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Prospects of synthetic fibers for deepwater mooring.

Leandro F. Haach[1], Delvone T. Poitevin[2], Milton Briguet Bastos[3]

Resumo

Com a descoberta de campos de Petróleo em águas cada vez mais profundas, como aqueles localizados na chamada camada pré-sal, torna-se necessário a realização de investimentos no desenvolvimento de sistemas de ancoragem que possibilitem linhas mais leves e mais rígidas. O desenvolvimento de linhas de ancoragem mais rígidas tem sido provocado pela necessidade de garantir os limites de passeio das unidades flutuantes a fim de não oferecer um risco excessivo às instalações que conectam a plataforma ao fundo do oceano. Em razão disso, mas atentos também ao ótimo desempenho apresentado pelos cabos de poliéster em uso há pelo menos quinze anos, se faz necessário o estudo de novas fibras, de maior módulo, como possíveis candidatas a serem utilizadas em um sistema de ancoragem. Dessa forma, neste trabalho, procurou-se analisar não apenas o desempenho em fios, mas principalmente verificar comparativamente o comportamento de sub-cabos fabricados com poliéster e sub-cabos fabricados com fios de PEN e LCP. O trabalho possibilitou observar resultados relativos às principais características de um cabo de ancoragem como acomodação, rigidez quase estática e rigidez dinâmica, resistência à fadiga, eficiência construtiva e tenacidade. A partir de uma análise técnica dos resultados encontrados e dos conhecimentos adquiridos neste processo, foi possível identificar e visualizar de forma mais clara os próximos passos da tecnologia de ancoragem com cabos sintéticos, avaliando ainda a continuidade do poliéster como principal material empregado nesta aplicação. Assim sendo, pode-se dizer que este estudo representa um primeiro e importante passo da Lupatech CSL com o intuito de identificar e investir em tecnologias novas para o futuro dos cabos de ancoragem.

Abstract

The discovery of new reserves of oil in deeper and deeper waters, like those located at called pre-salt layer, becomes necessary to make investments in development of mooring systems that allow lighter and stiffer lines. The development of mooring lines with higher stiffness has been driven by the need to ensure the offset of floating units in order to offer more safety to equipment that connects the platform to the ocean floor. As a result of this, but also attentive to the excellent performance presented by the polyester ropes in use for at least fifteen years, it is necessary the study of new fibers, with higher elastic modulus, as possible candidates for use in an anchoring system. Thus, in this study, we sought to analyze not only the yarn performance, but especially to compare the behavior of sub-ropes made with polyester with sub-ropes made with PEN and LCP yarns. This work allowed to observe results of the main features of a mooring rope as bedding-in, quasi-static and dynamic stiffness, fatigue resistance, tenacity and constructive efficiency. From a technical analysis of the results and lessons learned along this process, it was possible to identify and to visualize more clearly the next steps of synthetic ropes mooring technology and evaluating the continuance of polyester as the main material used to make ropes to this application. Therefore, could be said that this study represents an important step to Lupatech CSL in order to identify and continuously to invest in new technologies for the future of the mooring.

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[1] Ms, Quality and Innovation Manager – Lupatech CSL
[2] Chemical Engineer, R&D Coordinator – Lupatech CSL
[3] PhD, Fiber Consultant – MBB Enterprises

1. Introduction

The growth in demand for petroleum originated energy and products has led to the exploration of new reserves in deeper and deeper areas of the ocean. In the days when the depths involved remained in the range of up to 100 m (about 300 feet), exploration systems positioned by means of structures set in the seabed were common. For deeper water utilization, however, that kind of structure proved itself unfeasible and the switch to floating production units anchored in the seabed became necessary.

The positioning of floating units during oil exploration is assured by anchoring lines – which are flexible structures generally made up of extensions of wires, chains and polyester ropes. In Brazil, Petrobrás obtains most of its oil in deep waters.

To reach that level, great amounts of resources had to be invested over the last 20 years, which enabled a technological development that made Petrobrás a benchmark in this area. Production of petroleum in water depth greater than 1,000 m (3,000 feet) called for the development of several new technologies, one of them is the anchoring system that utilizes synthetic fibers – particularly ropes manufactured with high tenacity polyester filament yarns, a technology that has been used for almost two decades and which has been consolidating all over the world.

The new finds of oil fields in areas at increasingly deep waters, as is the case of the pre-salt reserves, have required not only new efficiency enhancing and cost cutting technologies but also the commitment of investment for the development of lighter systems with greater stiffness and tenacity anchoring lines.

This need comes about as a result of the length of the anchoring lines and of the imposition to restrict the sideway movement of the platforms, by limiting their displacement. This lateral motion restriction can be attained by using ropes with higher elastic modulus than the ones currently used for deep waters. Another fundamentally important factor is the ropes' length as well as their diameter (often over 200 mm) which have and more difficult.

High tenacity polyester was the material chosen when the development of synthetic fiber ropes began. The yarns used hence have been the same that were already marketed at the time for other end uses or purposes, such as strengthening rubber or plastic as in the case of tires and conveyor belts.

The market for offshore anchoring ropes has surged recently. The estimate is that , by 2014, it will hit the 10-thousand-ton mark. Technology for of polyester yarns has not evolved proportionally since its inception and the yarn is basically the same as 20 years ago. Definitely, the mechanical properties of the yarn have not been improved or optimized vis-a-vis its importance.

The development of anchoring systems, obviously depend on the design or the kind of construction used to the ropes. In the future, however, they will depend, more and more, on the properties of the materials employed.

For this reason, materials such as PEN, P-ARAMIDA, HMPE and LCP are constantly being evaluated as synthetic fiber alternatives. Based on their greater elastic modulus properties or also due to their breaking strength , the industry has sought to identify advantages and disadvantages displayed by each of these fibers for mooring applications.

2. Mooring Systems

For a brief discussion of the existing technological demand, we shall have to approach the matter starting with some basic concepts for mooring application.

A floating unit is constantly subject to environmental action (waves, wind and currents) which entail the exertion of external forces onto such a unit. Such environmental agents bring about forces that act upon the floating unit both horizontally and vertically. The horizontal forces are the ones that push and tow the unit at the plan of the water (i.e. horizontally) and drive it away from its initial location.

A mooring system aims to restrict the displacement on the horizontal plan by assuring the position of the floating unit thus providing the indispensable operational safety for the unit. The mooring system restricts the horizontal dislocation of the unit. Such as change in location in relation to the project, is called the "offset" of the unit.

Keeping the unit positioned within a location implies the acceptance of a certain variation in such location – within an acceptable range around the location as initially planned in the project. This spot (within the range) is usually determined by technical and operational requirements of the devices that connect the unit to its submerged equipments. To enable the floating unit to operate safely, the "offset" provided by the mooring system must be smaller than the radius that defines its region.

The stiffness of the mooring system is considered as a relation the restoring force of the system (brought about by the line strains with regards to environmental forces) and the respective offset. Hence, a system is deemed more or less stiff when, for a certain environmental force, the offset needed for the restoring force to balance environmental forces is smaller or larger.

The calculations to determine the stiffness of a system is directly associated to the calculations for the stiffness of each line. The composition and number of the mooring lines are calculated with the purpose of keeping the floating unit within certain horizontal limits (offset) usually measured as a percentage of the water sheet.

For drilling units, during normal operations, the maximum admissible drift is around to 6% of the water sheet. This limit is however, reduced to 2 to 3% in special operations, as is the case of the descent of BOP. For production units, the drift has to be diminished due to the characteristics of the flexible production lines connected to the unit. These lines must not undergo heavy traction. Generally, the maximum drift designed for production units lies in the range of 12% for systems made up of unbroken lines and 18% for systems containing one ruptured line.

With the need for longer lines in greater depth locations and the ensuing utilization of greater lengths of synthetic ropes, the length of the lines will also increase and thus the drift will increase and possibly entail more critical demands upon the equipment that link, connect of fasten the platform to the seabed. For this reason the industry has been evaluating new synthetic fibers that allow for smaller elongation for certain tension ranges.

2.1. Mooring Lines

Mooring lines are structures disposed in catenaries, taut-legs or tension legs. Their job is guarantee the restoring forces that hold floating units in their original or closest-to-original position. The most common materials used in the construction of mooring lines are steel chains, steel lines and (polyester) synthetic fiber. Due to attrition against the seabed and due to the enormous amount of marine life close to the surface, steel chains are usually preferred for both ends of the lines. Synthetic fiber ropes are usually positioned in the intermediate section of the line.

2.2. Polyester Mooring Ropes

Taking into account the main demands upon a rope while it is in use – particularly the ropes used in naval industry – designers and suppliers have always sought to balance the architecture of the synthetic fiber ropes in accordance with two fundamental premises: resistance to breakage and resilience. Naturally, though secondarily, features such as resistance to abrasion and capacity to endure exposition to weather elements have always been targeted.

With the coming of synthetic raw materials in combination with new geometrical models of ropes (8 and 12 strands) it has been possible to ally the constructive engineering of a rope to the inherent characteristics of the new fibers. This combination, in its turn, has enable the industry to improve the performance of the ropes in view of the specific requirements of each maritime application. At the same time, the industry has made the engineering and architecture of these structures more flexible and allowed for the polyester rope to subvert the concepts of resistance to breakage and resilience.

It is a well-known fact that the polyester mooring rope has to meet the minimum requirements to withstand the mooring of a floating unit. And such requirements are related not only to breaking resistance but, above all, fatigue resistance, stiffness and low creep. In this way, the design of an mooring rope takes into account the high tenacity of the polyester yarns, its high fatigue resistance, its low creep and, mainly, its low elongation. Furthermore, in the manufacturing process, the yarns are twisted so as to make the strands well balanced and homogeneous. Both design and manufacturing seek to decrease as much as possible the lay angle by means of the increase of the lay length of the sub-ropes. This building architecture boosts tenacity as it guarantees for the low elongation of the ropes, a fundamental premise to keep stiffness and the elastic modulus adequate for the mooring system.

However, once installed, the polyester mooring ropes undergo the effects of bedding-in, due, both, to their structure and their splices. People wrongly attribute high creep to polyester ropes due to this natural bedding-in. This elongation, however that polyester ropes go through is only expressed significantly after the first few months in operation and it is recovered through the retension of the mooring lines.

3. Elastic Modulus and Stiffness

Synthetic fibers, because of its polymeric origin and depend on the time scales and temperature taken, show a visco-elastic behavior, showing characteristics of both - elastic and viscous material. The curves of load-elongation fiber and synthetic fiber ropes are dependent not only the load applied on the moment, but also the loading history (visco-elastic behavior).

The tensile stress acting in a perfectly elastic solid, depend only on the corresponding deformation, i.e., obey Hooke's Law, which relates the tensile stress σ to strain ε according to Equation 1:

$$\sigma = E.\varepsilon \tag{1}$$

E is the Elasticity Modulus or Young’s Modulus and can be determined using the Equation 2:

$$E = \frac{\frac{F}{A}}{\frac{\Delta l}{l}} = \frac{F.l}{A.\Delta l} \qquad (2)$$

Axial stiffness (in force units), Equation 3, can be defined as the ratio between the load and strain variations between the minimum and maximum points:

$$K = \frac{\Delta F}{\Delta \varepsilon} \qquad (3)$$

ΔF is the variation of the applied force and $\Delta \varepsilon$ is the variation of strain occurred between these points (secant stiffness) or in an infinitesimal interval (tangent stiffness).

ISO 18692 uses a concept of non-dimensional stiffness, based on minimum breaking strength (MBS) of the rope. It is a practical measure used to mooring design (Equation 4):

$$K_r = \frac{\frac{\Delta F}{MBS}}{\frac{\Delta l}{l}} \qquad (4)$$

MBS is the specified minimum breaking strength and $\frac{\Delta l}{l}$ is the variation in elongation, measured over a length l in the middle of the rope and not disturbed by splices zone.

If *A* is the cross section area of the rope core:

$$K_r = \frac{E.A}{MBS} \qquad (5)$$

This non-dimensional stiffness (Kr), Equation 5, will be evaluated in this work for comparative purposes in sub-ropes made of high tenacity polyester yarns from three different manufacturers and two other high elastic modulus fibers - PEN and LCP - which we will present later.

4. Synthetic Fibers

The most widely used synthetic fiber for mooring ropes is the polyester, that allow the production of strong and lightweight mooring ropes with an extended lifespan at very competitive costs as compared with high modulus fibers such as HMPE, P-ARAMIDA, LCP, PEN, etc...

The high tenacity polyester yarn is based on the poly-ethylene-terephtalate (PET) that is an international commodity with a production of several million tons per year and widespread used in the production of textile and industrial fibers, films, as well as PET bottles for the packaging industry. This is the reason why the polyester nowadays has the best cost-performance as compared to any other synthetic fibers.

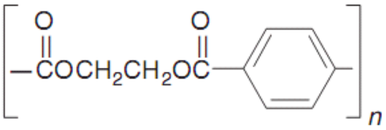


Figure 1. Polyester PET

Figure 1, shows the chemical structure of the polyester polymer. It can be noticed that the molecule backbone consists of one aliphatic segment (soft) followed by the aromatic segment (rigid). The combination of both segments in an amorphous and crystalline structure entitles both higher tenacity and flexibility for the yarn.

The properties of the stress-strain curve of the PET filament can be enhanced by the increased molecule size by the Solid State Polymerization of Post-condensation known as SSP. Mechanical characteristics can be further improved by the further spinning, drawing and heat treatment. The most modern process in use today is the single stage Spin-Draw-Yarn (SDY) process that can produce yarns with a higher tenacity than what was possible before at competitive costs.

Currently high tenacity multifilament polyester can reach strength levels from 0.78 N/tex to 0.84 N/tex and elongation at break between 13 and 15%. New modified polyester yarn with the adequate drawing and heat-setting process can achieve a lower breaking elongation of about 10%.

The other advantages of polyester are the UV resistance, abrasion resistance and maintenance of mechanical performance under wet conditions.

A new development of a modified PET fiber, that we denominated PET XM can be made with a reduced elongation and higher tenacity that can possibly be considered an alternative with mechanical properties falling between the PET and PEN.

The PEN (poly-ethylene-naphthalate) is synthesized with a double benzene ring structure (naphthalate) instead of the single benzene polyester PET, ensuring a higher rigidity molecular structure resulting in increased fusion and transition temperatures and well a much higher elasticity modulus as compared with the PET. The PEN has a similar chemical and morphological structure of the PET, therefore with similar UV and abrasion resistance as well as wet performance that are important advantages of the PET fibers.

The other performance fiber in use today is the para-(aromatic amide) or para-aramide (Figure 2) or poly-para-phenylene-terephthalamide (PPTA) that is a polyamide with the –NH-CO- is linked to the aromatic ring instead of the the -CH2- for the aliphatic chain of the polyamide (widely known as Nylon).

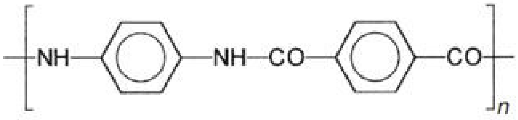


Figure 2. P-ARAMIDE

The PPTA or para-aramid is spun in dry spinning process using concentrated sulphuric acid as a solvent. Under this solution a highly crystallized domains is formed that is further oriented during the spinning process. The para-aramid fiber has high oriented polymer chains with high degree of crystalinity, excellent stiffness, tenacity and modulus and very low creep. As the weak points we can mention the low yarn-on-yarn abrasion, fatigue and axial compression as well as low UV resistance.

Another high performance fiber is obtained by the melt spun of Liquid Crystal polymers (LCP). The LCP are polyesters with molecules of fully aromatic sequence (figure3) that can be melted and associated with liquid crystal.

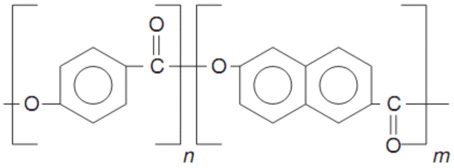


Figure 3. Liquid Crystal Polymer (LCP)

The LCP fiber can be produced with a melt spun process. The melt spinning process has a lower cost as compared to the dry spinning of para-aramid or either the gel spinning of the UHMWPE. The economic advantage is somewhat offset by the need of Solid State Polymerization (SSP) that requires additional thermal energy. The dynamic stiffness of LCP is very good as well a elasticity modulus, tenacity and low creep characteristics.

The Ultra High Molecular Wight Poly-Ethylene UHMWPE also known as HMPE is produced with the Gel spinning process. Ultra High Mw. Poly-Ethylene resin is dissolved in a polar solvent in order to coagulate into a viscous gel like substance that can be drawn more than 100 times to ensure a fiber with high degree of orientation with a high degree of crystalinity. There is a weak chain-to-chain bonding of the long and linear polymer chains compared to other performance fibers such as LCP for example but this the fiber with the highest tenacity of all synthetic fibers and has a low melting point with excellent abrasion resistance properties. The weakest point of this fiber is the high creep as a consequence of the low bulk linear polyethylene chain. Melt spinning of the UHMWPE is possible but the tenacity is much lower than gel spun fibers with a lower orientation and crystalinity with an even higher creep that makes this fiber also unsuitable for permanent mooring systems.

5. Yarn Analysis

These tests were realized to compare some of the properties of high tenacity polyester fibers with high elastic modulus fibers. Figure 4 presents the results of elongation at break and tenacity of the yarns from three suppliers of conventional high tenacity polyester yarns (PET1, PET2 and PET3), a product that we are nominating PET HM (lower elongation and higher tenacity), PEN, P-ARAMID, HMPE and LCP.

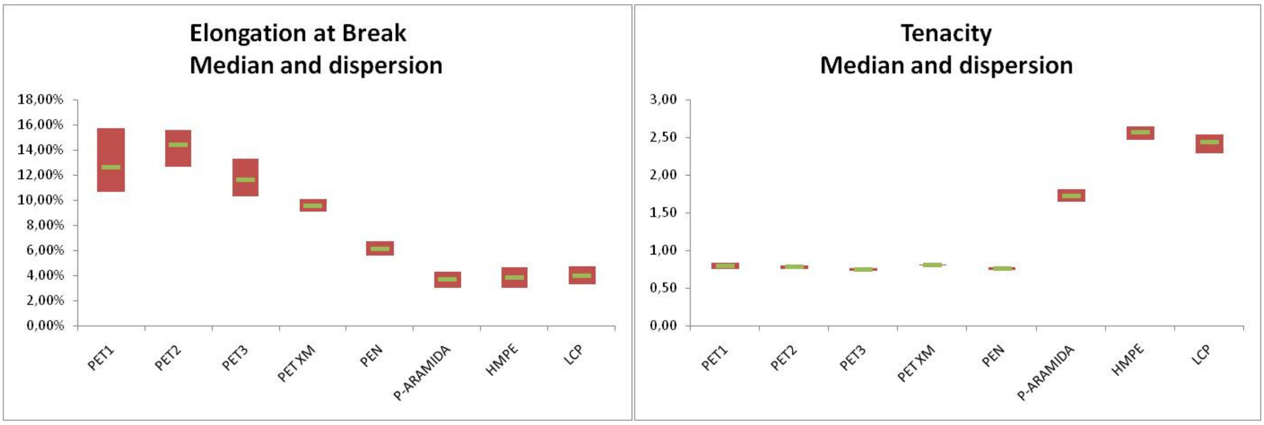


Figure 4. Elongation at break (%) and tenacity (N/tex).

It is known that due to the big ratio between the length and diameter of a yarn tested, the errors due to the kind of claw or termination are usually negligible for most fibers, however should be very careful with high elastic modulus fibers - the sample elongation is smaller and any stroke associated with the termination or claw will result in an error measurement too large. This explains some of the differences in tenacity and elongation found in these tests in relation to that are found in the catalog of the fiber manufacturer.

Continuous filament yarn can be considered as parallel or nearly parallel bundles of fibers, and in this case, at the limit, yarn testing can be reproduce all the fibers. To yarns with a certain degree of twist is possible to perceive the influence of twist - the slight increase of its tenacity and the decrease of the results dispersion. When a small amount of twist is inserted, the effect of it on a deformation can be negligible, but the break occurs abruptly like a cooperative effect in the yarn, with the breaking load slightly higher than a yarn without twist. If there is no twist or interlacing, the rupture of individual fibers will be occur in a range of stretching, with the breaking strength occurring after a few fibers had already broken. For this reason, all of our tests were made with about 60 twists per meter.

The results of yarn-on-yarn abrasion are presented in the graph shown in Figure 5:

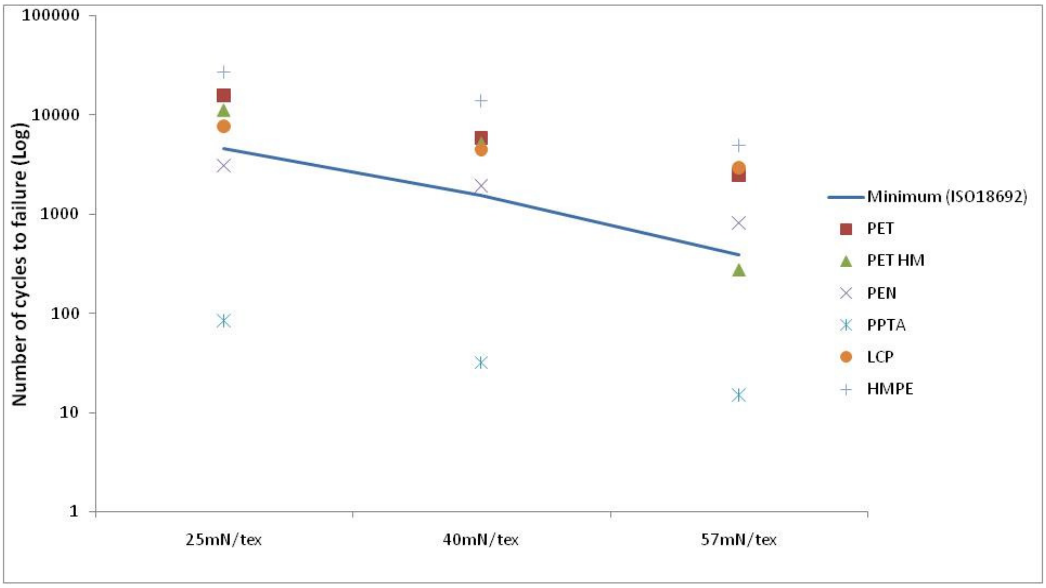


Figure 5. Yarn on yarn abrasion results (cycles to fail) for three different loads – 25, 40 and 57mN/tex.

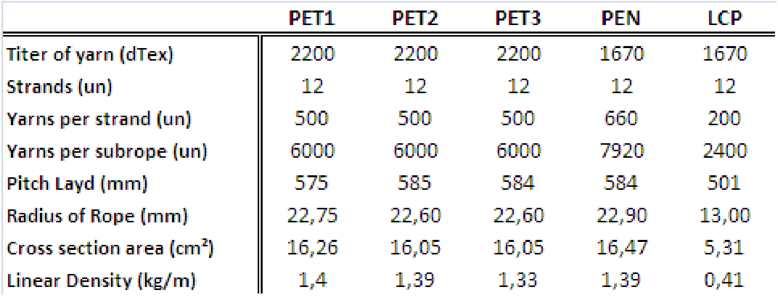
The blue line represents the minimum number of cycles to failure in accordance to CI 1503 and ISO18692.

The analysis of these results shows low resistance of P-ARAMID (PPTA) to the YOY abrasion. The performance of PEN in a lower load (25mN/tex) and the performance of PET HM sample in tests with the highest load (57 mN /tex) were lower than minimum acceptable too.

6. Sub-Ropes Results

Three different manufacturers of high tenacity polyester yarns (PET1, PET2 and PET3), one PEN and one LCP manufacturer were chosen to these tests. Sub-ropes were made in order to evaluate the performance of these fibers to the mooring application. The constructive characteristics of these sub-ropes are presented in Table 1:

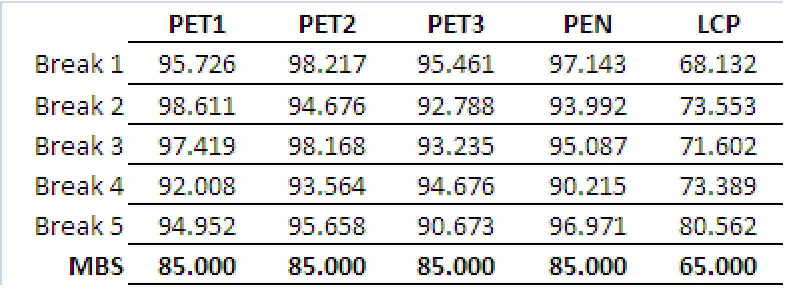
Table 1. Data from sub-rope construction.



	PET1	PET2	PET3	PEN	LCP
Titer of yarn (dTex)	2200	2200	2200	1670	1670
Strands (un)	12	12	12	12	12
Yarns per strand (un)	500	500	500	660	200
Yarns per subrope (un)	6000	6000	6000	7920	2400
Pitch Layd (mm)	575	585	584	584	501
Radius of Rope (mm)	22,75	22,60	22,60	22,90	13,00
Cross section area (cm^2)	16,26	16,05	16,05	16,47	5,31
Linear Density (kg/m)	1,4	1,39	1,33	1,39	0,41

Five (5) samples of each material were tested to pre-assess the MBS of each sub-rope. The results of these tests and the MBS defined for use in the cycling (accordance to Annex B from ISO 18692:2007) are presented in Table 2:

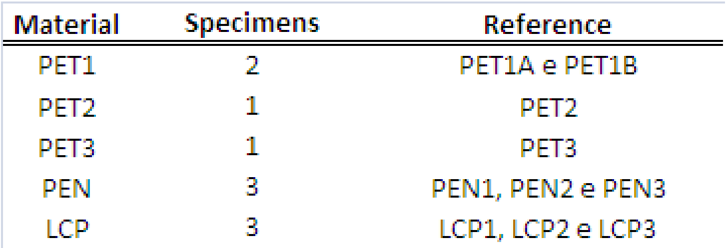
Table 2. Breaking tests to define the minimum breaking strengths (MBS).



	PET1	PET2	PET3	PEN	LCP
Break 1	95.726	98.217	95.461	97.143	68.132
Break 2	98.611	94.676	92.788	93.992	73.553
Break 3	97.419	98.168	93.235	95.087	71.602
Break 4	92.008	93.564	94.676	90.215	73.389
Break 5	94.952	95.658	90.673	96.971	80.562
MBS	**85.000**	**85.000**	**85.000**	**85.000**	**65.000**

With the minimum breaking strength (MBS) already defined for each sub-rope, two specimens of PET1 manufacturer, one of PET2 and one of PET3 manufacturer and three specimens of PEN and LCP fiber material were tested as presented in the Table 3:

Table 3. Specimens tested.



Material	Specimens	Reference
PET1	2	PET1A e PET1B
PET2	1	PET2
PET3	1	PET3
PEN	3	PEN1, PEN2 e PEN3
LCP	3	LCP1, LCP2 e LCP3

The specimens were tested in accordance to the procedure of Annex B from ISO 18692:2007, and all the steps - dynamic stiffness at the end of the bedding-in (between 10 and 30% of MBS), quasi-static stiffness (between 10 and

30% the MBS) and dynamic stiffness (100 cycles between 20 and 30%, 100 cycles between 30 and 40% and 100 cycles between 40 and 50% of MBS) - were performed in the same specimen.

The results are showed in Table 4:

Table 4. Specimens tested.

		PET1A	PET1B	PET2	PET3	PEN1	PEN2	PEN3	LCP1	LCP2	LCP3
Kr (x MBL)	Dynamic at end of bedding	23,80	17,88	19,92	20,92	40,78	36,91	34,59	56,54	58,81	58,74
	Quase-static	18,51	13,69	17,37	17,74	34,94	27,41	26,31	51,56	44,39	46,98
	Dynamic 20-30%	30,00	25,92	22,68	23,54	51,68	40,40	38,30	69,38	59,28	53,78
	Dynâmic 30-40%	29,91	29,04	32,36	33,20	56,35	43,57	42,11	75,54	60,31	59,63
	Dynâmic 40-50%	38,79	33,26	35,93	44,23	56,76	47,89	53,47	78,79	66,94	69,35
	Elongation at Break (%)	8,70%	8,10%	7,63%	7,90%	5,80%	3,72%	3,71%	3,60%	2,42%	4,12%
	Break	95.726	98.559	97.314	91.258	94.937	95.214	88.718	73.553	68.132	80.562

The value of the dynamic stiffness of a rope, increase with the mean load applied and is higher to high modulus fibers like PEN and LCP.

7. Conclusions

From a comparative analysis of the mechanical behavior of sub-ropes and yarns made of different materials and following the premises and tests recommended for the ISO 18692:2007, we sought to evaluate the performance of tenacity, stiffness and fatigue resistance of materials like a polyester PET, polyester PEN and LCP.

Although the performance of polyester PET is widely known, we evaluated it to compare with the other materials tested. Thus, even though that the polyester ropes technology used to mooring of floating units in deep and ultra-deepwater, unlikely will be completely replaced in a short period of time, this work justified the effort on researching about the potential of some candidates to be a successor of the polyester.

As a result of accumulated knowledge in this study, we present some comparisons (Figure 6) to promote a discussion about the different alternatives of fibers that were tested in this work.

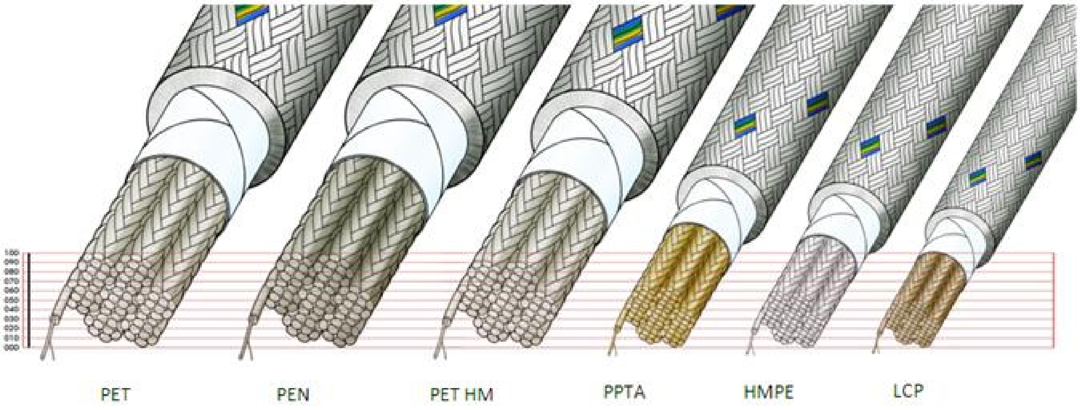


Figure 6. An estimated diameter ratio of ropes made of different materials.

These illustrations, taking as an initial scale an polyester PET rope, incite to think quickly in the operation of mooring as a whole, either from the perspective of cost, of safety or even under the best cost-benefit analysis, inducing us to think beyond a more efficient mooring line. These illustrations are mathematical models of tenacity versus diameters, considering our experience and results of constructive efficiency obtained in this work. Except for the polyester, that dispenses comments, we're talking about technologies that have not been experienced enough and, therefore, require further studies and some caution and vigilance in their employment.

By submitting different yarns to test the stress-strain, modulus and abrasion resistance, not necessarily we can reach a rope with a similar efficiency to that found in the yarn or fiber.

The sub-ropes made with PEN and LCP fibers were tested to fatigue resistance and showed no damage between fibers, and also didn't lose tensile strength after the samples meet nearly 10,000 cycles between 7.5 and 52.5% of the sub-rope MBS.

Another important learning process obtained especially with the LCP fiber rope was the splice process. Due to its high stiffness, LCP required a splice that allows the reduction of abrupt impacts of its bedding-in. In this case, the solution found, not yet completely exhausted, was the increase in the number of braids in a conical manner, allowing us to move from a constructive efficiency lower than 50% to around 70%.

However, when looking to the horizon of a mooring market in ultra-deep waters, one must pay attention not only to the terms of tenacity, stiffness or fatigue resistance of new fibers, but mainly on its economic viability. These variables make us to think, for example, about the best logistics solution for transport, handling and installation of the moorings lines. Obviously, we're talking about another line of research that was not the object of this study, but that will surely stand as a starting point for a next job.

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