

ARAMID–NYLON 6.6 HYBRID CORDS AND INVESTIGATION OF THEIR PROPERTIES

BERRIN YILMAZ*

KORDSA GLOBAL ENDUSTRIYEL IPLIK VE KORD BEZI SAN. VE TIC. A.S., IZMIT, KOCAELI-41310, TURKEY

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ABSTRACT

Hybrid cords of two different polyamide yarns, poly(p-phenylene terephthalamide; aramid) and poly(hexamethylene adipamide; nylon 6.6) have been investigated. Aramid is a high-tenacity, high-modulus, low-elongation, and thermally stable yarn material. Nylon 6.6 is a high-elongation, low-modulus, high-fatigue-resistant, and good adhering synthetic yarn. The combination of these two different synthetic yarns enables hybrid cords with a diversified range of mechanical properties. The hybrid cord product property diversification is achieved by proper combination of different cord-forming properties of individual plies, such as linear densities, twist levels, ply numbers, treating conditions, and so forth. The effect of linear densities, twist level of plies, and twist level of cabled cord and ply number on the cord properties and also cord performance have been summarized. Aramid yarn having an 1100 linear density has been combined with nylon 6.6 yarn with a different linear density, ranging from 940 to 2100, to form hybrid cord structures. Twisting of aramid and nylon 6.6 yarns has been kept between 150 and 450 twists per meter, while the ply number of aramid and nylon 6.6 yarns has been varied as one and two plies by keeping the total ply number of the cord as three. [doi:10.5254/rct.12.88970]

INTRODUCTION

Reinforcing of tire with yarns began with cotton at the beginning of the 20th century and was then followed by cellulosic yarn and rayon through the middle of the same century. After its development, synthetic nylon yarn became an important tire-reinforcing material. Later, in the second half of the century, different-generation polyester synthetic yarns replaced nylon in some types of tires. In recent years, aramid has been used in tire reinforcement as a novel yarn.

Hybrid cords of aramid, nylon, and polyester were reported earlier by Barron.¹ Various hybrid cord structures have been analyzed in terms of alternative methods of production, mechanical properties, and bias tire applications. In Barron's article, the benefits of hybrid cords were given as high strength, good fatigue resistance, and a versatile field to modify modulus, elongation, and shrinkage of the cords. The moduli of aramid and polyester hybrid cords were found to be higher and to have a lower growth rate; therefore, they can be useful where dimensional stability is required.

Hybrid cords made of polyester and nylon yarns were investigated in the PhD study of Aytaç.^{2–4} Numerous types of hybrid cords were created by using polyester yarn in the range of 1100 to 2200 dtex and nylon 6.6 synthetic yarns in the range of 940 to 1840 dtex. These hybrid cords were composed of one-ply polyester and one-ply nylon yarns—in total, two plies together. The mechanical, thermal, and performance analyses simulating tire behavior were analyzed. Depending on the linear densities and twist levels of the plies, the load-elongation curves of the hybrid cords were changed. In general, optimized cord properties were obtained at balanced twist levels of polyester and nylon plies and also at higher twist levels for polyester ply. The fatigue performance of hybrid cords with proper combinations was better than polyester cord fatigue performance.

Finite element analysis of nylon polyester hybrid cords was recently studied by Sevim and Yenmez.⁵ The expected benefits of hybrid cords were given, such as higher modulus compared with nylon, balanced elongations, retained adhesion, and thermal shrinkage compared with polyester cord. In the article, it was mentioned that nylon single ply in hybrid cords carries more load than that of a nylon ply in an all-nylon cord. On the other hand, polyester single ply in hybrid cords carries

*Corresponding author. email: berrin-yurttas@hotmail.com

less load compared with polyester single ply in an all-polyester cord. This was attributed to the lateral stiffness of the yarn materials. The finite element analyses showed that the breaking energy partitions of hybrid cord plies were not equal to each other if the twist level of the plies was the same. Polyester has a higher contribution to the breaking energy of hybrid cords.

A paper related to the properties and performance of aramid–nylon hybrid cords was presented at the Polymer Processing Society 2010⁶ and International Rubber Conference 2010⁷ congresses. In addition to the presenting aramid–nylon 6.6 hybrid cord, properties and different types of hybrid cords, such as polyester–nylon 6.6, polyethylene naphthalate (PEN)–nylon 6.6, and rayon–polyester (PET), were presented. The property and performance comparison of different types of yarn materials in different hybrid constructions were explained.

There are numerous patents related to either production or application of the hybrid cords. The processing of PEN–PET hybrid cords in a twisting machine was explained; hybrid cords with improved tensile strength retention were obtained.⁸ Aramid–nylon hybrid cords are used in tire applications for different concerns. Some of patents can be summarized as claiming that hybrid cords in radial tire belt bands improve high-speed running performance and weight reduction,⁹ that hybrid cords in tires improve running noise performance and high-running-speed resistance by tire architecture optimization,¹⁰ and that different hybrid cord constructions for radial tire overlay have excellent high-speed properties, good comfort, better rolling resistance, reduced flat spotting, low noise,¹¹ and so on.

In this article, the detailed analysis of aramid–nylon 6.6 hybrid cords was investigated. The effects of twist level, linear densities, and ply numbers of both aramid and nylon 6.6 synthetic yarns on the cord's mechanical, thermal, physical, and adhesion properties in dynamic and rubber performance were investigated.

EXPERIMENTAL

MATERIAL

Hybrid cords were prepared by using conventional yarns nylon 6.6 type 728 (Kordsa Global, Turkey) and Kevlar type K29 (DuPont, Richmond, VA) synthetic yarns. We used a 940 to 2100 dtex range of K 728 and 1100 dtex aramid.

MACHINE AND METHOD

Hybrid cords were prepared by using a twisting machine (Oerlikon Saurer, Kempten, Germany), and heat treatment was made by using a laboratory scale single end cord dipping machine (C. A. Litzler, Cleveland). The twisting process was a two-step process. First, single-ply twisting was carried out in one direction (z or s), and then single twisted plies were combined by twisting in the opposite direction of the single plies to achieve a cabled cord. In this study, single-ply twisting was made on Z, and cable twisting was made on S directions. The dipping of hybrids was carried out by using an aqueous epoxy-based solution followed by a resorcinol-formaldehyde-latex (RFL)-based adhesive solution.¹² The curing of both of the above-mentioned adhesive solutions was made at 235 °C and 225 °C during dipping.

Mechanical properties, stress relaxation, and creep analysis of all samples were analyzed by using the Instron Mechanical Testing Instrument (Instron, Norwood, MA). Instron testing was carried out in accordance with ASTM D885; the grip distance was 254 mm, and the grip speed was 300 mm/min. The stress relaxation test was made by fixing the cords to the grips of the Instron instrument, where the grip distance was 254 mm. The cords were kept at 1% strain for 500 min. The calculations were made by taking the ratio of the load at the 500th minute to the load at the first

minute of testing. The creep test was carried out by using the Instron instrument. The grip distance was kept as 254 mm. The cords were fixed to the grips and held at 20% of the breaking load of each individual hybrid cords. The calculations were based on the ratio of strain at the 500th minute to the strain at the first minute of testing.

Thermal dimensional stability behaviors of the cords were analyzed by using the Testrite instrument (Testrite Ltd, W. Yorkshire, England). The cords were held in the Testrite instrument at 177 °C for 2 min in the presence of 0.045 g/dtex pretension. The dimensional change along the yarn axis was measured. The shrinkage force of the cords was measured under the same conditions.

The weight of the cords was determined by weighing 5 m of cord and then converting to the dtex unit, where the weight of the cord was multiplied by 10 000 m and divided by 5 m.

The adhesion of the adhesive-treated samples to rubber was analyzed by using the pull adhesion method. The details of the adhesion method and rubber composition were similar to that given in the article by Jamshidi et al.¹³ The cords were embedded into the rubber at 153 °C for 25 min. The adhesion of the cords was measured by pulling out the cords from the rubber.

The dynamic performance of rubberized cords was carried out by using a dynamic tester (Wallace Instruments, Redhill Surrey, England). It is a tire simulation test to measure the fatigue performance of the cord. The details of this method have been explained in earlier articles.¹⁴ The fatigue testing was carried out at 70 °C for 30 000 cycles. At the end of the test, the retained adhesion and cord-breaking load were measured. The results of the fatigued samples were compared with the results of unfatigued samples. The ratio of the fatigued sample result to the unfatigued sample result was reported as %retained property.

Cure in rubber performance of the cords was measured by embedding the cords in rubber at 177 °C for 20 min. The cords were then pulled out from the rubber matrix. The mechanical properties of the rubberized cords were tested. The results were compared with the result of unrubberized cord samples. The ratio of unrubberized sample test results to the rubberized sample results was recorded as %retained property.

The microscopic analyses of the cords were carried out by using a Leica MZFIII microscope (Leica Microsystems GmbH, Wetzlar, Germany).

The mixed Taguchi method was used to design the experiment by using the Minitab statistical program. The orthogonal array used in this study is $L_{16}(4^4 1^2)$ involving 16 experiment. The factors were decided as nylon dtex, aramid, nylon and cable twist, and aramid ply number. The first four factors were designed with four levels, whereas the last factor was designed with two levels. A second set of analyses was designed by replacing the factor aramid ply number as nylon ply number with two levels. The levels of nylon dtex were chosen as 940, 1400, 1880, and 2100; the levels of twist were chosen as 150, 250, 350, and 450 tpm; and the levels of ply number were chosen as one and two. The design of experiment table for the study is given in Table I.

RESULTS AND DISCUSSION

The mechanical and thermal properties of aramid and nylon 6.6 are given in Table II. Aramid is strong yarn material; its tenacity is greater than 20 cN/dtex, it has very high modulus such as 710 cN/dtex, and it has limited elongation at a break value such as 3.5%. It has extremely good dimensional stability under thermal conditions, where its thermal shrinkage is as low as 0.2%. It decomposes above 500 °C without showing any glass transition and melting transition in thermal analysis. Nylon 6.6 yarn used in rubber reinforcement is high-tenacity yarn with 8.2–8.4 cN/dtex tenacity. The modulus of nylon 6.6 is about 90 to 96 cN/dtex, which is not comparable to the modulus of aramid. The breaking energy of nylon 6.6 is very high, which makes nylon 6.6 yarn a fatigue-resistant and high-energy-absorbing material under loaded conditions. The breaking energy of a synthetic fiber or cord is calculated as the total area under the load-elongation curve. The toughness

TABLE I
TAGUCHI DESIGN OF EXPERIMENT ARRAY OF HYBRID CORDS

Test number	Dtex ^a	Aramid twist level, ^a tpm	NY6.6 twist level, ^a tpm	Cable twist level, ^a tpm	Ply number ^a
1	1	1	1	1	1
2	1	2	2	2	1
3	1	3	3	3	2
4	1	4	4	4	2
5	2	1	2	3	2
6	2	2	1	4	2
7	2	3	4	1	1
8	2	4	3	2	1
9	3	1	3	4	1
10	3	2	4	3	1
11	3	3	1	2	2
12	3	4	2	1	2
13	4	1	4	2	2
14	4	2	3	1	2
15	4	3	2	4	1
16	4	4	1	3	1

^a NY66 dtex: 940, 1400, 1880, 2100; Twist levels: 150, 250, 350, 450 tpm; Ply numbers: 1, 2.

of the cord is the energy absorption ability of a fiber or cord per unit linear density dtex. For instance, the breaking energies of 940 dtex nylon 6.6 yarn is approximately 1.95 J, whereas that of 1100 dtex aramid is approximately 0.84 J. Although the linear densities of both materials are very close to each other, nylon 6.6 absorbs more than twice the energy of aramid yarn. As a consequence of breaking energy, the breaking toughness of nylon is about 2.1×10^{-3} J/dtex, the aramid breaking toughness is about 0.7×10^{-3} J/dtex, and the toughness of aramid stays on one third of nylon toughness. Nylon 6.6 yarn changes its dimensions by 5%–6% along the yarn axis upon thermal treatment along the yarn axis. Nylon 6.6 is a semicrystalline material; it shows glass transition and melting transitions by thermal analysis. Nylon yarn has sufficient functional polar groups to react with RFL-based adhesives; therefore its adhesion is excellent with known cord-dipping solutions and thus forms an integrated composite with rubber. On the other hand, an additional adhesive treatment is required for aramid to obtain a good adhesion level with rubber compound.

Twisting imparts a springlike structure and behavior to the twisted synthetic cords. The fine filaments are put into a more close packing structure, and each twist step acts as a mechanical interlocking of the filaments. The effect of twist level on the properties of nylon 6.6 and polyester

TABLE II
PROPERTIES OF ARAMID AND NYLON 6.6 SYNTHETIC FIBERS

	Tenacity, cN/dtex	Modulus, cN/dtex	Elongation at break, %	Thermal shrinkage, %	Density, g/cc ^a	Tm/Tg, °C ^a
Aramid	>20	710	3.5	<0.5	1.45	~500 decompose
Nylon 6.6	>8.2	90	17–19	5–6	1.14	255–260/40–60

^a Polymer Data Handbook, Copyright 1999 Oxford University Press Inc., pp. 149, 195, 198.

TABLE III
 PROPERTIES OF SINGLE-PLY TWISTED ARAMID AND NYLON 6.6 SYNTHETIC YARNS

	Dtex	Twist, tpm	Tenacity,	Elongation	EASL	Breaking
			cN/dtex	at break, %	44 N, %	energy, J
			Avg/std	Avg/std	Avg/std	Avg/std
Aramid	1100	150	20.6/0.20	3.8/0.05	0.96/0.01	0.99/0.03
Aramid	1100	450	14.5/0.20	5.0/0.08	2.1/0.04	0.81/0.02
PA66	940	150	8.4/0.12	18.4/0.62	9.8/0.09	1.98/0.17
PA66	940	450	7.8/0.09	19.7/0.83	11.8/0.18	1.80/0.13
PA66	1400	150	8.8/0.04	19.2/0.41	8.0/0.04	3.20/0.16
PA66	1400	450	7.9/0.07	21.7/0.52	11.1/0.04	2.79/0.14
PA66	1880	150	8.5/0.05	20.0/0.49	6.9/0.06	4.38/0.28
PA66	1880	450	7.9/0.09	26.5/0.77	10.1/0.18	4.98/0.26
PA66	2100	150	8.5/0.07	21.2/0.31	6.9/0.10	5.03/0.14
PA66	2100	450	7.4/0.07	26.5/0.42	11.4/0.17	4.60/0.11

cabled cords was reported in literature.¹⁵ Before going into details of cord properties, effects of single-PLY twisting on yarn properties will be discussed first in this article to gain a better understanding of hybrid cord structure. The effect of twisting on mechanical properties of aramid and nylon 6.6 is given in Table III and Figure 1. Twisting of 1100 dtex aramid between 150 and 450 tpm decreases the tenacity from 20.5 cN/dtex to 14.5 cN/dtex (i.e., upon twisting approximately 70% of the tenacity is retained). Within the same twist range, the elongation at break values of aramid is increased from approximately 3.8% to 5%, corresponding to an approximately 30% increase. Currently available commercial aramid synthetic yarn cannot possess such a high elongation at break values without twisting. The 44 N partial load elongations (EASL 44N) are increased from 0.9% to 2.1%; that is, the straight line character of the tenacity-elongation curve

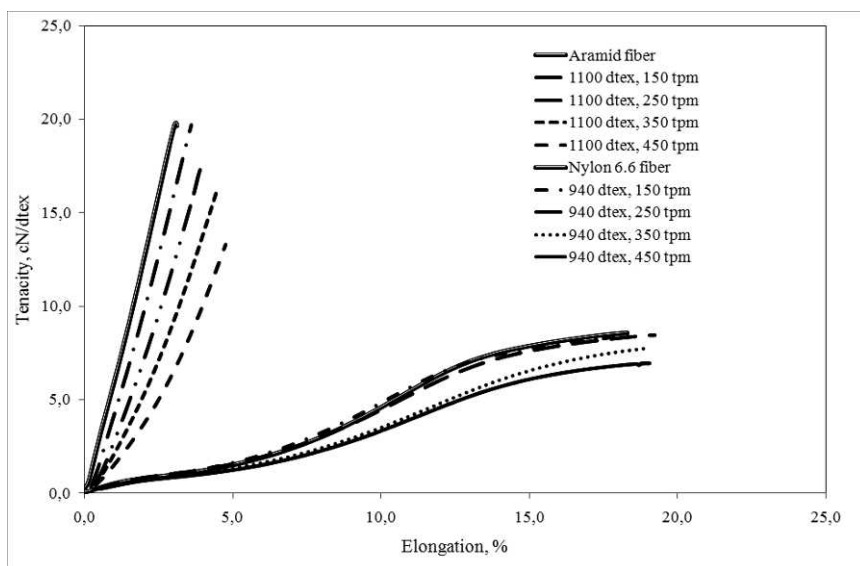


FIG. 1. — Tenacity/elongation curves of aramid and nylon 6.6 synthetic yarns and their single-PLY twisted forms.

changed to a slightly curved structure beginning in the lower part of the graph. In Figure 1, 940 dtex nylon 6.6 is given as an example. The average tenacity retention of nylon 6.6 upon twisting from 150 to 450 tpm ranges from 85% to 93% depending on the dtex of the nylon 6.6. For instance 940 dtex nylon 6.6 retains its tenacity by 93% at 450 tpm, whereas 2100 dtex retains only 85% of its initial tenacity. It is simply because of the linear density and thickness of the material. At higher twist levels, the parallel and uniform alignment of the filaments is disturbed and the twist angle is increased. Irregular alignment influences the mechanical properties and physical appearance of the twisted yarn. Nylon 6.6 already has high elongation; twisting increases the elongation at break and partial load elongations, but the impact is not as big as in the case of aramid.

The mechanical properties of aramid nylon 6.6 hybrid cords are determined by the property boundaries of both material, as given in Table III and Figure 1. A variety of hybrid cord properties can be engineered between these two boundaries. Twisting of aramid decreases the tenacity-elongation gap between aramid and nylon if the nylon twist level is kept as low as possible. However, twisting of nylon 6.6 increases the gap between aramid and nylon if the aramid twist level is kept as low as possible. Therefore in addition to the other cord-forming parameters, the level of twisting is one of the crucial points for hybrid cord property optimization.

The influence of cord-forming parameters such as twist level, ply number, and linear density on the aramid-nylon 6.6 hybrid cord properties was analyzed by using the mixed Taguchi method (details were given in the Experimental section). Analyses of Taguchi design were made to determine the main effect plots of factors and levels on the cord mechanical properties and thermal properties in rubber performance properties within the model. The evaluation of the main effect analysis was based on the delta values of the statistical analysis. Delta corresponds to the difference between the mean values of the two different levels. As the delta value increases, the effect of the factor on the desired property increases.³

The properties of hybrid cords made of 1100 dtex aramid and 940, 1400, 1880, and 2100 dtex nylon 6.6 are given in Table IV and Figure 2. The selected cord samples show the influence of twist, aramid, and nylon 6.6 contents. Figure 3 shows the main effect analysis for the breaking strength of hybrid cords. This curve was selected as an example of main effect analysis, which was carried out for all properties. Aramid ply number has the highest influence (delta 135) on the breaking strength of the cord. If a high breaking strength is required, without considering other cord properties, doubling of the aramid ply number certainly affects the breaking strength. However, cord properties are not limited to only breaking strength. The second effective parameter is the aramid twist level (delta 85). As explained above, upon twisting, aramid loses up to 30% of its breaking strength. However, as its twist level increases, its load-elongation behavior gets closer to nylon; in other words, the gap between nylon and aramid curves decreases, and therefore both materials can support each other upon tensile loading. At very high twist levels, such as 450 tpm, because aramid is loaded with a high twist, the parallelism of filaments may be destroyed, and the filaments are not free to move and cannot act uniformly upon tensile force or increased frictional surface contacts. As a result, the breaking strength gets lower. The next parameter is the nylon dtex (delta 71.7); in this case, the size and thickness compatibility of aramid and nylon plies are important. For instance, the contribution of 2100 dtex nylon to hybrid cord breaking strength is expected to be higher, probably because of the geometrical size difference, and the contribution is not so high. As the nylon ply number, cable twist, and nylon twist increase, the hybrid cord breaking strength decreases slightly. There is no significant difference between the last three parameters on the breaking strength.

Tenacity of hybrid cords is an intensive property of the cords; it shows the load-bearing capacity of the unit linear density of a cord. It is calculated by dividing the breaking load by the dtex of the cord. Aramid has very high tenacity (greater than 20 cN/dtex), whereas nylon 6.6 yarn has a tenacity of approximately 8.2 cN/dtex. The tenacity of hybrid cords given in Table IV stays between 8.9 and 12.6 cN/dtex. If the nylon contribution is high in the hybrid cord, the tenacity gets lower. For

TABLE IV
PROPERTIES OF RFL-COATED HYBRID CORDS MADE OF ARAMID AND NYLON 6.6

Hybrid cord	Cord definition ^a	Breaking strength, N		Tenacity, cN/dtex		Elongation at break, %		EASL 44 N, %		Breaking energy, J		Toughness, kJ/dtex	
		Avg/std	Avg/std	Avg/std	Avg/std	Avg/std	Avg/std	Avg/std	Avg/std	Avg/std	Avg/std	Avg/std	Avg/std
Hybrid A	1100x1+940x1 150/150/150	202.6/1.40	9.9/0.07	3.7/0.09	1.4/0.08	0.75/0.02	0.37/0.01						
Hybrid B	1100x1+940x1 250/250/250	218.1/1.90	10.7/0.09	4.8/0.12	1.9/0.09	0.98/0.02	0.48/0.01						
Hybrid C	1100x2+940x1 350/350/350	395.4/14.8	12.6/0.47	6.8/0.23	1.9/0.12	2.56/0.17	0.82/0.05						
Hybrid D	1100x2+940x1 450/450/450	342.3/9.69	10.9/0.31	8.3/0.13	2.7/0.12	2.62/0.16	0.84/0.05						
Hybrid E	1100x1+940x2 350/350/350	265.6/9.46	8.9/0.32	9.4/0.32	3.8/0.14	2.16/0.16	0.73/0.06						
Hybrid F	1100x1+940x2 450/450/450	266.5/7.86	8.9/0.26	13.4/0.29	5.29/0.06	3.14/0.19	1.05/0.07						
Hybrid G	1100x2+1400x1 150/250/350	294.7/15.3	8.2/0.42	5.6/0.19	1.59/0.12	1.64/0.16	0.46/0.05						
Hybrid H	1100x2+1400x1 250/150/450	266.6/12.7	7.4/0.51	9.1/0.35	3.73/0.34	2.09/0.19	0.58/0.05						
Hybrid I	1100x1+1400x1 350/450/150	212.1/6.5	8.5/0.26	3.6/0.16	0.93/0.07	0.87/0.05	0.35/0.02						
Hybrid J	1100x1+1400x1 450/350/250	231.2/6.2	9.2/0.21	6.3/0.14	2.42/0.06	1.36/0.05	0.54/0.02						
Hybrid K	1100x1+1880x1 150/350/450	184.7/10.5	6.2/0.35	5.9/0.24	2.17/0.06	1.11/0.09	0.37/0.03						
Hybrid L	1100x1+1880x1 250/450/350	220.5/2.7	7.4/0.07	5.2/0.09	1.58/0.04	1.17/0.03	0.39/0.01						
Hybrid M	1100x2+1880x1 350/150/250	454.8/7.9	11.2/0.20	7.8/0.07	2.14/0.14	3.22/0.14	0.79/0.03						
Hybrid N	1100x2+1880x1 450/250/150	392.6/6.2	9.6/0.14	5.0/0.09	1.07/0.03	2.09/0.07	0.51/0.02						
Hybrid O	1100x2+2100x1 150/450/250	383.3/15.4	8.9/0.36	4.5/0.13	0.95/0.05	1.87/0.14	0.44/0.03						
Hybrid P	1100x2+2100x1 250/350/150	426.3/4.3	9.9/0.13	4.3/0.03	0.83/0.03	2.00/0.06	0.47/0.01						
Hybrid R	1100x1+2100x1 350/250/450	256.1/4.8	8.0/0.15	9.7/0.18	3.67/0.11	2.24/0.09	0.70/0.03						
Hybrid S	1100x1+2100x1 450/150/350	287.2/4.1	8.9/0.14	11.0/0.18	3.94/0.14	2.87/0.11	0.90/0.03						

^a Aramid dtex × aramid ply number + nylon 6.6 dtex × nylon 6.6 ply number, aramid/nylon 6.6/cable twist levels.

^b Stress relaxation experiment, load measured at 500th minute divided by load at first minute multiplied by 100.

^c Creep experiment, %strain measured at 500th minute divided by %strain at first minute multiplied by 100.

^d Breaking load after cure in rubber (CIR) test is divided by breaking load before CIR test multiplied by 100.

TABLE IV
Extended

Hybrid cord	Modulus (Autoyoung), cN/dtex		Thermal shrinkage, %		Shrink force, cN		Weight, g/100 cm		Thickness, mm		Pull adhesion, N		%Load maintaining 1% strain ^b		%Strain maintaining 20% of breaking load ^c		Retained breaking strength after CIR, % ^d	
	Avg/std		Avg/std		Avg/std		Avg/std		Avg/std		Avg/std		Avg/std		Avg/std		Avg/std	
Hybrid A	383.7/3.38		1.4/0.0		307/5		22.2		0.50/0.01		75.8/6.5		77.4		112.0		72.0	
Hybrid B	361.9/3.14		1.5/0.06		302/8		21.8		0.50/0.01		93.2/5.1		73.2		109.8		86.3	
Hybrid C	282.5/3.55		1.1/0.06		373/6		34.8		0.67/0.01		172.3/11.8		77.3		109.3		100	
Hybrid D	211.3/4.20		1.1/0.06		338/9		35.5		0.65/0.01		149.2/10.2		72.7		109.0		100	
Hybrid E	174.7/2.26		2.2/0.06		455/3		32.3		0.66/0.01		167.9/19.1		60.0		110.0		94.8	
Hybrid F	116.4/2.29		2.5/0.06		446/10		33.8		0.65/0.01		173.1/9.1		57.1		110.4		98.8	
Hybrid G	207.0/5.11		0.8/0.06		479/4		40.9		0.73/0.01		207.0/5.1		77.8		113.4		89.9	
Hybrid H	142.6/6.65		1.1/0.06		272/12		42.2		0.73/0.01		150.3/17.6		75.6		107.9		95.1	
Hybrid I	279.2/3.77		2.1/0.06		615/7		27.0		0.66/0.01		132.9/9.1		78.3		114.6		82.1	
Hybrid J	242.0/8.30		1.7/0.00		466/8		34.5		0.64/0.01		151.9/11.2		66.2		109.8		88.2	
Hybrid K	158.7/4.51		1.3/0.00		605/10		34.9		0.77/0.01		159.6/8.5		70.9		117.8		92.7	
Hybrid L	212.7/2.57		1.3/0.00		724/10		33.7		0.79/0.01		167.3/4.8		66.6		118.8		85.4	
Hybrid M	229.9/2.42		1.5/0.00		573/4		43.9		0.77/0.00		187.4/12.9		67.6		108.8		94.1	
Hybrid N	249.5/4.37		1.3/0.06		642/4		44.0		0.77/0.01		116.5/17.2		74.7		111.4		92.4	
Hybrid O	247.2/2.21		0.7/0.06		806/9		49.0		1.04/0.01		167.8/14.2		80.8		117.8		97.0	
Hybrid P	279.6/3.16		0.9/0.06		1021/5		47.6		0.84/0.01		175.2/12.7		81.0		115.7		85.3	
Hybrid R	145.0/2.21		1.8/0.00		571/11		35.5		0.71/0.00		171.9/10.2		61.9		112.5		97.7	
Hybrid S	137.2/2.91		11.0/0.18		517/4		34.7		0.68/0.01		119.2/13.1		60.1		110.9		86.7	

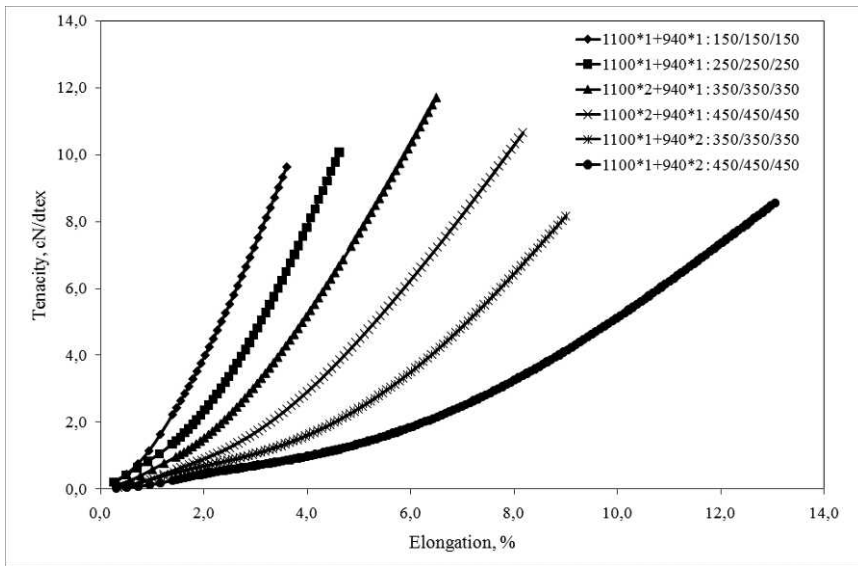


FIG. 2. — Tenacity/elongation curves of RFL-coated hybrid cords made of 1100 dtex aramid and 940 dtex nylon 6.6.

instance, hybrid cords E and F have the highest nylon content, approximately 63% in terms of linear densities, and they have the lowest tenacity, such as 8.9 cN/dtex. Hybrid cords C and D have the lowest nylon content (approximately 30%), and their tenacity is higher. Although aramid loses its tenacity upon twisting more than that of nylon, it is still the highest tensile member of the hybrid cords.

Elongation at break values basically is determined by cable twist (delta 5.72), as cable twist increases the elongation at break value increases. As the aramid twist level increases (delta 3.25), the elongation at the break value of the cord increases. The increase in nylon twist level decreases the elongation at the break value because the shift of the tenacity-elongation curve to the lower side and the elongation becomes limited to the elongation of aramid ply. Hybrid cords given in Table IV

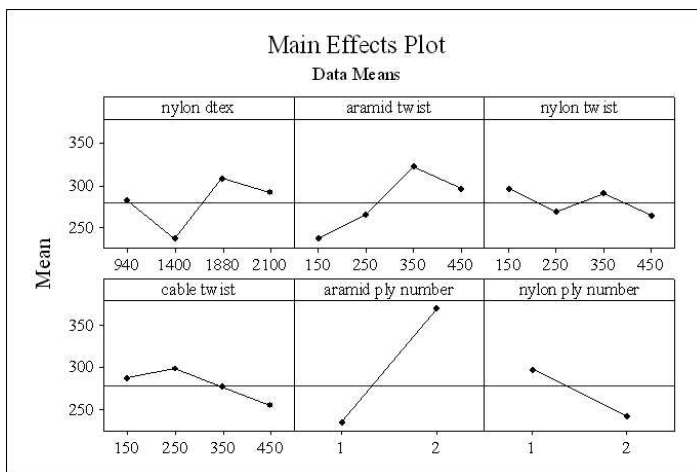


FIG. 3. — Main effect analysis for breaking strength of aramid–nylon 6.6 hybrid cords.

and Figure 2 show that the twist level and higher nylon content have a positive effect on breaking elongation.

Partial load elongation at 44 N behavior of hybrid cords is very similar to breaking elongation. Twist level and higher nylon content has the greatest influence on the partial load elongation (Figure 1; Table IV). For instance hybrid cords C and E have the same twist level; the first one has two-ply aramid, the second one has two-ply nylon, and the EASL at the 44 N value of hybrid cord E is double that of hybrid cord C, 3.8% versus 1.9%, respectively.

The effect of the aramid twist level and cable twist has great influence on the breaking energy of the hybrid cords. As mentioned previously, the load-elongation curve shift of aramid is valid again. Cable twisting improves springlike cord structure, and filaments are more protected. Regarding Table IV, as the twist level increases, the breaking energy of the hybrid cord increases; hybrid cords A and B have 0.75 and 0.98 J breaking energies. At high nylon content and at high twist levels, the maximum breaking energy is observed in hybrid cord F, such as 3.14 J.

The breaking toughness of hybrid cords shows the work required to reach the breaking load per unit dtex. Regarding the hybrid cords given in Table IV and Figure 2, it is observed that at low twist levels, hybrid cords possess low breaking toughness, in other words, low energy absorption ability (e.g., hybrid cords A and B have 0.37 and 0.48 kJ/dtex values, respectively). The same relation is valid for the other hybrid cord couples C and D, E and F. Considering the whole model, cable twist ($\Delta 0.34$) has the highest influence on the breaking toughness, as it increases the breaking energy per unit linear density increases. As the nylon dtex ($\Delta 0.24$) and nylon twist level ($\Delta 0.19$) increases, the energy per unit linear density decreases. An increase in aramid twist positively affects the energy per unit linear density in a positive way because of the shift of the aramid load-elongation curve.

The modulus (auto young) of hybrid cords is influenced mainly by nylon ply number, cable twisting, and nylon dtex. All have an adverse effect on the modulus of the hybrid cord (i.e., increase of any parameter mentioned above causes reduction of the modulus). In Table IV, at low twist levels such as 150 and 250 tpm, the highest modulus is achieved, such as 3.84 and 3.62 N/dtex. The steepness of the tenacity-elongation curve in Figure 1 confirms this value. Again in Table IV and Figure 1, hybrid cords C and D with high aramid content have higher modulus compared with high nylon content hybrid cords E and F.

The dimensional stability of synthetic hybrid cords on thermal treatment was measured, as explained in the Experimental section. The linear retraction percentage along the cord axis in the presence of heat and pretention is particularly important for the processing of tire in the molds. The thermal stabilities of aramid and nylon were explained above. As shown in Table IV, as the nylon content of hybrid cords increases, the thermal shrinkage of the cord increases (i.e., nylon dominates). As the aramid content of the hybrid cord increases, the thermal shrinkage of the hybrid cord decreases, and the aramid contribution becomes obvious. As the aramid twist increases, the thermal shrinkage of the hybrid cord increases because of the concurrent behavior of nylon and aramid plies. As the nylon twist increases, the thermal shrinkage decreases; most probably aramid ply contributes more and therefore thermal shrinkage gets lower.

The force required to retract the cords under thermal conditions was called shrink force and was measured under the same conditions as that of the shrinkage test. Synthetic 1100 dtex aramid yarn has approximately 200 g and 940 dtex nylon 6.6 has approximately 390 g shrink force values. The model study shows that nylon dtex ($\Delta 499$), cable twist ($\Delta 323$), and nylon ply number ($\Delta 216$) have the highest influence on the shrink force of the hybrid cords. Regarding the yarn shrink force values, it is clear that nylon contributes to the higher shrink force of the hybrid cords. The influence of cable twisting is interesting because there is an inverse relation: as cable twist increases, shrink force decreases. One of the explanations may be that as the twist level increases, the mechanical interlocking between plies gets higher and prevents free movement of the plies, and

thus the shrink force gets lower. Another reason may be that the angle of filaments to the horizontal cord axis gets higher, and the retraction force of filaments cannot be reflected to the cord axis. The higher the twist level, the more material in the unit length, but pretension is kept constant as 0.045 g/dtex; this may be another reason to have lower shrink force values. Regarding the cord samples hybrid cords A and B, C and D, and E and F given in Table IV, as the twist level increases, the shrink force of the hybrid cords decreases.

The stress relaxation analysis of hybrid cords was carried out at 1% strain for 500 min at room temperature to measure the load required to sustain this constant strain. This may simulate the behavior of tires under certain strain. The cords show a certain amount of stress relaxation when exposed to constant strain. Based on the model study, as the ratio of load at the end of 500 min to the load at the beginning of the test at 1 min, it seems that aramid twist and aramid ply number have the highest influence on the stress relaxation of hybrid cords. As aramid twist increases, the stress relaxation of the hybrid cords increases; as aramid ply number increases, stress relaxation of hybrid cords decreases. As nylon twist increases, the stress relaxation increases; as cable twist increases, stress relaxation decreases. Regarding the hybrid cords given in Table IV, hybrid cords A, B, C, and D have similar behavior; maintaining 1% strain is achieved by 73%–77% of initial load at the end of 500 min. The rate of stress relaxation is 1.5×10^{-3} N/min. The aramid content of these hybrid cords is higher in the cord structure, such as 30% and 54%. Hybrid cords E and F maintained 1% strain by 57%–60% of initial load; in other words, these two hybrid cords have more deformation. The nylon content of these two hybrid cords is about 63%. Considering the whole set of model analysis, load retention after the stress relaxation test is between 57% and 81%. The rate of change is in the range of 1.1×10^{-3} to 1.6×10^{-3} N/min.

Creep behavior of cords was measured by keeping the cords at a load of 20% of their breaking strength for 500 min to determine how the cords sustain loads for long periods. As nylon dtex, nylon ply number, and nylon twist increase, the creep of the hybrid cord also increases. As aramid twist, cable twist, and aramid ply number increase, the creep of the material decreases. The hybrid cords in Table IV have 9%–12% strain change and deformation under the above-mentioned testing conditions. The rate of change of strain is 2.2×10^{-3} % strain/min for all hybrid cord construction given in Table IV. Considering whole model test results, the percentage strain change is between 8% and 26% with a rate of 2.2×10^{-3} to 2.5×10^{-3} % strain/min.

Both aramid and nylon have good adhesion if proper adhesive systems and processing are applied. The hybrid cords of these two materials also have sufficiently good adhesion. The higher nylon content of hybrid cords generally affects the adhesion positively. In Table III, the adhesion of low twisted hybrid cords (A and B) seems to be low; because the filaments are in an open structure, during the pull out of cords from the rubber matrix, filament breakage occurs instead of cord removal. The adhesions of hybrid cords given in Table IV are good enough.

One of the main expected benefits of aramid nylon hybrid cords is the contribution of nylon to the hybrid cord to improve fatigue performance. Recalling the breaking energy of the yarns, nylon has a very high energy-absorbing ability; for example, 1100 dtex aramid has 0.99 J, and 940 dtex nylon has more than double that of aramid, such as 1.98 J, at the same 150 tpm twist level (Table II). Recalling previous explanations, the breaking energy gives an indication as to the fatigue performance of the tire cords. The higher the nylon content, the better fatigue performance. Nylon content can be increased either by increasing dtex or increasing the ply number of nylon. Aramid is a strong yarn but poor in fatigue performance; therefore, as the aramid ply number increases, the breaking strength retention after fatigue gets worse. Twist level of plies and cable have a positive influence on fatigue performance. The reason for this is that sufficiently higher twist levels provide springlike behavior to the cord. The other factor is that as the twist level increases, cords possess more of a close-packed structure, and individual filaments are protected sufficiently from breakage. Such a structure increases frictional surfaces, but filaments can act more simultaneously. In the case

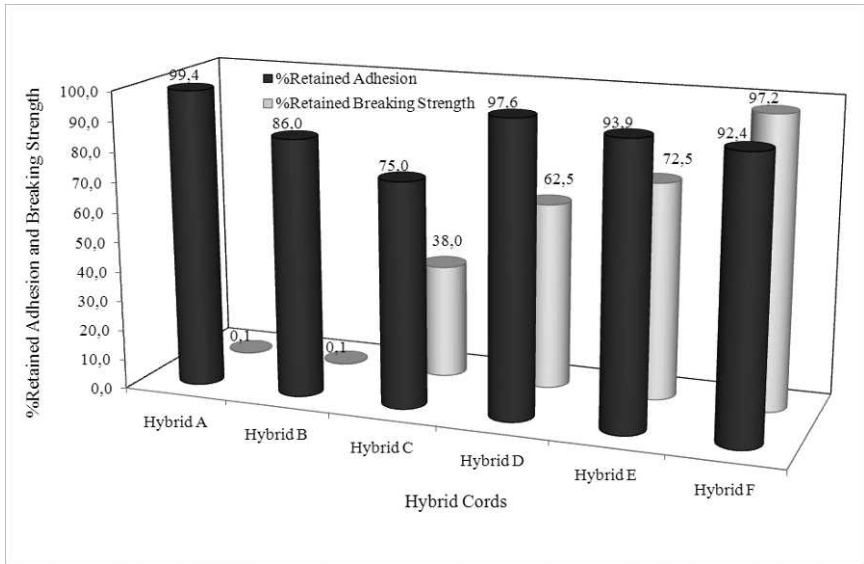


FIG. 4. — Adhesion strength retention and breaking strength retention after the fatigue test of aramid-nylon 6.6 hybrid cords.

of low twist levels, because filaments are loose, they adhere to the rubber individually, and filament breakage occurs rather than cord breakage. In summary, if a high fatigue performance is required, high nylon content should be combined with a sufficiently high twist level. In Figure 4, the individual fatigue behavior of hybrid cords A–F has been given. Hybrid cords A and B do not show any resistance to fatigue conditions because of lack of twist level. Hybrid cords do not have sufficient springlike behavior to dissipate the energy, and the filaments are more open, so filament breakages take place. Considering the couples of hybrid cords C and E, hybrid cords D and F, as the nylon content of the hybrid cord increases, the breaking strength retention of hybrid cord increases. Considering the couples hybrid cords C and D, hybrid cords E and F, as the twist level increases, the fatigue breaking strength is improved.

Cure in rubber analysis of hybrid cords was carried out to observe the property retention of hybrid cords when embedded into the rubber. The breaking strength retention of hybrid cords changes between 72% and 100% (Table IV). Hybrid cords with a low twist level usually seem as though they are losing more breaking strength (hybrid cords A and B) because of the open structure of filaments. Hybrid cords with high aramid content retain breaking strength without any loss (hybrid cords C and D). Hybrid cords with two-ply nylon have a breaking strength retention of approximately 95%–99%.

Some examples of the microscopic cross-sectional view of hybrid cords A, C, and F are given in Figure 5. The position of plies in a cross section changes depending on the dtex, twist level, and ply number. By using the same ply number and dtex plies, the twisting changes the cross-sectional appearance and outer appearance of the cord. In general, high twist level and compatible dtex plies give provide a close-packed cord cross section.

CONCLUSION

Constructing aramid-nylon 6.6 hybrid cords is a versatile means of creating numerous types of cords with varying properties. By adjusting the aramid or nylon content and twist levels, the cord

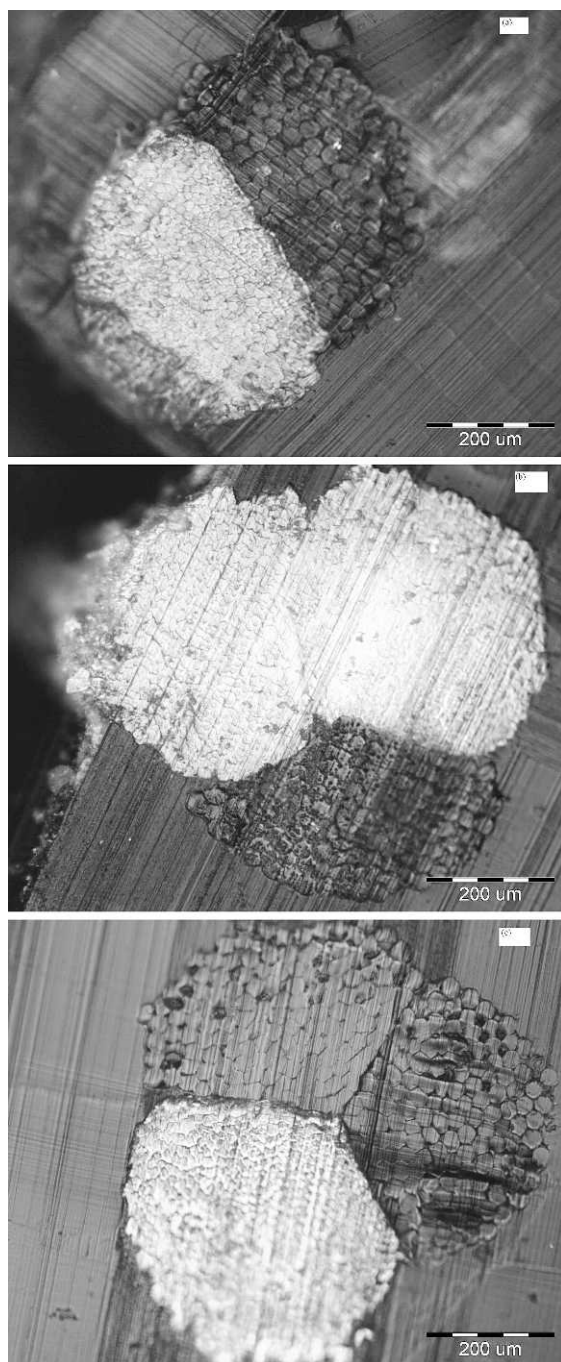


FIG. 5. — Microscopic cross-sectional views of hybrid cords (a) A, (b) C, and (c) F.

properties can be adjusted within the property boundaries of aramid and nylon 6.6 synthetic yarns. The beauty of the hybrid cord is the flexibility to engineer the cord properties by finding optimum combinations depending on the requirements of the application. Hybrid cords made of 1100 dtex aramid and 940, 1400, 1880, and 2100 dtex nylon 6.6 were designed and prepared based on the Taguchi model. The cords were then analyzed to understand how the static and dynamic properties were influenced by the design factors. It is really hard to obtain all ideal cord properties, such as high breaking strength, high modulus, high fatigue resistance, and so forth, in a single cord body. The study discussed in this article gave an overview of how the properties are interrelated and how a deficiency in a cord property was compensated for by an improvement in another cord property; for example, decreasing breaking strength with an increasing twist level was compensated for by an improvement in fatigue performance. Basic observations can be summarized as follows. The breaking strength of a hybrid cord was basically determined by high aramid content and twist level of aramid ply. The moduli of cords were adjusted by adjusting the proper twist levels to create a dual modulus cord; in particular, high twist levels contributed more to the dual behavior (i.e., low modulus at low elongations and high modulus at high elongations). The partial load and breaking elongations of hybrid cords were determined by cable and ply twist levels. In summary, the load-elongation behavior of hybrid cords actually stayed between that of aramid and nylon 6.6 curves; those having a low aramid twist level resembled more the aramid curve more closely. Thermal shrinkage of hybrids was at moderate levels and lower than that of nylon 6.6 shrinkage.

High fatigue performance was obtained by optimization of the twist level and the nylon content of the cords. The adhesion of hybrid cords to rubber was good enough. Sufficiently high strength retention after rubberizing was obtained. In general, more nylon content shifts the static and dynamic behavior of hybrid cords to the nylon side or vice versa.

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