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Mechanical characterization procedure of HMPE fiber for offshore mooring in deep waters

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ABSTRACT

For several offshore installations, especially those for exploration of offshore resources, such as Floating Production Storage and Offloading (FPSO), the stability of subsea pipelines and exploration risers are closely related to the mooring system. High performance polymeric fibers have been used in recent decades for offshore mooring, more recently polyester has been challenged by advancement in ultra-deep waters due to its considerable elongation. A candidate fiber for lower elongation mooring systems is high modulus polyethylene (HMPE). The work describes mechanical characterization procedures in high modulus polyethylene fibers envisioning the possibility of offshore mooring systems made entirely with HMPE, which allow deeper water depths, as well as stability to the pipelines. As a result, the fiber is suitable for mechanical strength and linear tenacity. It still shows good performance in abrasion resistance, and loss of inelastic portions in cyclic loads. However, the behavior in creep, due to its slightly high strain rates, restricts its use, but recent fibers known as "Low creep" can be studied, allowing complete mooring systems made with HMPE.

1. Introduction

Submarine pipelines are fundamental structures of several offshore installations, especially Floating Production Storage and Offloading (FPSO) thinking about exploiting existing resources under water. Its good performance is associated with its material, robustness, flexibility, stability, among other aspects. Subsea pipelines and risers used in offshore structures need to operate in a stable environment: they need the offshore structure as a whole to be stable and present a low offset and this affects the whole offshore mooring system (Ju et al., 2014 ; Reda et al., 2018; Wang et al., 2021; Cheng and Chen, 2022).

In the 1990s (Del Vecchio, 1992), one of the great evolutions in mooring systems was the introduction of synthetic fibers for such application, which not only changed the mooring material from steel to polyester, but also modified the mooring system itself from steel catenaries to the polyester Taut-Leg system. With his proposal, Del Vecchio revolutionized the use of polymeric fibers in the offshore and maritime field, and promoted several studies not only for polyester but for various high-performance fibers such as aramid, polyamide, polypropylene, polyethylene, high modulus polyethylene, Liquid Cristal Polymer (LCP), among others (Seo et al., 1997; Garza-Rios et al., 2000; Davies et al., 2003; Weller et al., 2015). Another factor driving research activities related to the offshore sector (and mooring system) are the challenges related to deep water and ultra-deep water (Bhat et al., 2002; Davies et al., 2002; Haach et al., 2010; Bastos et al., 2015).

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As installations move into deeper water depths, polyester, which is the most used fiber for offshore mooring, starts to fail some demands, especially due to its elongation. This culminates in less stability for submerged and riser pipelines, and can restrict operations, or even cause excessive expenditure on the material and technology of the pipelines to make the operation possible. One possibility to improve the stability of submerged pipelines and risiers of offshore installations is to improve the mooring system by reducing the platform offset, through the use of a fiber with lower elongation.

A promising polymeric fiber for such is the high modulus polyethylene (HMPE). As can be seen in Cruz, Clain and Guilherme (2022), as a comparison criterion, polyester at break presents elongations of around 13%, while HMPE presents elongations of less than 4%. Furthermore, the HMPE mechanical strength is higher than polyester, while the linear density of HMPE is lower than that polyester. In other words, HMPE is a fiber that is lighter, more resistant, and has a higher tenacity with less elongation.

For polymeric fibers in general, the mechanical characterization is very important. Experimental studies that evaluate properties of linear density, resistance to rupture, resistance to fatigue, resistance to creep, resistance to abrasion, resistance to impact, among others, can be seen in several literatures (Louzada et al., 2016; Duarte et al. , 2019; da Cruz et al., 2020; Melito et al., 2020; Belloni et al., 2021; da Cruz et al., 2022; Tempel Stumpf et al., 2022; Cruz et al., 2023). These studies present both quantitative data of the material addressed, as well as a quantitative and qualitative analysis of a comparative nature with results from other fibers under similar tests.

Evidently, the experimental aspect is crucial in understanding synthetic fibers, given their viscoelastic characteristics associated with nonlinear behaviors, inelastic portions, and dispersions. The study of mechanical tests applied to HMPE fibers contributes to advancing our knowledge of the material and the possibilities of analysis.

This paper aims to describe the methodology for experimental tests of mechanical characterization of polymeric fibers, especially for high modulus polyethylene in: linear density, rupture, linear tenacity, creep, abrasion and cyclic load. The results point to the possibility of an offshore mooring system in HMPE, which would allow advances in ultra-deep waters, and would also provide greater stability to submerged pipelines and risers. Although the tests are on multifilaments, it is based on the already known correlation between multifilaments and offshore ropes, combined with the comparison with other results in the literature.

2. Materials and methods

2.1 Material specification

The material under study is an 800 denier high modulus polyethylene (HMPE) synthetic polymeric fiber from a Chinese manufacturer. This material, in general, has properties known in the literature (Belloni et al., 2021; Hahn et al., 2022) such as density at 0.97 g/cm3 and elongations below 4%. The chemical chain is represented by (CH2-CH2)n and its structure is long, fully extended and highly oriented molecules that provide maximum strength and rigidity. The material code is provided as J200, and has characteristics of 240 wires for a 800 denier multifilament.

Although this fiber covers other applications, such as the manufacture of unidirectional bulletproof vests (Grujicic et al., 2008; Grujicic et al., 2009; Langston, 2017), such as for fibers slings and lifting operations (Lian et al., 2023), the focus here is on HMPE fibers specific to offshore moorings, which is among the many fibers available for use in the offshore industry. The specimens used in the mechanical characterization were extracted from a virgin traceable coil of the material. Basic performance information, known as the "Manufacturers Test Report", are attached to the coil and will be used to compare results. The data reported for this HMPE fiber are shown in **Table 1**.

Table 1. Manufacturer information

	HMPE J200
Linear density	88.7 tex
Linear tenacity	3.76 N/tex
Elongation at break	3.5 %
Modulus	151.0 N/tex

2.2 Initial mechanical characterization

In this stage of initial characterization of the polymeric synthetic fiber, tests are carried out: titration or linear density (mass/length ratio), rupture test or Yarn Break Load (YBL) and linear tenacity is obtained. The titer or linear density (or tex) of the material is defined with a series of mass measurements of samples to obtain the average and standard deviation per ASTM D1577. Twenty specimens with a standard length of 1000 millimeters are used, after a stabilization time of 9 minutes, the mass value is then acquired on the precision scale. The title unit is the tex (grams per kilometer), but you can use submultiples like decitex.

The rupture test or Yarn Break Load (YBL) complies with the ISO 2062 standard, being carried out in the Instron test equipment shown in Figure 1. For the sample quantity there are 20 specimens. The specimen is manufactured with a standard length of 1000 millimeters, with a twist of 60 turns per meter. When fixed in the equipment, the effective length for testing is 500 millimeters, the rupture is then performed with a constant extension rate of 250 millimeters per minute. The unit is of force, being obtained in Newtons.

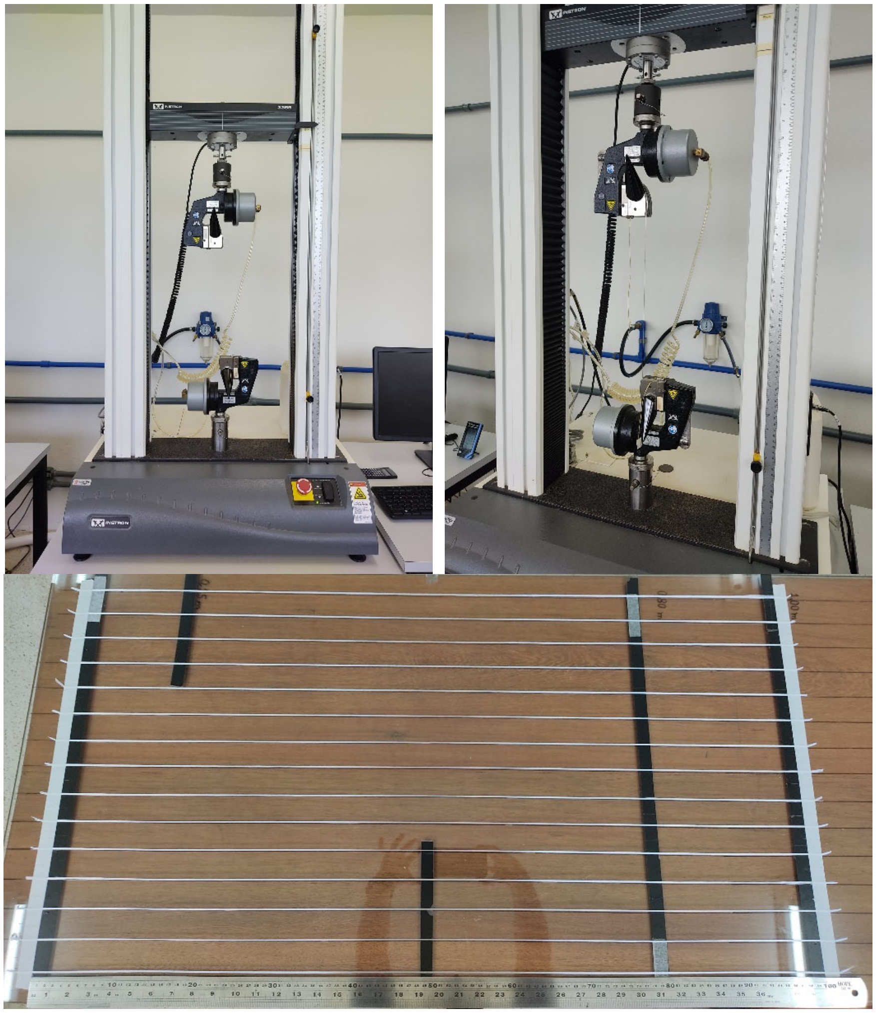

Fig. 1. Instron 3365 Equipment (left); Sample inside test machine (right); Sample preparation (below).

Linear toughness is mathematically determined with the average results obtained previously (linear density and rupture). It is calculated by dividing the rupture strength by the linear density, obtaining the linear toughness in Newtons per tex. During all tests, temperature and humidity conditions were monitored to meet ISO 139, with a temperature of 20 ± 2°C and relative humidity of 65 ± 4%.

2.2 Creep tests

ISO 18692-3 “Fibre Ropes for Offshore Stationkeeping – Part 3: High modulus polyethylene (HMPE)” standardizes the creep procedure. The standard generally specifies test methods related to high modulus polyethylene.

For high tenacity HMPE, the standard determines that the linear tenacity value must be greater than 2.5 Newtons per tex. The standard also indicates that the creep test is compatible with information provided by the manufacturer. The standard also describes the sample quantity in one characteristic sample, allowing the possibility of larger samples. To carry out the test, a visual inspection must be carried out in advance on the specimen extracted from the coil, avoiding parts with excessive ripples and rejecting specimens that already have broken filaments.

The creep test is carried out in an Instron equipment, **Fig. 1**. The specimen is initially made with a length of 1000 mm, twisted at a rate of 60 turns per meter. After fixing to the equipment, the useful length tested is 500 mm. For sample quantity of performed tests, 5 specimens were used for each group.

The creep test is strength controlled. The ramp carried out until the creep load must be smooth, being carried out at an evolution of 250 Newtons per minute. After reaching a certain load, the load is maintained so that the specimen remains fluent. The creep load groups tested for the material were: 70%, 80% and 90% of YBL, and all specimens were brought to rupture for said groups. Remembering that during all tests, temperature and humidity conditions were monitored to comply with ISO 139.

2.3 Abrasion tests

The abrasion test mechanism (Yarn-on-yarn) is designed in accordance with ASTM D6611-16 and CI 1503, with the following characteristics (**Fig. 2**): the upper pulley shafts are separated by 140 millimeters, the pulley shafts lower are 254 millimeters below a line connecting the shafts of the upper pulleys; this arrangement produces an apex angle of 34°. The crank is offset by 25 millimeters to the drive motor shaft, the geared motor drives the crank between 60 and 70 revolutions per minute, the wire must have three complete windings producing an angle between windings of 1080º. It should also be noted that during the test, the friction region is submerged in water.

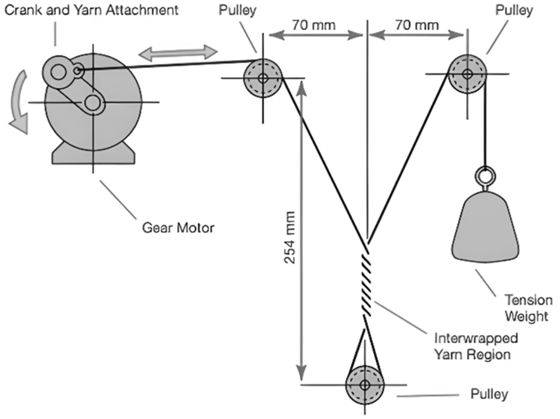

Fig. 2. Equipment layout.

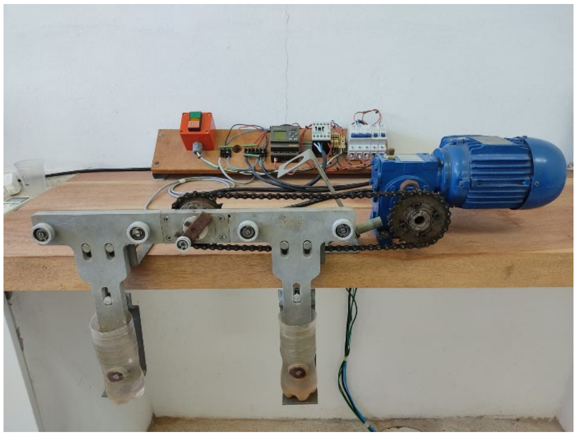

Fig. 3. Abrasion Equipment (Yarn-on-yarn).

The equipment is designed on a bench, **Fig. 3**. The abrasion cycles are counted by a Logical Programmable Controller (LPC) associated with an inductive sensor. The loads used for abrasion testing are also based on the YBL. Tests were performed for 4%, 5%, 6%, 7% and 8% YBL. For each group, the sample amount was 6 specimens.

2.4 Cyclic load tests

Unlike metals, where fatigue is associated with nucleation crack and propagation, in synthetic materials this phenomenon has different characteristics. In this case, the sensitivity to wear is increased by factors such as modulus, rate, frequency, load amplitude, temperature, relative humidity, in addition to fiber conditioning during the test (Humeau et al., 2018).

In synthetic ropes, it has already been observed that the greater the traction amplitude, the smaller the number of cycles until failure. Also, residual voltage is found after cyclic loading. And the fatigue life is directly affected by the ambient temperature. Thus, fatigue characterization is a separate field that involves load, amplitudes, frequency and temperature.

Although there is no specific standard that standardizes fatigue tests, there are some standards that deal with fatigue for wires and ropes, like ASTM D885 and API RP 2SK.

For multifilaments related to fatigue life studies, the test is often conducted until failure, under varied conditions so that fatigue life curves can be created. Other times, due to the viscoelastic characteristics of the material, the interest is not directly the failure in dynamic loading, but the evaluation of the removal of inelastic portions and the modification of the stiffness of the fibers.

For this work, the proposal is to carry out a cyclic load test (not exactly fatigue, as it does not reach rupture, and there is not a large number of cycles). This cyclic load test is controlled by force, with maximum and minimum load based on the YBL of the material, the minimum being 0% of the YBL, and the maximum 45% of the YBL, where 100 dynamic cycles are made with a frequency of 0.1 Hz The sample quantity is 3 specimens. The temperature and humidity conditions follow ISO 139. And the sample length can be adjusted, but a standard length of 250 mm is recommended. The applied method is represented in **Fig. 4**, both to represent the control per load, the number of cycles, and the repeatability of loading and unloading. The fatigue test is carried out on the Instron Electropuls E-3000 dynamic testing machine, **Fig. 5.**

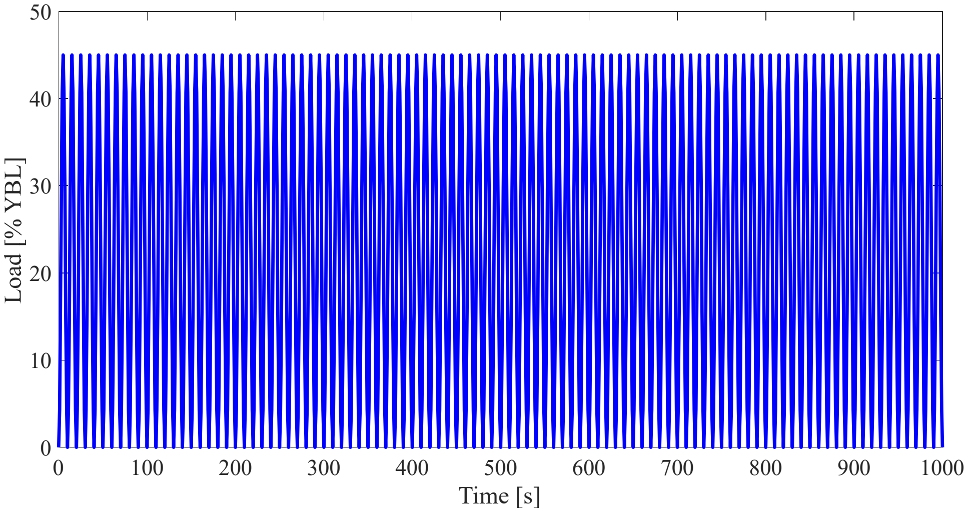

Fig. 4. Charge-Discharge for 0~45% YBL, 0.1 Hz & 10^3 cycles.

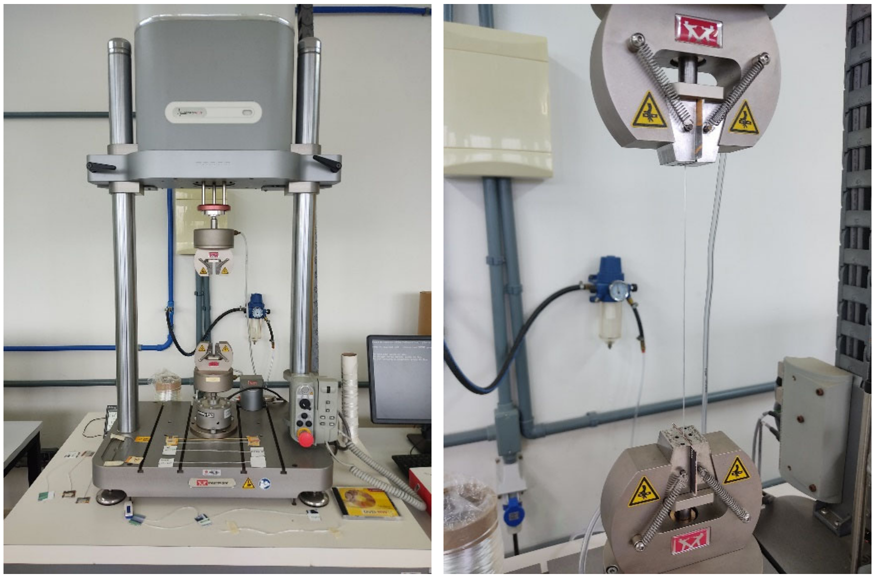

Fig. 5. Instron Electropuls E-3000 Equipment (left); Sample inside test machine (right).

3. Results

The results obtained for the initial characterization of the HMPE multifilaments are shown in Table 2, in relation to their averages and the respective standard deviation.

Table 2. Results of the characterization tests

	HMPE J200
Linear density	88.50 ± 3.40 tex
Rupture	303.54 ± 10.67 N
Linear tenacity	3.43 ± 0.26 N/tex
Elongation at break	2.67 ± 0.17 %

The breakout plot for all specimens tested in Yarn Break Load (YBL) is shown in **Fig. 6** and **Fig. 7**. The direct results observed for the analysis of HMPE fiber show a slight divergence in the linear tenacity value when comparing the values presented in **Table 1** and **Table 2**. Nevertheless, it is noteworthy that the obtained linear tenacity value, although lower than the "Test Report," is considerably higher than the standard criterion (>2.5 N/tex) and exceeds values reported in the literature for various HMPEs (da Cruz et al., 2022; da Cruz et al., 2023a), thus being a high quality product for the mechanical performance of HMPE fibers.

This high linear tenacity is reflected in the tensile strength value, proportionally greater than that of other HMPE fibers. da Cruz et al. (2023) present six fibers at the same multifilament level, and most of them have a rupture value lower than the

J200 fiber included in this study (it should be noted that proportionality must be considered, as nominally the fibers in the referenced study have a higher rupture value, but these are 1600 denier, while proportionally, for a density of 800 denier, the J200 fiber exhibits the highest rupture value).

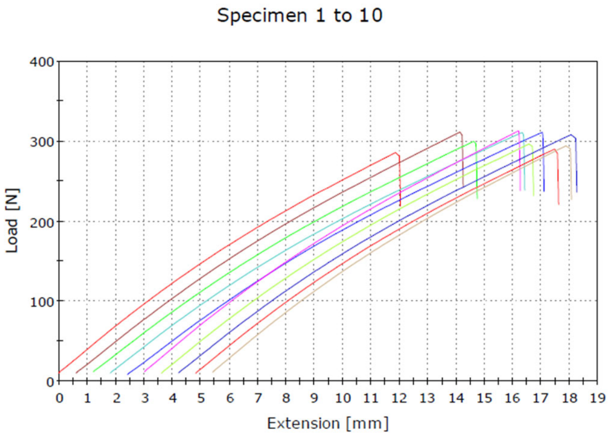

Fig. 6. Yarn Break Load results, specimen 1 to 10.

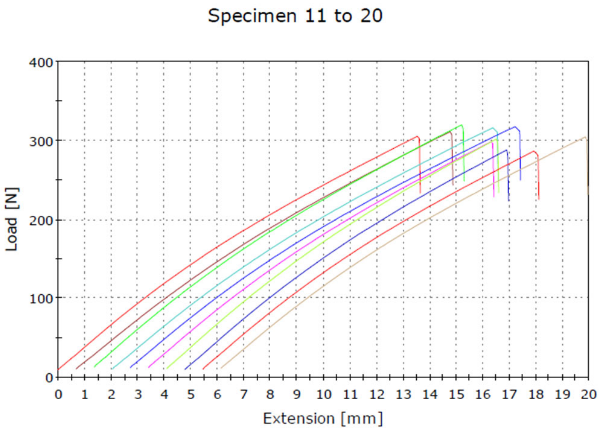

Fig. 7. Yarn Break Load results, specimen 11 to 20.

The creep and abrasion tests that follow have loads dependent on a percentage of YBL. The average rupture force divided by the acceleration of gravity "g", gives the mass that corresponds to 100% of the rupture value. Making the proper proportions, the masses and loads used for each percentage of the YBL in the creep and abrasion tests are shown in **Table 3**.

Table 3. Loads and masses for creep and abrasion

	YBL [%]	Loads [N]	Masses [kg]
Creep	70	212.48	21.660
	80	242.83	24.754
	90	273.19	27.848
Yarn-on-Yarn	4	12.14	1.238
	5	15.18	1.547
	6	18.21	1.857
	7	21.25	2.166
	8	24.28	2.475

For the creep-rupture results, **Table 4** was constructed, which compiles the average results of time and extension for the proposed loads made for the HMPE multifilament. Creep-rupture graphs for load condition are shown in **Fig. 8**, **Fig. 9** and **Fig. 10**.

Table 4. Resume of creep failure results

	Creep Time [s]	Time to rupture [s]	Extension in creep [mm]	Extension of rupture [mm]	Creep deformation [%]	Rupture deformation [%]
70 %	7675.28	7723.67	39.462	49.317	7.892	9.863
80 %	2019.10	2074.75	16.205	27.623	3.241	5.525
90 %	360.89	424.01	6.797	20.157	1.359	4.031

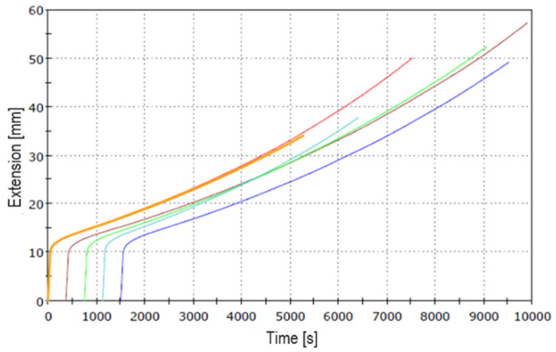

Fig. 8. Creep failure results 70%.

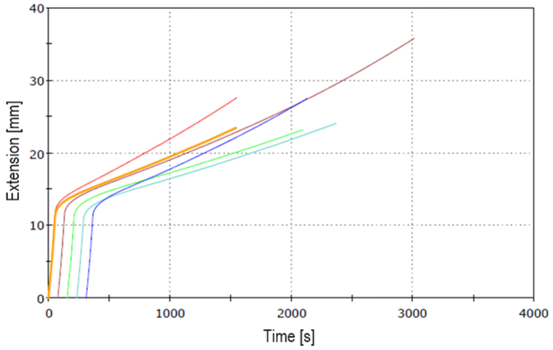

Fig. 9. Creep failure results 80%.

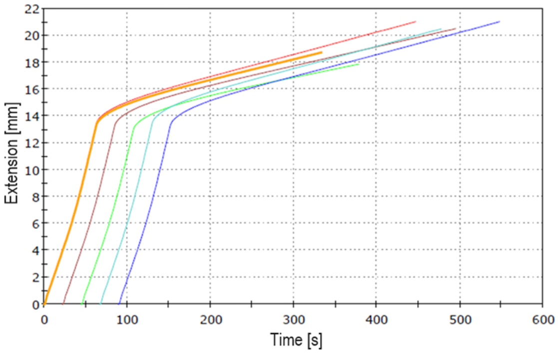

Fig. 10. Creep failure results 90%.

For the data obtained in the creep-rupture tests, the most suitable comparison is for the 80% YBL group, which provides results for the same load and temperature conditions as three other HMPE fibers in da Cruz et al. (2022). It is observed that the J200 fiber exhibits slightly inferior creep behavior; however, it is important to note that it is not classified as a 'Low Creep' fiber. Even without this designation, the creep resistance property is improved compared to previous generations of the same material, which had higher strain rates than those observed in the conducted tests (da Costa Mattos and Chimisso, 2011).

In the observational considerations of creep-rupture experiments on HMPE fibers, it should be noted that for the highest tested load (90% of the YBL in creep), the extension shows a certain linearity concerning time, while for the 70% of the YBL in creep, there begins to be a curvature. This effect is precisely due to the viscoelastic behavior of the material. In operation, a fiber resistant to creep is desired, but this viscous behavior of the material can be interesting because, as the load decreases, this curvature tends to accentuate gradually (the load is not intense enough to cause rupture, allowing the appearance of these viscous portions more pronouncedly, with increased extension over time). Offshore installations with synthetic fibers typically operate between 15 and 25% of the ropes mechanical strength (Mckena et al., 2004). This provides warning elements for the cable's integrity. Thus, for point moorings or short-duration applications, HMPE does not compromise its use due to lower creep resistance and can exhibit excellent performance due to its high mechanical strength.

It should be emphasized that creep and creep-rupture tests are crucial in characterizing viscoelastic parameters, which are common characteristics of synthetic fibers in general. In the literature, there are studies that model these viscoelastic parameters (Inn and Rohlfing, 2012; Iskakbayev et al., 2016), and specific approaches to viscous characteristics in HMPE fibers are also addressed (Huang et al., 2013; Lian et al., 2018).

For the results of the abrasion tests, **Table 5** shows the results obtained. Different from the previous tables of results that present only average values of the measurements, the abrasion table presents all 6 specimens made for each of the 5 abrasion loads, because proportionally it is the test that presents greater dispersions.

Table 5. Abrasion failure results (Yarn-on-Yarn)

YBL	4 %	5 %	6 %	7 %	8 %
Sample 1	1990	1369	878	528	365
Sample 2	1792	1590	1112	682	418
Sample 3	2240	1346	706	901	452
Sample 4	1919	1196	593	536	749
Sample 5	2213	1047	759	615	672
Sample 6	1903	1344	860	634	453
Max	2240	1590	1112	901	749
Average	2009.50	1315.33	818	649.33	518.17
Min	1792	1047	593	528	365
SD	179.87	182.39	178.02	136.66	154.32

As high-modulus polyethylene fibers have a low melting point and low thermal conductivity, they tend to break under conditions of repeated abrasion between fibers during tension-tension fatigue or bending-tension fatigue. Some studies aim to improve these characteristics (Ning et al., 2021). In the case of the experimental results presented and the use of these fibers in offshore cables, there is the benefit of abrasion occurring in water immersion. Nevertheless, polyester exhibits higher abrasion resistance than HMPE, both for polyester with Marine Finish and polyester without Marine Finish (Soares et al., 2010). Quantifying this, in the mentioned study, at 6% of the YBL, polyester averages 2000 and 1600 cycles of resistance (with and without Marine Finish, respectively), while the characterized HMPE fiber withstands 860 cycles.

With the abrasion data it is possible to plot to identify the behavior (**Fig. 11**), including building a regression curve.

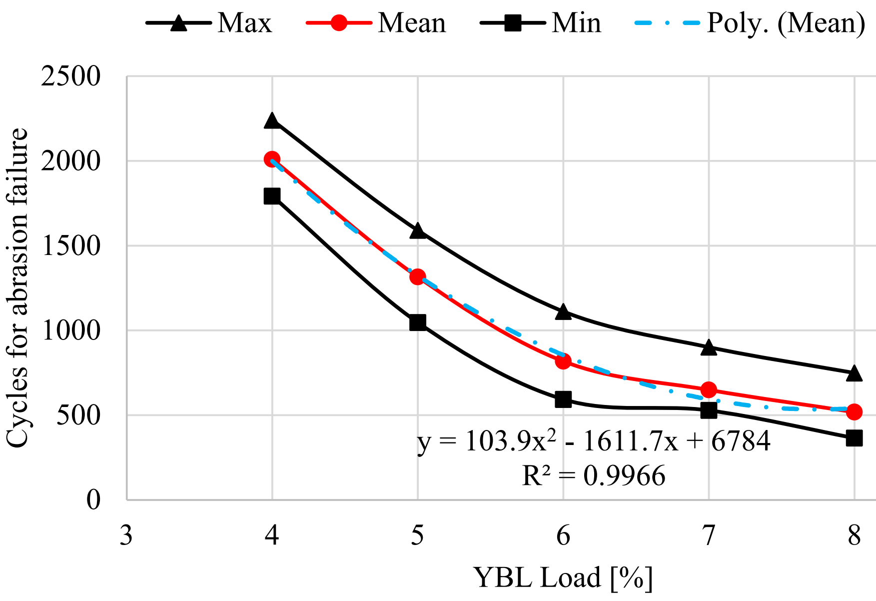

Fig. 11. Graph for abrasion failure datas.

As can be seen in **Fig. 11**, the behavior is not linear. In this case, the regression used was polynomial of order 2, obtaining a coefficient of determination (R^2) of 0.9966 and the equation indicated in **Fig. 11**. But there is an expectation that the measure that leads to lower load values, the behavior becomes asymptotic, thus modeling by a logarithmic or power model would become more adequate. The expression of the curve fit by logarithmic model as well as its coefficient of determination for the data is indicated in Eq. (1), and for the fit by power model and coefficient of determination is indicated in Eq. (2).

$$y = -2169 \cdot \ln(x) + 4884.6 \qquad R^2 = 0.9483 \tag{1}$$

$$y = 31515 \cdot x^{-1.994} \qquad R^2 = 0.9957 \tag{2}$$

For cyclic load tests, the load variation ranges from 0 to 45% of the Yarn Break Load (YBL), which, for the obtained rupture data (303.54 N), corresponds to a variation of 0 to 136.59 N. Throughout the mechanical protocol, deformation data are acquired from the specimen. With these data, it is possible to generate results approximating the hysteresis curve over the cycles (Figure 12), as well as the deformation trends at the peak of each cycle applied to the HMPE fiber (**Fig. 13**).

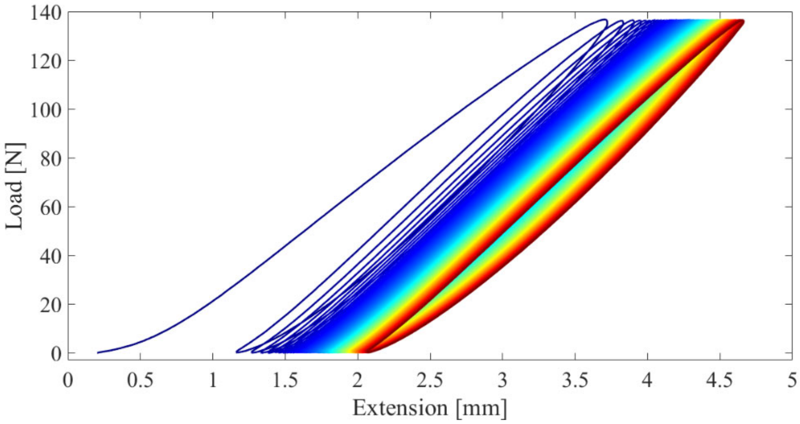

Fig. 12. Continuous force-deformation hysteresis graph throughout the cycles.

The direct observations from cyclic load results are crucial in the analysis of non-elastic portions. When examining **Fig. 12**, the force-extension mechanical hysteresis cycle shows rapid convergence. Visually, by the sixth or seventh cycle, a well-defined hysteresis cycle (closed) should be achieved, which, due to the material's characteristics, evolves over cycles with extension always more contained in the next cycle compared to the previous one. This can be visually seen in **Fig. 13**, where the evolution of deformations captured at the peak load in each cycle provides this indication. By proposing a relative difference (RD) between subsequent time steps (Equation 3), this becomes clearer. From cycle 1 to cycle 2, the evolution was 2.96%, from cycle 9 to cycle 10, the evolution was 0.49%, and even from cycle 99 to cycle 100, the evolution was 0.17%.

$$RD[\%] = \left(\frac{\varepsilon_n - \varepsilon_{n-1}}{\varepsilon_{n-1}}\right) \times 100 \quad (3)$$

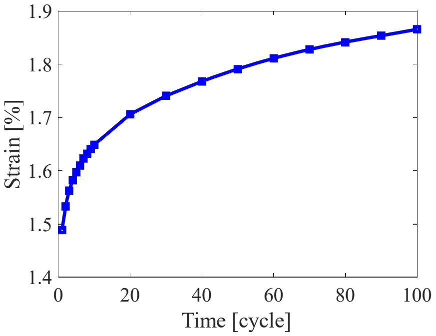

Fig. 13. Evolution of strain peaks throughout dynamic cycling.

Tempel Stumpf et al. (2022) employs a very similar methodology to simulate the constitutive behavior of various fibers in the offshore sector. In this case, the specific interest lies in the last cycle, which is the most stabilized one, with the least amount of non-elastic portions, for the various fibers studied, including HMPE. The same methodology applied to HMPE in this study was also investigated by da Cruz et al. (2023b) for numerical simulation, but in this case, it was specifically focused on polyester fibers.

4. Final Remarks

It is observed as a result of the initial characterization tests related to linear density, breakage and linear tenacity, a certain conference with other values obtained for multifilaments of high performance HMPE in the literature. The mechanical strength and low elongation at break show promising results for mooring systems made entirely of HMPE allowing advances in offshore installations for deeper waters, while allowing stability for submerged pipelines and operating risers.

On the other hand, the result of creep rupture is the mechanical test that should be more studied for high modulus polyethylene. That is because the strain rates for creep tests are high when compared to the behavior of polyester under the same percentage of YBL (Huntley and Whitehill, 1999; Vlasblom et al., 2012). In a way, creep rupture in operation is a concern of mooring systems in HMPE, usually the failure of this material is related to this phenomenon (Lian et al., 2015). Promising studies with high modulus polyethylene have been carried out for the creep field and fibers called "Low creep" have been developed and may allow the use of the fiber for offshore mooring (da Cruz et al, 2023a).

For abrasion data, the results are exploratory and experimental. The parameterization reveals little about the behavior, but it is noteworthy that there is considerable dispersion in relation to the maximum and minimum values when compared to the average. High-modulus polyethylene is not the best fiber in terms of abrasion resistance; comparatively, polyester with Marine Finish shows 2.32 times more resistance to abrasion cycles (with a reference of 6% of the YBL). However, many offshore polyester cable jackets can still be made with HMPE because it resists friction well, and the fact that it is immersed benefits its behavior. Additionally, there are HMPE fibers with finishes that enhance abrasion properties.

Regarding cyclic load results, it is observed that HMPE can quickly remove non-elastic portions, which means improving the fiber's stiffness. It might be interesting to evaluate future conditions of fatigue rupture and model the life under cyclic load for HMPE fibers.

In conclusion, it is evident that high-modulus polyethylene possesses characteristics of high strength, low elongation, high linear tenacity, good abrasion resistance, and a behavior of stiffness gain under cyclic loads. This envisions its use for total mooring of offshore structures, coupled with other factors that would allow greater stability of submerged pipelines and risers. Considering its performance, HMPE proves to be an excellent option, especially in terms of mechanical strength. It still offers avenues for continuous advancements in studies and may soon represent a substantial shift in the progress of installations in deeper waters.

References

American Petroleum Institute. (2005). API Recommended Practice 2SK, Design and Analysis of Stationkeeping Systems for Floating Structures. API: Washington.

American Society for Testing and Materials. (2014). D885/D885M Standard Test Methods for Tire Cords, Tire Cord Fabrics, and Industrial Filament Yarns Made from Manufactured Organic-Base Fibers. ASTM: West Conshohocken.

American Society for Testing and Materials. (2016). D6611-16 Standard Test Method for Wet and Dry Yarn-on-Yarn Abrasion Resistance. ASTM: West Conshohocken.

American Society for Testing and Materials. (2018). D1577-07 Standard Test Methods for Linear Density of Textile Fibers. ASTM: West Conshohocken.

Bastos, M. B., Haach, L., & Fernandes, E. B. (2015). Development of ultra-deep water FPSO mooring ropes using high modulus/high tenacity polyester yarn. In *Offshore Technology Conference Brasil* (p. D021S017R005). OTC. https://doi.org/10.4043/26224-MS

Belloni, E. da S., Clain, F. M., & Guilherme, C. E. M. . (2021). Post-impact mechanical characterization of HMPE yarns. *Acta Polytechnica*, *61*(3), 406–414. https://doi.org/10.14311/AP.2021.61.0406

Bhat, S. S., Cermelli, C. A., & Lo, K. H. (2002). Polyester mooring for ultra-deepwater applications. In *International Conference on Offshore Mechanics and Arctic Engineering* (Vol. 36118, pp. 513-518). https://doi.org/10.1115/OMAE2002-28267

Cheng, A., & Chen, N. Z. (2022). Structural integrity assessment for deep-water subsea pipelines. *International Journal of Pressure Vessels and Piping*, *199*, 104711. https://doi.org/10.1016/j.ijpvp.2022.104711

Cordage Institute. (2009). 1503 Test Method for Yarn-on-Yarn Abrasion. CI: Wayne.

Cruz, D., Silva, A., Clain, F., & Guilherme, C. (2023). Experimental study on the behavior of polyamide multifilament subject to impact loads under different soaking conditions. *Engineering Solid Mechanics*, *11*(1), 23-34. https://doi.org/10.5267/j.esm.2022.11.001

da Costa Mattos, H. S., & Chimisso, F. E. G. (2011). Modelling creep tests in HMPE fibres used in ultra-deep-sea mooring ropes. *International Journal of Solids and Structures*, *48*(1), 144-152. https://doi.org/10.1016/j.ijsolstr.2010.09.015

da Cruz, D. M., Barreto, M. A., Zangalli, L. B., Júnior, T. P., & Guilherme, C. E. M. (2023a). Experimental Study of Creep Behavior at High Temperature in Different HMPE Fibers Used for Offshore Mooring. In *Offshore Technology Conference Brasil* (p. D021S026R002). OTC. https://doi.org/10.4043/32760-MS

da Cruz, D. M., Clain, F. M., & Guilherme, C. E. M. (2022). Experimental study of the torsional effect for yarn break load test of polymeric multifilaments. *Acta Polytechnica*, *62*(5), 538–548. https://doi.org/10.14311/AP.2022.62.0538

da Cruz, D. M., da Silva Belloni, E., Clain, F. M., & Guilherme, C. E. M. (2020). Analysis of impact cycles applied to dry polyamide multifilaments and immersed in water. In *Rio Oil And Gas Expo And Conference*. https://doi.org/10.48072/2525-7579.rog.2020.199

da Cruz, D. M., Fondaik, F. P., Bastos, M. B., & Guilherme, C. E. M. (2022). Creep analysis of high modulus polyethylene (HMPE) multifilaments. In *Rio Oil And Gas Expo And Conference*. https://doi.org/10.48072/2525-7579.rog.2022.072

da Cruz, D. M., Júnior, T. L. P., de Ávila Barreto, M., Guilherme, C. E. M., & Stumpf, F. T. (2023b). Avaliação de modelos de energia para simulação numérica do comportamento mecânico de multifilamentos de poliéster. *The Journal of Engineering and Exact Sciences*, *9*(1), 15321-01e. https://doi.org/10.18540/jcecvl9iss1pp15321-01e

Davies, P., Chailleux, E., Bunsell, A., Grosjean, F., & Francois, M. (2003). Prediction of the long term behavior of synthetic mooring lines. In *Offshore Technology Conference* (pp. OTC-15379). OTC. https://doi.org/10.4043/15379-MS

Davies, P., François, M., Grosjean, F., Baron, P., Salomon, K., & Trassoudaine, D. (2002). Synthetic mooring lines for depths to 3000 meters. In *Offshore technology conference* (pp. OTC-14246). OTC. https://doi.org/10.4043/14246-MS

Del Vecchio, C. J. M. (1992). *Light weight materials for deep water moorings* (Doctoral dissertation, University of Reading).

Duarte, J. P., Guilherme, C. E. M., da Silva, A. H. M. F. T., Mendonça, A. C., & Tempel Stumpf, F. (2019). Lifetime prediction of aramid yarns applied to offshore mooring due to purely hydrolytic degradation. *Polymers and Polymer Composites*, *27*(8), 518-524. https://doi.org/10.1177/0967391119851386

Garza-Rios, L. O., Bernitsas, M. M., Nishimoto, K., & Matsuura, J. O. P. J. (2000). Dynamics of spread mooring systems with hybrid mooring lines. *Journal of Offshore Mechanics and Arctic Engineering*, *122*(4), 274-281. https://doi.org/10.1115/1.1315591

Grujicic, M., Arakere, G., He, T., Bell, W. C., Cheeseman, B. A., Yen, C. F., & Scott, B. (2008). A ballistic material model for cross-plied unidirectional ultra-high molecular-weight polyethylene fiber-reinforced armor-grade composites. *Materials Science and Engineering: A*, *498*(1-2), 231-241. https://doi.org/10.1016/j.msea.2008.07.056

Grujicic, M., Glomski, P. S., He, T., Arakere, G., Bell, W. C., & Cheeseman, B. A. (2009). Material modeling and ballistic-resistance analysis of armor-grade composites reinforced with high-performance fibers. *Journal of Materials Engineering and Performance*, *18*, 1169-1182. https://doi.org/10.1007/s11665-009-9370-5

Haach, L. F., Poitevin, D. T., & Bastos, M. B. (2010). Prospects of synthetic fibers for deepwater mooring. In *Proceedings of the Rio Oil and Gas Expo and Conference, Rio De Janeiro, Brazil* (pp. 13-16).

Hahn, G., Monteiro da Fonseca Thomé da Silva, A. H., Tempel Stumpf, F., & Marcos Guilherme, C. E. (2022). Evaluation of residual strength of polymeric yarns subjected to previous impact loads. *Acta Polytechnica*, *62*(4), 473–478. https://doi.org/10.14311/AP.2022.62.0473

Huang, W., Liu, H., Lian, Y., & Li, L. (2013). Modeling nonlinear creep and recovery behaviors of synthetic fiber ropes for deepwater moorings. *Applied Ocean Research*, *39*, 113-120. https://doi.org/10.1016/j.apor.2012.10.004

Humeau, C., Davies, P., Smeets, P., Engels, T. A. P., Govaert, L. E., Vlasblom, M., & Jacquemin, F. (2018). Tension fatigue failure prediction for HMPE fibre ropes. *Polymer Testing*, *65*, 497-504. https://doi.org/10.1016/j.polymertesting.2017.12.014

Huntley, E. W., & Whitehill, A. S. (1999). Creep-rupture models and experimental results for polyester rope. In *Oceans' 99. MTS/IEEE. Riding the Crest into the 21st Century. Conference and Exhibition. Conference Proceedings (IEEE Cat. No. 99CH37008)* (Vol. 2, pp. 681-689). IEEE. https://doi.org/10.1109/OCEANS.1999.804781

Inn, Y. W., & Rohlfing, D. C. (2012). Application of creep test to obtain the linear viscoelastic properties at low frequency range for polyethylene melts. *Applied Rheology*, *22*(1), 15260. https://doi.org/10.3933/applrheol-22-15260

International Organization for Standardization. (2005). 139 Textiles — Standard atmospheres for conditioning and testing. ISO: Geneva.

International Organization for Standardization. (2009). 2062 Textiles — Yarns from packages — Determination of single-end breaking force and elongation at break using constant rate of extension (CRE) tester. ISO: Geneva.

International Organization for Standardization. (2020). 18692-3 Fibre ropes for offshore stationkeeping — Part 3: High modulus polyethylene (HMPE). ISO: Geneva.

Iskakbayev, A., Teltayev, B., & Alexandrov, S. (2016). Determination of the creep parameters of linear viscoelastic materials. *Journal of Applied Mathematics*, *2016*. https://doi.org/10.1155/2016/6568347

Ju, X., Fang, W., Yin, H., & Jiang, Y. (2014). Stress analysis of the subsea dynamic riser baseprocess piping. *Journal of Marine Science and Application*, *13*(3), 327-332. https://doi.org/10.1007/s11804-014-1264-8

Langston, T. (2017). An analytical model for the ballistic performance of ultra-high molecular weight polyethylene composites. *Composite Structures*, *179*, 245-257. https://doi.org/10.1016/j.compstruct.2017.07.074

Lian, Y., Liu, H., Huang, W., & Li, L. (2015). A creep–rupture model of synthetic fiber ropes for deepwater moorings based on thermodynamics. *Applied Ocean Research*, *52*, 234-244. https://doi.org/10.1016/j.apor.2015.06.009

Lian, Y., Zhang, B., Ji, J., Pan, Z., Jiang, T., Zheng, J., Ma, G., Zhu, Z., Zhu, Z., & Chen, W. (2023). Experimental investigation on service safety and reliability of full-scale HMPE fiber slings for offshore lifting operations. *Ocean Engineering*, *285*, 115447. https://doi.org/10.1016/j.oceaneng.2023.115447

Lian, Y., Zheng, J., Liu, H., Xu, P., & Gan, L. (2018). A study of the creep-rupture behavior of HMPE ropes using viscoelastic-viscoplastic-viscodamage modeling. *Ocean Engineering*, *162*, 43-54. https://doi.org/10.1016/j.oceaneng.2018.05.003

Louzada, E. L. V., Guilherme, C. E. M., & Stumpf, F. T. (2016). Evaluation of the fatigue response of polyester yarns after the application of abrupt tension loads. *Acta Polytechnica CTU Proceedings*, *7*, 76–78. https://doi.org/10.14311/APP.2017.7.0076

McKenna, H. A., Hearle, J. W., & O'Hear, N. (2004). *Handbook of fibre rope technology* (Vol. 34). Woodhead publishing.

Melito, I., Belloni, E. S., & Bastos, M. B. (2020). Effects of mechanical degradation on the stiffness of polyester yarns. In *Rio Oil and Gas Expo and Conference* (Vol. 20, pp. 176-177). https://doi.org/10.48072/2525-7579.rog.2020.176

Ning, F., He, G., Sheng, C., He, H., Wang, J., Zhou, R., & Ning, X. (2021). Yarn on yarn abrasion performance of high modulus polyethylene fiber improved by graphene/polyurethane composites coating. *Journal of engineered fibers and fabrics*, *16*, 1558925020983563. https://doi.org/10.1177/1558925020983563

Reda, A., Sultan, I. A., Howard, I. M., Forbes, G. L., & McKee, K. K. (2018). Pipeline walking and anchoring considerations in the presence of riser motion and inclined seabed. *International Journal of Pressure Vessels and Piping*, *162*, 71-85. https://doi.org/10.1016/j.ijpvp.2018.01.003

Seo, M., Wu, H. C., Chen, J., Toomey, C. S., & Backer, S. (1997). Wear and fatigue of nylon and polyester mooring lines. *Textile research journal*, *67*(7), 467-480. https://doi.org/10.1177/004051759706700701

Soares, S. S., Fortuna, V., & Chimisso, F. E. G. (2010). Yarn-on-yarn abrasion behavior for polyester, with and without marine finish, used in offshore mooring ropes. In *Proceedings of "9th YSESM" Youth Symposium on Experimental Solid Mechanics* (p. 60). Gruppo Italiano Frattura.

Tempel Stumpf, F., Marcos Guilherme, C. E., Magalhães da Cruz, D., Monteiro da Fonseca Thomé da Silva, A. H., & Briguet Bastos, M. (2022). A general constitutive model for the numerical simulation of different synthetic fibres used in offshore mooring. *Ships and Offshore Structures*, 1-7. https://doi.org/10.1080/17445302.2022.2116766

Vlasblom, M., Boesten, J., Leite, S., & Davies, P. (2012). Creep and stiffness of HMPE fiber for permanent deepwater offshore mooring. In *2012 Oceans-Yeosu* (pp. 1-7). IEEE. https://doi.org/10.1109/OCEANS-Yeosu.2012.6263399

Wang, Y., Chen, H., Li, N., An, W., Lim, F., Wang, C., & Estefen, S. F. (2021). The motion response and hydrodynamic performance comparisons of the new subsea suspended manifold with two mooring scenarios. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *43*, 1-16. https://doi.org/10.1007/s40430-021-02851-7

Weller, S. D., Johanning, L., Davies, P., & Banfield, S. J. (2015). Synthetic mooring ropes for marine renewable energy applications. *Renewable energy*, *83*, 1268-1278. https://doi.org/10.1016/j.renene.2015.03.058