# ACCELERATED TECHNIQUE TO PREDICT STRESS-RUPTURE BEHAVIOUR OF ARAMID FIBRES

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ABSTRACT: The Stepped Isothermal Method (SIM) allows accelerated testing of materials to determine their creep response, and in particular, their creep-rupture behaviour. It relies on time-temperature superposition (TTS) concepts, where increasing the temperature accelerates the creep rate. This acceleration reduces the time needed for a given amount of creep to occur. Thus, elevated temperature creep experiments can achieve in a short time what can take many years, or even centuries, to accomplish under ambient conditions. The work on Kevlar 49, at load levels between 50 and 80% of the short term breaking load, shows a linear increase in the logarithmic rupture time with decreasing applied load. The rate of increase is similar to that which has been observed at higher loads in conventional tests, and allows engineers to specify these materials with greater confidence. Comparative creep tests have also been carried out as part of this work and are reported here.

## 1. INTRODUCTION

Aramid fibres have many structural applications. They are used as tendons in prestressed concrete, as stay cables in bridges and as ropes in marine industry due to their good tensile properties. However, uncertainty remains about their ability to carry significant loads under a period of time. Many stress-rupture models have been suggested to predict the long-term stress-rupture behaviour of aramid, but most are based on conventional creep tests at ambient conditions and on data obtained at high load levels (≥ 70 % ABL), when creep failures occur after a reasonable time at ambient temperature. For lower stress levels, creep to failure tests would take years and so extrapolation techniques have to be used. The degree of extrapolation and the lack of test data introduce many uncertainties and therefore for engineering design very large safety factors are applied.

As an alternative, the long-term stress-rupture point (time to failure under creep testing) of aramid fibres, at low stress levels can be obtained in shorter time scales by using accelerated testing, making use of the influence of environmental conditions such as temperature and humidity (Du Pont, 1991). In the present study it was decided to change only temperature and maintain humidity constant. Increasing the temperature accelerates the creep rate, reducing the time needed for a given amount of creep to occur. Failure can then take place in practical timescales.

Two accelerated methods are described in the literature to predict the creep-rupture behaviour at low stress levels; Time Temperature Superposition Principle (TTSP) and the Stepped Isothermal Method (SIM).

In TTSP testing a single specimen is subjected to a constant load at a certain temperature and a plot of creep strain vs. log (time) is produced. Similar experiments are conducted for different specimens at different temperatures. A reference temperature is selected and all individual curves are shifted along the log (time) axis, and by applying the principle of superposition a creep master curve is produced at the reference temperature.

The SIM was first set up by Thornton (1998) to predict the long-term creep behaviour of geogrids in soil reinforcement applications. Later, Alwis (2003) applied this method to Kevlar 49 yarns. The SIM involves loading a single specimen with a constant load in a chamber in which the temperature is increased in a series of controlled steps. At each temperature step a creep curve (strain vs. time) is obtained; these can be adjusted to compensate for the different temperature levels and a creep master curve at a reference temperature is produced. A stress – rupture point can then be determined as the very last point of each creep master curve. Four adjustments are required to produce the master curve, the detailed description of which is given elsewhere (Giannopoulos, 2007).

The use of a single specimen, instead of the many specimens required in the TTSP, eliminates concerns related to specimen variability and handling effects, which had been observed when using time-temperature superposition techniques, involving different specimens tested at different temperature exposures. Also, by considering the fact that the TTSP needs significantly greater time to produce a single creep master curve, it has been concluded that the SIM is much more advantageous than the TTSP.

## 2. MATERIALS AND EXPERIMENTAL SET-UP

Kevlar 49 yarns, available in reel forms, 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 445 N for Kevlar 49. All values obtained are in agreement with the literature (Du Pont, 1991). The yarn reels were kept before testing at constant room temperature (25 $^oC$) and humidity (50 % relative humidity) placed in a black polyester bag inside a box to protect them from ultra violet light.

Three different types of testing for the yarns were used:

- Tensile tests, using a mechanical strain gauge, were carried out to obtain accurate stress vs. strain curves at different temperature levels (Fig. 3). These curves were used to determine the initial strains for a given stress level at different temperatures.
- Accelerated creep tests (SIM tests) at different stress levels and increasing temperature levels.
- Conventional creep tests (CCT) at different stress levels under constant temperature and humidity.

Tensile and SIM tests were conducted using the same experimental set-up. Conventional creep tests were conducted using a different experimental set-up.

In the tensile and SIM tests the yarn was clamped at both ends by wrapping it around a spindle. The two clamps were fixed to an Instron machine by means of two Invar bars. The bottom clamp was kept stationary and the upper clamp was fixed to the movable cross-head of the Instron testing machine through a 1kN capacity load cell. Tests had to be carried out at various temperatures levels and for that reason the test apparatus included a Thermo center - Salvis Lab oven, as shown in Fig. 1. The end fittings passed through holes in the top and bottom of the oven, which were sealed by PTFE blocks, so that the two clamps and the yarn were fully inside the oven. The load was applied by moving the cross-head of the testing machine at a constant rate and was measured by a load cell. The cross-head movement was measured by a displacement transducer with an accuracy of 0.001 mm. The load cell, the displacement transducer and the thermo - couple were connected to a data logger and readings were taken at small time intervals, usually every minute.

Conventional creep tests were carried out in a special room where the temperature and humidity levels were controlled by an air-conditioning system. Test conditions were 25 $^oC$ and 50 % Relative Humidity (RH). Eighteen clamping devices, similar with the device used for tensile and SIM tests, were used. The top clamp was kept stationary and the lower clamp was free to move vertically between two metal rails, as shown in Fig. 2. Each yarn was subjected to a constant load by hanging dead-weights through a lever arm at the bottom clamp. Mechanical strain gauges of circular form were used to measure the elongation of the yarns.

Figure 1. Experimental set-up for tensile and SIM tests


Figure 2. Experimental set-up for CCT tests

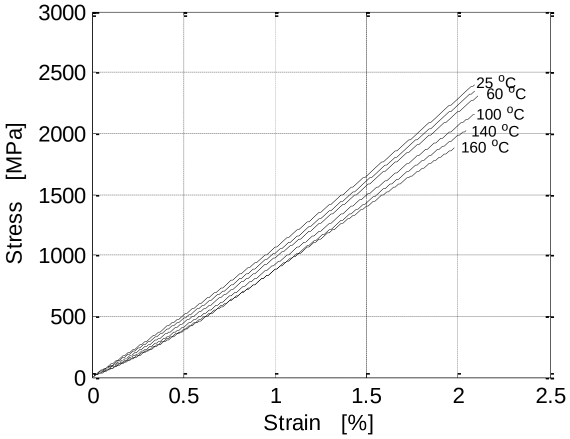



Figure 3. Stress vs. Strain curves at different temperatures

## Testing Procedure

SIM tests for Kevlar 49 yarns at different load levels and increasing temperature levels were carried out. The yarns were chosen from the same reel as those for the tensile tests. The nominal length of the specimen (distance between clamped ends) was 350 mm. An initial temperature of 25 $^{o}$C (chosen to be slightly above ambient) was reached in all SIM tests before applying load using the Instron machine.

A series of 4-5 temperature steps were then applied to the specimen, starting with 25 $^{o}$C and reaching up to 160 $^{o}$C. Each temperature step was chosen to last 5 hours, except the last one which lasted until failure of the specimen occurred. The temperature steps were chosen to give failure after about 24 hours so that a daily cycle of tests could be performed.

Eight tests were conducted at each load level: 50, 55, 60, 65, 70, 75, 80 % of Average Breaking Load (ABL), using four different temperature sequences, each repeated once. If the method is valid, similar master curves should be obtained from different temperature sequences. Experiments were not conducted below 50 % ABL, since Kevlar 49 shows a non-linear visco-elastic behaviour below 40 % ABL (Alwis, 2003).

Conventional creep tests were also carried out, each for 100 days, at different stress levels (10, 20, 30, 40, 50, 55, 60, 65, 70 % of ABL) under constant temperature and humidity. Two specimens were tested at each load level. The purpose of these experiments was to obtain creep strain vs. time curves for different load levels and compare them with the corresponding curves obtained from SIM tests, without reaching the rupture point, which would have required much longer times (at least 1 year).

3. RESULTS AND DISCUSSION

Detailed results are presented below for one test (at 75 % ABL on Kevlar 49) followed by a summary of all the results for Kevlar.

The test readings monitored throughout each SIM test were used to produce the following plots: specimen elongation ($\Delta l$) vs. time (t) (Fig. 4), applied load (P) vs. time (Fig. 5) and temperature (T) vs. time (Fig. 6). The variation of load shown in Fig. 5 is very small and is caused by the control system of the testing machine trying to maintain a fixed value.

The elongation vs. time curve, for a given constant applied load, was then converted to a strain vs. time curve. This was done by using the following relationships:

$$\sigma = P/A$$
$$\varepsilon = (\Delta l - s)/l_{eff} \qquad \text{where } l_{eff} = l_{nom} + l_{jaw}$$

The initial slack s and the jaw effect $l_{jaw}$ have been determined by the method described elsewhere (Giannopoulos, 2007) and were found to be 0.42 mm and 140.0 mm respectively for Kevlar 49.

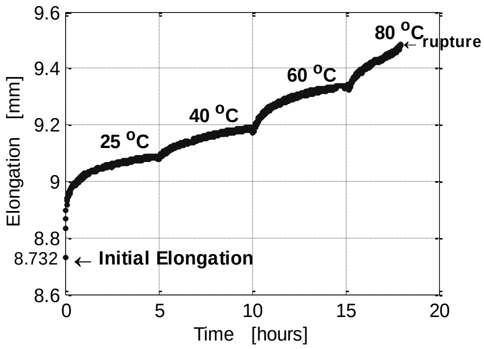



Figure 4. Elongation vs. Time curve

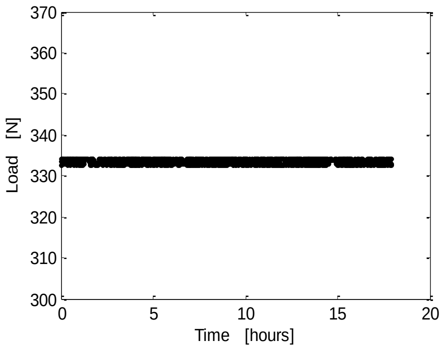
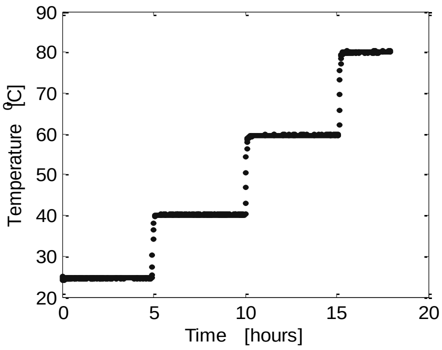



Figure 5. Load vs. Time



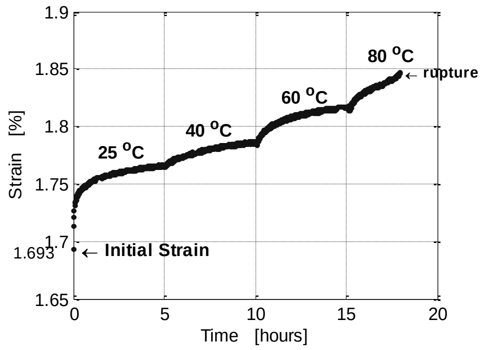




Figure 6. Temperature vs. Time

Figure 7. Strain vs. Time curve

The resulting strain vs. time curve at an applied stress level is adjusted up and down to give an initial strain at zero time which is the same as that from the stress vs. strain curves of Fig. 3 obtained by the mechanical strain gauge. In the present test at 75 % ABL the initial strain value is:

$$\varepsilon_{o,initial} = (\Delta l_{initial} - s)/l_{eff} = (8.732 - 0.42)/(350 + 140) = 1.696\ \%$$

and this is adjusted to 1.693 %. The final resulting strain vs. time curve after the initial vertical adjustment is given in Fig. 7.

A local drop of strain is observed at each temperature change caused by the negative coefficient of axial thermal expansion of aramids, as seen in Fig. 8, which shows an enlarged portion of the curve around the second temperature jump (40 – 60 $^{o}$C). The as-measured strain vs. time curve given in Fig. 7 is adjusted vertically to remove this effect: both curves are shown in Fig. 9.

Each part of the curve of Fig. 9, corresponding to a different temperature level, has to be rescaled by horizontal shifting in order to take into account the thermal history of the specimen and to form a creep master curve at a reference temperature. In order to obtain a smooth master curve a third order polynomial was fitted to the curves just before and after each temperature jump (Fig. 10); the result is the final smooth master curve (Fig. 11). The very last point of this curve corresponds to the creep–rupture point of the specimen. For the examined test the rupture time is $10^{3.72}$ hours = 219 days = 0.599 years. Details of all applied adjustments mentioned above are given elsewhere (Giannopoulos, 2007).

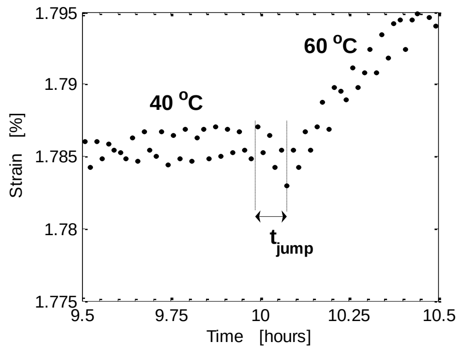



Figure 8. Strain vs. time curve at the temperature jump 40-60 °C

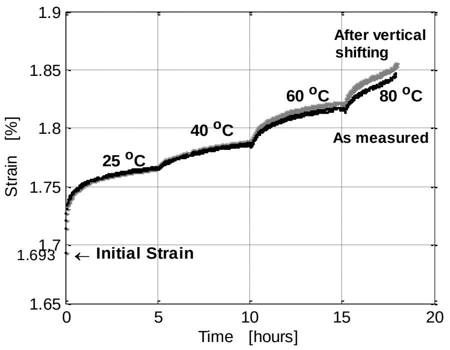



Figure 9. Strain vs. time curves as measured and after vertical shifting

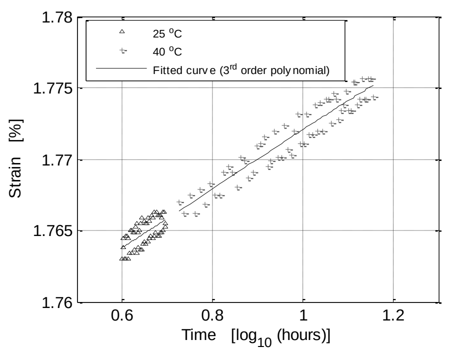



Figure 10 Smooth match of strain vs. time curve at the temperature jump 25-40 °C

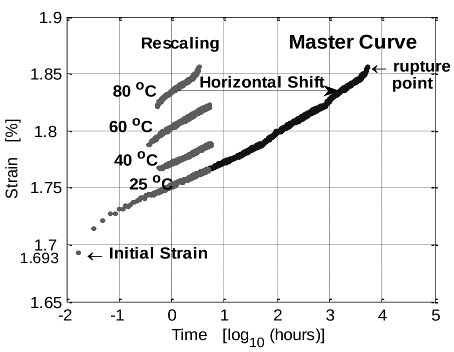



Figure 11 Individual creep curve after rescaling and master curve after horizontal shifting

The above procedure is followed at all load levels: 50, 55, 60, 65, 70, 75, 80 % ABL. All master curves from all tests are shown together in Fig. 12. Examining the SIM master curves at each load level, which resulted from eight tests with different temperature histories, shows that they match both in form and position with some experimental scatter. The shape of the curves is in general agreement with those found from conventional creep tests on parallel-lay aramid ropes, at various load levels (25 – 82 % NBL), carried out by Chambers (1986) and Guimaraes (1988, 1992) (Fig. 13). The curve is divided into three regions corresponding to primary, secondary and tertiary creep. The primary creep region is curved downwards, the secondary region is almost linear with a slope, and the tertiary region is curved upwards leading to failure.

By plotting the shifting factors, obtained from the horizontal shifting, with the inverse of temperature (K), a linear variation is observed with a small experimental scatter (Fig. 14). This indicates that creep can be regarded as an Arrhenius process. Fig. 15 shows the combined results for all load levels; the overlapping curves imply that the activation energy E of the reaction is constant and therefore the same creep mechanism is operative at each temperature level and at each load level. For Kevlar 49 the mean activation energy was found to be 119 kJ·mol$^{-1}$.

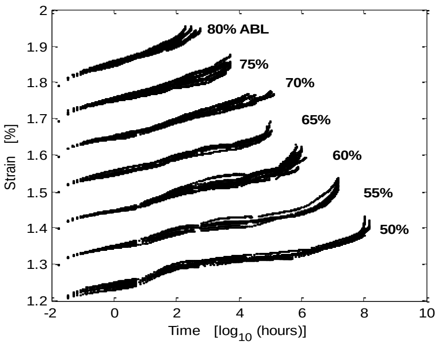



Figure 12. All SIM master curves at all load levels for Kevlar 49

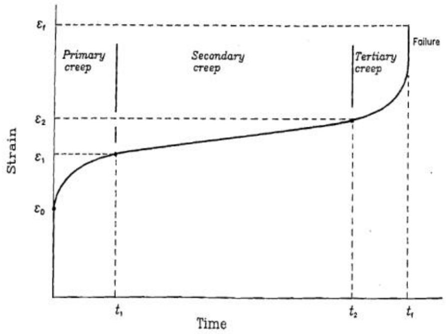



Figure 13. Schematic creep curve (Guimaraes, 1988)

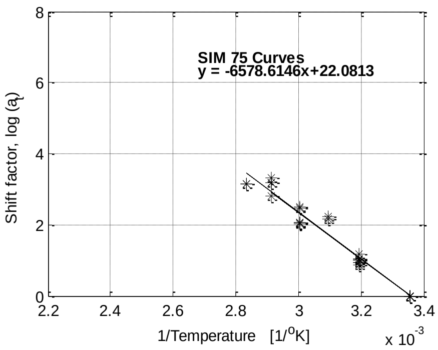



Figure 14. Arrhenius plot of SIM curves at 75% ABL

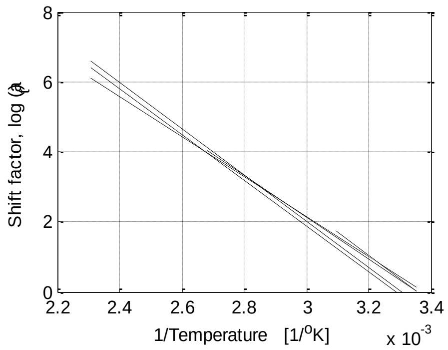



Figure 15. Arrhenius plot of all SIM master curves

All accelerated SIM tests at various load levels were carried out until failure of the specimen (Fig. 12). The very last point of a master curve corresponds to the rupture time of the specimen at the reference temperature (25 °C). The creep-rupture-time values are plotted at various load levels (Fig 16). It is observed that for load levels between 50 and 80% ABL there is a linear increase of the rupture logarithmic time with decreasing applied load, given by equation:

$$\log (t_r) = 17.07 - 0.18\,P$$

The variation of the test data at all load levels about this line is small, indicating the success of the SIM in deriving rupture times which by conventional creep tests would have required months or years.

The conventional creep test data between 80% and 95% ABL for Kevlar 49 shown in Fig. 16 fit very well to the predictions obtained from SIM testing. Conventional creep testing below 80% ABL is not possible in the available timescale.

The rupture times of the SIM tests and CCT for Kevlar 49 yarns of the present work are compared in Fig. 17 with the data from other researchers: Alwis (2003) (SIM tests at 50 and 70% ABL on Kevlar 49 yarns) and Chambers (1986) & Guimaraes (1988) (conventional creep tests on parallel-lay aramid ropes (1.5, 3 and 60 tonne) at 25 – 82% ABL). It is observed that Alwis rupture time data for Kevlar 49 yarns are in good agreement with the fitted line obtained in the present work. The fitted line for ropes proposed by Guimaraes has similar slope to the present line valid for Kevlar 49 yarns, which means that the rate of increase is the same, but is shifted down, which is probably due to the bundle effects which alter the initial breaking load of a multi-yarn rope.

A series of conventional creep tests (CCT) lasting 100 days have been performed for comparison purposes with SIM tests. All CCT curves (dark color) are plotted with SIM master curves (gray color) at the reference temperature (Fig. 18). The corresponding curves match reasonably closely, which proves that the SIM technique is working well.

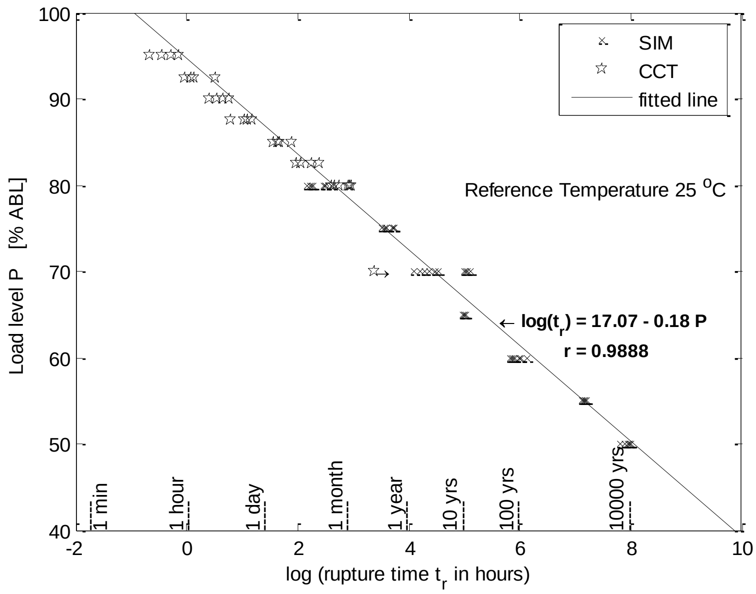



Figure 16. Rupture times of SIM tests and CCT tests for Kevlar 49

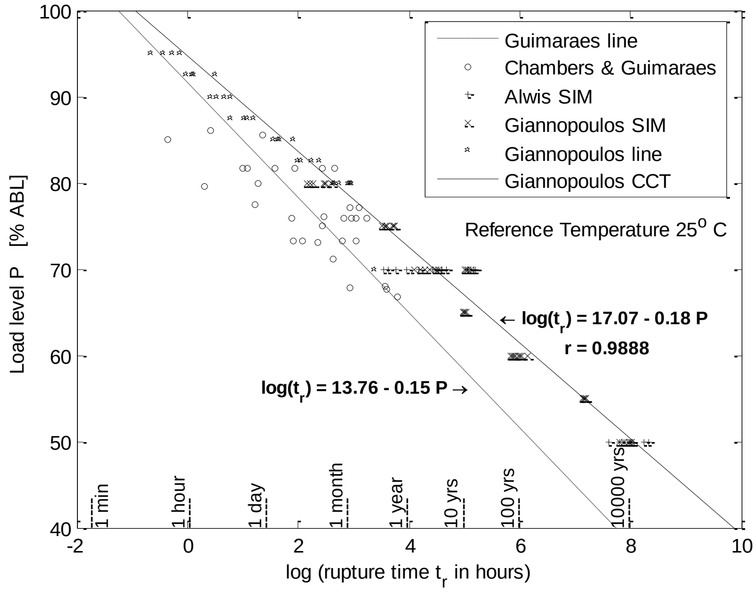



Figure 17. Rupture times of SIM tests and CCT tests for Kevlar 49 and data from the literature

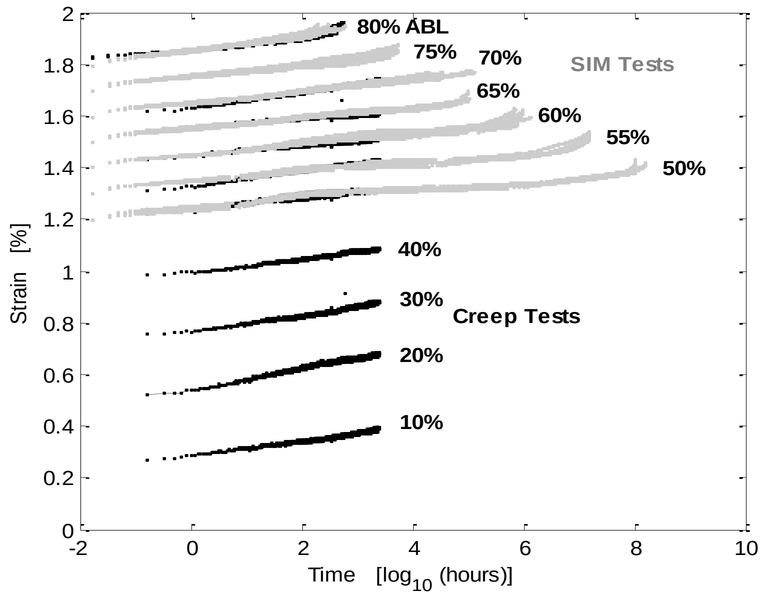



Figure 18. Creep strain curves from SIM tests and CCT tests for Kevlar 49

## 4. CONCLUSION

SIM tests have been successfully carried out on Kevlar 49 yarns for a wide range of loads (50-80 % ABL). The test data are used to determine the stress-rupture time of Kevlar 49. A linear increase in the logarithmic rupture time with decreasing applied load is shown. The present work is compared together with data from other researches and a good agreement of the data is observed. Last, SIM tests are compared with conventional creep tests at ambient conditions, and is shown that they match both in form and position.

It can be concluded that SIM is a reliable accelerated creep testing technique which can be applied successfully to high-modulus aramid fibres. This allows more certainty about the stress-rupture relationships for different fibres, which will in turn allow more realistic safety factors to be applied when designing engineering applications with these materials.

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