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The Effect of Braiding Parameters on the Mechanical Properties of Braided Ropes

Abstract
In this study, the effects of braid pattern and take-up rate on the mechanical properties of the tubular braided ropes of polypropylene were investigated. Strand fineness of 70 tex and 150 tex, braid pattern of 1/1 and 2/2, and high & low take-up rates were selected. For both strand finenesses, the highest values for maximum tenacity, modulus and yield tenacity were obtained with the high take-up rate and the 2/2 pattern. However, the highest values for maximum strain and yield strain were obtained with the low take-up rate and the 1/1 pattern. There were statistically significant differences between the results of other mechanical properties, except for the maximum strain value for braided ropes produced with a different pattern. There were statistically significant differences among the results of all the mechanical properties tested for braided ropes produced with different take-up rates.

Key words: *braided rope, braid pattern, take-up rate, mechanical properties.*

Introduction

A braid is a textile structure produced by the intertwining together of three or more parallel strands. Because of its structural integrity, durability, design flexibility and precision, braided structures have been used for many critical applications [6, 7].

A simple tubular braid is formed by crossing a number of strands of material diagonally in such a way that each group of strands pass alternately over and under a group of strands laid up in the opposite direction. The resulting structure is oriented at an angle to the longitudinal axis of the braid [2, 3, 5, 6].

In analysing the mechanical behaviour of braided structures, two useful analogies come into play. The spiral nature of the yarns in the braided structure is similar to the geometry of fibres in a twisted yarn, and the interlacings created by the braiding process are isomorphic to a woven structure on a local level [6].

The braid pattern consists of the intersection repeat of the yarn groups. Several patterns of interlacing are commonly used, as in plain, twill, panama weave, etc. [1, 6]. Different patterns influence the order of interlacing points in the braid structure. Therefore, the pattern types affect the mechanical properties of the braid's structure.

One repeat of the braid measured along the braid axis is called a pick (S). Pick count is the number of 'S' per unit length in a single line parallel to the braid axis. One repeat of the braid across the braid normal to the braid axis is called a line (L) (Figure 1). The number of carriers on a braiding machine determines the number of individual yarn strands, and is generally related to the size or diameter of the braided product. Tubular braids are made with an even number of strands, and this number equals four times the number of lines [1, 2, 3, 6].

The resulting braid geometry is also defined by the braid angle θ, that is, half the angle of the interlacing between the two sets of strands of a braid. The angle will decrease or increase as the braid is extended or contracted along its axis. Braid angles of 10 to 85 degrees are achievable. A low braid angle (greater axial contribution) results in a stiffer product lengthwise; a high braid angle improves radial hoop strength [1, 2, 6].

The ratio of the speed of the carriers to the take-up device that removes the finished braid determines the 'braid angle'. Since the speed of the yarn carriers is constant, the braid angle (yarn orientation) can be controlled by changing the take-up rate on the braiding machine [1]. Yarn orientation is one major factor to be considered when designing braids, since it has a significant effect on the mechanical properties [4].

In this study, the aim is to ascertain the influence of braiding process parameters

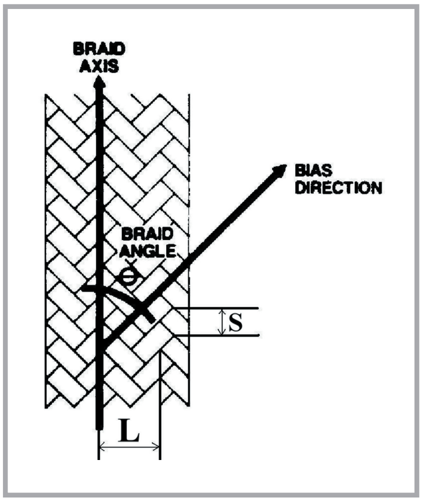

Figure 1. Schematic illustration of structural parameters of a braid [6].

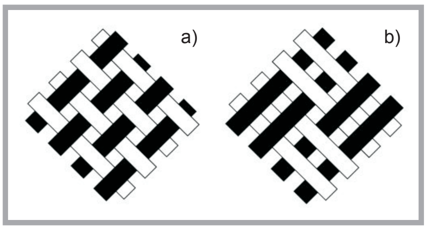

Figure 2. The braid patterns used; a - 1/1 pattern, b - 2/2 pattern.

such as braid pattern and take-up rate on the mechanical properties of braided structures.

Experimental

In this study, tubular braided ropes of polypropylene (PP) multifilament strands were produced on a braiding machine under controlled process conditions. Polypropylene (PP) twistless multifilament strands of two different finenesses were used, namely 70 tex f60 and 150 tex f125. The production of tubular braided ropes was carried out on a braiding machine with 12 carriers.

To determine the influence of the braid pattern on the mechanical properties of the braid, braid structures of 1/1 and 2/2 pattern were produced by changing the carrier settings. As in a plain weave, the 1/1 pattern has an alternation of one yarn passing above and then below the other yarns. As in a 2/2 panama weave, the 2/2 pattern passes above two and below two in a repeat. Pick count was not influenced by the braid pattern. The 1/1 and 2/2 braid patterns are illustrated in Figure 2.

In this study, two different take-up rates (high and low) were chosen. To obtain a high take-up rate, the take-up speed was set at 2 m/min. To obtain a low take-up rate, the take-up speed was 1.2 m/min. The take-up rate was changed by using change gears. The change gears determined the braid angle and the pick count. The braid angle was not influenced by the braid pattern. When the take-up rate increased, the pick count decreased.

Table 1 shows the structural parameters of eight different tubular braided ropes produced according to the experimental plan. Table 2 shows the mechanical properties of the strands used in the tubular braided ropes. Figure 3 and 4 show the pictures of the tubular braided ropes produced.

Table 1. The structural parameters of tubular braided ropes.

Group no.	Code	Strand fineness, linear density, tex	Take-up rate	Braid pattern	Braid fineness linear density, tex	Pick count, 1/cm	Braid angle, °
1	70L2	70	Low	2/2	891	8	30
	70L1	70	Low	1/1	915	8	30
	70H2	70	High	2/2	834	5	22
	70H1	70	High	1/1	848	5	22
2	150L2	150	Low	2/2	2154	8	39
	150L1	150	Low	1/1	2256	8	39
	150H2	150	High	2/2	1900	5	32
	150H1	150	High	1/1	1921	5	32

Table 2. The mechanical properties (mean ± standard deviation) of strands used in the tubular braided ropes.

Strands	Maximum load, N	Maximum tenacity, cN/tex	Maximum strain, %	Modulus, cN/tex	Yield tenacity, cN/tex	Yield strain, %
70 Tex f60	17.80 ± 0.60	25.42 ± 0.86	98.50 ± 13.21	280.30 ± 8.50	24.56 ± 0.75	33.76 ± 4.15
150 Tex f125	31.10 ± 0.50	20.75 ± 0.36	200.90 ± 7.70	105.60 ± 11.40	18.10 ± 0.30	48.56 ± 3.77

Prior to the tests, all braided ropes were conditioned in standard atmospheric conditions (20 °C and 65% relative humidity) for 24 hours. The mechanical tests on the braided ropes produced were performed on the Instron 4301 tensile tester. The distance between the jaws was 250 mm, and the gauge speed of the Instron was 300 mm/min. All tests were repeated five times for all braid types. During the tests, mechanical properties such as maximum load, maximum tenacity, maximum strain, modulus, and yield point (yield tenacity and yield strain) of all materials were obtained. The means and standard deviations of the data were determined. The results of all the mechanical properties were also tested for significant differences using a two-way analysis of variance in the Costat statistical package, separately for each one.

Results and discussion

The mechanical properties of the tested braided ropes are given in Table 3. The graphic charts of the test results of the braided ropes are shown in Figure 5. The P values and significance levels from the analysis of variance are given in Table 4.

Mechanical Properties

Maximum Tenacity

The test results showed that for each take-up rate at both groups, the 2/2 pattern had higher maximum tenacity values (3-6%) than the 1/1 pattern. The P values also showed that there were statistically significant differences between the maximum tenacity values for braided ropes produced with different patterns. At the low take-up rate, the effect of pattern on the maximum tenacity was greater.

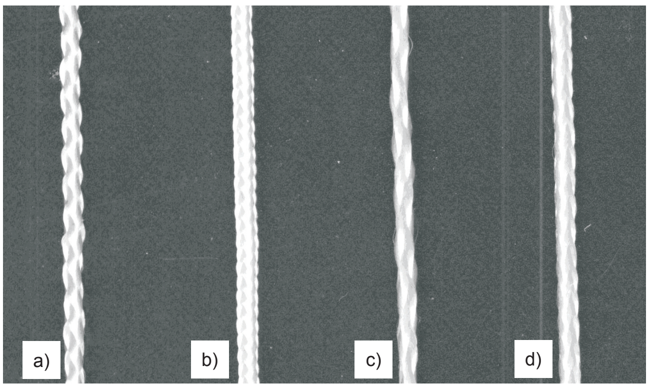

Figure 3. The tubular braided ropes produced with 70 tex PP strands; a) 70L2, b) 70L1, c) 70H2, d) 70H1.

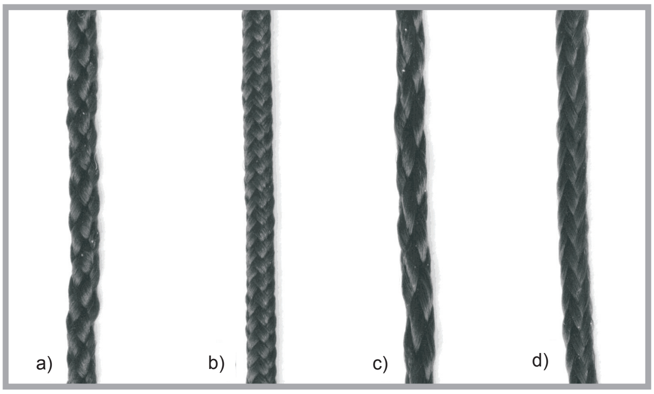

Figure 4. The tubular braided ropes produced with 150 tex PP strands; a)150L2, b) 150L1, c) 150H2, d) 150H1.

The test results showed that for each pattern at both groups, the high take-up rate provided higher maximum tenacity values (8-19%) than the low take-up rate. The P values also showed that there were statistically significant differences between the maximum tenacity values for braided ropes produced at a different take-up rate. In the second group, the effect of take-up rate on the maximum tenacity was greater.

In the braided ropes in both groups, while the highest maximum tenacity value was obtained with the high take-up rate and the 2/2 pattern, the lowest maximum tenacity value was obtained with the low take-up rate and the 1/1 pattern. The *P* values showed that the effect of interactions between the take-up rate and pattern was statistically insignificant in the first group for maximum tenacity values, and was statistically significant in the second group for maximum tenacity values.

Maximum Strain

The test results showed that for each take-up rate at both groups, the 1/1 pattern has higher values for maximum strain (1-4%) than the 2/2 pattern. However, the *P* values showed that there were statistically insignificant differences between the maximum strain values for braided ropes produced with different patterns.

The low take-up rate provided higher maximum strain values (9-31%) than the high take-up rate for each pattern in both groups. The P values also showed that there were statistically significant differences between the maximum strain values for braided ropes produced at different take-up rates. At the second group, the effect of take-up rate on the maximum strain was greater.

In the braided ropes in both groups, while the highest maximum strain value was obtained with the low take-up rate and the 1/1 pattern, the lowest maximum strain value was nevertheless obtained with the high take-up rate and the 2/2 pattern. However, the effect of interactions between the take-up rate and pattern was statistically insignificant in both groups for maximum strain values.

Modulus

The 2/2 pattern had 1-16% higher modulus values than the 1/1 pattern for each take-up rate in both groups. The *P* values also showed that there were statistically significant differences between the modulus values for braided ropes produced with different patterns. At the low take-up rate, the effect of pattern on the modulus was greater.

The test results showed that for each pattern at both groups, the high take-up rate provided values for modulus (48-168%) which were higher than the

Table 3. *The mechanical properties (mean ± standard deviation) of tubular braided ropes.*

Group no.	Code	Maximum load, N	Maximum tenacity, cN/tex	Maximum strain, %	Modulus, cN/tex	Yield tenacity, cN/tex	Yield strain, %
1	70L2	164.70 ± 1.70	18.49 ± 0.19	96.57 ± 3.34	96.78 ± 1.63	17.48 ± 0.08	35.21 ± 0.75
	70L1	161.40 ± 1.10	17.64 ± 0.12	100.40 ± 3.37	85.23 ± 1.21	16.54 ± 0.07	38.21 ± 0.93
	70H2	166.40 ± 1.00	19.95 ± 0.12	88.43 ± 3.30	142.80 ± 1.20	19.72 ± 0.22	28.40 ± 0.65
	70H1	162.80 ± 1.60	19.20 ± 0.21	89.96 ± 4.45	141.20 ± 2.40	18.95 ± 0.01	28.64 ± 0.56
2	150L2	293.10 ± 3.50	13.61 ± 0.16	142.70 ± 2.50	36.39 ± 0.81	11.99 ± 0.12	58.29 ± 1.37
	150L1	289.60 ± 1.20	12.84 ± 0.05	144.30 ± 4.70	31.38 ± 0.47	11.23 ± 0.04	63.84 ± 1.76
	150H2	299.00 ± 3.00	15.74 ± 0.16	109.20 ± 5.70	85.08 ± 0.68	14.81 ± 0.09	36.85 ± 0.62
	150H1	293.80 ± 1.80	15.29 ± 0.09	113.60 ± 1.40	84.10 ± 0.35	14.37 ± 0.04	37.59 ± 0.83

Table 4. *The results of the variance analysis (P values); ns: non-significant.*

Group no.	Factor	Maximum tenacity	Maximum strain	Modulus	Yield tenacity	Yield strain
1	Take-up rate	0.0000	0.0000	0.0000	0.0000	0.0000
	Pattern	0.0000	0.1231 ns	0.0000	0.0000	0.0002
	Take-up rate X pattern	0.6577 ns	0.4997 ns	0.0000	0.2557 ns	0.0007
2	Take-up rate	0.0000	0.0000	0.0000	0.0000	0.0000
	Pattern	0.0000	0.1086 ns	0.0000	0.0000	0.0001
	Take-up rate X pattern	0.0094	0.4441 ns	0.0000	0.0003	0.0003

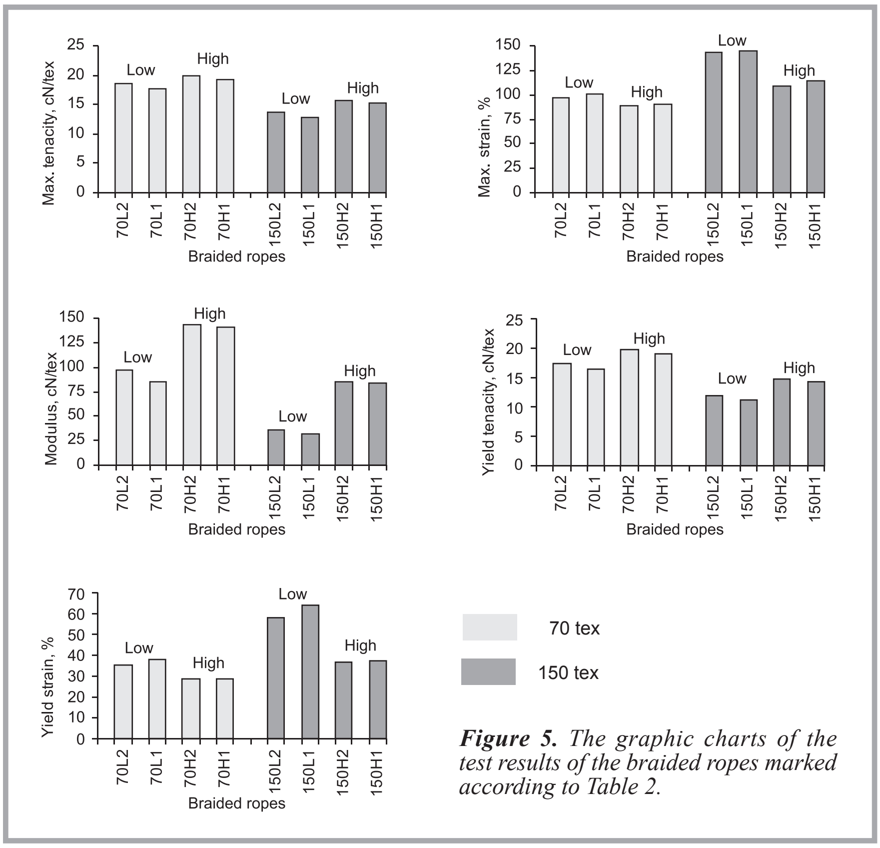

Figure 5. *The graphic charts of the test results of the braided ropes marked according to Table 2.*

low take-up rate. The *P* values also showed that there were statistically significant differences between modulus values for braided ropes produced with different take-up rate. In the second group, the effect of take-up rate on the modulus was greater.

In the braided structures in both groups, while the highest modulus value was obtained with the high take-up rate and the 2/2 pattern, the lowest modulus value was obtained with the low take-up rate and the 1/1 pattern. The *P* values also showed that the effect of interactions between the take-up rate and pattern was statistically significant in both groups for modulus values.

Yield Tenacity

The test results showed that for each take-up rate at both groups, the 2/2 pattern had higher yield tenacity values (3-7%) than the 1/1 pattern. Similarly, there were statistically significant differences between the yield tenacity values for braided ropes produced with different patterns. At the low take-up rate, the effect of pattern on the yield tenacity was greater.

The high take-up rate provided 13-28% higher yield tenacity values than the low take-up rate for each pattern at both groups. The P values also showed that there were statistically significant differences between yield tenacity values for braided ropes produced at a different take-up rate. In the second group, the effect of the take-up rate on the yield tenacity was greater.

In the braided structures in both groups, while the highest yield tenacity value was obtained with the high take-up rate and the 2/2 pattern, the lowest yield tenacity value was obtained with the low take-up rate and the 1/1 pattern. However, the *P* values showed that the effect of interactions between the take-up rate and pattern was statistically insignificant in the first group for yield tenacity values, yet was statistically significant in the second group for yield tenacity values.

Yield Strain

For each take-up rate in both groups, the 1/1 pattern had higher values for yield strain (1-10%) than the 2/2 pattern. The *P* values also showed that there were statistically significant differences between the yield strain values for braided ropes produced with different pattern. At the low take-up rate, the effect of pattern on the yield strain was greater.

The test results showed that for each pattern at both groups, the low take-up rate provided higher yield strain values (24-70%) than the high take-up rate. The *P* values also showed that there were statistically significant differences between the yield strain values for braided ropes produced at a different take-up rate. In the second group, the effect of take-up rate on the yield strain was greater.

In the braided structures in both groups, while the highest yield strain value was obtained with the low take-up rate and the 1/1 pattern, the lowest yield strain value was obtained with the high take-up rate and the 2/2 pattern. The *P* values also showed that the effect of interactions between the take-up rate and pattern was statistically significant at both groups for yield strain values.

According to the results obtained in this study, it was seen that the effects of the braid pattern and the take-up rate on the mechanical properties tested of the braided ropes were clear. If the other parameters such as strand fineness, take-up rate, thickness, etc. hold constant, then the shear forces in the braided structure will increase as they have many connection points in unit length, as in the 1/1 pattern, and sharper deflection of strands at the connection points depending on the braid pattern. This situation causes lower values for maximum tenacity, modulus and yield tenacity. On the other hand, when the connection points are greater, the strand lengths in unit braid length are greater due to high crimp. This situation caused higher values for maximum strain and yield strain.

In both groups, if the pattern holds constant, it is seen that the braided rope has higher values for maximum tenacity, modulus and yield tenacity when the take-up rate is increased. At the high take-up rate, when the braid angle (i.e. the orientation of strands toward the braid axis) decreased, the axial tensile forces applied to the braided material caused lower resultant loads on the strands. Similarly, if the pattern holds constant, the pick count also decreased when the braid angle decreased. When the braid angle decreased, the strand length in the unit length of the braided material also decreased, due to lower crimp. Therefore, the maximum strain value and yield strain value decreased in the braided ropes produced with the low braid angle.

It was observed from the results that the braided ropes of the first group had higher values for maximum tenacity, yield tenacity and modulus, and lower values of maximum strain and yield strain than the braided ropes in the second group produced under the same production parameters. These results originated from the fact that the strands (70 tex f60) of the braided ropes in the first group showed higher maximum tenacity by 22.5%, higher yield tenacity by 35.7%, higher modulus by 165.4%, lower maximum strain by 50.9% and lower yield strain by 30.5% than the strands (150 tex f125) of braided ropes in the second group (see Table 2). Furthermore, although the braided ropes of the first and second group were produced under the same production parameters, the braided ropes of second group constructed from a higher numbers of filaments had higher braid angles than those constructed from a lower numbers of filaments (see Table 1). This leads to a lower parallel alignment of the filaments to the braid axis, and to a higher crimp than those of the first group. As a result, the braided ropes of the second group had lower maximum tenacity and higher maximum strain than the braided ropes of the first group of braided ropes.

Tenacity-Strain Average Curves

The tenacity-strain average curves of the tested braided ropes are shown in Figure 6 and 7. For both groups, the tenacity-strain curves of the braided ropes produced with different take-up rate were different from each other. This difference was considerably clearer in the second group. This showed that the effect of the take-up rate of the braided ropes in the second group was more significant on all mechanical properties compared to those in the first group.

In both groups, when the take-up rate remained the same, the tenacity-strain curves were parallel to each other for both patterns. In the curve of the 1/1 pattern, the tenacities were low and the strains were high.

At the high take-up rate in both groups, the maximum tenacity and the yield tenacity were high, but the maximum strain and the yield strain were low compared to the low take-up rate. At the high take-

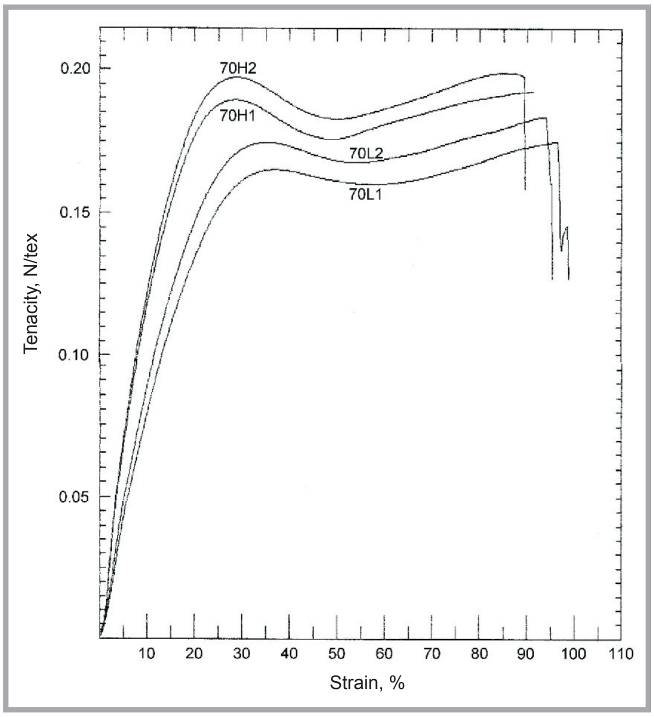

Figure 6. The tenacity-strain average curves of the braided ropes produced with 70 tex PP strands.

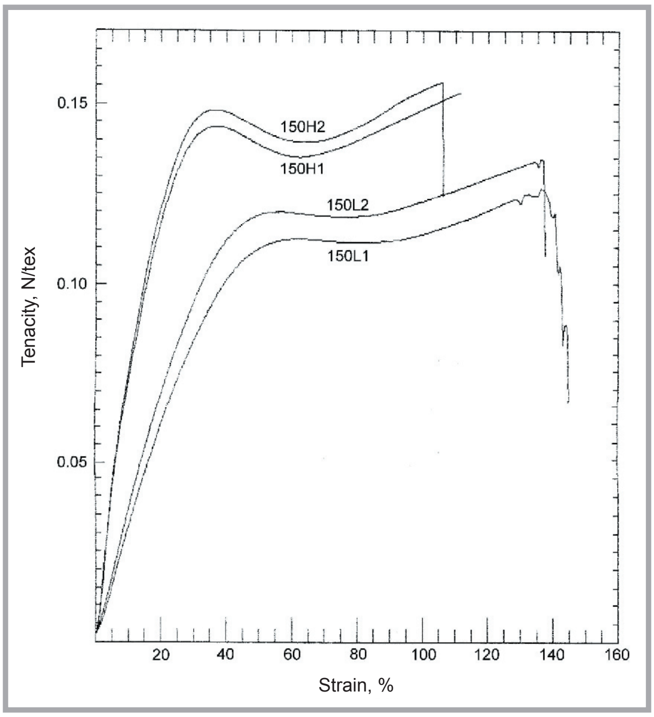

Figure 7. The tenacity-strain average curves of the braided ropes produced with 150 tex PP strands.

up rate, the tenacity fell rapidly and strain softening appeared after the yield point. On the other hand, at the low take-up rate, the braided material extended rapidly after the yield point.

Materials start to deform permanently after their yield point; they cannot recover to their original dimensions after the removal of the external force. At both groups, the highest plastic elongation were obtained with the high take-up rate and the 1/1 pattern. This structure had a lower braid angle and pick count.

Conclusions

The braided structures in the first group had higher maximum tenacity value, lower maximum strain value, higher modulus value, higher yield tenacity value and lower yield strain value than those produced with the same parameters in the second group. These differences were more apparent at the low take-up rate.

In both groups, higher values for maximum tenacity, modulus and yield tenacity and lower values for maximum strain and yield strain were obtained with the 2/2 pattern. On the other hand, higher values for maximum tenacity, modulus and yield tenacity and lower values for maximum strain and yield strain were obtained with the high take-up rate.

For both groups, the highest values for maximum tenacity, modulus and yield tenacity were obtained with the high take-up rate and the 2/2 pattern. This structure had the lowest braid angle and pick count. The highest values for maximum strain and yield strain were obtained with the low take-up rate and the 1/1 pattern. This structure had the highest braid angle and pick count.

When the braid angle and pick count were increased for both groups, the plastic deformation started later, and so the value of plastic elongation decreased.

For both groups, there were statistically significant differences between the results of other mechanical properties (excluding maximum strain) for the braided ropes produced with different patterns. At the low take-up rate, the effect of pattern on the mechanical properties (excluding maximum strain) was greater.

Statistically significant differences were observed between the results of all mechanical properties tested for the braided ropes produced with different take-up rates for both groups. In the second group, the effect of take-up rate on the mechanical properties was greater.

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