

EXPERIMENTAL STUDY OF THE TORSIONAL EFFECT FOR YARN BREAK LOAD TEST OF POLYMERIC MULTIFILAMENTS

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ABSTRACT.

Polymeric multifilaments have gained a significant interest in recent decades. In the studies of mechanical characteristics, although there are different types of tests, such as rupture, abrasion, creep, impact and fatigue, it can be said that the main mechanical characterisation is the tensile rupture strength (Yarn Break Load, YBL), which also serves as a parameter for other tests. The objective of this work is to evaluate the results of breaking strength under different torsional conditions in polymeric multifilaments and to determine optimal twists for failures. The test were carried out with the following materials: polyamide, polyester, and high modulus polyethylene (HMPE), and for torsional conditions: 0, 20, 40, 60, 120, 240, and 480 turns per metre. As a result, for these torsion groups, curves were obtained for the three materials that present an optimal point of maximum rupture value, which was also experimentally proven. The twist that optimises the breaking strength of HMPE is 38 turns per metre, 56 turns per metre for polyester, and 95 turns per metre for polyamide. The twist groups that exceed the optimal torsion have a deleterious effect on the material, where the multifilament ceases to be homogeneous and starts to create an excessive "spring effect". The results found differ from the recommendation of the standard that regulates the YBL test, and thus, a relationship is built between groups of optimal torsion and linear density that provides evidence that the increase in linear density causes the optimal torsion for rupture to also increase, while the standard places a condition of 30 turns per metre for linear densities greater than 2200 dtex, and 60 turns per metre for linear densities less than 2200 dtex. In addition to optimal torsion values, this conclusion is paramount, the test procedure makes a general recommendation that does not optimise the breaking strength.

KEYWORDS: Yarn Break Load, twist effect, maximum breaking strength, polymeric multifilaments.

1. INTRODUCTION

The last few decades have provided significant advances in the field of material engineering and its applications. There has been a significant increase in academic production and commercial focus on polymers [1]. It is noteworthy that over time, some of the polymers could be produced at low cost with very similar properties, and even superior to those of natural ones [2]. Thus, polymers have become, in certain applications, a viable and promising alternative to classic engineering materials.

In technical terms, polymers have several advantages as compared to other materials. Highlights are: low specific weight, high toughness (sometimes similar to metallic materials), good vibration dampening, low friction coefficient, thermal insulation, and high corrosion resistance. Their limitations are related to low stiffness, lower levels of hardness and resistance to abrasion, and heat sensitivity [3].

Synthetic polymers, when extruded, have a stretch orientation to provide textile yarns [4]. Due to this elongation in fabrication, the ultimate tensile strength becomes greater, also having an effect of reducing the

maximum elongation. The mechanism responsible for this improved performance is the orientation of the polymeric chains, with a possible formation of oriented crystals and a reduction of the amorphous phase [5].

One of the prominent uses of such polymeric materials is in offshore mooring systems, these synthetic fibre ropes have replaced traditional steel ropes due to their better properties in the marine environment and low weight [6]. There is a constant development of mooring ropes; since it is desired that they are more rigid to guarantee limits on the movement of floating units, their mechanical performance is fundamentally studied [7, 8].

On offshore moorings, the synthetic polymeric multifilaments for ropes can be made from different materials, but polyamide, polyester and high modulus polyethylene (HMPE) stand out. Polyamide can be highlighted by recent studies in mooring for Offshore Energy Conversion Systems, such as for FOWT floating wind turbines [9]. Polyester is a material already established in offshore mooring systems, it can be said that it is the most used in these applications, and studies that address it have excellent references in the

literature [10]. High modulus polyethylene (HMPE), however, is a newer material, also more expensive, but it has excellent mechanical performance and there are studies for Mobile Offshore Drilling Unit [11, 12].

For mechanical characterisation of polymeric materials, the work carried out with multifilaments stands out, where the conditions of use involve multiple variables, such as temperature, humidity, and types of loads (static, sudden, cyclic). Predicting the behaviour of these materials is a challenge due to their non-linear characteristics [13]; this complexity means that much of the research is carried out experimentally [14].

From this mechanical characterisation carried out in several researches with polymeric multifilaments, the tensile rupture (Yarn Break Load, YBL) stands out as the main one. This is because YBL serves as a parameter for several other mechanical characterisation tests, such as impact, creep, abrasion, fatigue, quasi-static stiffness, and dynamic stiffness. As load, they usually use a specific percentage of the standard YBL breaking load, as seen in several works that attest YBL as a parameter for performing other mechanical characterisation tests on multifilaments [15–19].

ISO 2062 standard regulates the execution of the Yarn Break Load test. In this standard, several parameters are determined, but no requirement is stated about the twist that must be applied to the multifilament. Only a torsional recommendation exists in the standard norm based on the dTex (linear density). Due to this standard, most of the papers that show the YBL in the experimental data use either 60 twists per metre or no twists at all. To provide break values (YBL) that serve as a reference for each material, the results from the cited literature can be used, [15] for HMPE, [16] for polyamide, and [17] for polyester.

Furthermore, a study on torsional effect in aramid and LCP yarns can be mentioned [20]. The results show that yarn strength can be improved with a slight twist, but a high degree of twist damages the fibres and reduces the yarn's tensile strength. The approach defined in the study by Rao & Farris [20] is based on torsional angles and shows a general tendency that there is an ideal torsional angle group for each material to achieve a maximum strength.

Thus, the aim of this study is, through an experimental approach, to study the torsion effect on Yarn Break Load (YBL) tests, which are the main test used for mechanical characterisation of multifilaments: in particular analysing the effects on the values of breaking force. The hypothesis is that, as found in [20] for aramid multifilaments, there is a torsion group that optimises the breaking strength for polyamide, polyester, and HMPE.

2. MATERIALS AND METHODS

2.1. MULTIFILAMENT MATERIALS AND TORSION CONDITIONS

In this study, the following materials are analysed: polyamide, polyester, and high modulus polyethylene. The materials tested were characterised by measuring their linear density and breaking load according to current standards, as shown in Sections 2.2 and 2.3.

Each material is initially tested with the following twist group: 00 (no torsion), 20, 40, 60, 120, 240 and 480 turns per metre.

Also, all tests followed standard atmosphere determinations of ISO 139:2005. The specimens are conditioned during the test with a temperature of $20 \pm 2^\circ\text{C}$ and a relative humidity of $65 \pm 4\%$ [21].

2.2. LINEAR DENSITY TEST, TEX

In the characterisation methodology of each of the multifilament materials, the weight by length is very important, even as a parameter to determine the linear tenacity of the multifilament. The density linear test (mass/length ratio) was performed for each material with a series of 10 specimens to obtain the mean and standard deviations according to ASTM D1577 [22].

The same procedure was performed for all materials: polyamide, polyester, and HMPE. For a sample with a length of $1000 \pm 1\text{ mm}$, the mass was measured on a highly accurate balance with a resolution of 0.0001 grams. For each sample, a 3-minute stabilisation period was set before recording the mass data indicated by the balance. Using the mass and length data, the linear density in grams per metre was determined. It should be highlighted that the unity usually appears in the literature in tex [g/km], and can also be presented in submultiple notation as decitex [dtx].

2.3. YARN BREAKING LOAD TEST

The multifilament break test follows the methodology of the ISO 2062:2009 standard and is called Yarn Break Load (YBL) [23]. The main parameters of the test being: tested useful length – 500 millimetres, speed – 250 millimetres per minute, and environmental standard ISO 139:2005. The Yarn Break Load test gives the breaking value as well as the maximum elongation of the tested specimen. This result is also important to determine the linear tenacity of the multifilament. Breakage tests were performed on 12 specimens for each of the 7 torsion groups and for each of the 3 materials, resulting in 252 specimens. Data were statistically filtered using Box-plots, leaving 8 values for each group that characterise the mean of the required condition and make up the standard deviation. In the box-plot tool, values that differ greatly from the set are outside an accepted range. These atypical and extreme values are known as outliers and are excluded from the treatment [23].

2.4. CURVE PARAMETERIZATION FOR OPTIMAL POINT

In the work of Rao & Farris [20], an optimal point of twist angle is presented. The expectation that something similar will occur in relation to the torsion groups in turns per metre is what motivates the parameterisation of the curve to an optimal point. Theoretically, increasing the twister condition increases the breaking strength to an optimal point, and increasing the twist any further decreases the breaking strength.

With the rupture results for each of the torsional groups, graphs of the torsional groups versus YBL were plotted, where the axis x corresponds to the twist value and the axis y corresponds to the rupture strength. Then, the optimal point is determined by three sets of discrete data, for each of the groups tested: the highest breaking strength data are used, also taking into account the groups immediately before and immediately after. It should be noted that the non-linear characteristics of polymeric materials are what hinder a general approach to the results. Furthermore, it would be very difficult to predict a curve with a satisfactory coefficient of determination that passes through all 7 or 8 discrete points for each material.

With these 3 sets of data, it is possible to perform a quadratic regression and determine a second degree polynomial that passes through the 3 points. In fact, this determination is a precise mathematical methodology that makes a perfect fit. Since R^2 represents a quantitative measure to predict whether a given mathematical model is satisfactory for the described behaviour, in this case, it forces a perfect fit, an R^2 equal to 1 [24]. By definition, the maximum and minimum points of a given function are equivalent to a first derivative of the function equal to zero, and this will be able to provide the ideal torsional groups for maximum breaking strength for each of the materials [25]. After finding the ideal twist point, all materials were tested again for this ideal twist condition to verify the experimental YBL value with the one obtained mathematically.

2.5. RELATIONSHIP BETWEEN OPTIMUM TWIST AND LINEAR DENSITY

The recommendation of the standard that regulates the Yarn Break Load test, ISO 2062:2009 is: “A twist of 60 ± 1 turns/m for yarns below 2200 dtex and a twist of 30 ± 1 turns/m for yarns above 2200 dtex are recommended. Other twist amounts may be allowed on agreement of the interested parties” [26].

It is not a requirement of the standard, but based on that recommendation, it is possible to infer that the optimal torsion group is a function of the linear density (Tex) of the material. Based on this and taking into account the optimal experimental results, perhaps it is possible to make a mathematical model for torsion per metre as a function of the linear density value

in Tex [g/km]. The methodology used is the least-square method associated with the concept of the best coefficient of determination, that is, $R^2 = 1$ [24, 27]. It should be emphasized that this step depends on the experimental results and on the aforementioned methodology itself.

3. RESULTS AND DISCUSSIONS

3.1. LINEAR DENSITY FOR MULTIFILAMENTS

The results of linear density measurements are shown in Table 1 for each material measurement series. It is observed that polyamide is the material with the highest linear density, while the high modulus polyethylene is the material with the lowest linear density; it should be noted that the difference linear density between these two materials is significant.

The standard deviation (SD) is very satisfactory. The results show the linear density values in tex [g/km] for each of the respective materials: 284.4 tex for polyamide, 225.5 tex for polyester, and 185.4 tex for high modulus polyethylene.

For a comparison, and even validation, results from the literature can be cited for each of the materials. In [16], the linear density for the polyamide was 284.6 tex. For polyester, in [17], the value of 233.8 tex can be found. And for the HMPE, in [15], a linear density of 176.4 tex was found.

	Polyamide	Polyester	HMPE
Average	0.2844	0.2255	0.1854
SD	0.0011	0.0006	0.0009

TABLE 1. Linear density results in grams per metre [g/m].

3.2. YARN BREAKING LOAD FOR TORSION GROUPS

For the Yarn Break Load criterion, the breaking force is used for each of the twist groups. Table 2 shows the mean and SD for YBL of the 8 sets of filtered data, as described in Section 2.3, for each group of torsion.

Although there is no data in the literature for all torsional conditions, the results presented in Table 2 can be compared to specific literature cited in the introduction [15–17]. In the reference works, a breaking force for HMPE of 500.84 Newtons with a standard deviation of 16.37 Newtons was measured [15], but the torsion used was not specified, although the need for adherence to the standard suggests that it was 60 turns per metre. For polyamide, the average breaking strength found for an untwisted condition was 210.47 N with a standard deviation of 3.78 N [16]. A value reference for YBL polyester can be an average breaking force of 174.04 N with a standard deviation of 3.20 N for a twist condition of 60 turns per metre [17]. As can be seen, they are numerically different but similar values in a very consistent way. These

Torsion [rev/m]	Polyamide		Polyester		HMPE	
	Maximum Load [N]	Strain [%]	Maximum Load [N]	Strain [%]	Maximum Load [N]	Strain [%]
0	210.08 ± 3.90	17.68 ± 1.00	172.36 ± 2.48	12.52 ± 0.17	467.17 ± 10.74	2.53 ± 0.12
20	214.31 ± 2.50	17.19 ± 0.61	176.58 ± 4.23	13.15 ± 0.48	532.00 ± 8.15	2.81 ± 0.09
40	218.45 ± 0.72	19.81 ± 0.33	179.14 ± 1.17	13.50 ± 0.30	546.45 ± 5.47	2.96 ± 0.04
60	220.32 ± 1.82	19.68 ± 0.32	181.34 ± 2.18	13.29 ± 0.28	522.60 ± 7.85	2.85 ± 0.05
80	-	-	176.56 ± 1.12	12.91 ± 0.30	-	-
120	221.15 ± 1.61	21.17 ± 0.69	175.62 ± 2.29	13.24 ± 0.44	474.16 ± 21.67	2.96 ± 0.17
180	210.40 ± 2.49	21.49 ± 0.57	-	-	-	-
240	190.87 ± 4.72	20.39 ± 1.11	151.66 ± 4.53	13.76 ± 0.38	193.93 ± 21.13	3.24 ± 0.25
480	95.39 ± 2.85	28.03 ± 2.70	67.03 ± 3.08	16.15 ± 1.71	94.25 ± 13.44	7.78 ± 1.05

TABLE 2. Yarn Break Load results for polyamide, polyester and HMPE

sensitive differences can even be justified by the coil manufacturer or polymerisation method. Thus, the values presented in Table 2 are values verified in the literature in coherent ranges for each material (mainly for untwisted groups and with 60 turns per metre).

Of the initial 7 torsion groups, the 80-turns-per-metre group for polyester and the 180-turns-per-metre group for polyamide were added, as can be seen in Table 2. The reason for these additions is due to the higher tensile strength in the group immediately preceding the aggregate, the intention was to verify the behaviour of the breaking force for some marginally intermediate group that would allow interpretations, since in relation to the initial values the torsion gaps were large. There is also the intention of verifying an increasing and then decreasing behaviour, because the absence of a hold level confirms a result similar to that of [20], that is, there is a maximum point that optimises resistance, quoted for torsional angle in the literature and for a torsional ratio in turns per metre in the present work.

The results can be graphically represented for each material, Figure 1 for polyamide, Figure 2 for polyester and Figure 3 for HMPE.

There is a torsional group that provides the highest break value in the yarn break load test, which differs for each material. For polyamide, the maximum break value is 221.15 Newtons for a twist of 120 turns per metre, polyester breaks at 181.34 Newtons for a twist of 60 turns per metre, and for HMPE, the maximum break is 546.45 Newtons for a twist of 40 turns per metre.

In the table and graphs, there is important information about stretching. An increasing trend towards elongation is observed. At certain points, the mean even decreases, but if the standard deviation is considered, it can be said that there is an increase in elongation as more twist is added to the specimen.

The addition of torsion promotes a densification of the multifilament, the effect of this torsion is man-

ifested in the elongation in what can be called the “spring effect”. As the “spring effect” increases, the elongation increases in a contained manner, until reaching the point in which the multifilament starts to fold in on itself. In approximately 200 or 240 turns per metre, when this “self-folding” of the multifilament occurs (indications in red circles in Figure 4b), the elongation data grows exponentially for the YBL test. Understanding that this more expressive increase in elongation is not a characteristic of the material, but is the removal of excessive “self-folding” torsion through traction.

In the rupture graph, this removal of “self-folding” is evident by the abrupt decays that occur during the test, taking away the visual homogeneity of the graph, Figure 5.

These groups of excessive elongations also appear to be the groups with the lowest breaking strength. What happens is that the excessive twist promotes shear forces, so a much larger amount of twist promotes more shear forces in the multifilament when it is pulled, and therefore the break value is lower.

It is noteworthy that the effect of any torsion group has an important characteristic from the point of view of homogenising the moment of rupture, even due to the effect of densifying the multifilament. For all materials in this study, this homogeneity in rupture can be observed for a group that has the torsion. Taking polyamide as an example, in Figure 6 and Figure 7, the untwisted and 20-turns-per-metre graphs are displayed respectively.

In Figure 6, this rupture is seen unevenly, and in Figure 7, where there is a torsion in the specimen, the rupture is much more homogeneous.

3.3. DETERMINATION OF THE OPTIMAL TORSION GROUP

From the results already shown, it is found that there is an optimal group for each material. As described in Section 2.4, for each material and its discrete data

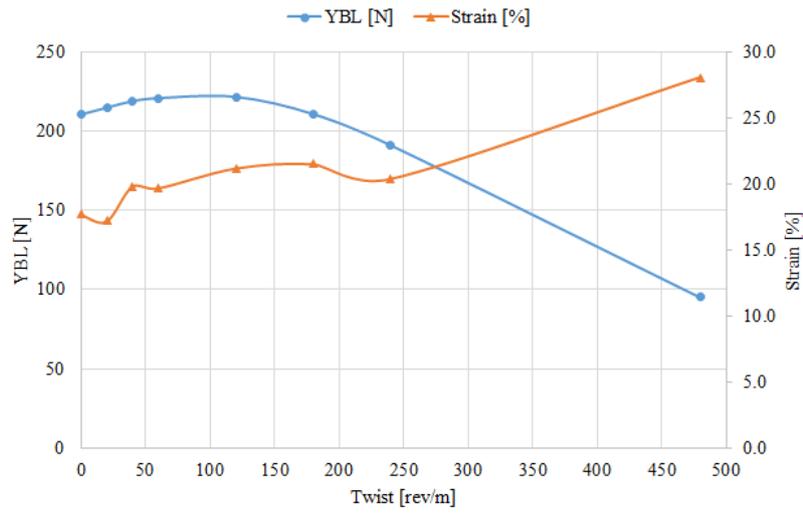


FIGURE 1. Twist x YBL for polyamide.

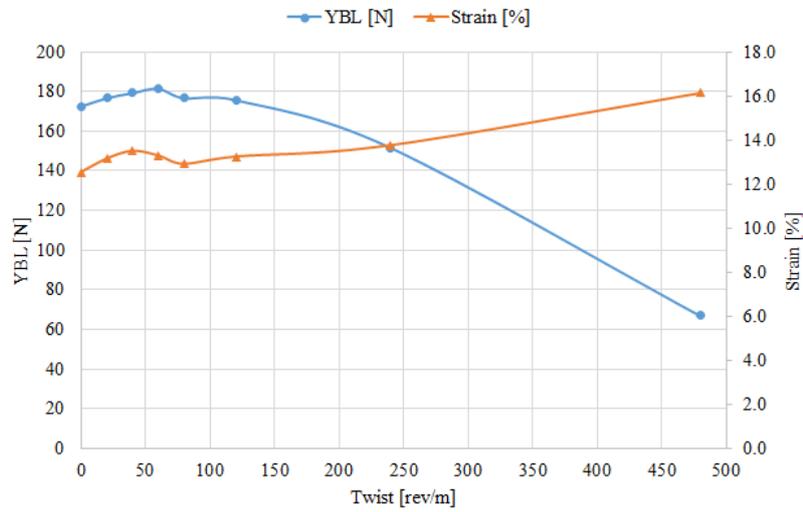


FIGURE 2. Twist x YBL for polyester.

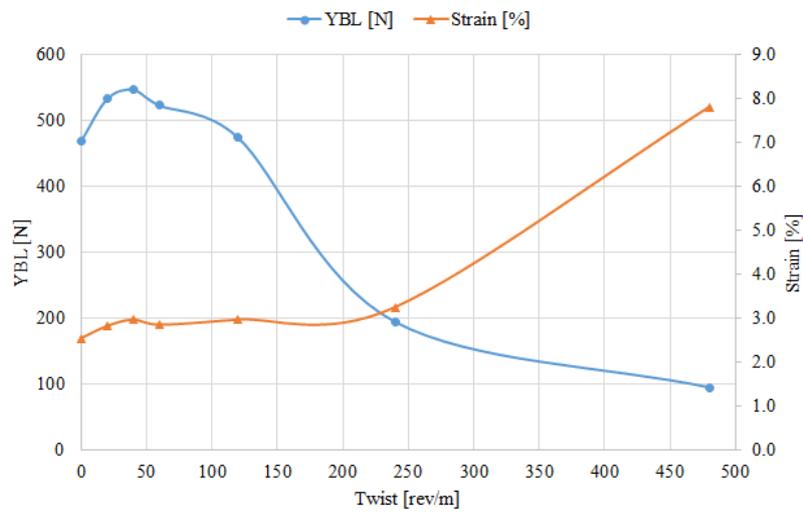


FIGURE 3. Twist x YBL for HMPE.

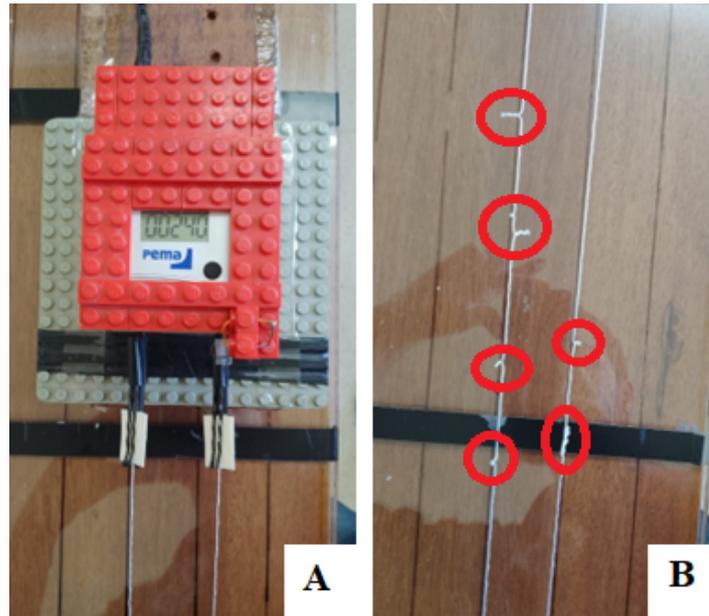


FIGURE 4. (A) Counter-turn display in 240 turns per metre, (B) Appearance of "self-folding".

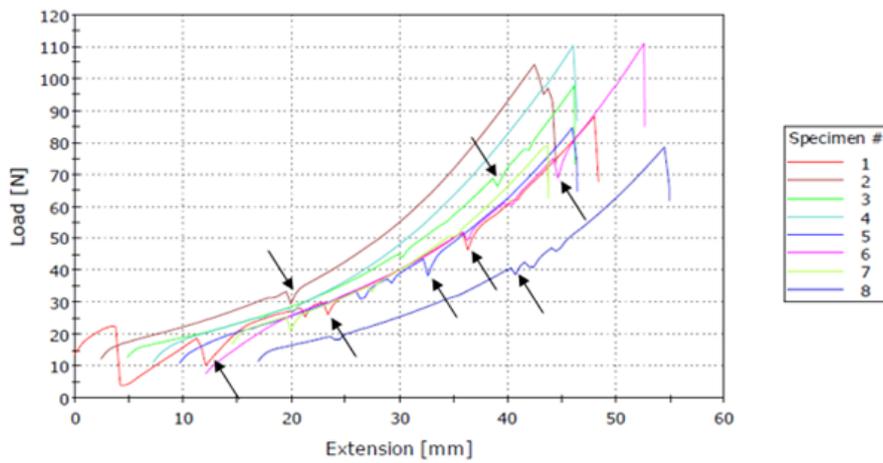


FIGURE 5. Graphic effect of self-folding removal on the HMPE specimen.

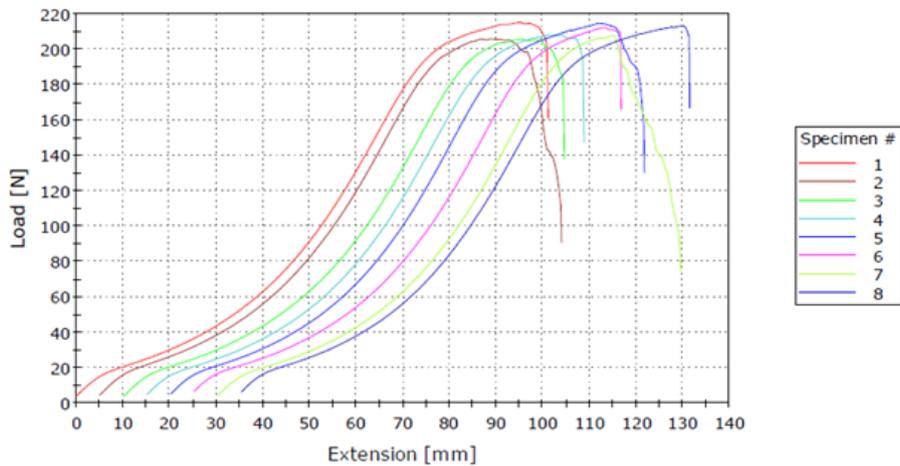


FIGURE 6. Graph of the YBL test results for polyamide, 00 turns per metre.

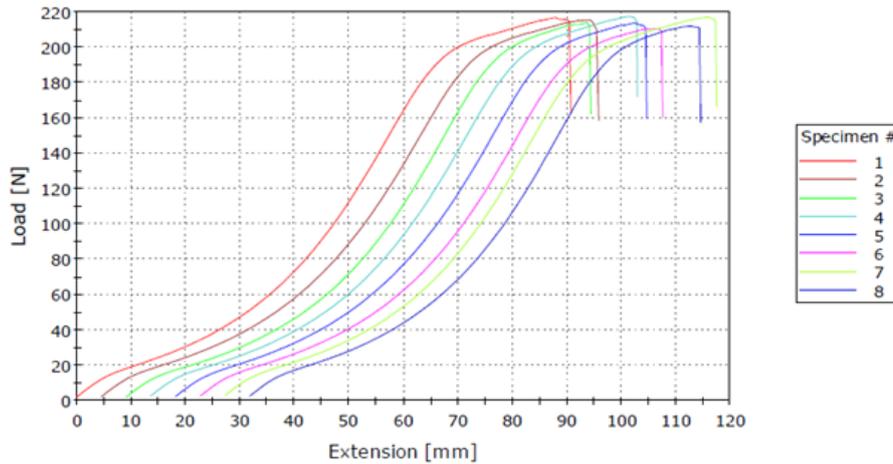


FIGURE 7. Graph of the YBL test results for polyamide, 20 turns per metre.

set, a system of equations was created. The matrix condition was solved by Gauss, thus providing the coefficients of the quadratic model of Equations (1), (2) and (3).

For polyamide, Equation (1):

$$y = -0.0016 \cdot x^2 + 0.3031 \cdot x + 207.92. \quad (1)$$

For polyester, Equation (2):

$$y = -0.0087 \cdot x^2 + 0.9819 \cdot x + 153.82. \quad (2)$$

For HMPE, Equation (3):

$$y = -0.0479 \cdot x^2 + 3.5945 \cdot x + 479.26. \quad (3)$$

The approximated curves, developed by the quadratic model, are shown in Figure 8 (polyamide), Figure 9 (polyester) and Figure 10 (HMPE).

The first derivative of a function equal to zero represents the maximum and/or minimum points of the function [25], as in all models, there is a downwards concavity of the parabola, it is the maximum of the function which, when equal to zero, will result in the optimal torsion group for the maximum breaking value.

For polyamide, Equation (4):

$$\frac{d}{dx} [-0.0016 \cdot x^2 + 0.3031 \cdot x + 207.92] = 0. \quad (4)$$

For polyester, Equation (5):

$$\frac{d}{dx} [-0.0087 \cdot x^2 + 0.9819 \cdot x + 153.82] = 0. \quad (5)$$

For HMPE, Equation (6):

$$\frac{d}{dx} [-0.0479 \cdot x^2 + 3.5945 \cdot x + 479.26] = 0. \quad (6)$$

Thus, the optimal torsional groups, rounded to whole numbers, are: 95 turns per metre for polyamide, 56 turns per metre for polyester, and 38 turns per metre for HMPE. With these torque values, it is possible

to return to the respective models, Equations (1), (2) and (3) respectively, and determine the expected force value for the optimal point.

For polyamide, Equation (7) is developed:

$$y(95) = -0.0016 \cdot (95)^2 + 0.3031 \cdot (95) + 207.92 = 222.2745 \text{ [N]}. \quad (7)$$

For polyester, Equation (8) is developed:

$$y(56) = -0.0087 \cdot (56)^2 + 0.9819 \cdot (56) + 153.82 = 181.5232 \text{ [N]}. \quad (8)$$

For HMPE, Equation (9) is developed:

$$y(38) = -0.0479 \cdot (38)^2 + 3.5945 \cdot (38) + 479.26 = 546.6834 \text{ [N]}. \quad (9)$$

Observing the rupture forces obtained for optimal mathematical groups, the values are higher than those of the works taken as reference [15–17], and it is possible to infer the improvement in strength with a given twist per metre. It is important now to verify if the experimental breakage values are coincident for the same optimal groups obtained by the mathematical models above.

3.4. YBL RESULTS FOR OPTIMAL TORSION

Having determined the appropriate ideal torsional groups, as well as the expected breaking force, it is possible to verify experimentally whether these torsions correspond to the maximum breaking response in the yarn breaking load test. The results of these tests are presented in Table 3, which contains the experimental results and the results of the predicted force in the quadratic mathematical model.

Very low relative differences in maximum breaking load occurred between the square model and the experimental data, which confirms that these are the ideal torsional groups for each material.

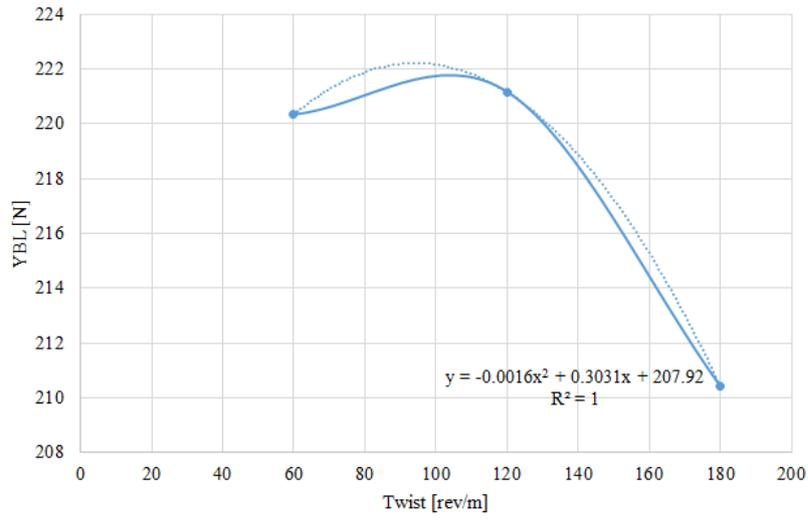


FIGURE 8. Square model for optimal stitch, polyamide.

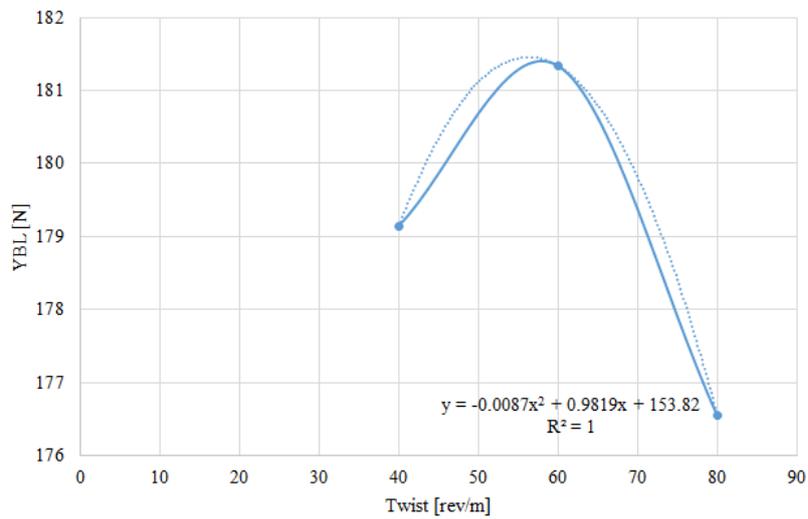


FIGURE 9. Square model for optimal stitch, polyester.

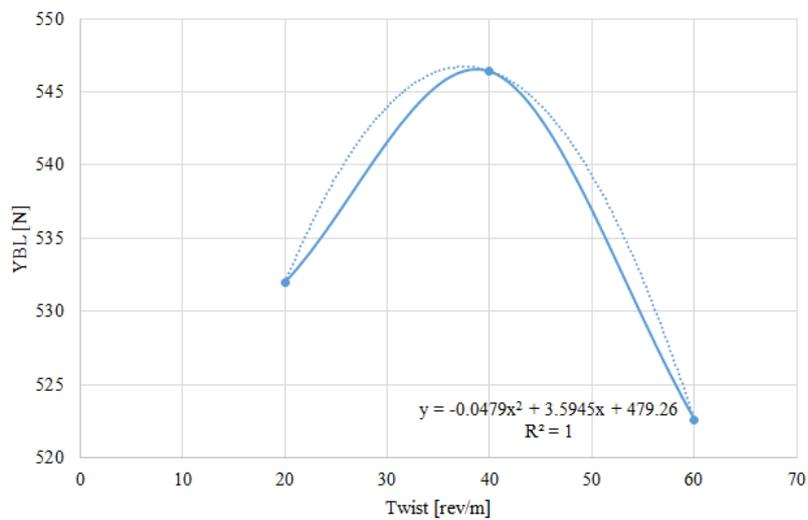


FIGURE 10. Square model for optimal stitch, HMPE.

	Square Model	Experimental	
	Maximum Load [N]	Maximum Load [N]	Strain [%]
Polyamide - 95 [rev/m]	222.2745	222.45 ± 1.23	20.60 ± 0.40
Polyester - 56 [rev/m]	181.5232	182.68 ± 2.11	13.24 ± 0.36
HMPE - 38 [rev/m]	546.6834	548.60 ± 15.95	2.87 ± 0.08

TABLE 3. Experimental results for the optimal torsion group of each material.

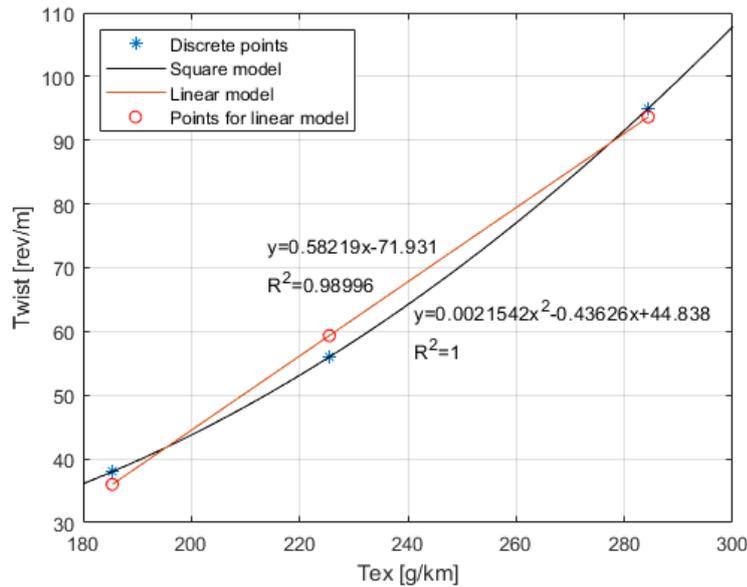


FIGURE 11. Mathematical model, optimal torsion as a function of linear density.

3.5. CURVE RATIO FOR OPTIMAL TORSION AND TEX

As described in Section 2.5, and considering that there are reasons for the optimal torsion to be related to the linear density, a mathematical model related these variables. There are, therefore, 3 discrete data sets, relating to polyamide (284.4 Tex; 95 rev/m), polyester (225.5 Tex; 56 rev/m) and HMPE (185.4 Tex; 38 rev/m). Thus, to force a perfect coefficient of determination ($R^2 = 1$), a square model of these discrete data sets is made. The mode system can be set up in its matrix form to determine the coefficients of the quadratic equation, and can be solved by the Gauss method, obtaining Equation (10).

$$y = \frac{16790}{7794237} \cdot x^2 - \frac{3400351}{7794237} \cdot x + \frac{10590325}{236189}, \quad (10)$$

$$y \cong 2.1542 \cdot 10^{-3} \cdot x^2 - 0.43626 \cdot x + 44.838.$$

The coefficient that accompanies the square term is very small, which allows a linear model approximated by the method of least squares to be satisfactory. The programming was done in Octave, and the curves, equations and coefficients of determination indicated in Figure 11 were obtained.

The linear model is obtained using the least-square method [27] and returns the equation of the straight

line shown in Equation (11).

$$y = 0.58219 \cdot x - 71.931 \quad (11)$$

As can be seen, the model allows to consider the interrelationship between the linear density and a certain optimal torsion. However, if the norm standard recommendation is observed, it states that a reduction in torsion leads to an increase in linear density, and in the constructed model, exactly the opposite is verified, that the increase in linear density causes the optimal torsion to also increase for the maximum break value. In other words, the standard recommendation can contribute to a lower performance of polymeric multifilaments, but it should always be emphasized that the standard norm recommendation is generalised, here, we are describing a model for specific synthetic polymeric materials.

4. CONCLUSIONS

In this study, it is evident that the amount of twists applied to the specimens influences the Yarn Break Load results. The gradual increase in twist densifies the multifilament, making its breakage more homogeneous. A consequence of this densification is also an increase in the breaking load up to a certain optimal twist. In this study, optimal twists were determined for: polyamide (95 turns per metre), polyester

(56 turns per metre) and HMPE (38 turns per metre). After the optimal twist, the addition of torsion causes the shear forces to increase and consequently causes it to reach lower breaking values.

Another conclusion is related to the relationship between linear density and optimal torsion (Figure 11). The prescribed mathematical model proves to be very satisfactory both in the form of a quadratic model and a linear model. The model obtained in the study demonstrates that the increase in linear density causes the twist optimal value to increase up to the maximum breaking force, which is exactly the opposite of the recommendation of the standard ISO 2062 standard for yarn breaking load testing. That is, the standard makes a general recommendation that is comprehensive, and that does not optimise the performance of the material in terms of breaking strength.

In this study, the torsion effect for the YBL test was evaluated. Likewise, future studies can be carried out with the same purpose of evaluating the torsion effect in other multifilament mechanical tests, such as creep, fatigue, and abrasion.

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