EXPERIMENTAL CREEP ANALYSIS ON HMPE SYNTHETIC FIBER ROPES FOR OFFSHORE MOORING SYSTEMS

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Abstract: *The present experimental work has the intention of analyze the creep behavior of HMPE multi-filaments (High Module Polyethylene), used in the manufacture of synthetical ropes for deep-water mooring using the "Taut-Leg" system. To do so, it has been compared the behavior of two multi-filaments of HMPE: Dyneema® SK75 and SK78. The results were compared among them and with the results obtained in similar tests performed on polyester multi-filaments (PET). A methodology was developed for the experimental research, which evaluated the mechanical resistance and the linear weight of the multifilament, with the purpose of generate knowledge regarding the creep behavior of the analyzed synthetical fibers. It had been performed short term creep tests (executed in a tension test machine) with constant load values between 60% and 90% of the YBL (Yarn Break Load) of the multifilament and long term creep tests with constant load values of 15% and 30% of the YBL (using dead weights). The results of these tests show evidences that the HMPE Dyneema® SK78 fiber is a possible candidate to replace the polyester fiber, for some applications, even though it still has creep values that cannot be despised on environmental temperatures.*

Keywords: *Mooring Systems, Synthetic Ropes, Yarns, Creep, HMPE.*

1. Introduction

With the development of oil fields in deep waters over 1000 meters, the replacement of steel ropes used for the mooring of floating structures, by other with lesser linear weight, became a necessity. In shallow waters, the petroleum drilling and production flotation units are anchored by conventional systems: chains and steel ropes in catenary configurations. For deep waters the "Taut-Leg" system was developed, using synthetic ropes with lesser linear weight, where the tension is the preponderant effort (Bosman and Cloos, 1998). The architecture of a synthetic rope in the mooring of oceanic platforms consists of: multi-filaments (yarns) forming a leg, some twisted legs forming one subrope and finally several subropes, all together in parallel, forming a rope. Now a days these deep water mooring ropes, are made of polyester (PET) and they provide the necessary conformity to the taut-leg system by means of the natural elastic properties of the fiber, which replaces the need of long catenary configurations used in the conventional mooring systems.

In the design of a mooring synthetic rope, creep, and the possibility of creep rupture, must be considered as well as all the other failure possibilities. In oil production unities anchored in the Taut-Leg system, the ropes are installed only once and stay tensioned for all its useful life. The long term exposure of the lines to solicitations with low amplitude variation without the environmental behavior, suggest the creep as the most likely way of failure.

Due to the appearance of other synthetical fibers in the market, which intend to improve the performance of the proper mooring system, it became necessary to analyze and verify the mechanical properties of these fibers.

This is the case of HMPE, High Module Polyethylene, which has show up it the market as the polyester possible substitute, due its combination of low density and high mechanical resistance.

This work presents an experimental research used to evaluate the creep behavior in multi-filaments of HMPE on environment temperatures. To do so, it has been compared the behavior of two multi-filaments of HMPE: Dyneema® SK75 and SK78. The results were compared between themselves and with the results obtained in similar tests performed on multi-filaments of polyester (PET).

It has been determined the tension rupture load and the linear weight of the multi-filaments for their characterization (OCIMF, 2000). It has been performed short term creep tests with constant load values of 60%, 70%, 80% and 90% of the YBL (Yarn Break Load) of the multifilament and long term creep tests with constant load values of 15% and 30% of the YBL (creep test using dead weights). The results were analyzed and the mechanical behaviors of the two fibers were compared.

2. Materials

The HMPE fiber is produced from the ultra high molecular weight polyethylene (UHMW-PE) by the gel-spinning process, according to “DSM – High Performance Fibers, 2003”. In this process the molecules of UHMW-PE fiber are dissolved in a solvent. The obtained solution is successively pulled through small holes and afterwards solidified by cooling it. This process produces a fiber with a chemical structure composed by chains with a high molecular orientation degree (over 95%), as shown in Fig. 1. This molecular structure, with high crystalinity degree (up to 85%) and a little amorphous content, gives the fiber a high modulus and a high rupture load. Worldwide, there are two companies that commercially produce this fiber.

The Netherlands company DSM in co-operation with Toyobo company from Japan produces the Dyneema® (SK60/65, SK75, SK76 e SK78) series. Honeywell company produces in United States the Spectra® (900, 1000 e 2000) series. HMPE fibers have density a little below 1.

HMPE	PET
Orientation > 95%	Low Orientation
Crystalinity up to 85%	Crystalinity < 60%

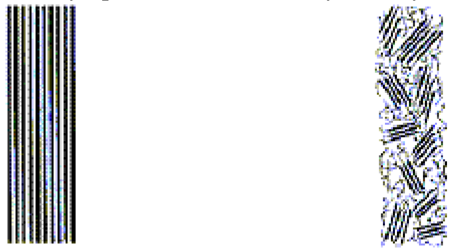


Figure 1. Orientation and Crystalinity representation of the HMPE and Polyethylene Fibers

The HMPE multi-filaments tested in this work were the Dyneema® SK75 with linear weight of 1760 dtex and SK78 with linear weight of 1766 dtex (where 1tex = 1 g /1000m). For the comparison their behavior, it has been tested the polyester Diolen® 855 TN-1 F100 with mean linear weight of 2200 dtex. Table 1 shows the nominal characteristics of these multi-filaments.

Table 1. Mechanical proprieties provided by the manufacturer (NP – Not Provided).

	HMPE	**HMPE**	**POLYESTER**
Series	Dyneema SK78	Dyneema SK75	Diolen 855 TN-5
Manufacturer	DSM	DSM	COBAFI S/A
Tenacity	NP	32.7 cN/dtex	8.24 cN/dtex
Strain on Rupture	NP	3.6%	14.1%

3. Creep

Creep is a permanent elongation of a material submitted to a constant solicitation, or almost constant, as a time function. The parameters that affect the creep phenomenon are: load, time and temperature. Load and temperature affect directly the phenomenon, in other words, as much as its magnitudes are higher, more accentuated would be the material permanent strain. Creep in the metals, occur due to the movement of the imperfections that exist in the crystalline structure (with more intensity on high temperatures). In the polymeric materials (Sloan, 2002), creep occurs after the alignment of the molecular chains of the amorphous region (reversible) and with the beginning of the sliding and the ruptures of the molecular chains of the amorphous and crystalline regions (irreversible).

On high temperatures the synthetical fibers reach a high elongation in a short period of time. The same can be said when the loads are high. The creep strain rates of the synthetical fibers strongly depend on the tension and the temperature levels.

Creep of a material can be evaluated submitting it to a constant tension solicitation and measuring its elongation during the time (the specimens used in HMPE creep tests are similar to the ones used in the tension tests). For creep evaluation in multi-filaments of a synthetical material it can be performed the following tests: non-rupture creep test and rupture creep test.

In the non-rupture creep test the constant solicitation is kept along the time and the strain occurred on the material is evaluated. The test lasts generally for over 1000 hours. The test provides a strain curve along the time, and, due its low solicitation, it is not necessary to let the specimen go to rupture.

In the rupture creep test, the specimens are always taken to rupture. For this, it is used higher loads. The results obtained in this test are: the time for the specimen’s rupture and the elongation close to rupture.

4. Test procedures and determination of the mechanical characteristics

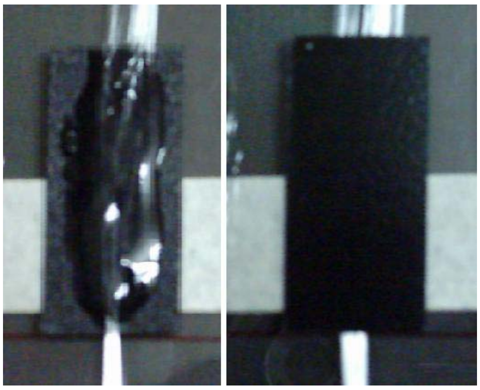
4.1 Tensile tests

The objective of the tensile tests is to obtain the mean rupture loads for the HMPE – SK78, SK75 multi-filaments and the polyester fiber, comparing themselves.

This tests were performed in an electromechanical test machine (EMIC model DL 2000) with special pneumatic clamps for yarn tests, a load cell with a 1 kN capability, as shown in fig.2, in an atmosphere controlled room, with the following environmental conditions: 55 ± 2% of humidity and 20 ± 2º C of temperature. Considering the final strain, in the tests of the HMPE multi-filaments (ISO 2062, 1993) it was used as an initial measuring length 500 ± 1mm and a test speed of 500 mm/min. In the test of polyester (ASTM D885, 1998), where the elongation is greater than the HMPE, the multi-filaments have an initial measuring length of 300 ± 1mm and a test speed of 250 mm/min.

For the HMPE multi-filaments occurred sliding on the clamps, due its high rupture load and low friction coefficient, and this created some hard difficulties. To overcome those difficulties, a terminal system was developed which was composed of small plates of PVC (Vinyl Policlorite) glued with an epoxy resin, as shown in fig. 3.

Figure 2. EMIC DL2000 Test Machine



(a) Unfinished specimen (b) Finished specimen

Figure 3. Terminal system composed by small PVC plates

4.2 Long term creep tests

In these tests there have been used constant loads of 15 and 30% of YBL. Such load values were used to represent the load conditions that a synthetic mooring line, a Taut-leg kind, can face in operation. For a storm condition, the maximum solicitation of a mooring line shouldn't exceed 30% of MBL (Minimum Break Load) of the rope. And for normal work conditions, the rope solicitation should be at least 15% of the MBL of the rope.

During the creep test, the material under constant solicitation has successive reduction in its mechanical strength due an internal damage process resulting in length changes. In this way, it is interesting to analyze the creep phenomenon for the largest amount of time that would be possible. In the creep behavior evaluation of the researched HMPE fibers, it has been performed long-term tests in a "Dead weight device", as shown in fig. 4.

For these tests the specimens were prepared with the length of 1000 mm, within its terminations, and the distance between measurement marks (Lo) was 900±1mm, 50mm adjacent to each termination, as shown in fig.5. Due the great difficulty in fixing the HMPE specimens in the traditional devices (reels, mechanical and pneumatic clamps) because of the low friction coefficient, it has been developed terminal systems formed by wooden plates glued with an epoxy resin and mounted in aluminum supports pressed by screws, as shown in fig. 6. The elongation was taken as being the difference between the positions of the two measurement marks.

Figure 4. Creep test device using dead weights.

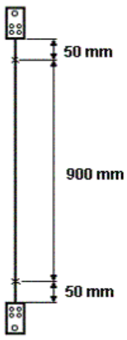


Figure5. Specimen dimensions.

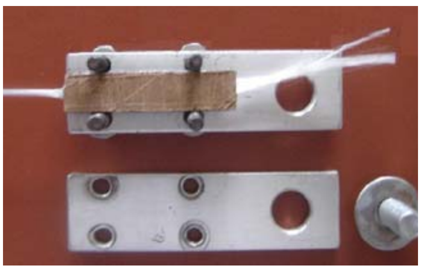


Figure 6. Terminal system used in the long term creep tests.

4.3 Creep rupture tests

In the creep rupture tests it has been applied testing loads corresponding to 60, 70, 75, 80, 85, and 90% of the mean rupture load of the material. Among the objectives of these tests there were the determination of the failure timing under high and constant loads, and the obtaining of an equation that could relate the failure timing with the respective load.

5. Results

5.1. Tension Tests

Table 2 shows the results in tension, average values of 10 tests, for the multi-filaments. The multi-filaments of HMPE – SK75 and SK78 practically do not present differences regarding its mechanical resistance. It is verified a higher tenacity when they are compared with the multi-filaments of polyester.

Tabela 2. Tension tests.

Sample	HMPE SK78	HMPE SK75	POLYESTER
Load (N)	540.70	532.25	171.10
Strain (%)	3.15	3.24	12.67
Linear weight (dtex)	1766	1760	2200
Tenacity (cN/dtex)	30.62	30.24	7.78

5.2 Creep

5.2.1 Long-term

Figures 7 and 8 compare the results obtained for the SK75 multi-filaments with the obtained for the SK78 multi-filaments, with a 30% and 15% solicitation of the YBL, respectively.

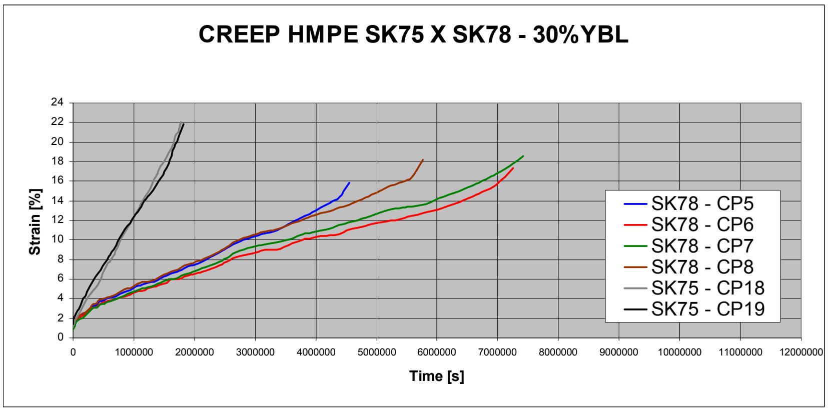


Figure 7. Results for the long term creep tests, 30%YBL.

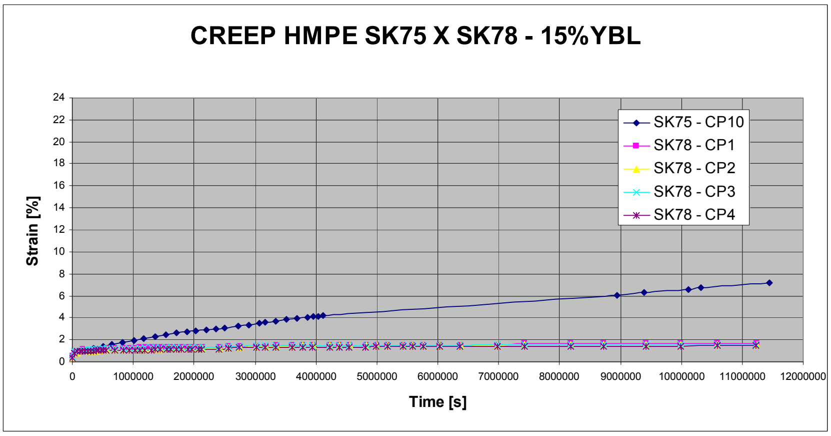


Figure 8. Results for the long term creep tests, 15%YBL.

Figure 9 shows the results of a long-term creep test, up to the rupture, for a specimen of HMPE – SK78 with 30% YBL. The curve presents three creep stages with its respective tendency curve, equations and correlation coefficients.

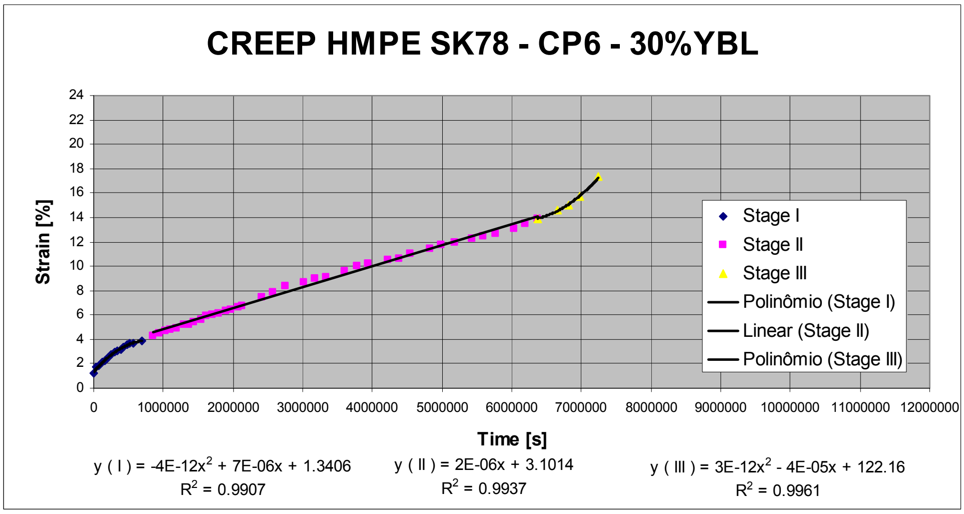


Figure 9. Results for the long term creep tests, for HMPE – SK78, 30%YBL.

The HMPE – SK75 fiber when is tested on 30% of its nominal rupture load (Lopes, 2003) show a low resistance to creep failure, breaking around a 22 days period. Figure 10 shows the results of a long-term creep test, up to rupture, for a HMPE – SK75 specimen with 30% of the YBL.

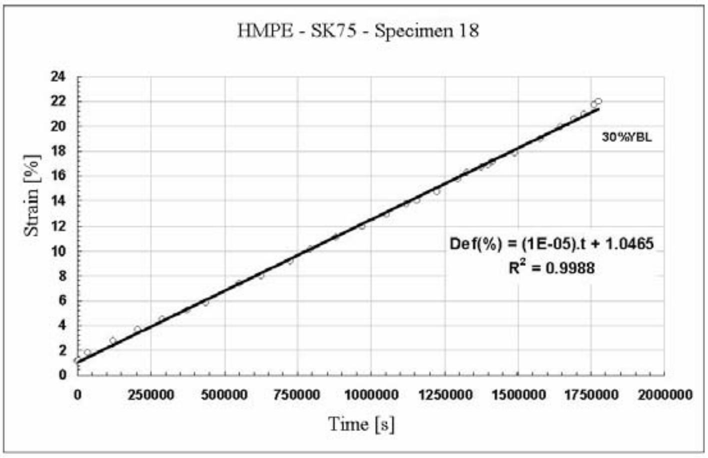


Figure 10. Results for the long term creep tests, for HMPE – SK75, 30%YBL.

Figure 11 shows the result for creep strain for polyester multi-filaments loaded with 50% of its rupture load. It has been proved that this material has low creep strain.

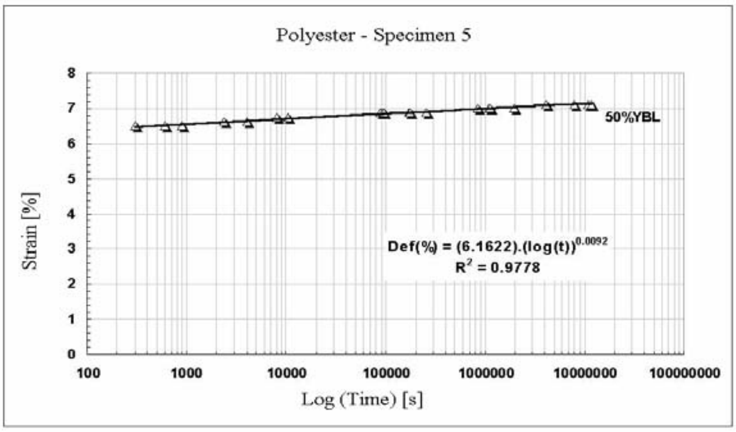


Figure 11. Results for the long term creep tests, for Polyester, 30%YBL.

Table 3 shows the equations obtained, using the EXCEL program, in the long-term tests for the applied load of 15% and 30% of the YBL and its corresponding correlation coefficients.

Table 3. Creep strain for long periods of time.

Material	Load [%YBL]	Equation	Linear Regression analyses (R^2)
HMPE – SK75	15%	$def(\%) = 4.10^{-7}(t) + 2.446$	0.9961
	30%	$def(\%) = 1.10^{-5}(t) + 1.045$	0.9988
HMPE – SK78	15%	$def(\%) = 0.1827(t)^{0.1349}$	0.949
	30%	Stage I - $def(\%) = -4.10^{-12}(t)^2 + 7.10^{-6}(t) + 1.3406$	0.9907
		Stage II - $def(\%) = 2.10^{-6}(t) + 3.1014$	0.9937
		Stage III - $def(\%) = 3.10^{-12}(t)^2 - 4.10^{-5}(t) + 122.16$	0.9961
Polyester	30%	$def(\%) = (4.3496).(t)^{0.0095}$	0.9705
	50%	$def(\%) = (6.1383).(\log(t))^{0.0095}$	0.9815

5.2.2 Creep rupture

Table 4 shows the results for the creep tests, on several load rates, for the HMPE – SK75 and SK78. In the time for rupture column, it is shown the average values referring to the performed tests.

Table 4. Results for the creep rupture tests performed on the multi-filaments of HMPE – SK75 and SK78.

Applied Load [% Nominal YBL]	Time for rupture [s]	
	HMPE – SK75	HMPE – SK78
90	1.40	15.52
85	13.82	418.00
80	44.22	4,016
75	397.40	5,500
70	4,995.40	9,296
60	25,620	71,930

Figures 12 and 13 show, as an example, the strain curves for creep obtained in the tests of the multi-filaments of HMPE – SK75 and SK78 with 60% of its nominal rupture loads and with an initial load rate of 500N/min. It can be observed the first, second and third creep stages, with the material failure. The secondary stage has the tendency to become linear along the time.

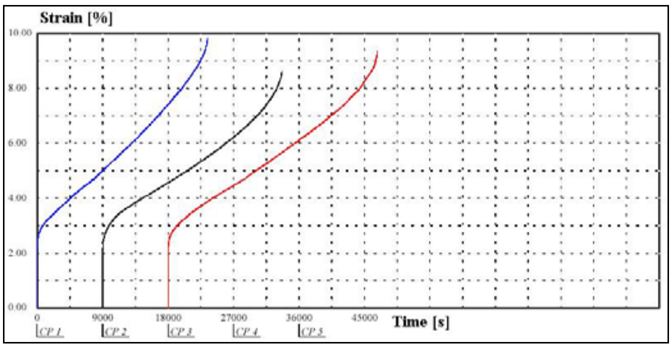


Figure 12. Creep rupture tests for HMPE - SK75, 60% YBL.

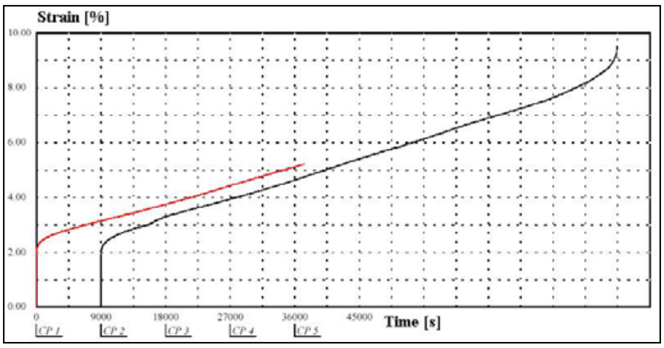


Figure 13. Creep rupture tests for HMPE - SK78, 60% YBL.

Figures 14 and 15 show, as an example, the strain curves for creep obtained in the tests of the multi-filaments of HMPE – SK75 and SK78 with 80% of its nominal rupture loads and with an initial load rate of 500N/min. It is verified that the multifilament of HMPE – SK78 has lesser creep than the multifilament of HMPE – SK75.

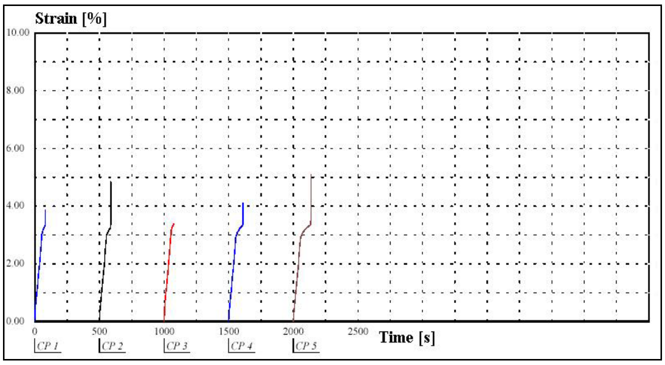


Figure 13. Creep rupture tests for HMPE - SK75, 80% YBL.

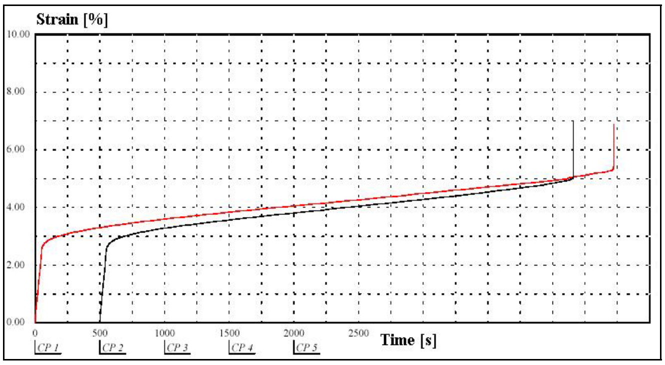


Figure 15. Creep rupture tests for HMPE - SK78, 80% YBL.

6. Conclusions

The present experimental work has the intention of analyze the creep behavior of the multi-filaments of HMPE (High Module Polyethylene), used in the manufacture of synthetical ropes for deep water mooring using the “Taut-Leg” system. To do so, it has been compared the behavior of two multi-filaments of HMPE: Dyneema® SK75 and SK78. The results were compared between themselves and with the results obtained in similar tests performed on multi-filaments of polyester (PET).

In the rupture resistance tests it was verified that the HMPE multi-filaments have a high rupture load associated to a small strain. It can be observed the high values of the elasticity modulus of the multi-filaments of HMPE – SK75 and SK78 (high load and low rupture strain), when comparing it with the polyester multi-filaments.

The HMPE - SK75 and SK78 multi-filaments have similar rupture loads and elongations. When they are compared, it is verified that the HMPE tenacity is much higher than the polyester tenacity. In the creep tests, both in the long-term and in the rupture ones, it was verified that the multifilament of HMPE - SK75 has low creep resistance where it might, with constant loads of small intensity, present the danger of a quickly failure. When they are tested on 30% of its nominal rupture load the multi-filaments of HMPE-SK75 have shown a short life failing in about 22 days. When they are tested on 15% of its nominal rupture load, they have shown less creep, even though it is still considered high for the mooring of platforms with the “Taut-Leg” system, as it can be seen in figures 7, 8 and 10.

The HMPE - SK78 multifilament has a higher creep resistance for small solicitation values. When they are tested on 30% of its nominal rupture load the multi-filaments of HMPE – SK78 have shown a life of about 72 days. When they are tested on 15% of its nominal rupture load, they have shown a considerable reduction in the creep effect, as it can be seen in figures 7, 8 and 9.

Due to the adverse results regarding creep, the use of SK75 multi-filaments as a fiber for the manufacture of mooring ropes, is not appropriated. The high mechanical resistance of this fiber (high rupture load with low strain) can be compared to the resistance of steel ropes, what makes possible its use for other important engineering applications. Using this fiber as a rope submitted to creep solicitations implies in wasting its best characteristics.

On the other hand, the SK78 shows similar mechanical resistance as the SK75, with better creep behavior, allowing its use for some applications. The use of the SK78 multifilament can have some specific applications, always observing the creep limitations. For example, according to Smeets *et al.* (2001), the SK78 can be used in tug operations for the movement and mooring of ships and for mooring operations of drilling platforms as MODU (Mobile Offshore Drilling Unit).

7. Acknowledgements

The authors would like to thank **FINEP** – Financiadora de Projetos and **PETROBRAS** – Petróleo Brasileiro SA, for sponsoring this work.

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