Characterisation of long term behaviour of polyester fibres and fibre assemblies for offshore mooring lines

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Abstract

As the oil industry is looking into exploiting fields in deeper and deeper water, the conventional steel wire ropes used for platform moorings have to be replaced. Polyester lines are being progressively introduced as a lighter alternative anchoring system, but a lack of knowledge on the behaviour of such structures, especially long term, leads to the use of excessively high safety factors in the mooring design process.
This paper focuses on three of the technical issues that have to be investigated for the optimisation of synthetic moorings: the choice of polymer, the determination of a relevant experimental scale for studying the behaviour of ropes, and the long term characterization.
Mechanical characterisation is presented for two different materials: Polyethylene Terephthalate (PET), which is already used for offshore mooring, and Polyethylene Naphthalate (PEN), a recently developed polymer with rather few applications which is twice as stiff as PET. Results for both types of fibre show very similar behaviour, and suggest that PEN could be a possible competitor for offshore mooring application, its higher stiffness resulting in lower offset and smaller mooring lines.
The characterisation was performed at different scales, from that of the approximately 20 micron-diameter fibres to an assembled rope of several hundred tons breaking load. Although some of the rope's characteristics are related to its construction geometry, results show that its global behaviour is controlled by that of the fibre, which is the fundamental component.
Finally, in order to obtain information on the long term behaviour of these structures, an accelerated creep test known as the Stepped Isothermal Method was used. The method enables creep data for simulated times of several hundred years to be obtained from 24 hour tests.

Key words

PET, PEN, fibre, yarn, rope, tensile loading, creep, fatigue, failure, accelerated creep, SIM.

Introduction

The oil industry is progressively exploiting fields in deeper and deeper water, down to 3000m. At such depths, the usual platform mooring systems composed of steel chains and ropes become technically inapplicable as the weight of the mooring line itself becomes too important. It is therefore necessary to turn to alternative anchoring methods.
One option that has been investigated for the past 15 years or so is the replacement of steel by synthetic materials, which are much lighter [1]. The replacement material, as well as being light, must also show a combination of good mechanical and chemical properties: sufficient modulus and strength, resistance to the fatigue process caused by the platform's environment (waves, currents, wind…), durability in sea water, and limited creep to prevent an excessive offset of the platform are some of the requirements. Polyester presents a fair compromise between the different properties needed for offshore mooring, and is therefore already used in some areas where meteorological conditions are not too severe [2]. It also has one more advantage, as the configuration used with synthetic ropes is taut, whereas steel ropes are used in catenary configurations: this reduces the footprint on the seabed, which is an undeniable benefit in sites that are often congested.
However, these materials are relatively new for this type of application, and there is little knowledge on the behaviour of such structures, particularly their long term properties. When designing mooring systems with synthetic ropes this results in excessively high safety factors, that counterbalance the advantages of using light material. It is therefore crucial to further investigate the behaviour of polyester mooring ropes, in order to optimise their utilisation. Various topics have to be considered, in order to cover all the properties involved in the long term resistance of the ropes:
- The choice of material: there is a very wide range of polymers manufactured, and even one single type of polymer can show a range of properties depending on its manufacturing process [3];
- The structure: ropes are assemblies of fibres and behave differently from the bulk material or from a single fibre, so that the type of specimens use for the characterisation has to be investigated [4], [5];
- Short and long term mechanical data such as tensile, creep and fatigue test results, necessary to predict the behaviour of the ropes [3], [6];

- The possible degradation effects of sea water on the synthetic rope [7];
- Rope termination: this is a subject of high interest as the connection from the end of the rope to the platform is often a weak point for the rope [8];
- Modelling tools, which can also be useful for prediction of structures' behaviour [9].

In this paper experimental results that address some of these concerns will be presented.

We first compare some relevant mechanical properties for two different polyesters: one that is already used for offshore mooring applications (Polyethylene Terephthalate, or PET), and the other is a possible contender (Polyethylene Naphthalate, or PEN).

We then highlight an important aspect when studying the behaviour of synthetic ropes: the choice of a scale at which to perform characterisation tests.

Finally we present an experimental technique for an accelerated creep test. Based on the time-temperature superposition principle, it enables creep curves for several thousand years to be obtained from a one day long test.

Study on PET & PEN

Material description

Polyethylene terephthalate (PET) and Polyethylene naphthalate (PEN) are two different polyesters, with a similar molecular structure as shown in Figure 1. The backbone of PEN differs from that of PET in that it contains an additional aromatic ring, giving the molecule a higher stiffness.

Both polymers have a similar density (1.3 to 1.4). Due to its limited application and small production, the price of PEN is currently rather high compared to that of PET.

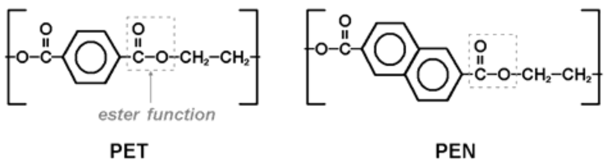

Figure 1: Molecular structures of PET and PEN

For this study, both types of fibre were provided by the manufacturer as yarn bobbins. The yarns were parallel assemblies of monofilaments, containing 192 filaments for PET and 140 for PEN. The diameter of each filament sample was measured with a Mitutoyo laser scan micrometer before each mechanical test, and the average diameter value was found to be 22.9µm for PET and 27.9µm for PEN.

Tensile behaviour

Tensile tests were performed on single filaments, using an apparatus called the Universal Fibre Tester [10]. The device can be considered as a reduced scale tensile machine with high precision sensors. It consists of one fixed and one mobile clamp, the displacement of the latter being controlled by means of an electric motor and measured to within 1µm with a LVDT transducer. The load applied to the fibre is measured by a load cell with 0.01g sensitivity.

A total of thirty tensile tests were performed on PET filaments in order to take into account the scatter of behaviour from one specimen to the other. The load-strain curves obtained are shown on Figure 2. They revealed a non-linear behaviour. The average breaking strain was about 14%, and the average breaking load about 0.47 N.

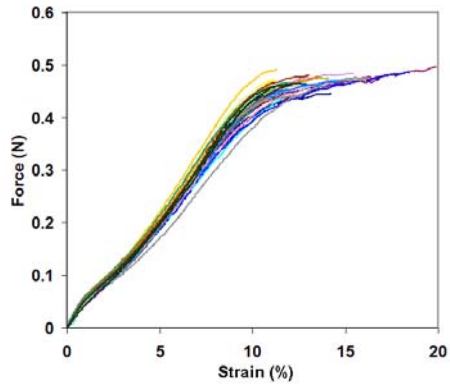

Figure 2: Load-strain curves for PET filaments

Similar tests were performed on PEN filaments (see Figure 3). The tensile behaviour appears to be very similar to that of PET, with a load-strain curve showing the same non-linearity. The average breaking strain was about 7%, and the average breaking load about 0.7 N. Taking into account the fact that the average diameter of a PEN filament was larger than the one for PET, the normalised ultimate tensile strength (UTS) of both fibres was actually rather similar. As a result of the lower strain of PEN filaments the latter are stiffer than PET.

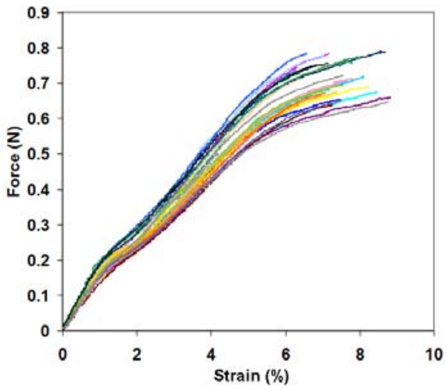

Figure 3: Load-strain curves for PEN filaments

The evolution of the modulus during tensile tests could be estimated for both fibres by calculating the slope of the load-strain curve at each point. An average curve was chosen for each type of fibre. To take into account the difference of diameter, the load was normalised. In the synthetic rope industry, it is common practice to normalise the load by the linear mass of the structure, expressed in tex (1 tex = 1 g/km). The evolution of PET and PEN filaments' modulus expressed in N/tex, as a function of strain, is represented on Figure 4.

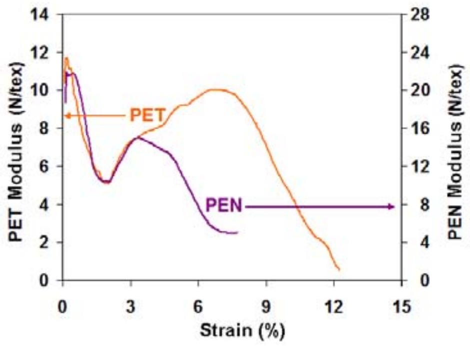

Figure 4: Evolution of modulus as a function of strain for PET and PEN filaments

Both fibres showed a variation of modulus in four distinct phases. In a very short first phase, the modulus slightly increased to its first peak value. Then it decreased to about half. In the third phase it increased again to another peak, before a final decrease. The curves for PET and PEN were superposed up to the second peak. Considering that the values for PET were read on the left axis, those for the PEN on the right axis, and that the latter is double of the former, the modulus of PEN can be estimated to be the double of that of PET.

This result is of interest for the application considered: the stiffness of PET is sufficient for platform moorings, but a higher stiffness could be an advantage as it would result in lower offset and smaller mooring lines.

Creep behaviour

Creep tests were performed on both types of filament, at various percentages of their UTS, using the same apparatus as that used for tensile tests.

One parameter of interest is the speed at which the material creeps, or creep rate. Literature indicates that creep of polyester is generally considered linear on a logarithmic time scale. The following equation was found to be applicable for the creep of polyester ropes [11]:

$$\varepsilon(t) = \varepsilon_0 + A_C \times \log\left(1 + \frac{t - t_0}{t_a}\right)$$

with ε = strain in %, t = time in s, ε_0 = initial strain at the instant when the load was applied, Ac = "creep rate" in % per decade, t_0 = instant when the load was applied, and t_a = time constant. This equation was applied to all creep data obtained. An example of the creep curve obtained at 60%UTS for PET filament and the corresponding curve fitting are represented on Figure 5. A creep rate Ac of 0.17 was measured.

Figure 6 presents all values of Ac obtained from creep tests performed on PET and PEN filaments for loads comprised between 5 and 75%UTS.

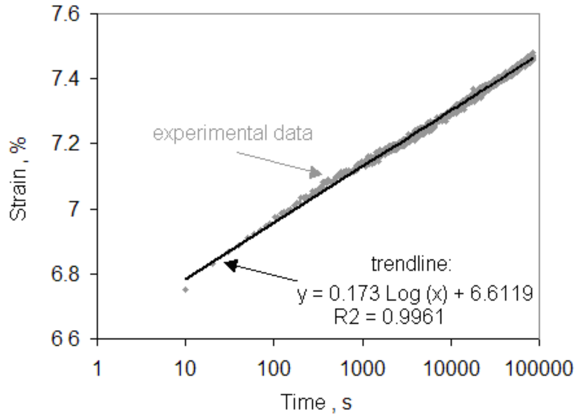

Figure 5: Example of curve fitting on creep data

The results show a similar evolution of creep rate for PET and PEN, in three steps. Up to a load of about 0.1N/tex, the creep rate increased from a value close to zero to approximately 0.15% per decade. Then it stabilised or even slightly decreased for creep loads up to 0.35N/tex. Finally it increased dramatically to reach values that rapidly caused failure.

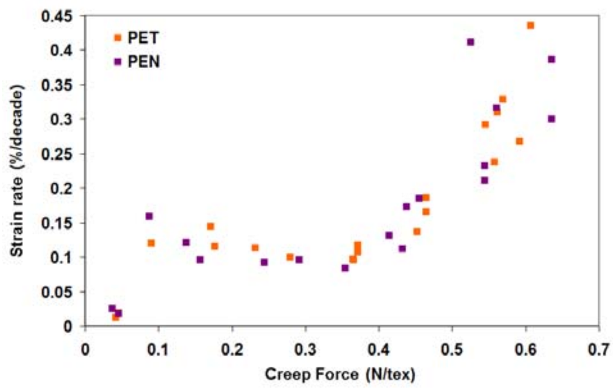

Figure 6: Strain rate values obtained from creep tests on PET and PEN filaments

The remarkable result here was that the numerical values obtained for PET and PEN at each load were very close. Intuitively, one would have thought that PEN, which is stiffer, would have shown lower creep rates. This would have been an additional advantage for the offshore mooring application, where one of the main objectives is to reduce the platform offset. Nevertheless, similar values to those of PET show that the creep characteristics of PEN are acceptable for this application.

Fatigue behaviour

Cyclic loading tests were performed on PET and PEN filaments at two different frequencies, with a sinusoidal load pattern. The same apparatus as described above was used, and tests were run at 50 and 0.1 Hz. Tests at 50 Hz were performed using rather high maximum loads to obtain failure of specimens within a reasonable time. For these tests the fixed clamp of the apparatus was equipped

with a vibrator, operating on the same principles as a loud speaker.
The lifetime values measured at 50 Hz for various maximum loads (with a minimum load of 2% UTS to avoid kinking of the filament) are shown on Figure 7.

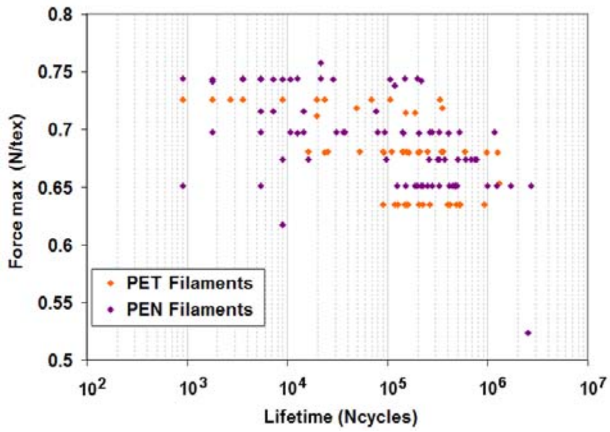

Figure 7: Lifetimes measured after cyclic loading at various max. loads at 50Hz on PET and PEN filaments

Both materials presented a high scatter in the measured lifetimes for a given maximum load. Globally, PET and PEN filaments showed very similar behaviour.
The tests at 0.1 Hz enabled the evolution of load and strain during each cycle to be measured. Polyester materials show hysteresis when they are loaded and then unloaded: the load-strain curve follows a different path during the loading and unloading phases. The area of the hysteresis represents the energy dissipated during the cycle. It has been shown that the dissipated energy is an important factor in the fatigue performances of polyester fibres [12]. The dissipated energy over different cycles during the cyclic loading at 0.1 Hz was determined from the load and strain data for fatigue tests at maximum loads of 50% and 80% UTS. The values obtained for the first, tenth, hundredth, thousandth, and eight thousandth cycles are given in Figure 8.

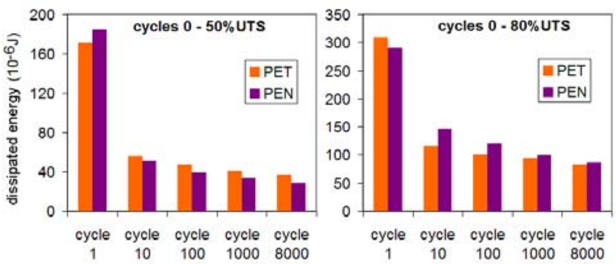

Figure 8: Dissipated energy during cyclic loading tests at 0.1Hz on PET and PEN filaments

The results show that dissipated energy values are virtually the same for both fibres at each cycle and for both values of maximum load.
Like creep, were a limited creep rate was desirable, good fatigue performance is a critical parameter for offshore mooring applications. Since PET performances are considered sufficient, PEN should also be considered to be as a possible competitor.

Multi-scale study

Samples description

Marine synthetic ropes can be of different constructions: they can be made from a parallel assembly of filaments, or from twisted or braided sub-structures, the substructures themselves being parallel, twisted or braided assemblies.
As the ropes used for offshore mooring have to sustain very important loads, they are of very large diameter. Characterising such structures can be technically difficult, and costly. Therefore it is of interest to know whether characterising small scale structures can be sufficient to know the behaviour of large ropes.
In this study we tested different components of a twisted rope. The hierarchy of the rope's structure is described in Figure 9. Mechanical tests were performed at the scale of sub-rope, rope-yarn, yarn and filaments. For all scales the fundamental component was the same PET filament as the one for which results have been presented previously.

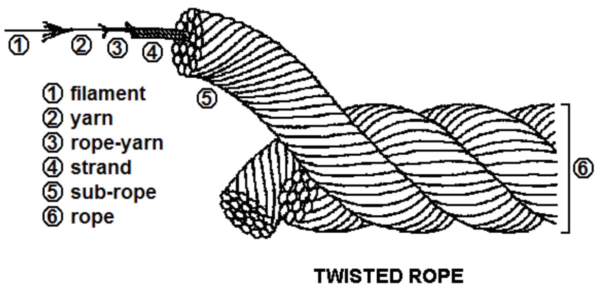

Figure 9: Example of construction geometry of a typical marine synthetic rope

The typical diameters and linear masses of the different scales are given in Table 1.

Table 1: Sizes of the different PET samples tested

	Sub-rope	Rope-yarn	Yarn	Filament
Diameter	32 mm	4 mm	0.4 mm	23 µm
Linear mass	6×10^5 tex	7×10^3 tex	110 tex	0.6 tex

Tensile behaviour

Tensile tests were performed at all scales. Details on the tests conditions and apparatus can be found in [4]. The load-stain curves obtained on all scales are shown on Figure 10. The load values have been normalised by the respective linear mass of each scale.
A similar non linear behaviour was observed at all scales. However, larger structures presented lower strength and lower modulus.
This loss of strength and modulus could be associated, for these twisted structures, with the number of fundamental elements and the twisting angle. Some models of rope behaviour from the literature that take these phenomena into account were tested. They show that the behaviour of

a rope can be relatively easily deduced knowing its geometry and the behaviour of its fundamental component, here the filament.

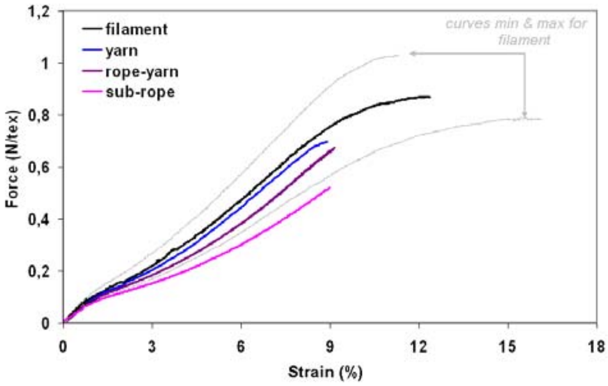

Figure 10: Tensile curves for PET samples of different sizes

Creep behaviour

Creep tests were performed on PET rope-yarns at various load values, and the creep rate for each load value was determined in the same way as for filaments. The comparison of creep rates measured on PET rope-yarns and filaments is presented on Figure 11.

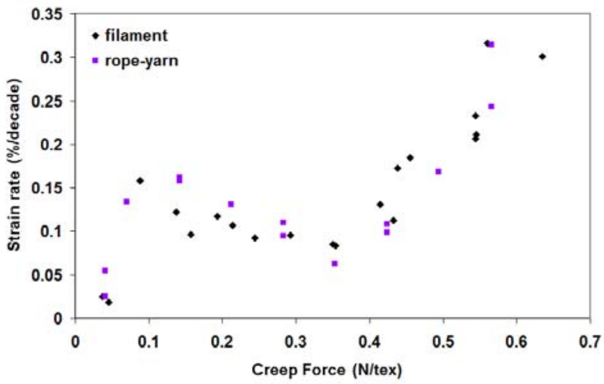

Figure 11: Strain rate values obtained from creep tests on PET filaments and rope-yarns

As was observed for filaments, rope-yarns also exhibit an evolution of creep rate in three steps: it first increases, then slightly decreases, and finally increases to critical values. It was also noticed that the local maximum and minimum vales were located at the same normalised load values (respectively 0.1 and 0.35N/tex). The numerical values for strain rate were globally very similar for these two scales. This indicates that no scale effect has to be taken into consideration and the creep behaviour of the rope-yarn could have been directly deduced from the behaviour of its fundamental component.

Fatigue behaviour

Fatigue tests were performed only at the filament scale, and the results were presented above. However, a collection of rope data could be gathered from literature references [6], [13]. The data concerns the lifetime under cyclic load of PET ropes and assemblies of different sizes. In order to compare the results, all the information concerning the geometry of the ropes and their constitutive elements was analysed. The load applied during fatigue was evaluated as a percentage of the breaking load of the filament. The uncertainty was taken into account by considering a minimum and a maximum value for each data point extracted from the literature. The results obtained were then compared to the lifetimes measured directly on single filaments, as shown on Figure 12.

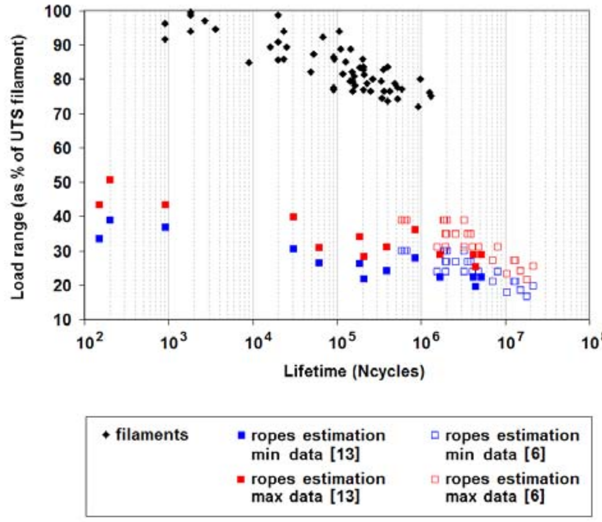

Figure 12: Lifetimes measured after cyclic loading at various max. loads at 50Hz on PET filaments compared to literature data for PET ropes

The comparison of data for filaments and ropes showed an important difference in fatigue performances: for lifetimes of around 10^3 cycles, the load ranges involved when testing single filaments were about 95% UTS, whereas they were only about 40% for ropes. At lifetimes of 10^6 cycles, the loads leading to failure were around 75% UTS for filaments and 35% for ropes.

Various phenomena are generally considered to explain the fatigue failure of ropes: creep, abrasion, internal heating, kinking… The comparison we made shows that fatigue failure of ropes is related to the nature of the samples, which are assemblies of elements, and effect purely linked to this type of structure, such as abrasion effects, certainly have a great influence on the fatigue performance of the rope. The fatigue behaviour of ropes cannot be simply explained by the fatigue behaviour of the fundamental component. Some characterisation tests at a sufficiently representative scale are therefore always necessary in this case.

Accelerated creep test

Description of the Stepped Isothermal Method

For the application that we are considering here, the synthetic ropes are meant to be installed on site for long periods, 20 years or more. Besides failures that can be

caused by phenomena such as abrasion, one of the concerns in the long term is the elongation of the rope, as one of its functions is to limit the offset of the platform. Therefore long-term creep of ropes is a subject of interest. However, few long-term creep tests have been performed in literature, as this kind of test is costly.
One way to overcome this difficulty is to perform accelerated creep tests. It is common with polymer testing to accelerate the creep process by elevating the temperature. These tests are based on the Time-Temperature Superposition Principle (or TTSP). Creep tests are performed on several specimens at the same load but different temperatures (see Figure 13).

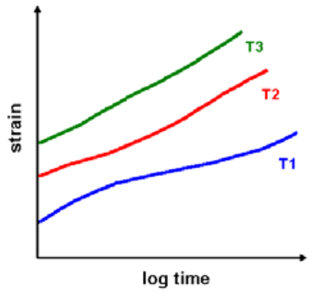

Figure 13: Creep tests performed to apply TTSP

The curves of strain versus log (time) at the higher temperatures are then shifted along the log-time axis to match the curve at the desired temperature (see Figure 14).

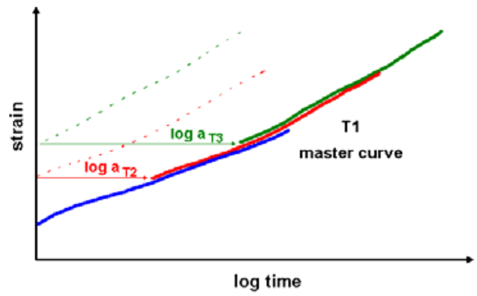

Figure 14: Master creep curve after applying TTSP

A master curve is obtained at this temperature, showing the evolution of strain for much longer durations than the real test duration.

The Stepped Isothermal Method (or SIM) is derived form TTSP, and was first developed for creep testing of polymer geotextiles used to reinforce the soil in the construction industry [14], [15].
SIM enables one of the issues raised in TTSP tests to be overcome: when testing different specimens at a same load and temperature, the initial strain often shows considerable scatter. Because the shifting of the curves in TTSP can depend on this initial strain value, it becomes necessary to multiply the number of tests in order to obtain an average value of initial strain. With SIM, the whole procedure is applied to the same specimen: the specimen is under constant load while increasing temperature steps are applied. Each section of the strain curve corresponding to one period of constant temperature is then considered separately, and various shifting processes enable a final master curve to be obtained. These shifting processes are divided in three steps.
The first step consists of a vertical shift (see Figure 15). It compensates for the phenomenon of shrinkage that occurs in polyester fibres when they are under tension and subject to a temperature rise.

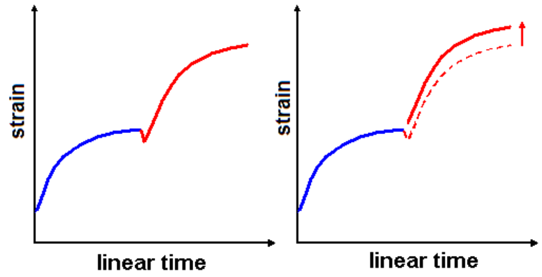

Figure 15: First step in applying SIM: vertical shift

The second step is a horizontal shift along the time axis (linear). This shift is done in order to compensate for the thermal and mechanical history of the specimen: its objective is to "replace" the curve on the time axis as if the test had been started at the temperature of the section that is being considered. This is done by extrapolating the strain value on the left side of the curve up to what should be the initial strain value found for this creep load at this temperature (the initial strain value is determined by performing tensile tests for each temperature value that is applied in the SIM test). The curve is then shifted so that this point corresponds to the initial time t= 0 (see Figure 16).

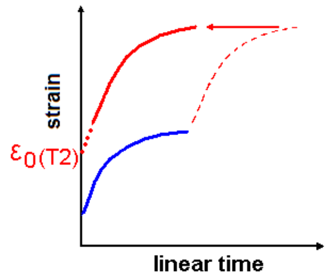

Figure 16: Second step in applying SIM: horizontal shift along linear time axis

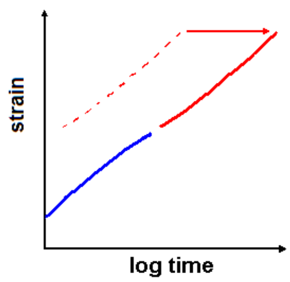

Figure 17: Third step in applying SIM: horizontal shift along log time axis

When the second step is done for all strain sections, the shifted data is similar to what one would obtain from TTSP. The third step then consists, as for TTSP, of a horizontal shift along the log-time axis in order to achieve a smooth master curve at the desired temperature (see Figure 17).

Application of SIM to PET yarns extracted from marine ropes

SIM tests were performed on PET yarns extracted from marine ropes. All the tests were done on an Instron tensile testing machine within which was fitted a Thermocenter Salvis Lab oven. The clamps were fixed to the Instron machine by means of two steel rods. The yarns were clamped at both ends after the extremities had been surrounded with small pads of yarn (see Figure 18).

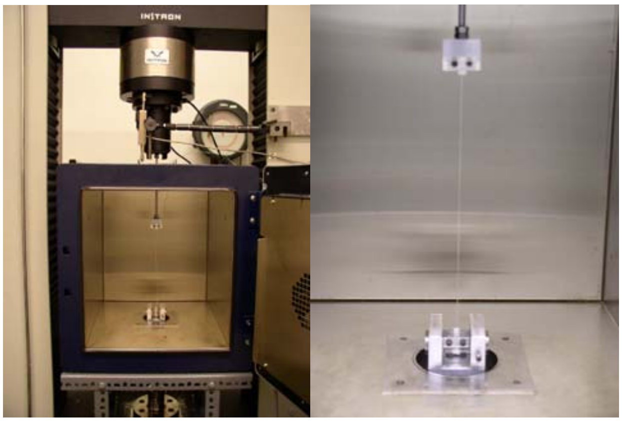

Figure 18: Equipment used for SIM tests

The test parameters were chosen to be similar to those described in the literature for polyester geosynthetics: the temperature steps were performed at 25, 40, 55, 70, 85 and 100ºC and their durations were between 3 and 10 hours. The creep loads were chosen relatively high (50, 60, 70 and 80% of the yarn UTS) in order to obtain failure of some specimens. Each test lasted for one to two days. Results obtained after shifting of the curves are presented on Figure 19.

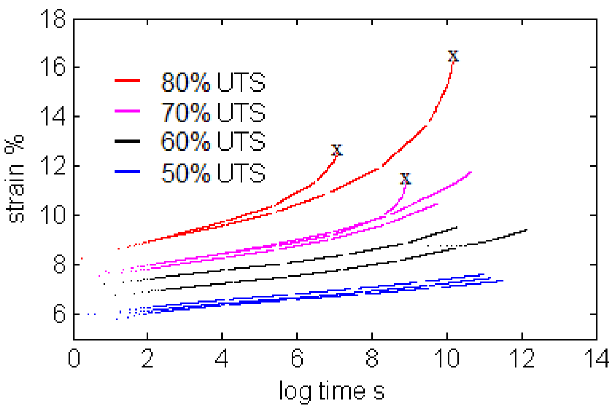

Figure 19: Master curves obtained after SIM tests on marine grade PET yarns

The curves obtained showed a smooth evolution of strain, up to durations between 10^7 and 10^{12}s (~100 days to 30,000 years). The tests leading to rupture (represented by a black cross) showed an acceleration of strain evolution prior to rupture, as is generally observed for failing specimens during conventional creep.

Conclusions

Several subjects related to the introduction of synthetic ropes as mooring lines for offshore platforms were addressed.
The first subject concerned the choice of material. The comparison of results from different mechanical tests performed on PET and PEN fibres showed that PEN, which is a relatively new polymer with few current applications, had a behaviour similar to that of PET, which is already used for offshore mooring lines. Therefore PEN can be considered as a potential replacement material.
A similar mechanical characterisation was then performed on PET structures, but with various scales of specimens made from twisted assemblies of filaments. The specimen went from 23µm-diameter filaments to 32mm-diameter twisted ropes. The behaviour of the assemblies was shown to be easily deducible from that of the fundamental component for different characteristics (tension, creep). However, the fatigue results from the literature showed the introduction of phenomena associated with the structural nature of the specimen, such as abrasion. In that case the behaviour of high scale specimens could not be directly related to that of the filament. The results showed the necessity to perform tests at a realistic scale for studying some properties, even though these tests are technically and economically more difficult to realise than reduced-scale ones.
Finally a method for performing accelerated creep tests, known as the Stepped Isothermal Method, was studied and applied to PET yarns. The method was shown to be robust, enabling extrapolated creep data for durations up to 30,000 years to be obtained from tests lasting one or two days. The method should prove very useful for applications like offshore mooring lines, where the ropes can be on site for 20 years or more.

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