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OBTAINING CREEP CURVES FOR POLYMER MATERIALS USING THE STEPPED ISOTHERMAL METHOD

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Abstract. *The stepped isothermal method (SIM), which was originally developed to be used with geosynthetic materials, has been applied over time to studies involving polymer fibers, as it makes possible to determine the creep lifetime of such materials from a single specimen. This method excels among the common creep tests by reducing the costs, time, and by giving the complete creep curves with low stress levels, due to the progressive increase of the temperature over the same test. A particularity of this method is the rescaling and shifting that must be applied in order to generate a master creep curve, since polymers exhibit an atypical behavior when submitted to temperature changes. The results obtained with the SIM method provides, for long periods of time, more consistent data compared to the usual extrapolations in classic creep tests.*

Keywords: *SIM method, creep curve, polymers, offshore anchorage.*

1. INTRODUCTION

The physics of creep was observed for the first time in 1834 in steel cables, according to Vicat (1834), and can also act in other materials because of the failures in the microstructure and crystalline network of these elements (Findley *et al.*, 1976). Creep takes place when the material is held under constant tension load, which sometimes can lead to rupture with a stress level below the tensile stress of the material. According to Ferry (1980), this phenomenon has three main parameters of interference: load, time and temperature. However, it can be noted that temperature is the factor that most influences the behaviour of the polymers under creep, mainly due to its contribution in the relief of microstructural tensions and in creep activation energy. The higher the temperature that a material is exposed, the lower is the internal stress, helping the propagation of material discordances. If the materials do not have defects in the crystalline network, as is the case of monocrystals, creep does not occur (Findley *et al.*, 1976).

In terms of engineering structures, polymeric anchorage cables of offshore platforms are used for long periods of time, during which they are submitted to high creep rates caused mainly by the wind and water stream. For that reason, one must know how these structures behave facing creep rates, mostly in order to predict their behaviour, ensuring the safety of the mooring system.

The purpose of studying polymeric materials applied to anchoring cables under constant force is to relate the parameters "force", "time" and "temperature", in order to obtain a way to answer the following question: how long does it take to lead the material to fail by creep, while it is subjected to a constant force F in an environment at temperature T ? The most direct way to answer this question is to submit a test specimen to the constant force F in an environment at temperature T and wait until creep rupture occurs. For the most common materials applied to ropes, in situations where the temperature and force applied are high enough (from about 40 % of its tensile strength and at 40° C) the tests show to have short to medium durations (few hours or days), making it possible to make use of real-time creep experiments. However, in service, these structures are immersed in water depths where the temperature is relatively constant and equal to 4° C, and the forces to which they are subjected are considerably low compared to their tensile strength (approximately 10% to 15%), which makes it impossible to perform real-time tests of the service situation and opens the opportunity for the application of acceleration techniques.

The Stepped Isothermal Method (SIM) is alternative, being distinguished from the classic creep tests or time temperature superposition principle (TTSP), since a single specimen is used for the whole duration of the test, along which the temperature is periodically risen, over defined time intervals. The SIM is promising and powerful for providing material breakage data at low stress levels, making it cheaper and faster, when compared to the classical methodology. The goal of this paper is to obtain the time-strength-temperature relationship to predict lifetime under creep conditions of synthetic materials applied to anchoring ropes.

2. THE STEPPED ISOTHERMAL METHOD

The SIM requires some data manipulation in order to obtain a complete creep curve (master curve). These manipulations, which can also be called adjustments, are divided in three steps: the *vertical shift* is the first adjustment, where time is plotted horizontally and strain in the vertical axis; *rescalling* is the second part and is needed in order to compensate deformations while the temperature is rising; and the third part of the process requires a *horizontal shift*, where linear time is changed to a logarithmic scale with the purpose to compare the behavior of the material at different temperatures and to equalize the activation energy of the creep process. Several researchers have investigated the temperature dependence on these materials and proposed empirical equations for the curve shifts. The WLF equation (Williams–Landel–Ferry) is often used (Ferry, 1970), but it is restricted to materials above the glass transition temperature. Since some polymeric fibers used in mooring systems, like aramid, do not exhibit glass transition, maintaining crystalline form at all temperatures, the relationship between the temperature and the *horizontal shift* factor is based on the Arrhenius equation, according to Alwis and Burgoyne (2008). This equation takes into account that creep is a thermally activated process and will obey the kinetic rate theory. In a recent research, Achereiner *et al.* (2013) showed that this equation can also be used to determine the maximal temperature which still provides consistent results for a given initial test temperature. Besides that, in order to verify the applicability of the Arrhenius empirical equation, Alwis and Burgoyne (2008) had tested and confirmed that there is similar activation energy to all stress and temperatures levels that they studied, which implies that for a large interval of temperatures, the same creep mechanism will act.

The adjustments made in the SIM have the purpose of creating a smooth creep curve and minimize the margin of error generated by the temperature increases. According to Alwis and Burgoyne (2008), the *vertical shift* is an adjustment made to compensate the variation in the length of the sample and the creep that occurs along the short period during which the temperature rises. Figure 1 shows the contraction presented by some polymeric materials, in this case the High Modulus Polyethylene (HMPE) when the new temperature step is being initiated.

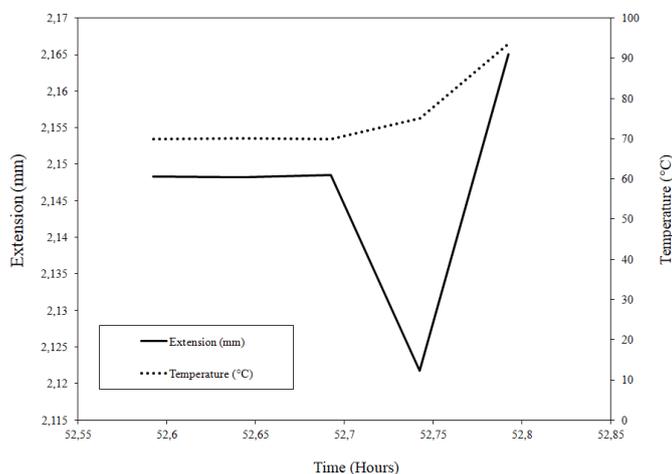


Figure 1. Detailed HMPE contraction for the temperature step of 70° C to 100° C.

The second adjustment, *rescalling*, that aims to smooth the curve has as main factor the thermal energy history that the material was submitted to. The fact that the sample has already been submitted to a thermal load influences the results that will be obtained in the next temperature step. This parameter is not taken into account in tests such as TTSP, where there is a sample for each temperature. In a recent work, Alwis and Burgoyne (2008) showed that the energy history that needs to be considered is unique to stepped isothermal methods. In the *rescalling* it is assumed that only the rate of creep changes with the increase of temperature, keeping the mechanism of creep the same for all steps.

The third step of manipulating and correcting the data of the SIM, called *horizontal shift*, involves the execution of numerical procedures and auxiliary tests, in order to minimize the amount of errors generated by the optimization of the

classical methods. Alwis and Burgoyne (2008) presented that adjustments, *rescalling* and *horizontal shift*, are considered together to generate a master curve that provides a useful rupture data in the end.

3. EXPERIMENTAL PROCEDURE

This research was carried out to verify the potentiality of the SIM when applied to fibers used in mooring cables. The material tested was HMPE, which have a specific weight of 0,97 g/cm³ and high tenacity, which allows high temperature and stress level tests. Before the SIM was initiated, 10 HMPE samples were tested and the material yarn break load (YBL) was obtained: 487 N. All subsequent load levels during SIM will be presented as a percentage of this YBL (Alwis and Burgoyne, 2008).

The creep tests using the SIM were performed in a universal test machine (INSTRON – 5969), with a temperature variation chamber, shown in Fig. 2, where a HMPE yarn specimen of 200 mm length was subjected to temperature steps. The test started at 40° C and the temperature was risen up to 70° C and then to 100° C, with constant load, which was defined as 10% of the YBL of the material. The entire test lasted approximately 7 days. Table. 1 describes the sequence of the process and the temperature steps that were used for the first tests.



Figure 2. Universal test machine (INSTRON-5969) used for SIM tests.

Table 1. Description of the test using the stepped isothermal method.

Sample	Duration (h)	Temperature (°C)
HMPE – 200 mm	26	40
	29	70
	110	100

4. RESULTS AND DISCUSSION

With the results of experimental creep tests using the SIM, all the three adjustments can be applied in the data points and, according to Thomton *et al.* (1998), one is able predict the lifetime of the material in service conditions. After plotting the data points acquired by the machine, the curves illustrated in Fig. 3 are obtained. This is the first step of the analysis and the *vertical shift* would be applied here. The changes in the master curve are in the scale of 0.02 % of strain, which means nothing compared to the high safety factors that are used in the mooring cables. So, the *vertical shift* was not applied and the curve was smoothed by removing the points that presents contractions, in temperature transitions.

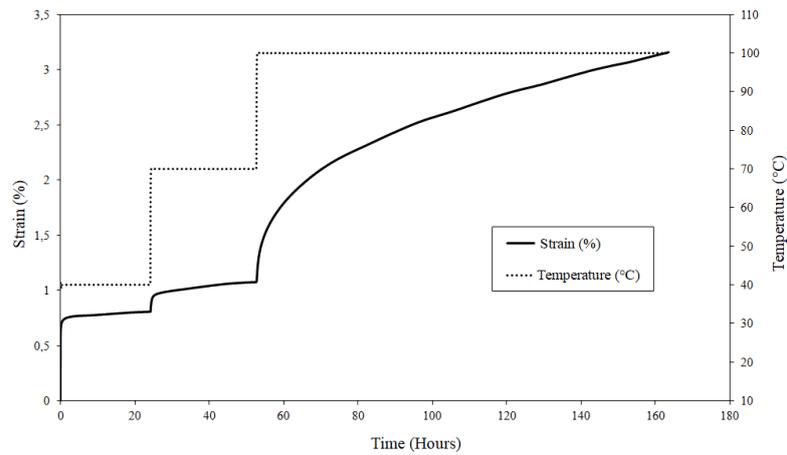


Figure 3. Complete creep curve for HMPE by SIM method.

The next step needed in the SIM is the *rescalling* and it is a procedure used to compensate the creep history of the specimen that already has a strain damage caused by extensions that took place at previous temperature steps. The adjustment should be applied by moving the strain curves, obtained in the temperature steps, to the left of the linear time scale, as Fig. 4, and the curves are spread out like if the tests had been done individually, similar to TTSP tests. The *rescalling* procedure helps the next step of adjustments in which will be use a logarithmic scale of time. The *horizontal shift* can only be applied if the *rescalling* has been done and it is a process that requires the transformation of linear time in logarithmic for the same curves showed in Fig 4. To complete the horizontal shift, the curves will be united again, by moving curves 2 and 3 until their starting places. The Figures 5 and 6 resumes the third adjustment procedure.

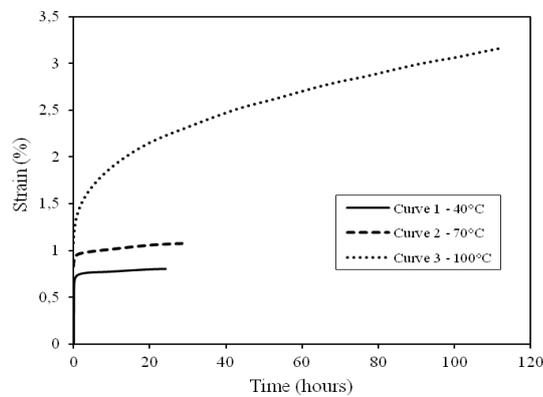


Figure 4. Rescalling procedure for HMPE sample with 10% YBL applied.

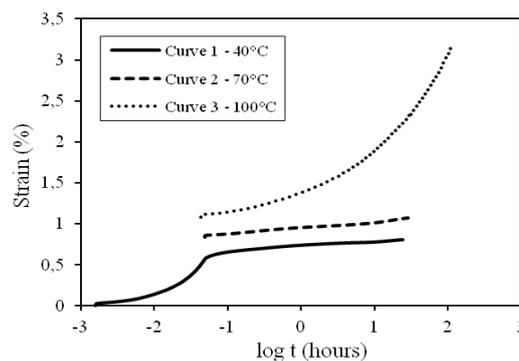


Figure 5. Change in linear time scale to logarithmic.

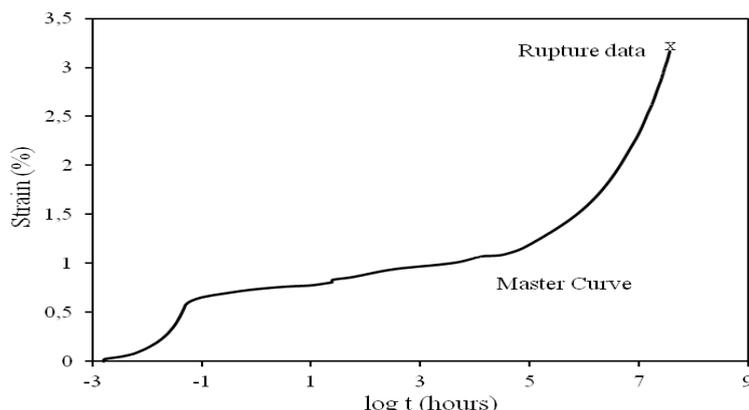


Figure 6. SIM master curve at 10% YBL for HMPE material.

5. CONCLUSIONS

The SIM has the capacity to provide interesting results for the study of mooring systems used in offshore structures. The practical impossibility of performing real-time creep tests in these structures can easily be bypassed by making use of acceleration techniques such as the SIM, and long-time experiments can be shortened to a few days. Using the master curve obtained in Fig. 6, it is possible to predict, through a 7-days experiment, that HMPE, when submitted to a creep load of 10% of its tensile strength, will fail by creep after 416667 days, or 1,141 years, longer than a millennium.

6. REFERENCES

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