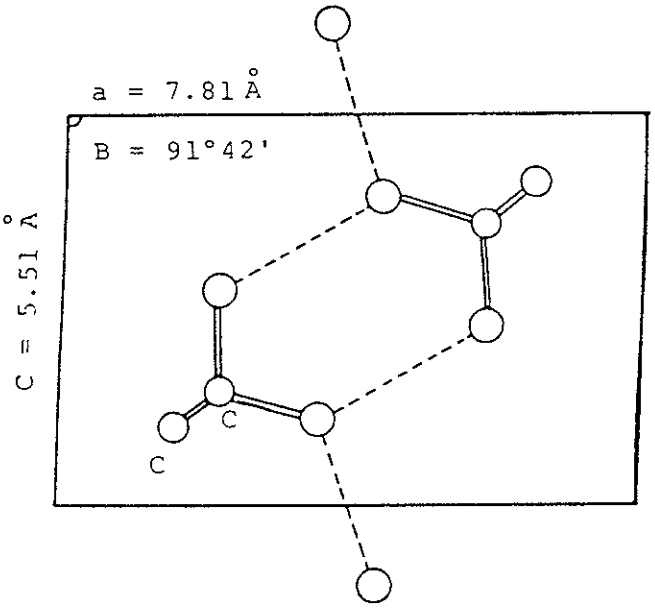


Figure 1 Bunn's model (b-axis projection)

used for this investigation have dimensions; length = 6mm and diameter ≈ 14 μm and mechanical properties as follows:

Tenacity (Tensile strength)	1534 N/mm^2	(12.0%)
Initial modulus	36573 N/mm^2	(22.6%)
Elongation at break	7.4%	(0.8%)

The figures in brackets represent the variation coefficient. The major criteria for assessing ageing in PVA fibres were:

(a) The observation of possible damage; for example fibrillation or kinking using the SEM.
(b) Possible changes in the crystallographic structure using X-ray diffraction analysis.
(c) A possible decrease in tensile strength using special tensile testing equipment.

TEST RESULTS

Influence of composite production processing on PVA fibres

During the production processing of fibre cement products on the Hatschek process, the PVA fibres are subjected to a highly alkaline environment. Also at the curing stage after production the temperature of the finished product can rise to 80°C for several hours. In order to ensure that these conditions did not have any adverse influence on the fibre properties a simple test was developed. This test involved the treatment of the fibres at different temperatures in a cement slurry for 24 hours. The results given in Table 1 indicate that for temperatures from 40°C to 80°C no significant change in the tensile properties took place. It may therefore be assumed that any temperature increases and high alkalinity which may be present during the production process would not influence the properties of the PVA fibres to any extent.

Mechanical damage occurring during the production process, however, may not necessarily be neglected. As pointed out later, 'kinking' of the fibres may take place during the production stage and this could lead to a drop in the measured tensile strength of the fibre. Scanning electron microscope observation of fibres extracted from the products do occasionally show evidence of abrupt kinking (Figure 2a). The fibres are continuous with little indication of gross deformation or damage in the way of fibrillation. Compared with the virgin fibre (Figure 2b) there is evidence of small amounts of adhering particulate material on the extracted fibres.

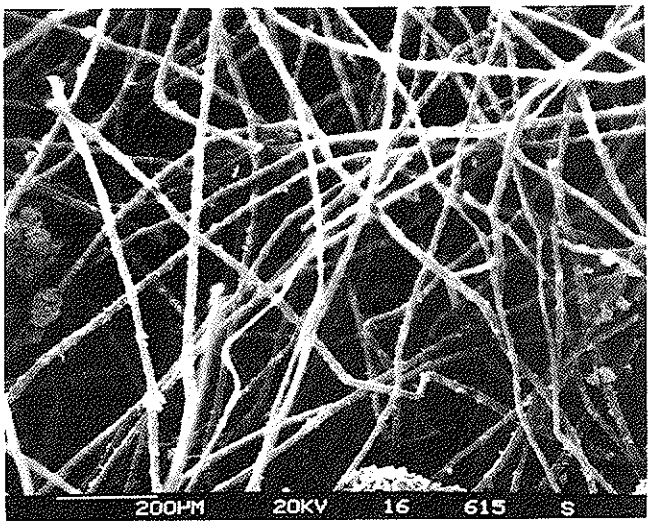


Figure 2(a) SEM micrograph of extracted aged PVA fibres

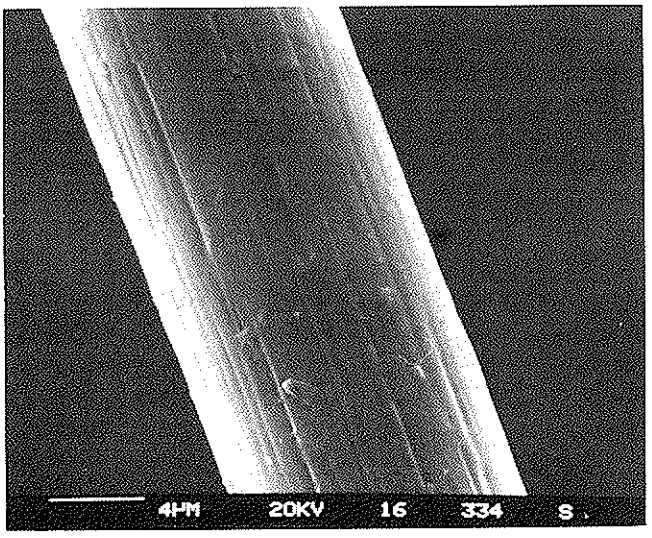
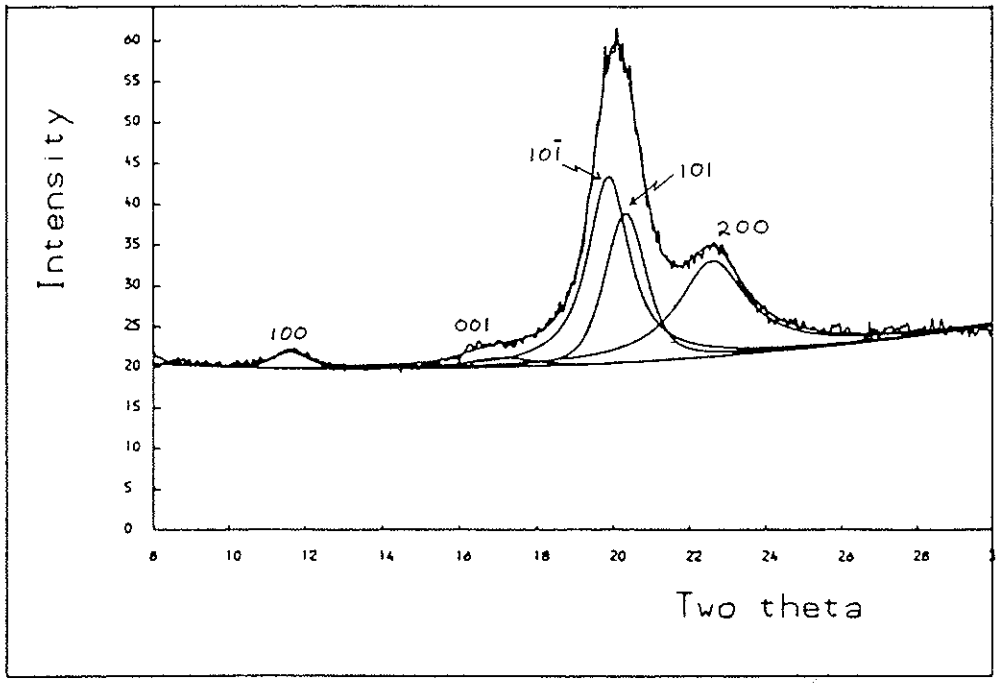
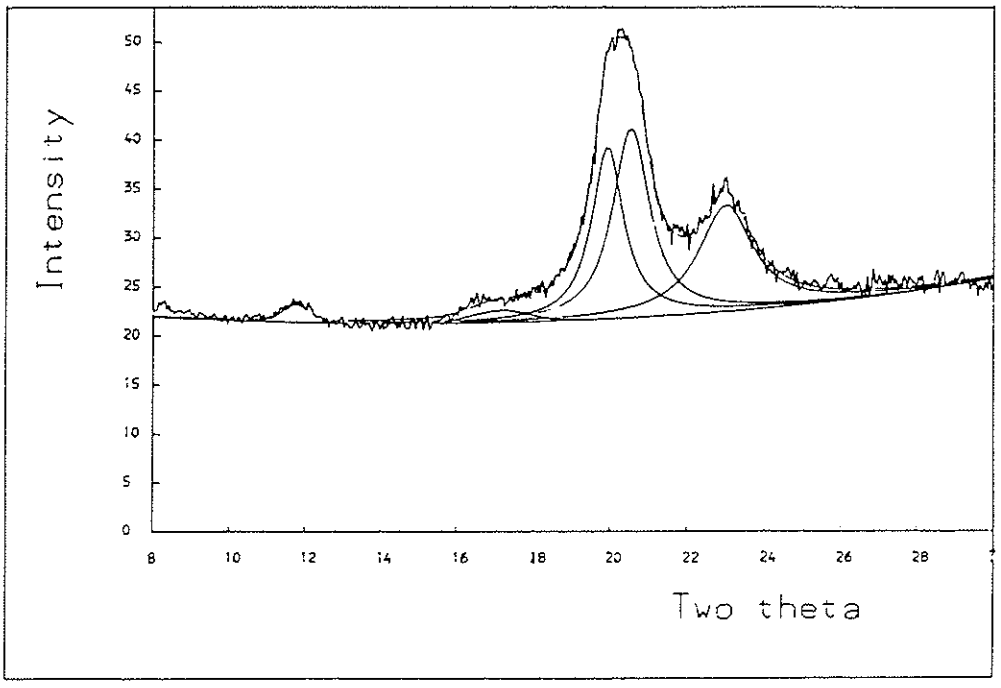


Figure 2(b) SEM micrograph of a virgin fibre



(a)

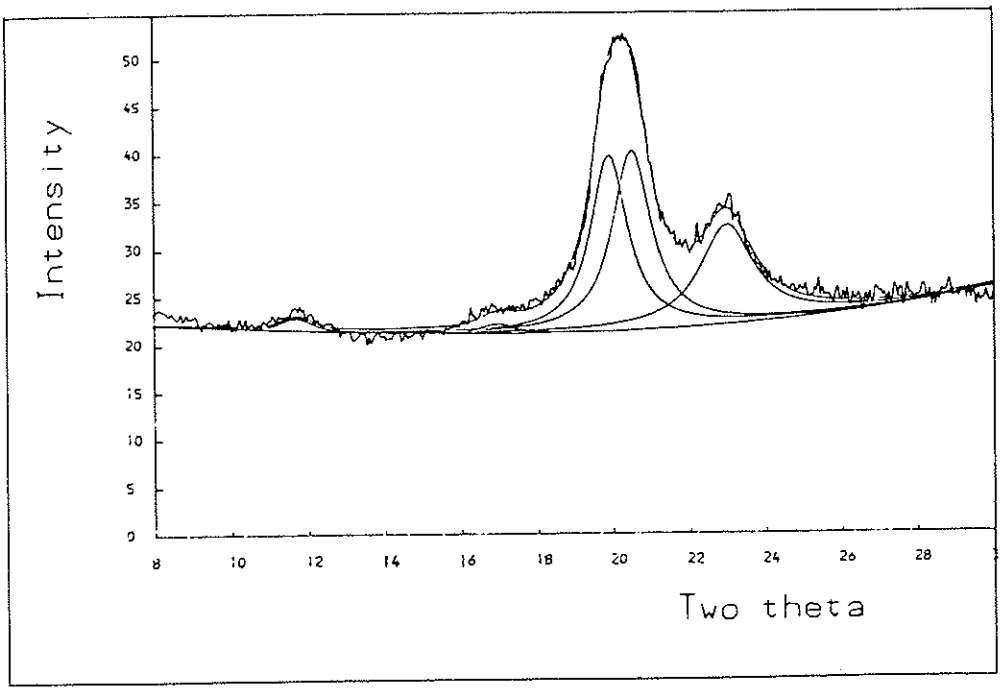


(b)

Figure 3
(a) X-ray diffraction traces of virgin; (b) accelerated aged fibres 1 m; (c) accelerated aged fibres 2 m

Accelerated ageing tests on virgin PVA fibres
This test may be regarded as a rather extreme accelerated ageing test involving elevated temperatures, high alkalinity oxidation and wet/dry cycling.

Tensile properties The results given in Table 2 indicate that for ageing times of 1 month the fibre properties are only slightly affected by this treatment, whereas, after 2 months' accelerated ageing, a substantial decrease in the tensile strength can be observed. For a direct comparison with results presented later in this paper, the ageing test was repeated using 100 mm length PVA staple fibres under identical conditions. The results presented in Table 3 confirm basically the findings obtained with the long PVA fibres. It should be appreciated that the test results presented later, deal with 6 mm fibres extracted from the products after ageing. Therefore the influence of gauge length on the tensile test results had to be clarified for comparative purposes.



(c)

X-ray diffraction analysis The resolved diffraction trace for a typical fibre is given in Figure 3a. The parameters for height A, width W, corrected position P, together with the crystallite size L and ratio of the 200 to 101 + $10\bar{1}$ areas R are given in Table 4. Each figure (Figures 3 to 5) shows the normalised diffraction trace, the best-fit mathematically resolved peaks, the best-fit envelope of the resolved peaks, and the background above which the best fit is made. It must be noted that the 200 peak arises from the planes normal to the planes containing the hydrogen-bonded molecular chains. Since the 200 peak is the only peak resolved to high accuracy, only the d-spacing for this peak is given. The 200 d-spacing may be compared with the value of 0.390 nm given by the Bunn unit cell.

By comparison, the accelerated-aged virgin fibres, (Figures 3b and 3c) show very little change from normal virgin fibres (Figure 3a) and have similar parameters (see Table 4), particularly the ratio of peak area R (around 0.40). It may be concluded that there is no significant change in the crystal structure of PVA virgin fibres subjected to the accelerated ageing tests in a cement slurry for periods of 1 and 2 months.

Table 1 Influence of temperature on fibre properties

Fibre properties (tested at 20 °C and RH of 65%)	Tensile strength N/mm²	Elongation at break %
Temperature of cement slurry in °C		
Control 20°	1612 (10.6%)*	7.5 (0.6%)
40°	1560 (8.4%)	8.5 (0.8%)
60°	1547 (13.6%)	8.5 (1.1%)
80°	1494 (16.7%)	8.3 (1.1%)

* % scatter in results n = 50 variation coefficient

Table 2 Influence of ageing on fibre properties

Ageing time	Tensile† strength N/mm²	Elongation† at break %
Control	1560 (8.4%)*	7.3 (0.2%)
7 days	1402 (15.0%)	8.7 (0.6%)
14 days	1493 (6.1%)	7.6 (0.4%)
30 days	1362 (9.6%)	7.8 (0.3%)
60 days	1021 (1.3%)	7.1 (0.4%)

* % scatter in results n = 50 variation coefficient
† gauge length 60 mm

X-ray diffraction studies on extracted PVA fibres extracted from the composite

Naturally weathered products Resolved X-ray diffraction traces from rotated PVA fibres extracted from naturally weathered products are illustrated in Figures 4a

Table 3 Influence of ageing on fibre properties

Ageing time	Tensile† strength N/mm²
Control	1690 (17.0%)*
30 days	1794 (19.0%)
60 days	1507 (21.7%)

* % scatter in results n = 50 variation coefficient
† gauge length 1 mm

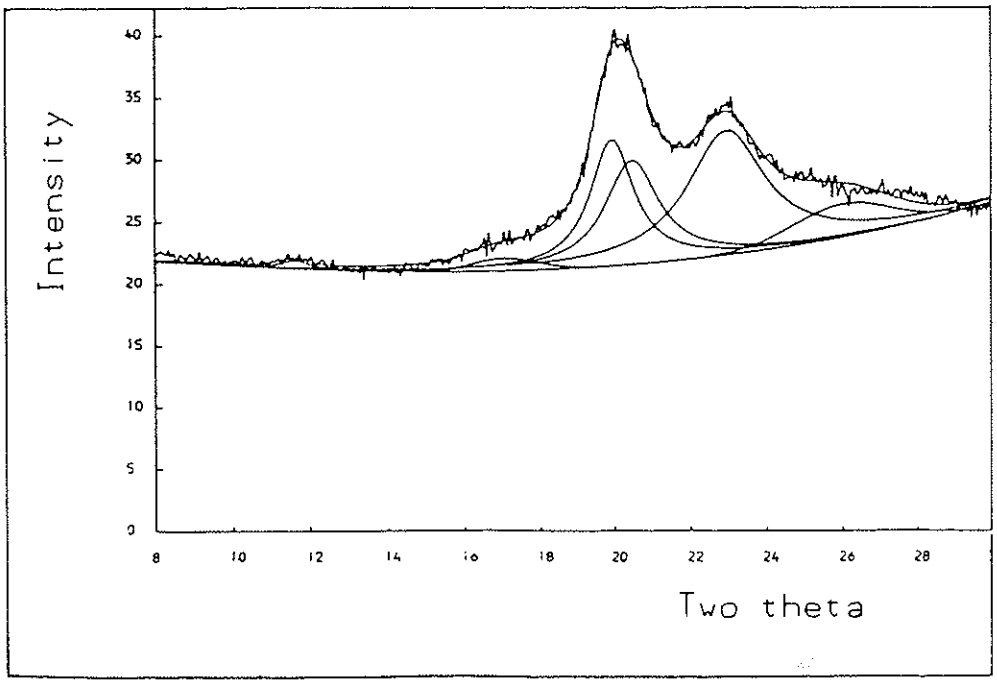
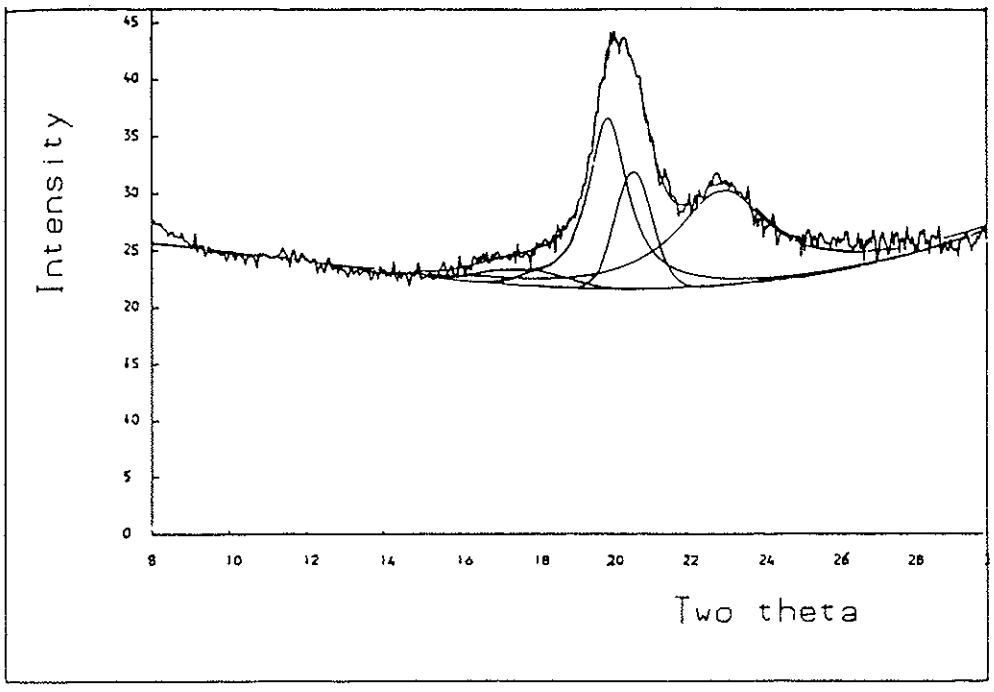


Figure 4
Resolved X-ray traces of various natural weathered products

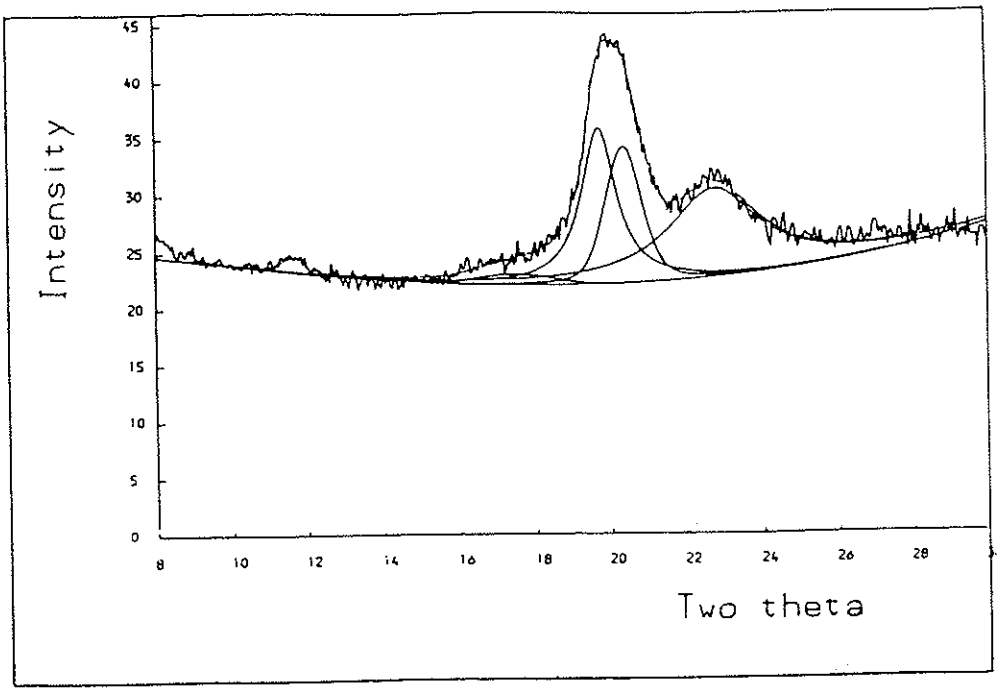
(a) Product A aged 7 years



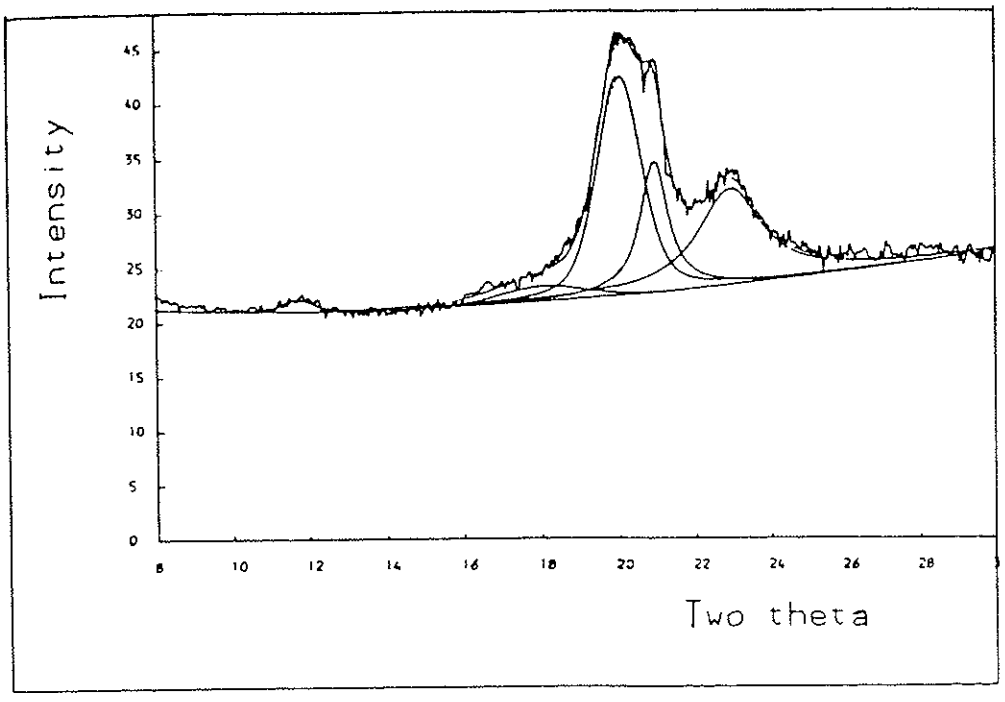
(b) Product B aged 6 years

to 4d, with the parameters given in Table 5. Product A was somewhat difficult to resolve, requiring an additional peak (not included in Table 5) to achieve a good fit. The 200 peak has a relatively large amplitude and is broad compared to the 200 peaks in virgin fibres, indeed the peak area ratio R is 0.73 compared to 0.43 for a typical virgin fibre. However, repeated experiments on the extracted fibres from the same product gave R values of 0.54 and 0.43.

There is no significant change in the crystallite sizes measured from the 101 and $10\bar{1}$ profiles, despite the change in proportions of scatter with respect to the 200 peak. It may be concluded that some crystallites remain unaffected by the ageing process whereas others become disordered into effectively separate sheets of hydrogen-bonded chains. Product B (6 years aged) and product C (4 years aged) have high peak area ratios of 0.63 and 0.60 respectively. It would seem that there is a



(c) Product C aged 4 years



(d) Product D aged 3 years

good indication of change due to natural weathering in these three samples, with the sheets of hydrogen bonded chains becoming somewhat disordered with time. Because the 200 peaks are broadened, no importance can be attached to the measured d spacings.

Product D (3 years aged) shows no significant change from the virgin fibres with a sharper 200 peak than products A and C and with an R value of 0.44.

Accelerated aged product Figures 5a to 5d illustrate the X-ray diffraction traces from rotated specimens of PVA fibres from Product E in the non-aged and accelerated aged states after 2, 4 and 6 months. The resolved peak parameters are given in Table 6. The most noticeable change is the surprising increase in the height of the 200 peak after 2 months ageing; this is followed by a reduction after 4 months and 6 months ageing. There is

no significant change in crystallite size or in the 200 d-spacing despite the variation in height. The changes in the ratio of the 200 profile to the combined 101 and $10\bar{1}$ profiles are given in Table 6. The value of R for the 2 months aged sample (0.85) is higher than that for the longest naturally aged specimen, but after 4 months the value of R (0.40 and 0.45 respectively) is no different from the virgin sample. A repeat experiment with a similar product gave values of 0.98 and 0.45 for the 2 month accelerated aged specimens.

Tensile properties of extracted PVA fibres from the composites

The results of the tensile tests on various virgin PVA fibres and fibres extracted from naturally aged and accelerated aged products are given in Table 7. From the data obtained with 1 mm gauge length specimens it is clear that the extracted fibres are appreciably weaker than the virgin fibres, although there appears to be no significant difference between the strengths of extracted fibres subjected to different ageing periods. Also there is no significant difference between the fibre tensile strengths of the non-aged and aged products. The significant difference between the extracted fibres and virgin fibres may however be related to the production processing techniques used in the Hatschek process as indicated in the results given in Table 7. The products manufactured for this study were processed according to the 'old' preparation technique and recently the production process has been modified.

Composite property development with age

The development of the mechanical properties and density of the products exposed to natural weathering and accelerated ageing tests are presented in Table 8. The general trend in all products exposed to natural weathering was an increase in flexural strength, E-modulus and density with age. Similar trends were found with the accelerated aged product with one exception however and that was the 2 month exposure period. This phenomenon cannot be explained at this stage in time, however, a repeat experiment on a similar product gave a value of 22.9 N/mm^2 indicating that no decrease in flexural strength had occurred.

DISCUSSION OF TEST RESULTS

The aim of the studies described in this paper was to investigate the durability of the PVA fibres used to reinforce cement-based composites. It has been pointed out that during the production of the products, temperatures of up to 80°C, which could be achieved at the curing stage in the stack, and the high alkalinity of the cement do not in any way have an adverse effect on the PVA fibres. However, mechanical damage may occur during the production processing if certain precautions are not taken. It was found that production techniques used during the early stages of the development of asbestos-free products resulted in a kinking of the PVA fibres which caused a localised weakness within the fibre. This would not be revealed by X-ray diffraction analysis which effectively averages many fibres.

Table 4 Peak parameters for virgin PVA-fibres and accelerated aged fibres

Sample	Parameter	Peak (hkl) 100	001	$10\bar{1}$	101	200
Virgin	A	2.04	1.10	23.06	18.40	11.84
PVA fibre	P	10.97	16.44	19.43	19.88	22.19
non-aged	W	1.13	2.12	1.31	1.28	2.15
	L	7.1	4.1	5.7	6.3	3.9
	d	–	–	–	–	0.400
	R	0.43				
Accelerated	A	1.81	1.24	17.63	19.40	10.85
aged	P	11.03	16.54	19.45	20.09	22.60
1 month	W	0.83	1.77	1.00	1.15	1.65
	L	10.5	4.84	7.09	6.32	4.71
	d	–	–	–	–	0.393
	R	0.41				
Accelerated	A	1.31	1.02	18.46	18.85	10.43
aged	P	10.95	16.32	19.43	20.04	22.60
2 month	W	0.97	0.97	1.17	1.20	1.69
	L	8.04	8.08	6.20	6.03	4.63
	d	–	–	–	–	0.393
	R	0.37				

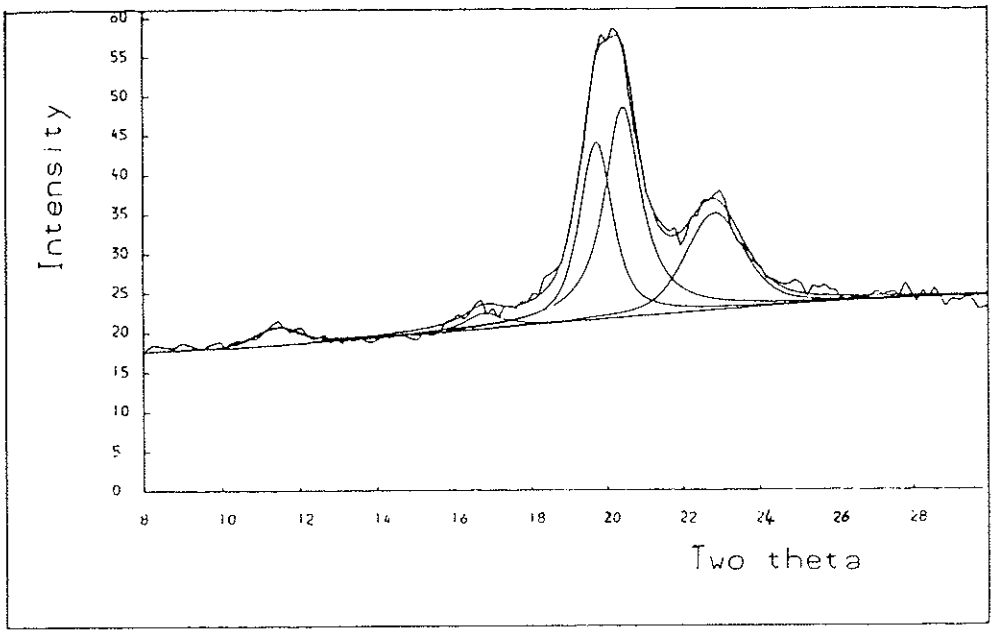
A, Amplitude (electron units); P, Corrected position (two theta); W, Width (theta); L, Crystallite size from W (nm); d, Interplanar spacing (nm); R, Ratio of areas 200/$10\bar{1}$ + 101

Table 5 Peak parameters for naturally aged PVA fibres extracted from the composite

Sample	Parameter	Peak (hkl) 100	001	$10\bar{1}$	101	200
Product A	A	0.62	1.00	10.16	8.36	10.00
	P	11.14	16.65	19.63	20.17	22.67
(7 yrs)	W	0.93	1.96	1.41	1.71	2.45
	L	8.5	4.4	5.2	4.6	3.6
	d	—	—	—	—	0.392
	R	0.73				
Product B	A	0.05	1.32	15.09	10.34	8.34
	P	11.15	17.29	19.61	20.31	22.67
(6 yrs)	W	0.77	2.49	1.28	1.16	2.99
	L	11.4	3.64	5.76	7.43	3.23
	d	—	—	—	—	0.392
	R	0.63				
Product C	A	1.29	0.96	13.86	12.10	7.77
	P	11.19	17.09	19.41	20.07	22.47
(4 yrs)	W	0.70	2.31	1.11	1.13	2.89
	L	12.6	3.83	6.43	7.17	3.29
	d	—	—	—	—	0.396
	R	0.60				
Product D	A	1.06	1.34	20.08	12.08	8.79
	P	11.08	17.47	19.59	20.49	22.52
(3 yrs)	W	1.00	2.54	1.31	0.85	2.02
	L	8.5	3.6	6.1	8.2	4.1
	d	—	—	—	—	0.395
	R	0.44				

Table 6 Peak parameters for accelerated aged PVA fibres extracted from the composites

Sample	Parameter	Peak (hkl) 100	001	$10\bar{1}$	101	200
Product E	A	2.13	2.02	22.61	26.83	12.36
	P	11.00	16.41	19.41	20.12	22.57
non-aged	W	1.29	1.10	1.04	1.14	1.79
	L	6.9	7.4	8.2	7.1	4.8
	d	—	—	—	—	0.394
	R	0.35				
	A	1.98	1.06	21.74	22.86	23.33
	P	10.98	16.32	19.46	20.08	22.56
aged 2 months	W	1.15	1.95	1.24	1.43	1.83
	L	8.0	4.5	6.8	5.6	4.6
	d	—	—	—	—	0.394
	R	0.85				
	A	1.42	1.01	15.66	14.53	8.48
	P	10.99	16.56	19.42	20.10	22.54
aged 4 months	W	1.21	2.03	1.13	1.11	1.77
	L	7.0	4.3	6.3	6.8	4.5
	d	—	—	—	—	0.395
	R	0.40				
	A	1.65	1.49	20.99	16.96	11.62
	P	11.06	16.54	19.49	20.14	22.57
aged 6 months	W	1.40	1.86	1.14	1.10	1.81
	L	6.1	4.6	6.3	6.5	4.4
	d	—	—	—	—	0.394
	R	0.45				



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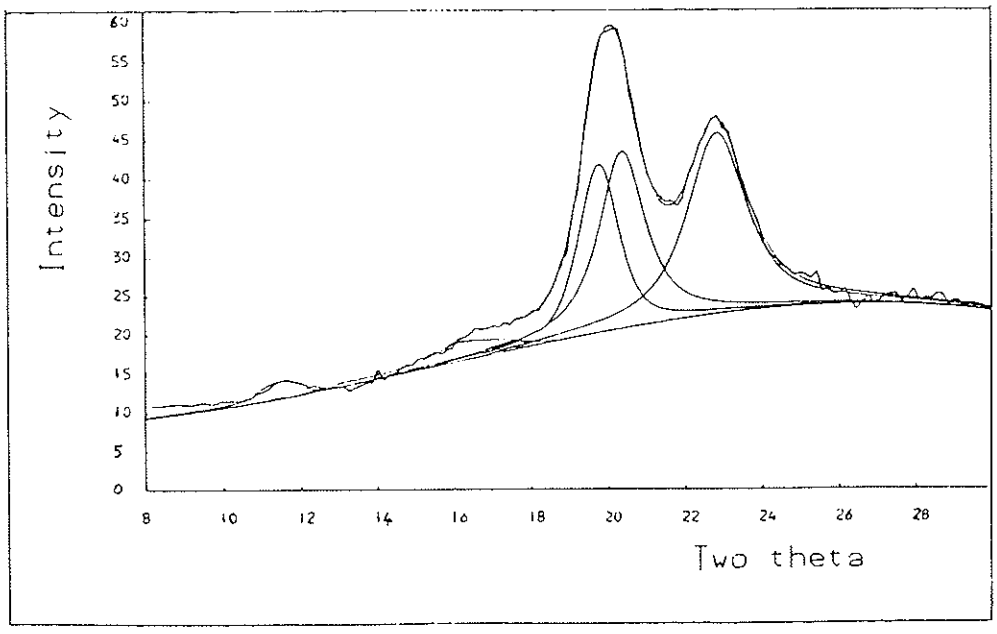


(b)

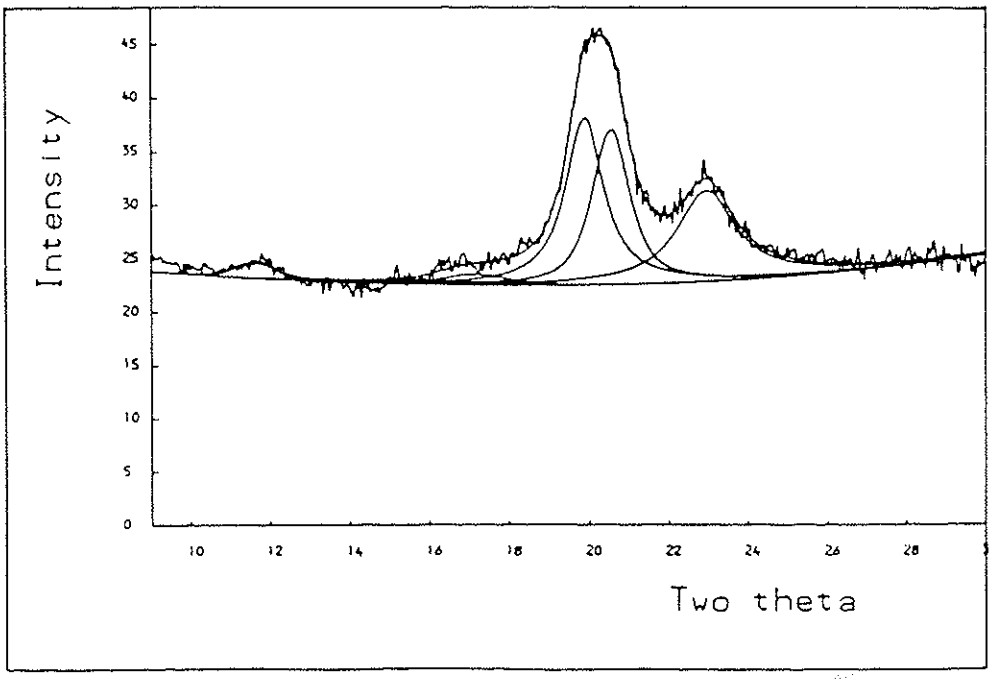
Figure 5
Resolved X-ray traces of Product E products. Non aged (a) and accelerated aged (b) aged 2m, (c) aged 4m and (d) aged 6m

However, because of the nature of the tensile test on the single fibres, the fibres will naturally break at their weakest point resulting in lower tensile strengths than the undamaged virgin fibres and fibres prepared according to the modified production processing used today in the industry.

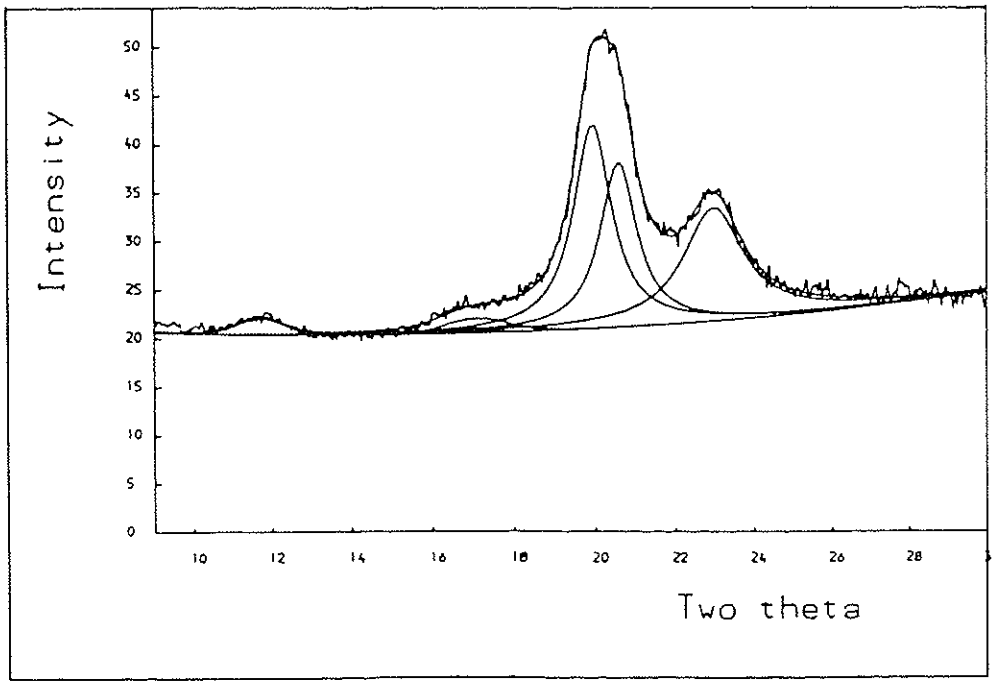
It may in turn be argued that the kinking of the fibres could adversely influence the composite properties. It is suggested however, that this is less likely as the fibres are completely embedded in the cement matrix and the probability of the fibre breaking exactly at the 'kink' when subjected to a flexural test is very remote.

In order to assess the durability aspects of the PVA fibres accelerated ageing tests on the single fibres and composites were conducted and compared with ageing of composites in natural weathering. The accelerated ageing tests on single fibres indicated no significant change in tensile properties or crystal structure over a period of 2 months. This test is regarded as rather a severe test and the positive results obtained from the tests provided the first evidence that the fibre should be durable.

X-ray diffraction studies conducted on extracted fibres from naturally aged products and accelerated aged products showed evidence of a change in the crystal structure of the fibres suggesting that sheets of hydrogen bonded chains become disordered with age. However, it should be pointed out that in some repeat



(c)



(d)

experiments on the same or similar products no difference could be detected between the aged and non-aged products. There appeared to be a large scatter in test results obtained from extracted fibres. As this was not the case for tests conducted on virgin fibres it is suggested that there could be localised patches within the products where fibres do undergo changes.

Although there appear to be minor changes in crystal structure taking place during ageing this has no influence on the tensile properties of the extracted fibres. Furthermore, the mechanical property development of the composite with age does not suggest any negative change in PVA fibres which would adversely influence the behaviour of the product during weathering.

It should be pointed out that the absolute values given for flexural strength in Table 8 indicate a very significant increase for product A whereas for product B rather insignificant changes occur. This may be related to various matrix additives which varied from product to product depending on the stage of the asbestos-free development programme.

Table 7 Tensile properties (breaking load in kN) of single PVA fibres extracted from products (compared with virgin fibres)

Virgin fibres	25.8 ± 4.4 kN
Extracted fibres from products	
(old preparation technique)	
non-aged (Product E)	14.3 ± 4.4 kN
natural weathering	
7 years (Product A)	15.9 ± 3.7 kN
6 years (Product B)	9.9 ± 2.9 kN
4 years (Product C)	11.9 ± 4.3 kN
3 years (Product D)	12.7 ± 5.8 kN
accelerated aged (Product E)	
2 months	13.7 ± 4.9 kN
4 months	10.1 ± 2.8 kN
6 months	12.0 ± 4.3 kN
Extracted fibres from 'green' sheets	
old preparation technique* (Hatschek)	16.8 ± 3.1 kN
new preparation technique* (Hatschek)	23.8 ± 5.0 kN

n = 50
± = standard deviations
* the old and new preparation techniques referred to are confidential to the industry and therefore are not elaborated on

CONCLUSIONS

1. The PVA fibres studied are resistant to high alkalinity, temperatures up to 80°C and show no indication of mechanical damage such as fibrillation or kinking when the modern Hatschek processing technique is used.

2. Accelerated ageing tests conducted over a period of 2 months on the PVA fibres show some evidence of deterioration in tensile properties but no changes in crystal structure.

3. X-ray diffraction studies reveal in certain cases a reduction in overall scatter with age of fibres extracted from naturally aged products, compared with non-aged material. This is probably due to a disordering of the hydrogen-bonded sheets.

4. This disorder was also revealed in a product exposed to accelerated ageing tests for two months. Variations in test results may be related to localised changes within the product.

5. Although there might be minor changes (according to X-ray diffraction analysis) in the PVA fibres in some cases with age, these do not appear to influence the tensile properties of the individual fibres.

Table 8 Development of the mechanical properties and density of the fibre–cement composite with age

Natural weathering in Switzerland

Product	Manufacture date	Period of exposure	Flexural strength development (tested wet) N/mm² non-aged	aged	E-modulus development kN/mm² non-aged	aged	Density development kg/m³ non-aged	aged
A	1979	7 years	17.3 ±1.6*	27.4 ±1.3	11.1 ±1.2	12.5 ±1.8	1610 ±10	1660 ±10
B	1980	6 years	13.2 ±1.0	14.7 ±0.6	8.7 ±1.5	16.2 ±1.7	1720 ±10	1770 ±50
C	1982	4 years	18.1 ±1.1	19.8 ±0.8	15.3 ±2.1	20.6 ±0.6	1870 ±10	1930 ±10
D	1983	3 years	18.2 ±0.7	20.6 ±1.3	16.5 ±1.3	19.8 ±1.2	1820 ±10	1930 ±20

Accelerated aged (laboratory environment)

Product E exposure period	Flexural strength (tested wet) N/mm²	E-modulus kN/mm²	Density kg/m³
Non-aged	22.8 ±1.5	17.1 ±1.7	1830 ±10
2 months	18.3(22.9) repeat ±0.9 test	17.9 ±1.3	1830 ±10
4 months	23.1 ±2.1	20.8 ±0.6	1870 ±10
6 months	23.9 ±1.8	21.0 ±0.8	1870 ±20

* standard deviatcn

6. Flexural strength of the products increase with age; this is partly associated with matrix carbonation and an increase in interfacial (fibre/matrix) bond with age.

7. It appears from the composite and single fibre properties presented in this paper that the PVA fibres are adequately durable over a period of 7 years natural weathering and there is every reason to believe that this should not significantly change over extended periods of time.

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