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Creep of Kevlar 49 fibre and a Kevlar 49–cement composite

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The creep strain responses of Kevlar 49 fibres and a Kevlar 49 – cement mortar composite board to sustained stresses have been studied over an extended period in excess of four years at ambient temperature. Single filaments of Kevlar 49, 900 mm in length, were stressed in tension in the range 830 to 1830 MPa. The relationship between creep and elapsed time is represented by the power function At^n where A is a function of stress and n is a constant. The creep strain in Kevlar 49 was low compared with other polymers. For example after 1000 days at a stress of 1830 MPa the creep strain was 13% of the initial elastic strain and is predicted by the power function to increase to 14.6% after 4000 days. The Kevlar 49 – mortar composite was subjected to bending stresses in the range 6 to 35 MPa and the creep deflection was monitored. The relationship between creep and time could again be represented by the power function At^n with A dependent on stress and n constant. The creep was similar to that expected from the matrix alone. The ratio of the creep deflection to the initial deflection after 1000 days at a stress of 6.15 MPa (well below the matrix cracking stress) was 1.31 and at 23.5 MPa (well above the matrix cracking stress) was 1.63.

1. Introduction

The study of time–dependent strain in a visco-elastic material often requires a considerable amount of effort over an extended period of time [1]. This is particularly true for cement based materials such as concrete where so many factors unrelated to applied stress have such a marked influence on time–dependent deformations. The literature on creep in concrete is extensive, see for example, Neville [2] and many attempts have been made to model the phenomena for predictive purposes. For the relatively new fibre reinforced cements and concrete materials, however, there is only a limited amount of published data on their creep behaviour [3–5] and it is often assumed that as the proportions of the fibre in these composites are rather small, the creep of the composites would depend almost entirely on the matrix used.

It has been shown previously [6] that aramid fibres (Kevlar* 49) can reinforce a cementitious matrix efficiently, improving the bending and impact strength of cements by substantial amounts. The present paper describes the long-term creep behaviour of Kevlar 49 fibres and of a cement composite made from them. We are unaware of any comparable data in the literature on Kevlar–cement composites but the creep of the fibres have been studied by a number of workers among them, Bunsell [7], Ericksen [8] and Horn *et al.* [9].

2. Materials

Fibres of Kevlar 49 were obtained from the manufacturer Du Pont de Nemours International SA, in the form of continuous roving. The roving consisted of about 3300 filaments 11.8 μm in diameter. The filaments had a quoted tensile strength of 2.9 GPa, Young's modulus of 129 GPa, elongation to break of 2.4 per cent and density of 1450 kg m^{-3}.

*E I Dupont Trademark.

The materials used as the matrix for the composite were ordinary Portland cement (OPC) to BS 12 and Leighton Buzzard sand passing a 3 mm mesh sieve, mixed in the proportions of 70 parts OPC to 30 parts sand.

3. Composite fabrication

A composite board was made by spraying a thin slurry of cement, sand and water together with a continuous stream of chopped Kevlar 49 fibres to form a well mixed uniform layer on a flat mould measuring 1500 mm by 900 mm and having a porous base. The fibres lay flat in the plane of the mould giving a two-dimensional random distribution. Three layers were applied giving a finished board thickness of 8.6 mm.

The water/cement ratio was reduced to 0.28 by removing water through the porous base of the mould by applying suction. The board was cured in a damp condition at room temperature for 28 days, during which time the entire board was cut into 135 test coupons measuring 150 mm by 50 mm. After curing, the coupons were kept in air at a temperature of 20° C and a relative humidity of 50% RH. The fibre volume content of the finished board was estimated to be 2.4 per cent.

4. Method of test

4.1. Measurement of creep in Kevlar 49 fibre

Single filaments, about one metre long, were loaded in direct tension by suspending weights from them. This was achieved by fixing aluminium tabs to the ends of the fibres with an epoxy adhesive which were then hung from firmly mounted supports. Weights of 9.10, 13.00, 20.06 and 27.09 g, were hung on the lower tabs. Two fibres were used at each stress level. The whole assemblage was enclosed in a draught proof, glass fronted case.

Two gauge marks were established on each fibre by glueing two 5 mm lengths of Kevlar fibre to them at right angles. The gauge length was nominally 900 mm.

The length and extension of the fibres were obtained by measuring the separation of the gauge marks with an optical cathetometer. This method enabled changes in the gauge length to be measured with an accuracy of 0.02 mm without any contact with the fibre. Measurements were continued over a period of 23 800 h (2.71 years).

The apparatus was housed in a room having the air temperature controlled at 19° C and the humidity at 30% RH.

4.2. Measurement of creep in Kevlar 49 – OPC composite

Coupons cut from the composite board were stressed in the bending mode using third-point loading with a major span of 135 mm and a minor span of 45 mm. The coupons were loaded with weights of 17.5, 32.5, 67.5 and 92.5 kg. The experiment was conducted in a room with the air conditioned to 20° C and 50% RH. The central deflection of the coupons was monitored by permanently fixed dial gauges. The early deflections of the most highly stressed coupons were measured electronically and logged on punched paper tape at ten second intervals. Measurements were continued over a period of 38 800 h (4.43 years).

The ultimate bending strength of the composite was determined in separate tests using the same bending configuration.

5. Results

5.1. Kevlar 49 fibre

The measurement of the lengths of the fibres was commenced one minute after loading, which was the earliest practical time, and continued at intervals for a period of 2.71 years. The lengths of the fibres before loading were not used in strain calculations because the fibres were not entirely straight. The initial conditions were inferred from an extrapolation of fibre lengths after loading back to a time of one second after loading and calculating the unloaded lengths from the known values of stress and Young's modulus. Strain was calculated simply from the relation: strain $= (L_t - L_u)/L_u$ where L_t is the length of the fibre at time t, and L_u is the unloaded length.

The two fibres loaded with the 27.09 g weights failed in less than three minutes after loading and no creep data were obtained. The calculated stress in these fibres was 2425 MPa.

Stresses in the remaining fibres were 1830, 1280 and 830 MPa. The time-dependent strain in these fibres was small as can be seen in Fig. 1 which shows total strain with elapsed time plotted on a log scale. The graphs are not linear but show an increasing slope with the logarithm of time. A useful and more sensitive measure of the time-dependent strain is the creep coefficient, defined here as the ratio of the time-dependent part of the strain to the elastic strain. This is given by the rela-

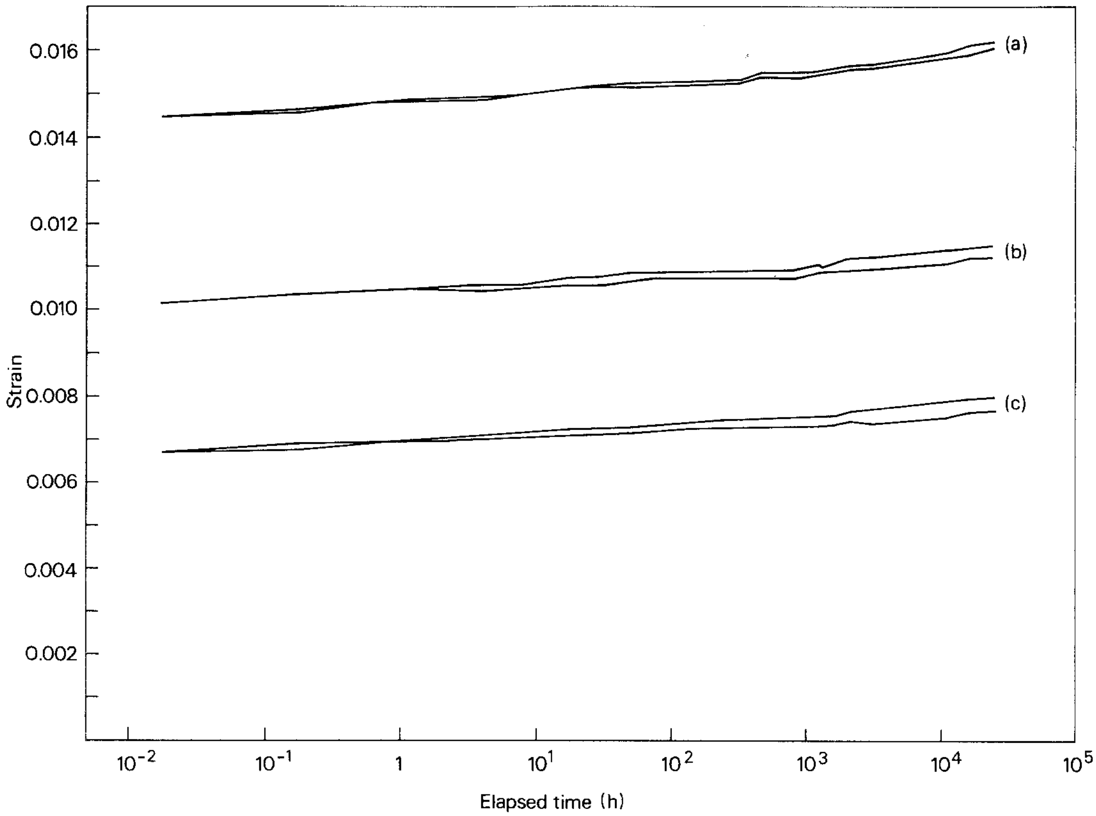

Figure 1 Total strain against the logarithm of time in Kevlar 49 single filaments stressed at (a) 1830 MPa (b) 1280 MPa and (c) 830 MPa.

tion: creep coefficient $= (L_t - L_e)/L_e - L_u)$ where L_e is the fibre length immediately after the load is applied (in this case one second after). The other symbols are as before. Plots of creep coefficient against elapsed time, both on logarithmic scales, in Fig. 2 show a linear relationship, after one hour, with equal slope for all stresses.

The data in Fig. 2 were fitted to the expression:

$$\log(\text{creep coefficient}) = A + n \log(\text{time}) + \text{error}$$

assuming the errors to be normally distributed. This assumption was tested and found to be reasonable. In the computations A was allowed to take different values for each stress level but n (the slope) was restricted to a single value after it was found that adjustments in the value of n did not improve the deviance of the model significantly. Expressed in power form, the creep coefficients of Kevlar 49 fibres at different stress levels could be described as $0.086t^{0.086}$ at 830 MPa, $0.062t^{0.086}$ at 1280 MPa and $0.055t^{0.086}$ at 1830 MPa where t is the elapsed time in hours.

5.2. Kevlar 49 – OPC composites

The bending strength tests on the composite gave the following properties: ultimate stress: 40.0 MPa (S.D. 3.0 MPa); central deflection at ultimate stress: 6.45 mm (S.D. 0.66 mm); stress at limit of proportionality: 10.6 MPa (S.D. 1.2 MPa); central deflection at limit of proportionality: 0.160 mm (S.D. 0.027 mm); Young's modulus of linear region: 20.1 GPa (S.D. 3.3 GPa).

The nominal stresses applied to the samples in creep experiments were 6.15, 11.4, 23.5 and 34.4 MPa calculated from the expression Modulus of Rupture $= 6M/(bd^2)$ where M is the applied bending moment and b and d are the breadth and depth of the samples.

The central deflections of the creep samples are plotted against elapsed time on a logarithmic scale in Fig. 3. Both the samples stressed at 34.4 MPa broke within four hours of loading. One of the samples stressed at 23.5 MPa failed after 5500 h. The creep deflections were large, in some cases exceeding the initial deflections.

The creep deflection coefficient defined here as

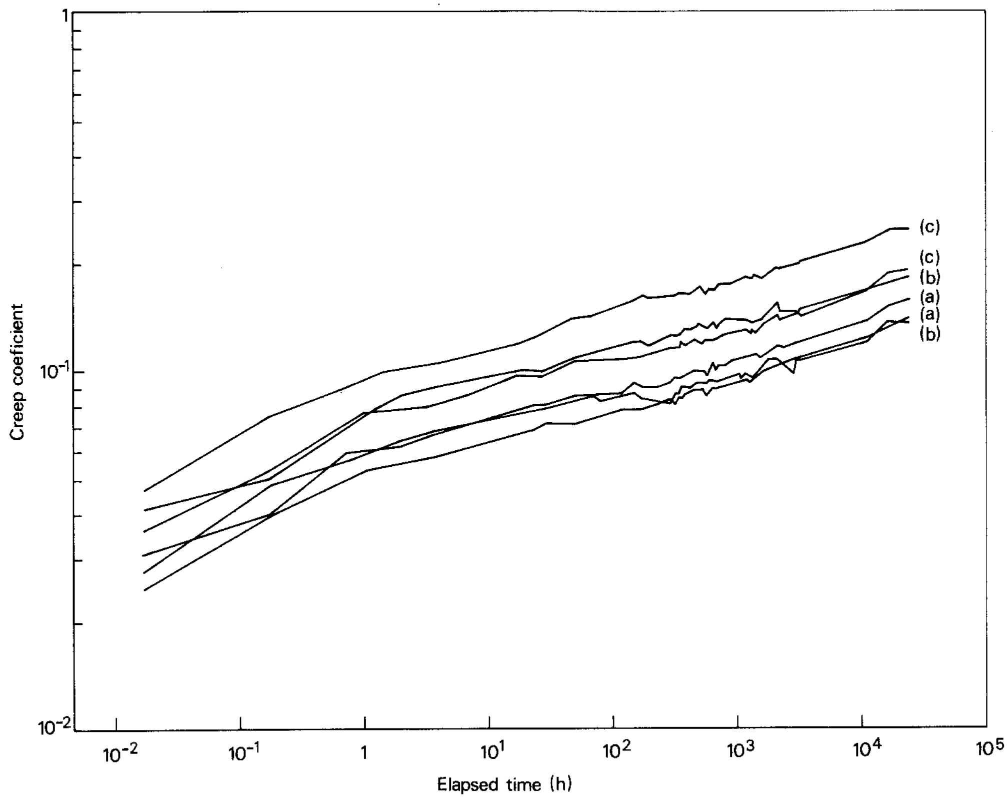

Figure 2 Increase of creep coefficient with time for Kevlar 49 single filaments stressed at (a) 1830 MPa (b) 1280 MPa and (c) 830 MPa (log axes).

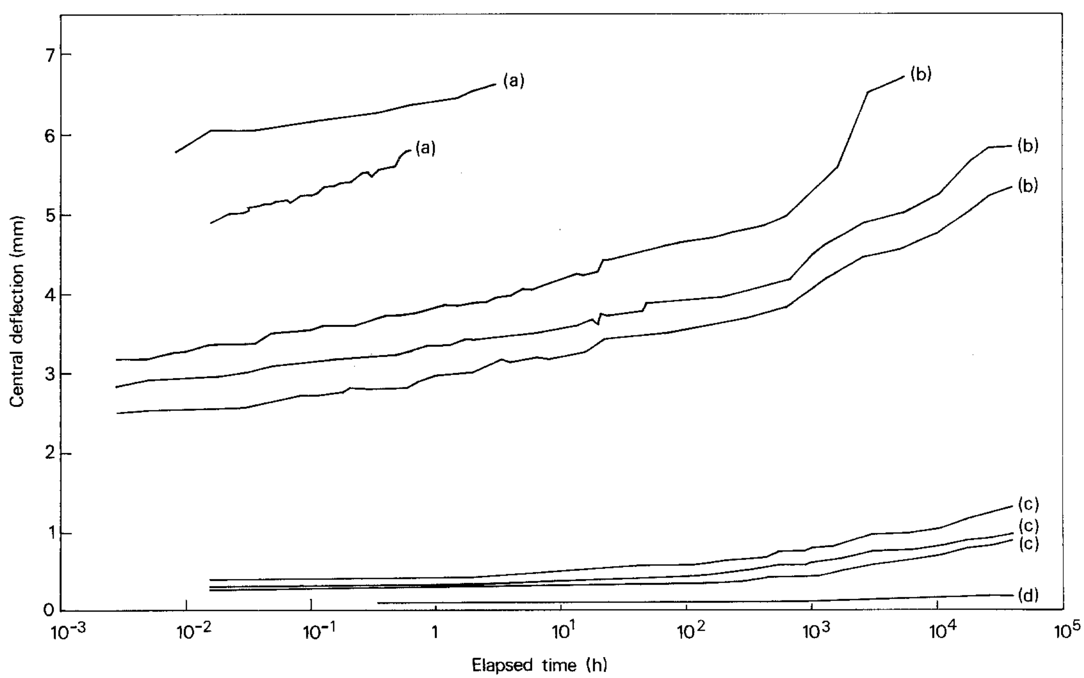

Figure 3 Central deflections of Kevlar 49–mortar composite beams stressed at (a) 34.4 MPa (b) 23.5 MPa (c) 11.4 MPa and (d) 6.15 MPa shown against the logarithm of time.

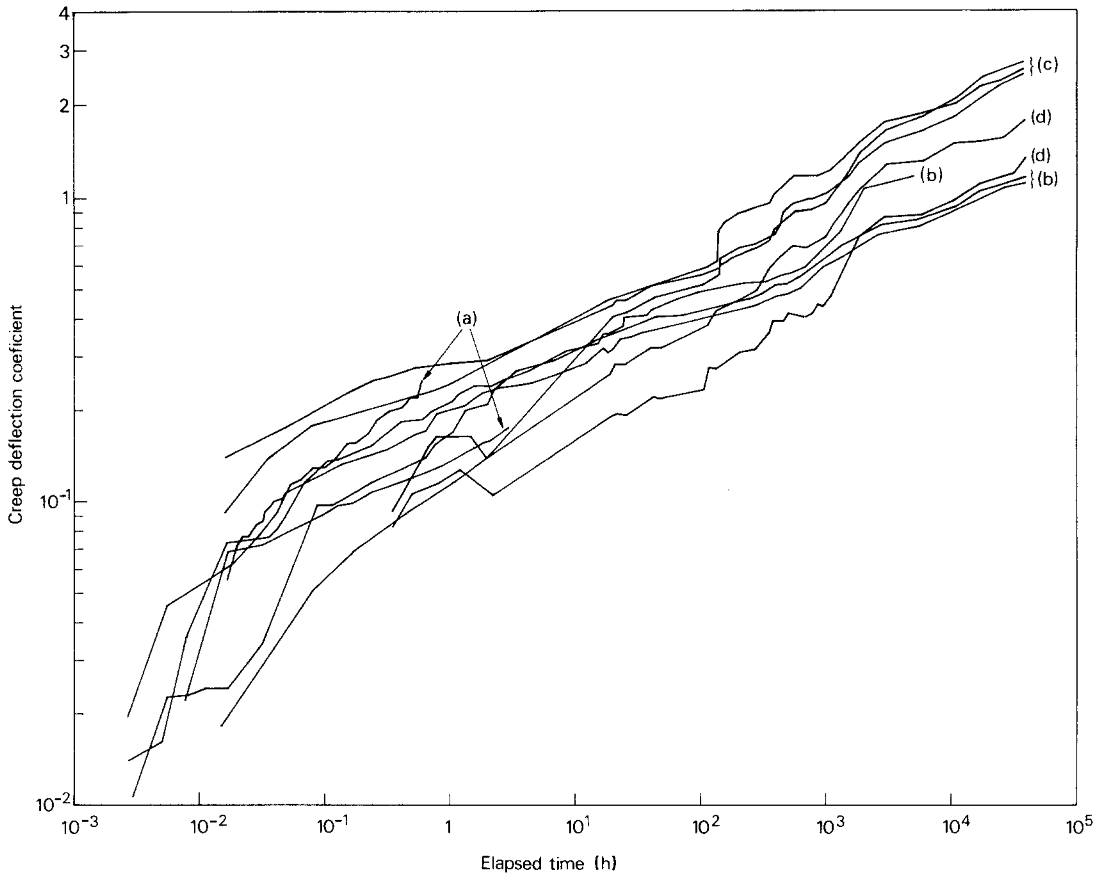

Figure 4 Increase of creep deflection coefficient with time for Kevlar 49–mortar composite beams stressed at (a) 34.4 MPa (b) 23.5 MPa (c) 11.4 MPa (d) 6.15 MPa (log axes).

the ratio of the time-dependent deflection to the initial deflection registered after the application of the load is plotted against elapsed time, both on a logarithmic scale, in Fig. 4 for the different stress levels. If elastic bending theory is assumed, the creep deflection coefficient is numerically equal to the creep coefficient.

The creep deflection coefficients against time curves shown in Fig. 4 are typical of the sand cement mortar. They exhibit a substantially linear relationship with similar slope for all stress levels. The data were fitted to the model

$$\log(\text{creep deflection coefficient}) = A + n\log(\text{time}) + \text{error}$$

assuming the errors to be normally distributed. This assumption was tested and found to be reasonable. At first A and n were both allowed to assume different values for each stress level but as no significant improvement in the deviance of the model was achieved by assuming different slopes (n), n was restricted to a single value. The fit resulted in the following relationship, expressed in power form: creep deflection coefficient = $At^{0.237}$ where t is the time elapsed in hours. The values of A were 0.12, 0.21, 0.15 and 0.20 at applied stress levels of 6.15, 11.4, 23.5 and 34.4 MPa, respectively.

6. Discussion of results

6.1. Fibre

Power functions of time have been used successfully to describe the creep behaviour of a wide range of engineering materials both in the early stages and over long time spans, see for example [1, 2].

The fit of the Kevlar 49 fibre creep data obtained in this study to a power expression appears to be good over five decades of time. The power function implies that creep is unlimited as t increases although the rate of creep is always decreasing. This is contrary to the observation of Bunsell [7] that when loaded to 85% of its break-

TABLE I Constants for creep equation $cc = At^n$

Material	Temperature (°C)	RH (%)	Stress (MPa)	A	n	cc at $t = 24\,000$ h
Kevlar 49	19	30	830	0.0865	0.0861	0.206
			1280	0.0624	0.0861	0.149
			1830	0.0552	0.0861	0.132
Polyethylene	25	50	1.55	0.763	0.089	1.87
Poly (vinyl chloride)	25	50	6.89	0.0864	0.155	0.412
Polycarbonate	24	50	13.8	0.0577	0.15	0.262
Glass polyester laminate	23	50	68.9	0.142	0.09	0.352
Stainless steel	596	–	73.2	0.661	0.195	4.72

ing stress the extension due to creep in Kevlar 49 fibres stabilizes after five minutes, showing no further extension up to thirty minutes. Ericksen [8] on the other hand, observed fibre extensions due to creep for all times up to 1000 h, the longest examined. His data plotted linearly on a strain against log time plot. Using Kevlar yarn Horn *et al.* [9] also obtained a linear plot for % creep strain against log time out to two years at an applied stress level of 50% of the fibre breaking strength.

It is apparent that the value chosen for the length of the fibre at t_0, i.e. the time at which creep is considered to be zero, is somewhat arbitrary since the application of the load cannot be instantaneous. The creep strains at short times are very sensitive to this initial value for the length of the fibre. Preconditioning of the fibre, for example by subjecting it to a loading cycle, will also affect the early creep strains. These initial conditions will have a marked effect on the shape of the strain–time trace at short times and may account for the different time functions chosen by different workers. In the present study emphasis has been placed on the long-term trends.

The constants for the power function obtained for Kevlar 49 are compared in Table I with those of some other materials described in [1]. The values of A given in the table are normally dependent on the temperature and applied stress and are not therefore strictly comparable; however, it is evident the creep in Kevlar 49 is lower than that of other synthetics. The last column of Table I lists the calculated values for the creep coefficients of the materials after a time span of 24 000 h.

The premature failure of the fibres at 2425 MPa was rather unexpected. Using an empirical equation suggested by Chiao *et al.* [10] on the basis of accelerated ageing tests carried out with Kevlar 49–epoxy composites at elevated temperatures a lifetime of about 50 h would have been expected for the fibres at the stress applied. However the authors noted that at room temperatures real lifetimes tended to be much shorter than the predicted ones for the highly stressed fibres. Further reduction in lifetime, as in the present work, may be attributed to the long fibre length used, variations in fibre strength and damage caused to the fibres during the mounting process.

6.2. Composites

The main features of the tensile stress–strain response of the Kevlar 49–cement composites have been described previously [6]. In common with other brittle matrix composites reinforced by strong fibres [11, 12] they show (a) the linear elastic region where the matrix is uncracked, (b) the multiple cracking region where the strain increases at a more or less constant or slowly rising stress and (c) the region where the load is borne entirely by the fibre until the composite fails. The nominal bending stresses applied to the Kevlar–cement composites in the creep tests were chosen to represent these different regions where the creep behaviour might be expected to be different. Two stress levels (11.4 and 28.5 MPa) corresponding to the beginning and end of the multiple cracking region were used to identify region (b).

In non-linear materials such as Kevlar–cement composites the actual maximum tensile and compressive stresses due to bending are likely to differ considerably from the nominal maximum bending stresses [13]. Provided the data on the strain on the tension and compression faces can be recorded continuously during a bend test along with the applied bending moment, the entire tensile and compression stress–strain curves can be calculated [13, 14]. The data from the creep tests allowed only the average strain to be calculated but it is probable that at large strains the maximum tensile stress applied was as low as half the nominal stress

TABLE II Constants for the creep equation; creep deflection coefficient = At^n

Matrix	Fibre	Condition	Stress (MPa)*	A	n	Creep coefficient at 24 000 h	Reference
opc	none	dry	4.32 b	0.22	0.39	11	15
opc	none	–	6.4 c	0.16	0.39	6.0	16
opc	none	–	32 c	0.56	0.32	14	16
opc	none	–	2.4 t	0.404	0.42	28	16
concrete	none	dry	– c	0.44	0.22	3.9	2
opc	4% glass	wet	– b	0.78	0.20	5.9	5
opc/sand	4% glass	wet	– b	0.29	0.22	2.7	5
opc	4% glass	dry	4 t	0.12	0.33	3.3	4
opc	4% glass	dry	8.3 t	0.22	0.33	6.1	4
opc/sand	1.5% glass	dry	2.2 b	0.12	0.34	3.8	3
concrete	1% steel	dry	2.1 b	0.13	0.33	3.5	3
opc/sand	2.7% Kevlar	50% RH	6.15 b	0.12	0.24	1.3	Present work
opc/sand	2.7% Kevlar	50% RH	11.4 b	0.21	0.29	2.3	Present work
opc/sand	2.7% Kevlar	50% RH	23.5 b	0.15	0.24	1.6	Present work
opc/sand	2.7% Kevlar	50% RH	34.4 b	0.20	0.24	2.1	Present work

*b – bending, c – compression, t – tension

whereas the maximum compressive stress might have been higher by a factor of three. For the maximum bending stress (MOR) of 34.4 MPa used in the present study this would indicate a maximum tensile stress in the Kevlar fibres of the order of 2150 MPa and a maximum compressive stress in the matrix of the order of 100 MPa.

Despite the wide variations in the stress and strain distributions in the samples subjected to the creep tests, the creep deflection coefficients are well represented by the power function At^n, in which n is constant for all the stress levels and A varies by no more than a factor of 2. Power functions have been used to describe creep in both concrete (see for example [2]) and hardened cement paste [15, 16], with n ranging between 0.25 to 0.33 for concrete and 0.3 to 0.4 for plain cement. A few examples of the values for A and n have been derived from the data in the literature [2, 15, 16] by assuming, where required, a value for the initial strain. A is strongly dependent on the mix design, the applied stress level and test conditions such as relative humidity. In Table II these computed values of A and n and the predicted creep coefficients after 24 000 h are compared with those obtained for Kevlar–cement composites in this study and those derived from published data [3–5] on other fibre cement composites.

Although it is difficult to draw valid conclusions from the data in Table II because of the differences in the matrix formulations, test environments, stress distributions, etc. used for different types of cement composites it appears that, relatively speaking, the creep in Kevlar 49–cement composites is low, although comparable estimates are obtained from glass reinforced cement mortar [5] prepared with a w/c ratio of 0.29.

The data available at present on the creep properties of the maxtrix alone, are insufficient to allow an analysis of the separate roles of the matrix and fibre in the mechanism of creep under the non-uniform stress distribution in the composite. While the matrix remains uncracked the proportion of the applied load borne by the fibres is only 1 to 2% and hence the fibres are unable to have much influence on creep behaviour. It is in this condition that the lowest creep coefficient was measured which is consequently attributed largely to the properties of the matrix. Since the creep coefficient is of similar order at higher stresses, when the matrix is cracked, the creep may still be governed by the matrix properties.

7. Conclusions

1. Creep strains in Kevlar 49 fibres are low at room temperature amounting to less than 20% of the initial elastic strain after several years under stress. The creep coefficient decreases as the stress increases.

2. Creep deflection in Kevlar 49–cement mortar beams is of the same order as that expected from plain mortar which may be higher than twice the initial deflection after several years under stress.

3. The creep–time relationship of both fibre and composite can be described by power func-

tions which can be used to predict long term strains. Premature failure at low strains may occur due to creep rupture. The mechanism of this mode of failure in the composite requires further study.

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