Viscoelasticity of Kevlar 49 fibres

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ABSTRACT: Aramid fibres are being considered for use in many structural engineering applications. Many of these would require knowledge of the long term creep behaviour under constant loads. Creep tests at ambient conditions are considered to be the most reliable way of predicting the creep behaviour of aramids; at the same time useful conclusions about the viscoelastic properties of the material can be made.

In the past, many researchers have carried out creep tests at ambient conditions with the specific aim of determining the viscoelastic behaviour of aramid fibres. However, their conclusions are not consistent and it is still an open question whether aramid fibres exhibit linear or non-linear viscoelastic behaviour.

Creep tests have been carried out covering a wide stress spectrum (10-70% Average Breaking Load) for a long period of time. The results indicate that Kevlar 49 yarns show a non-linear behaviour at stresses below 40% of the breaking load and a linear behaviour at stresses above 40%. This result resolves the matter of viscoelasticity and explains also the contradictions in earlier works.

INTRODUCTION

In the last twenty years, composite materials, such as carbon, glass and aramid fibres, have been considered for use in concrete structures. These fibres have become increasingly popular in many structural applications due to their unique mechanical properties. They possess a combination of high strength, high stiffness, good resistance to corrosion; they are also lightweight and easy to handle (Burgoyne, 1992). At the present time these materials are several times more expensive than steel, but their unique properties can compensate for the additional first cost if whole life costing is considered (Balafas et al., 2003).

In the literature there is still debate about whether aramid fibres exhibit linear or non-linear viscoelastic behaviour. There have been several studies that have not

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resolved the matter and their conclusions are not consistent, which may be because different versions of aramid fibres were tested. Aramid fibres are available under a variety of grades and trade names. Kevlar (manufactured by Du Pont) and Twaron (manufactured by Akzo) may differ slightly in their physical structure, but they have very similar chemical structure. It is reasonable to believe that they exhibit similar viscoelastic behaviour, although the creep rates can be expected to differ. Technora (manufactured by Teijin) and Vectran (manufactured by Kuraray) differ chemically, so they are expected to behave differently. In the present paper, creep tests were carried out Kevlar 49 yarns and conclusions for the viscoelastic behaviour are presented.

Many researchers have worked on the creep behaviour of Kevlar 49 for many years. Schaefgen (1983) showed that Kevlar 49 fibres exhibit linear behaviour. Similar results were obtained by Guimaraes et al. (1992), who showed that Parafil ropes made from Kevlar 49 possess a linear viscoelastic behaviour using a series of creep tests. However, Northolt et al. (1985) used crystallite models to try to explain the viscoelastic behaviour of PPTA fibers and concluded that they exhibit a non-linear behaviour. Walton et al. (1983) showed that the viscoelastic behaviour of Kevlar 49 fibres is non-linear. Ko (1980), Chambers (1986) and Amaniampong (1992) have carried out stress-relaxation tests on Kevlar fibers, Parafil ropes and parallel-lay ropes respectively and claimed that the viscoelastic behaviour is non-linear. More recently, Baltussen and Northolt (2001) conducted a series of creep tests below 1.25 GPa (= 50% ABL(Average Breaking Load)) on PPTA fibres and showed a non-linear viscoelastic behaviour. Most recently, Alwis et al. (2008) carried out creep and stress-relaxation tests on Kevlar 49 fibres covering a wider stress spectrum and showed that Kevlar 49 shows non-linear behaviour below 40% ABL and a linear behaviour above 40% ABL. Unfortunately, his tests were affected by malfunctions of the air-conditioning and data-logging systems, so his tests only lasted for a maximum of about 1000 hours. The objective of this work was to carry out confirmatory tests over a longer period of time.

One of the problems with many of these studies is that the results for the viscoelastic behaviour were often obtained as by-products of other work. Most creep testing was carried out as part of creep-rupture studies. Thus, high loads levels were applied (> 70% ABL), when creep failures can be expected in a short time period. On the other hand, relaxation tests were conducted to determine the losses of forces that would be expected at the loads to which fibres are permanently exposed. In many ropes applications there is significant uncertainty about the loads, so large safety factors are applied. Hence, relaxation tests have often been carried out at low load levels (< 50% ABL). Therefore, there is almost no data that has been obtained for *the same* stress levels for both creep and relaxation tests.

The lack of overlap would not be a critical problem if the material behaviour was unique at different stress levels. But there is evidence that the material stiffens at high loads. An early work by Chambers (1986) showed that aramid ropes made from Kevlar 49 stiffen at about 50% ABL. Recent studies by Alwis et al. (2008) and Giannopoulos (2009) observed similar behaviour for Kevlar 49 yarns.

The main objective of this paper is to investigate the creep and viscoelastic behaviour of Kevlar 49 fibres using creep tests at ambient conditions. All tests have been carried out for durations that range from 100 days to 1 year covering a wide stress spectrum (10-70% ABL).

Viscoelasticity

Viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. Viscous materials, like honey, resist shear flow and strain linearly with time when a stress is applied. Elastic materials strain instantaneously when stretched and just as quickly return to their original state once the stress is removed. Viscoelastic materials have elements of both of these properties and, as such, exhibit time dependent strain. Most metals exhibit elastic behaviour at lower stress levels whereas most polymeric materials possess visco-elastic behaviour (Williams, 1973).

Viscoelasticity can be explained by using the state theory (Williams, 1973). This theory is based on the assumption that there exists a unique relationship between stress σ, strain ε_c and time t. The simplest possible form of constitutive equation is given in Eq. 1:

$$\varepsilon_c = \phi\ (\sigma, t) \tag{1}$$

State theory can be represented as a three-dimensional surface that is unique for a given material (Fig. 1). Sections drawn through the surface at constant stress levels give creep curves and sections at constant strain give relaxation curves as shown in Figs. 2a & 4c respectively. Another important cross-plot, which is shown in Fig. 2b, is a stress vs. strain curve at a specific time (isochronous curve).

A linear viscoelastic material has a linear isochronous stress vs. strain curve, which can be used as a simple check on this property.

If the variables of Eq. 1 are separable, then the equation can be rewritten as:

$$\varepsilon_c\ (t)= \phi\ (t)\ f(\sigma) \tag{2}$$

If the material is linearly viscoelastic, then $f(\sigma) = \sigma$, and

$$\varepsilon_c\ (t)= \phi\ (t)\ \sigma \tag{3}$$

where $\varepsilon_c\ (t)$ is the creep strain
$\phi\ (t)$ is the creep compliance
σ is the stress (normalized as a fraction of ABS)

Another method to check whether a material is linearly viscoelastic is to plot creep compliance ($\phi(t)$ ($=\varepsilon_c(t)/\sigma$)) vs. stress (σ) at different times. Such a plot for a specific time $t=t_0$ is shown in Fig. 2d. If the points for a range of stresses fit on a straight line, which is parallel to the σ axis, this means that the creep compliance is constant and implies that the material is linearly viscoelastic for this stress range and specific time t_0.

On the other hand, materials whose strain at any state is a function of both time and stress (Eq.2) are defined as non-linearly viscoelastic materials. From Eq. 2 it can be concluded that the isochronous curves are not straight and the creep compliance value is stress dependent.

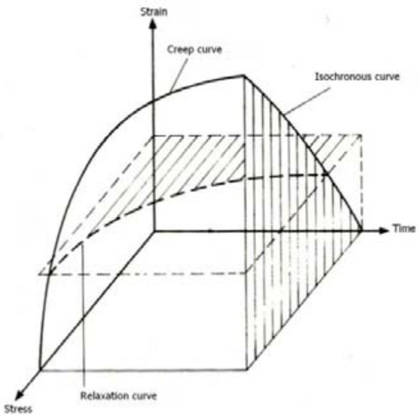

Figure 1 The three-dimensional stress-strain-time surface (Williams, 1973)

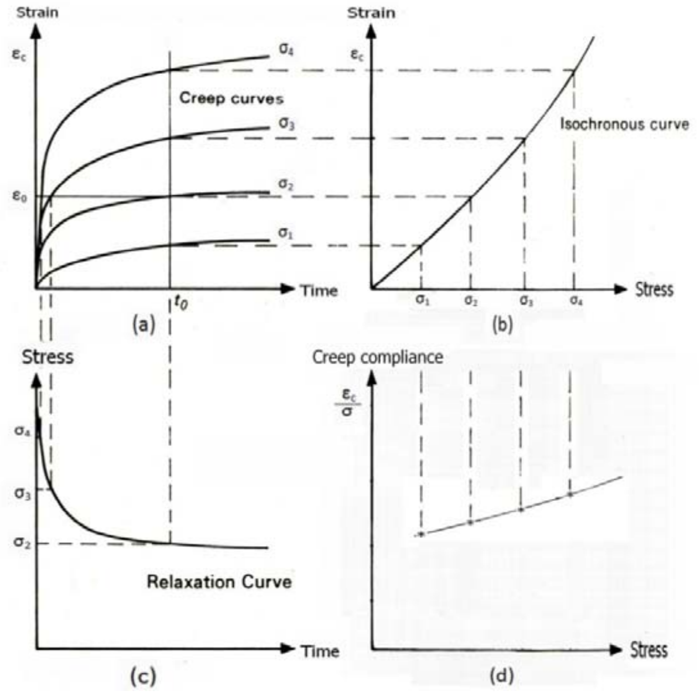

Figure 2 The cross-plot method for an equation of state (Williams, 1973)

MATERIAL AND EXPERIMENTAL SET-UP

Material

Kevlar 49 yarns, available in reel form, were used for all tests. The cross sectional area (A) of the yarns, after removing moisture, was found to be 0.17497 mm^2. The breaking load was determined by testing twenty different specimens and found to be 444.6 N for Kevlar 49, with a standard deviation of 8.22 N. All values obtained are in agreement with the literature (Du Pont, 1991). Before testing the yarn reels were kept at constant temperature (25^{o}C) and humidity (50% relative humidity) placed in a black polyester bag inside a box to protect them from ultra violet light, which may affect the properties of the material.

Experimental set-up

Creep testing was carried out in a special room where the temperature and humidity levels were controlled and kept constant by an air-conditioning system.

Eighteen clamping devices were mounted on stiff frames that were bolted to a wall. The top clamp was kept stationary and the lower clamp was free to move vertically between two metal rails, as shown in Fig. 3. Each yarn was subjected to a constant load by hanging dead-weights at the bottom clamp. The load was applied by concrete weights on a threaded rod, acting via a 5:1 lever arrangement. Minor adjustments were made to the load by adding small bags of sand, so that the desired load level was applied. The dead-weight was applied smoothly by supporting it on a small scissors-jack and lowering it slowly by turning a handle (Fig. 4). Mechanical strain gauges of circular form were used to measure the elongation of the yarns.

The mechanical strain gauge consisted of two strips of spring steel, spot welded to two small metal plates forming a 200 mm diameter ring. Four electrical strain gauges were glued to the sides of the steel strips and connected by wires and formed a full electrical bridge circuit. The self-weight of the strain gauge is around 1 N and the spring force in it at the maximum extension is a fraction of a Newton. Therefore, the yarn specimen is not practically influenced by the strain gauge. Before testing, all mechanical strain gauges were calibrated.

The mechanical strain gauge in all yarns, the room thermo-couple and the room humidity-couple were connected to a data logger, which was connected to an Uninterruptible Power Supply (UPS), and readings could be taken at user-defined time intervals and saved directly to a computer.

Figure 3 Experimental set up of the creep experiment

Figure 4 Loading arrangement of the creep test

TESTING PROCEDURE

Creep tests for Kevlar 49 yarns at different load levels, under constant temperature and humidity conditions, were carried out using the testing arrangement described before. It was decided to keep the temperature at 25^oC and the humidity at 50% RH. All yarns were wrapped at each end around a spindle and fixed to a grip in the clamp. The nominal length of the specimen (distance between clamped ends) was taken equal to 350 mm. Then mechanical strain gauges were attached on the yarns and initialized to zero, following which the dead load was applied.

The above procedure was followed for testing between 2 and 4 yarn specimens at each load level: 10, 20, 30, 40, 50, 55, 60, 65, 70% of ABL at constant temperature and humidity. Experiments were not conducted above 70% ABL, since failure above this level is expected in a short time due to stress-rupture (Giannopoulos et al., 2008 and 2009a), and when it occurs vibrations are introduced in the support frame and the adjacent specimens are disturbed. A test plan of all creep tests carried out is given in Table 1. Each test is identified by a test label, e.g. CCTK-70-02, where 'CCT' denotes Conventional Creep Tests, 'K' denotes Kevlar, '70' denotes the load level, '02' denotes the repetition of the test.

Some creep tests were carried out for 100 days (01 & 02 repetition), and some of those were extended up to 1 year (03 & 04 repetition). No failure of the specimens was expected within this period, since all loads were below 70% ABL.

RESULTS AND DISCUSSION

Creep tests were carried out as described in the previous section and details of all tests are summarized in Table 1. The readings obtained from each test were used to plot the corresponding strain vs. time curves. The individual curves from all tests on Kevlar 49 are given elsewhere (Giannopoulos et al., 2009b). A typical creep strain vs. time curve is given for test CCTK-70-04 (Fig. 5). The observed spread in the curves is due to the inherent noise of the measuring equipment (accuracy of strain gauges ±0.0003). For calculation purposes, in order to diminish this noise, the value of strain at any time is the one corresponding to the centre of the spread (mean value).

Some creep tests, for example test CCTK-70-01 (Fig. 6), had to be discarded, because slip events were observed. These were caused by slip between the mechanical strain gauge and the yarn or due to a sudden change of the testing room temperature (when visiting the room), which caused small jumps in the creep curves.

The temperature and humidity variation with time in the testing room is shown in Fig. 7 and it verifies that they were kept practically constant throughout the testing period.

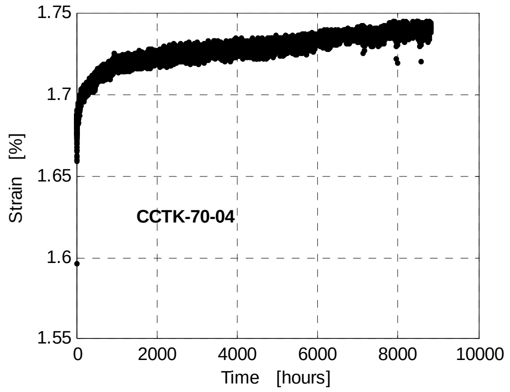

Figure 5 A typical strain vs. time curve

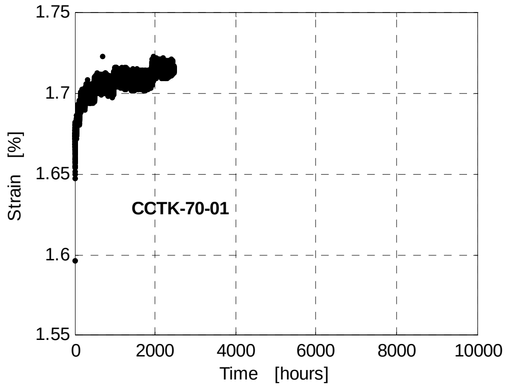

Figure 6 A typical abandoned strain vs. time curve

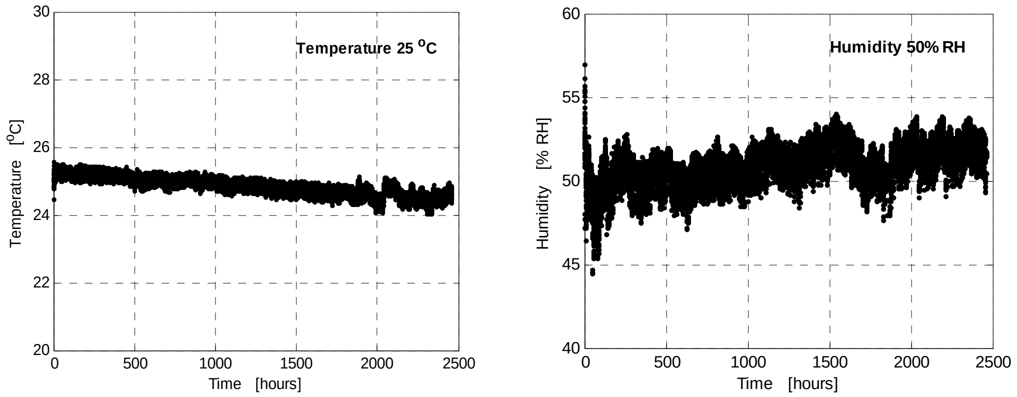

Figure 7 Temperature and humidity variation with time in the room

The shape of all strain vs. time curves is similar, showing a primary creep region which levels out and a secondary creep region which starts at about 1000 hours and is almost linear with a slope. No tertiary region is present since all creep tests were stopped at 100 – 365 days, and the tertiary region at 70% ABL is expected to start at about 5 years (Giannopoulos et al., 2008 and 2009a).

All creep curves (strain vs. $\log_{10}(t)$) for Kevlar 49 (set 1 - 4) are plotted in Fig. 8. It is observed that using a logarithmic time scale the creep curves are practically straight.

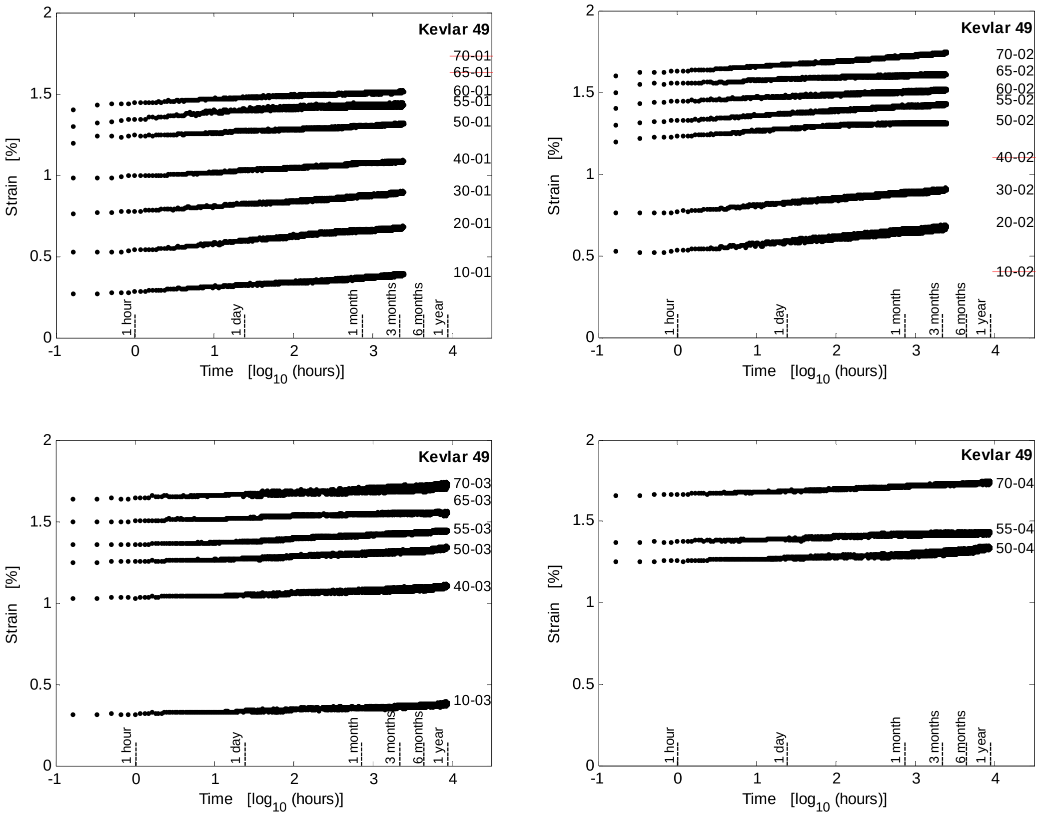

Figure 8 Creep curves for Kevlar 49 (Sets 1-4)

To check the viscoelasticity of Kevlar 49, creep compliance ϕ(t) values are calculated for each test at different elapsed times t_0 (= 10, 50, 200, 800, 1500, 2400, 4800 and 8760 hours). All values are given in Table 1 and plotted in Fig. 9.

From Fig. 9, which include all creep compliance values from all tests, the following can be observed:

a) At any stress level creep compliance ϕ(t) increases with elapsed time t_0.
b) For the stress range 40–70% ABS, and at every elapsed time t_0, the creep compliance ϕ(t) values fit practically on a straight line parallel to the σ axis. This means that the creep compliance is constant at every elapsed time t_0 and implies that Kevlar 49 is linearly viscoelastic for this stress range.
c) For stresses lower than 40% ABS, and for all elapsed time t_0, the creep compliance ϕ(t) values increase with decreasing stress level, which means that the materials will creep faster at lower stress levels. Therefore below 40% ABS, Kevlar 49 exhibits nonlinear creep behaviour.

	Test Label	**Creep Compliance $\phi(t)$ (= $\varepsilon_c(t)/\sigma$) [t in hours]**							
		$\phi(10)$	**$\phi(50)$**	**$\phi(200)$**	**$\phi(800)$**	**$\phi(1500)$**	**$\phi(2400)$**	**$\phi(4800)$**	**$\phi(8760)$**
Kevlar 49 fibres	CCTK-10-01	0.00415	0.00618	0.00748	0.00947	0.01085	0.01174	-	-
	~~-02~~	DAMAGED							
	-03	0.00563	0.00669	0.00798	0.00851	0.00871	0.00899	0.01005	0.01141
	CCTK-20-01	0.00263	0.00432	0.00575	0.00665	0.00727	0.00769	-	-
	-02	0.00221	0.00380	0.00496	0.00627	0.00683	0.00749	-	-
	CCTK-30-01	0.00287	0.00401	0.00456	0.00525	0.00562	0.00593	-	-
	-02	0.00153	0.00257	0.00333	0.00411	0.00442	0.00479	-	-
	CCTK-40-01	0.00077	0.00134	0.00175	0.00224	0.00236	0.00250	-	-
	~~-02~~	DAMAGED							
	-03	0.00146	0.00174	0.00207	0.00234	0.00239	0.00247	0.00264	0.00302
	CCTK-50-01	0.00122	0.00159	0.00182	0.00212	0.00225	0.00237	-	-
	-02	0.00135	0.00187	0.00210	0.00223	0.00229	0.00227	-	-
	-03	0.00136	0.00161	0.00192	0.00216	0.00226	0.00232	0.00251	0.00293
	-04	0.00143	0.00167	0.00182	0.00202	0.00213	0.00223	0.00251	0.00287
	CCTK-55-01	0.00159	0.00197	0.00219	0.00228	0.00233	0.00237	-	-
	-02	0.00104	0.00146	0.00179	0.00211	0.00217	0.00232	-	-
	-03	0.00126	0.00157	0.00191	0.00211	0.00225	0.00230	0.00244	0.00265
	-04	0.00158	0.00184	0.00199	0.00225	0.00225	0.00227	0.00228	0.00245
	CCTK-60-01	0.00113	0.00138	0.00153	0.00170	0.00178	0.00188	-	-
	-02	0.00111	0.00133	0.00153	0.00172	0.00178	0.00189	-	-
	CCTK-65-~~01~~	DAMAGED							
	-02	0.00114	0.00134	0.00147	0.00155	0.00166	0.00167	-	-
	-03	0.00111	0.00137	0.00151	0.00161	0.00165	0.00168	0.00166	0.00174
	CCTK-70-~~01~~	DAMAGED							
	-02	0.00086	0.00118	0.00145	0.00179	0.00190	0.00205	-	-
	-03	0.00123	0.00145	0.00159	0.00176	0.00182	0.00182	0.00193	0.00226
	-04	0.00116	0.00134	0.00152	0.00171	0.00178	0.00182	0.00191	0.00208

Table 1 Creep test plan and Creep Compliance values at different times for all load levels (Kevlar 49)

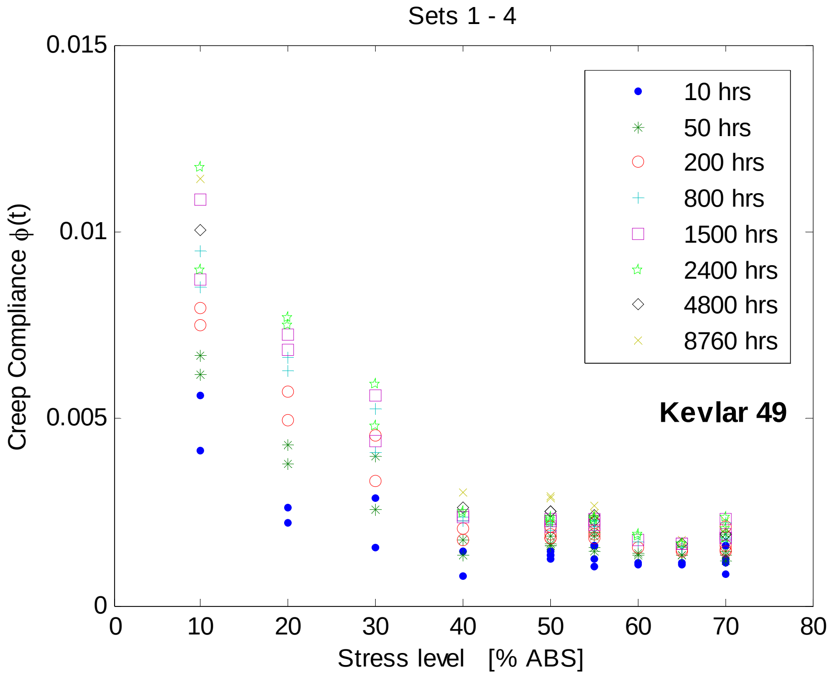

Figure 9 Creep compliance values for Kevlar 49 (Sets 1-4)

d) It is now possible to understand the reason why several studies in the past have not resolved the matter of linearity and why their conclusions are not consistent to each other. Some of them were carrying out creep tests at high stress levels, where the two materials behave linearly, so they were getting linear viscoelastic behaviour. On the other hand, other studies were carrying out stress-relaxation tests at low stress levels, where the two materials behave non-linearly, so they were getting non-linear viscoelastic behaviour. The advantage of the present study is that creep tests are conducted covering a wide stress spectrum and therefore the results are more consistent.

e) The results presented here confirm the conclusions reached by Alwis, but have been obtained from a larger and more extensive set of data.

CONCLUSIONS

Creep tests were carried out successfully on Kevlar 49 yarns under constant temperature (25^{o}C) and humidity (50% RH). The tests covered a wide stress spectrum (10–70% ABS) and lasted up to 1 year. The creep and viscoelastic behaviour has been investigated and has been found that for stresses higher than 40% ABL Kevlar 49 is linearly viscoelastic at every elapsed time. For stresses lower than 40% ABL, the material exhibit nonlinear creep behaviour.

No creep data for such a long period of time has ever been reported in the past for Kevlar 49 or for other aramid fibres. Considering that the use of this material in various structural applications requires knowledge of the long-term creep behaviour, this set of data is very valuable and allows a designer to have much more confidence when using this material.

REFERENCES

Alwis K.G.N.C and C.J. Burgoyne (2008). "Viscoelasticity of aramid fibres", Journal of Material Science, Vol. 43: pp. 7091-7101.

Balafas, I. and C.J. Burgoyne (2003). "Optimal cost design for beams prestressed with FRP tendons", Proc. of the 6th Int. Conf. On Fibre Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-6), Singapore, July: pp. 1391-1400.

Burgoyne, C. J. (1992). "Aramid fibres for civil engineering applications", Construction Materials Reference Book, ed. D.K.Doran, Butterworths.

Chambers, J. J. (1986). "Parallel-lay aramid ropes for use as tendons in prestressing concrete", University of London, PhD.

Du Pont (1991). "Data manual for fibre optics and other cables", E. I. Du Pont de Nemours and Co. (Inc.).

Giannopoulos, I. P. (2009). "Creep and creep–rupture behaviour of aramid fibres", University of Cambridge, PhD thesis.

Giannopoulos, I.P. and C.J. Burgoyne (2008). "Stepped Isothermal Method (SIM) test results for Aramid Fibres", 5th Conf. on Advanced Composite Materials in Bridges and Structures (ACMBS-V), Paper 79, Winnipeg, Canada.

Giannopoulos, I.P. and C.J. Burgoyne (2009a). "Stepped Isostressed Method for Aramid Fibres", 9th Int. Conf. On Fibre Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-9), Sydney, July.

Giannopoulos, I.P. and C.J. Burgoyne (2009b). "Creep tests at ambient condition for Kevlar 49 and Technora yarns", Technical Report, Cambridge University Engineering Department.

Guimaraes, G. B. and C. J. Burgoyne (1992). "Creep behaviour of a parallel-lay aramid rope", Journal of Materials Science, Vol. 27: pp. 2473-2489.

Northolt, M. G. and R. v. d. Hout (1985). "Elastic extension of an oriented crystalline fibre", Polymer, Vol. 26: pp. 310-316.

Northolt, M. G. and J. J. M. Baltussen (2001). "The viscoelastic extension of polymer fibres: creep behaviour", Polymer, Vol. 42: pp. 3835-3846.

Schaefgen, J. R. (1983). "Aramid fibres: structures, properties and applications", The strength and stiffness of polymers, ed. by Zachariades, et. Al, Marcel Dekker Inc., New York, pp. 327-335.

Walton, P. L. and A. J. Majumdar (1983). "Creep of Kevlar 49 fibre and a kevlar 49-cement composite", Journal of Materials Sc., Vol. 18: pp. 2939-2946.

Williams, J. G. (1973). "Stress analysis of polymers", Longman Group Limited, London.