Kirk-Othmer Encyclopedia of Chemical Technology.

TIRE CORD

Since the introduction of the pneumatic tire (1–3) the reinforcing strength or tensile member has been some form of textile or steel fiber, usually in the form of a cord. Early tires used fabrics in the form of square woven fabrics; however, this was replaced by a unidirectional arrangement of tire cords utilizing woven fabric or creel calendering. The development of textile reinforcements for tire cords has been driven by the tire need for better mechanical properties and therefore better tire performance (4, 5). Tire cord development has been paralleled by the emergence of other markets for new fibers (qv) in the apparel and industrial textile sectors. Thus, tire cords have progressed from natural fibers (cotton), through man-made (rayon) to the present totally synthetic suite of reinforcement candidates (nylons and polyesters). Furthermore, high performance fibers have found use in specialty areas (aramids and carbon fiber) and as new fibers are developed, the potential for tire use will be examined. Although each of these fibers is referred to herein as a single type, there has been and continues to be significant product development associated with each of the man-made or synthetic fibers, leading to stages of product development. In common with the rest of technology, the time between generations continues to diminish as a result of market pressure and research and development by the fiber producers and tire manufacturers. The evolution of the various tire cords in terms of annual consumption in North America is illustrated in Figure 1.

1. Cotton

Cotton (qv) was the first material to be used in mass production of tires. Its relative abundance and well-established handling make the fiber naturally amenable to industrial usage. Also, the chemical structure of cotton allows for good adhesion to rubber thus facilitating a useful composite structure. However, as tire usage and performance demands rose, specifically in the areas of strength and fatigue resistance, the need for better reinforcement arose. This need was met by a number of organic and inorganic tire cords (6, 8, 9).

2. Rayon

Introduced commercially in 1938 and developed through generations of product to the present Super III rayon (6), rayon is a man-made regenerated cellulose fiber derived from wood pulp (qv). The process, which must be rigorously controlled to be environmentally acceptable, involves extraction of alkali cellulose with carbon disulfide, maturation, and spinning into fibers. The fiber, which also has wide use in textile markets, has outstanding dimensional stability but only moderate strength-to-weight ratio. Rayon fibers do not possess the intrinsic ability to bond with rubber and thus require development of suitable adhesive systems in the form of resorcinol–formaldehyde–latex (RFL) dip systems (*vide infra*). Although in declining use due to the increased cost associated with environmental aspects of the fiber production, rayon continues to be useful in specialty high performance tires.

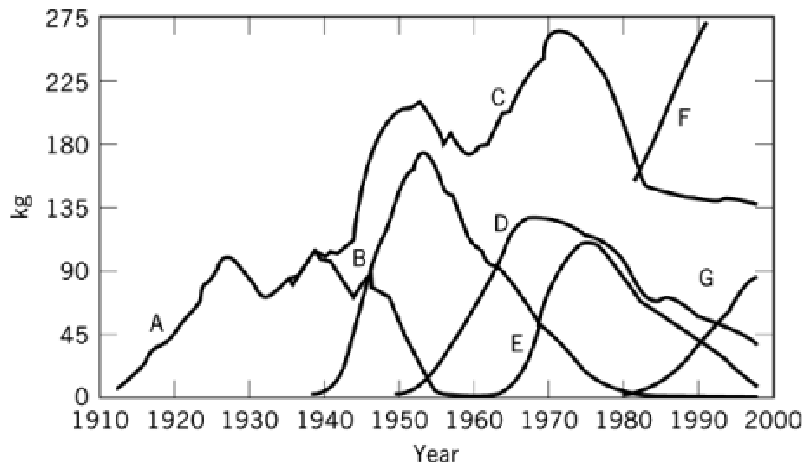

Fig. 1. U.S. reinforcement consumption for tires, where A shows cotton; B, rayon; C, total all-fibers; D, nylon; E, conventional poly(ethylene terephthalate) (PET); F, steel cord; and G, high modulus low shrink (HMLS) PET (6, 7).

3. Nylon

Nylon, an aliphatic polyamide, was introduced as a commercial tire cord in 1947 and grew in usage to ~5.4 billion kg/yr (~2 billion lb/yr) in the 1990s (10, 11). Nylon-reinforced tires use nylon-6 polymer (polycaprolactam) fibers as well as nylon-6,6 (poly(hexamethylenediamine adipamide)) fibers. Nylon tire cords are characterized by extremely good fatigue resistance in compression and good adhesion to most rubber compounds with simple RFL adhesives.

4. Polyester

Polyester is the newest of the tire-reinforcement fibers to achieve volume usage of ~2.7 billion kg (~1 billion lbs) in the form of poly(ethylene terephthalate) (PET) fiber introduced in 1962 (12). As such, it has developed through several product generations beginning with a so-called standard modulus product up to the generation of high modulus low shrink (HMLS) or dimensionally stable polyester (DSP) forms of the 1990s (13). With respect to nylon, polyester fibers display lower thermal shrinkage and higher modulus. More complex adhesive systems tend to be required for polyesters to bond to rubber. Developers of polyester have explored other monomer types such as the liquid crystal polyesters (14) and the naphthalate-based copolymer with ethylene (15).

5. Aramid

Introduced in 1972, the wholly aromatic polyamide, poly(*para*-phenylene teraphthalamide), termed aramid, was the subject of extensive evaluation as a tire cord in all types of tires (8, 14). As of the late 1990s, however, only specialized applications have emerged for aramid tire cord that draw on their high strength-to-weight ratio to produce tires with lower weight (16).

6. Glass

Introduced successfully for tires in 1967, glass fibers had properties that made them very attractive for use in tires (5, 8). The brittleness of glass fibers, however, imposed some limitations on the final tire cord properties because of the requirement that each fiber be individually coated with a rubbery adhesive to avoid interfilament damage during fabrication and use. This additional treatment step is introduced at the fiber manufacturing stage. For several years fiber glass was used extensively in bias-belted and radial tires, but was ultimately replaced by steel belts in radial tires.

7. New Fibers

Whenever a new high strength fiber is developed, its potential for tire cord use is always explored because of the commercial attraction of large volumes available in the tire market. Few materials have emerged to displace the current two major fibers, nylon and polyester (14). Nonetheless, many examples of fibers offering attractive properties for tire cords have been reported in the literature, eg, polyethylene ketone (17), poly(paraphenylene benzobisoxazole) (18), acrylics (19), and high strength poly(vinyl alcohol) (20) (see Vinyl polymers).

8. Fiber Development for Tire Cord Use

The fundamental requirements for a useful tire cord fiber are high strength and modulus coupled with good dimensional stability (ie, resistance to deformation under temperature and load), and durability (fatigue and chemical stability) at favorable economics (21–23). The search for new fibers is driven by a wide array of potential nontire applications such as protective textiles (eg, against fire), ballistic protection, apparel, ropes, netting, geotextiles (qv), boat sails, and composite reinforcement. For load-bearing applications, the goal is to devise or utilize molecular structures that take full advantage of the inherently high strength of the C–C bond (24). One approach includes the area of molecular architecture, ie, polymer chemistry, to control features such as molecular weight, chain alignment, and chain–chain interactions. The aspects of processing (25) must also be considered when forming a fiber with suitable properties that will take full advantage of the polymer's potential and maintain viable economics. Although a wide array of reinforcement options appear to be available based on technical feasibility, the underlying features of cost vs value and the ease of integration into a manufacturer's process will dictate what is used in mass-produced tires. Thus, the market for organic tire cord remains divided between nylon and polyester fibers and will likely remain so for the medium-term future.

9. Fiber Properties

A tire reinforcement's use is dependent on several physical properties (26). Some of the most important are tabulated in Table 1. These properties effectively screen candidates for use in tires. The secondary features define a fiber's potential for tire use.

A key feature implicitly included in the use of organic fibers for tire reinforcement is the ability to retain strength and modulus characteristics at elevated temperatures (80–120°C for most tires) sufficient to sustain service demands. Thus, a tire which may appear to be overdesigned at room temperature is, in many cases, reflecting the changes in properties experienced at operating temperatures.

Table 1. Mechanical Properties for Reinforcing Fibers[a]

Name	Strength, cN/Tex[b]	Modulus, cN/Tex[b]	Thermal shrinkage	Density	T_g, °C	Mp, °C	Compression fatigue resistance
rayon(III)	52	1,200	0.2	1.53		210	good
nylon-6	84	300	7.5	1.13	20	220	excellent
nylon-6,6	86.5	400	7.4	1.14	50	254	excellent
standard modulus polyester	90	1,000	13.0	1.38			good
high modulus polyester	70	1,000	3.9	1.38	75	260	good
aramid	200	4,900	0.1	1.44		454[c]	poor
carbon fiber	300–370	33,500–15,250	0.0	1.83		3700[c]	poor
high tensile steel	43.4	2,680	0.0	7.85		1600	good
fiber glass (E-glass)	100	2,200	0.0	2.55		1180	poor

[a]Strength and modulus normalized to linear density $(\mathrm{Tex} = (\mathrm{g{\cdot}wt})/\mathrm{km})$, an appropriate basis for materials of similar density; however, this breaks down for dense materials (eg, steel) because the basis for tire use is better described by properties per unit cross section (MPa) rather than weight.
[b]To convert cN/Tex to $\mathrm{MPa(N{\cdot}mm^{-2})}$, multiply by density $(\mathrm{g{\cdot}cm^{-3}})$ by 10.
[c]Decomposition temperature.

9.1. Fatigue Resistance

Although tensile strength and modulus governs the amount of material required to reinforce a particular tire design, a critical service parameter is fatigue resistance. The extent of service fatigue (compressive stress) is governed by tire design and service conditions (5, 6, 27–29). Thus laboratory fatigue testing performance has a critical impact on materials selection depending on tire design and expected service. For example, the design of a bias tire imposes more fatigue stress on a tire cord than a typical radial tire. Fatigue testing data are highly dependent on the nature of the testing geometry, and many different tests exist (see Table 1).

9.2. Dimensional Stability

Dimensional stability refers to how a fiber changes length under the influence of load or heat. Conventionally described in terms of fiber shrinkage (ASTM D885-64) at a defined temperature, the term has also come to mean time dependent length change or creep. In general, more highly oriented and therefore higher modulus fibers tend to exhibit lower shrinkage and less creep. Creep is an important factor in the control of tire dimensions during service and in certain aspects of tire appearance (30).

9.3. Toughness

Toughness is generally used to describe a fiber's ability to absorb energy before failure, defined as the area under the load vs elongation curve (energy to break). This parameter is important in controlling how well a tire cord resists impact damage, such as curb or pothole strikes. Although intrinsic strength controls quasi-static strength, for example, tire burst strength (as affected by the total load exerted on a tire cord) energy is a more significant parameter for impact damage.

9.4. Heat Generation

During tire operation, ie, rolling, reinforcing cords experience cyclic deformations (31). Because textile reinforcements are not perfectly elastic, this deformation results in energy loss that is mostly in the form of heat buildup. This process is known as hysteresis and such losses contribute to rolling resistance. Excessive heat buildup can accelerate tire cord thermochemical degradation, thus shortening tire lifetime.

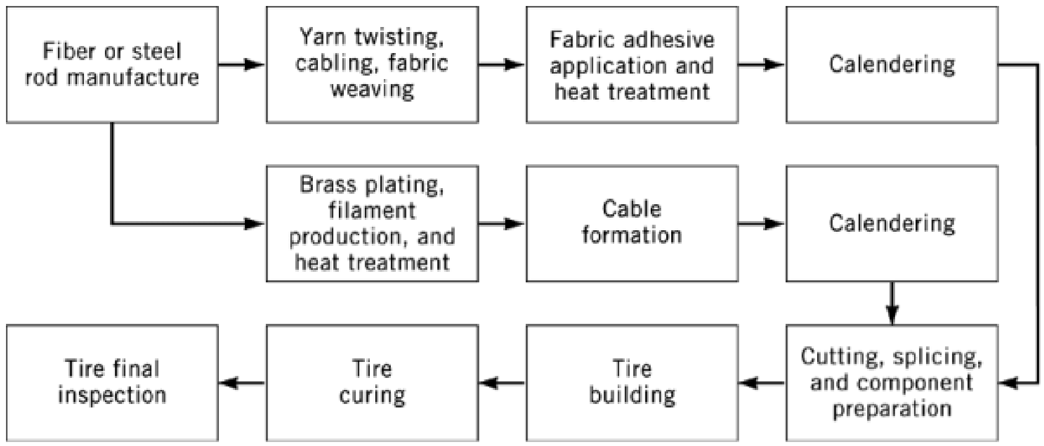

Fig. 2. Tire production process.

9.5. Thermal and Chemical Stability

In addition to load-bearing properties, tire reinforcement must be able to resist degradation by chemicals in cured rubber and heat generation. The most critical degradant depends on the material in use. Most thermoplastic reinforcements are either modified directly or stabilized with additives to offset some, mostly thermal, degradation (32, 33).

10. Processing

The basis for reinforcement of a pneumatic tire requires placing the strength or tensile member in a preferred direction, depending on the location and cord function in the tire. An overview of the tire production process, including essential elements of transforming a continuous yarn into a useful embodiment for tire reinforcement, is shown in Figure 2.

10.1. Linear Density

Linear density is defined as the weight per unit length (usually defined as denier), weight in grams of 9000 m or Tex, gram weight of 1000 m of yarn or cord (26). Tex is often used as dTex $(\text{Tex} \times 10)$ and is related to denier because $\text{dTex} = \text{denier} \times 1.111$.

10.2. Twist

Twist (23) is measured in numbers of turns per unit original length, turns per inch, cm, or meter.

10.3. Construction

Reinforcing cords are normally constructed by combining single bundles of twisted yarns (plies) in an operation known as cabling (23). The final cord is defined by the linear densities of the individual plies and the twist applied during the ply and cabling operations. For example, a common polyester construction is 1100/1/3 315×315. That is, an 1100 dTex yarn is twisted 315 turns per meter (tpm), three of which are then cabled together by twisting in the opposite direction 315 tpm.

Table 2. Constructions for Tire Cord Use

Name	Construction	Typical application
polyester (1100 dTex 350 tpm twist)	1100/3350 × 350	radial tire carcass
nylon (1400 dTex 390 tpm twist)	1400/2390 × 390	bias tire carcass
nylon (940 dTex 470 tpm twist)	940/2470 × 470	radial tire overlay

10.4. Twisting

The function of twisting (23) is to combine individual fiber filaments to improve the tensile properties by the cooperative interactions between the filaments, and to form into a bundle that is more easily manipulated in manufacturing processes. More importantly, the function of twisting fibers to form a ply (single) and then a cable or cord is to impart required properties of fatigue resistance and abrasion resistance. Cords are formed by twisting the fiber bundle into a ply, usually in the Z direction (anticlockwise spiral), then combining two or more plies by twisting together in the S direction (clockwise spiral). By convention and for ease of manufacture, the numerical values of twist in ply and cable are usually matched. The process of ply twisting and cabling may be accomplished in two discrete steps or, with modern direct cabling equipment, in a single operation. Proper handling of the sometimes fragile filaments is critical at the twisting stage, before fibers are transformed into the more robust cord structure. This is especially true of high modulus fibers such as aramids. In general, as the degree of twist (sometimes characterized by the twist factor index) is increased, the tensile properties of strength and modulus decrease. In contrast, the fatigue resistance rises as a cord is twisted. The amount of property gain or loss is governed by the fiber type, linear density, construction, and twist. Therefore, selection of the appropriate twist is a compromised decision guided by the needs of the final application. Some typical cord constructions are provided in Table 2.

10.5. Processing Oils

Individual fibers used for reinforcement purposes are quite small, on the order 10–20 micrometers in diameter, and are sensitive to damage resulting from abrasion by contact with machine parts during manufacture. Oils are applied during this process and serve to lubricate the filament bundle and act as wetting agents to assist the spreading and adhesion of coatings applied at later stages of processing (34). As such, processing oils must be amenable to a wide range of uses. Their formulation is highly proprietary based in general on the use of modified fatty acid esters. Other types of finish can also act as adhesive activators for later processing.

10.6. Weaving

After cord forming, a loose fabric is made by weaving the cords (as the warp) at a density in the range 6 to 12 cords/cm, depending on the construction using weft or pick cords to hold the fabric together. Pick cords are generally cotton, rayon, or polyester single-ply yarns used at densities of 50–75 threads per meter. Later, the pick cords may be broken to allow the fabric to expand laterally when formed into a tire, thus requiring that pick cords be relatively weak. Another method used, which avoids the need to break pick cords, is to use high elongation-fill pick cords with low modulus for ease of stretching. In addition, pick cords should be compatible with all later stages of processing, such as adhesive dipping and tire curing.

10.7. Adhesive Application and Heat Treating

This step represents perhaps the most critical phase in preparing a tire cord where a suitably strong adhesive is applied to bond the fiber to the rubber, thus forming a useful composite (35, 36). In addition, the cords

Table 3. RFL Dip System for Nylon[a, b]

Product	Value
water	407.7
sodium hydroxide, 10% (aq) solution	8.0
penacolite resin R2170, 75% (aq) solution	26.7
formalin, 37% (aq) solution	20.3
vinylpyridine latex, 40%	250.0

[a]Ref. 5.
[b]This system results in a 18% solids by weight dispersion.

are heat treated to impart desired physical (tensile) characteristics depending on the final tire performance requirements. Adhesive formulations for tire cord use have been developed since rayon was introduced as a tire cord. The basis of application for almost all types is the so-called resorcinol formaldehyde latex (RFL) system (35–38). Such adhesives are usually waterborne dispersions and solutions of ingredients designed to form a network or matrix to bond to the reinforcement and the rubber, and serves to transmit stress from the rubber to the reinforcement. In general, the role of the resin component (RF) is to develop adhesion to the fiber, and the latex (L) adheres to the rubber. The mechanisms of RFL-to-rubber adhesion are quite complex and have been the subject of many years of development and manipulation (37). After dipping and fabric/adhesive curing, the coated fabrics become completely dry and develop adhesion to the rubber during the tire cure cycle. Although basic RFL formulations are similar, many variations have been made to suit particular cord and rubber requirements. For instance, polyester can be usefully treated with a single RFL formulation or by two discrete formulas (pre-dip and post-dip). An alternative for polyester is the application of an adhesive-activating material, usually an epoxy, by the fiber producer which enables the tire cord producer to apply a single, more simple dip system. Furthermore, highly inert materials such as aramid require an additional pre-dip non-RFL adhesive or similar modification techniques before an RFL-type adhesive can be applied to bond with rubber.

A typical formulation for nylon tire cord adhesives are given in Table 3. Modifications to the formulations can, for example, include the use of different resin-forming agents, various latexes and mixtures thereof, and different adhesives applied in more than one step. Some processes have been developed to incorporate a fiber surface modification as part of the adhesive application using surface treatments (39, 40). Special adhesive systems have been developed for fiber glass, using agents to bond to the glass surface and a softer, more rubbery matrix to separate and protect the individual filaments in a bundle (36, 41).

Because organic tire cords are mostly thermoplastic polymers (except rayon and aramids) they can be modified by further heat stretch during dipping steps (42, 43). This is in addition to the principal fiber alignment operation that takes place during the fiber spinning steps. The process conditions used are highly dependent on fiber properties and therefore are the subject of detailed study and optimization by individual tire cord producers. In addition to heat setting, process conditions must be suitable for (*1*) applying the correct amount of adhesive and (*2*) exposure to the correct temperature for completion of adhesive curing reactions.

10.8. Creel Calendering and Nonconventional Tire Manufacturing

An alternative to the fabric weaving and dipping approach is to assemble the final in-rubber treatment directly from the individual cords. Such processing is known as creel calendering and is commonly used in coating steel cord with rubber for tire use. An additional complication for organic tire cords over steel involves adhesive and cord processing that must be included in the calendering process. Although such processing is colloquially referred to as single end, production facilities process many cords or ends (ca 50) simultaneously. Such processing eliminates any requirement for weaving fabric and the need for and subsequent inclusion of pick cords in tires.

The basic principles and approaches to manufacturing pneumatic tires have been in place for many years, and because of the scale of modern tire production, radical change is slow. However, developments of new tire production processes continue (44, 45) and as new methods take hold, it is likely that changes in tire cord handling and preparation will be required.

11. Steel Tire Cord

Steel tire cord provides a unique combination of strength, ductility, dimensional stability, resistance to fatigue, rubber adhesion, and consumer value that led to a dramatic increase in steel cord consumption for the last decade (46, 47).

11.1. Materials and Process

The steel chosen for tire cord is a eutectoid carbon steel containing 0.7% carbon, 0.5% manganese, 0.2% silicon, and a very low amount of sulfur and phosphorus (9, 48). The steel rod is cleaned with acid, rinsed, drawn through tungsten carbide dies to reduce its diameter from 5.5 to ~ 3.0 mm, heat treated (patented) to increase ductility for further drawing to ~ 1 mm, then patented again.

The patented wire is again cleaned with acid, rinsed, and brass plated just before the second drawing. The brass acts as a drawing lubricant and as well as an adhesive to rubber. The brass composition is typically 60–70% copper with zinc as the remainder. The patented, brass-plated wire is drawn into filaments of 0.15–0.38 mm diameter.

11.2. Steel Cord Construction

Filaments or wires are twisted into strands and then combined into cords. The lay length is the axial distance required to make a 360° revolution of any component in a strand or cord and is expressed in millimeters. Direction of lay is the helical disposition of components of a strand or cord. Strands or cords have an *S* (left-hand) lay if, when held vertically, the spirals around the central axis of the strands conform in direction of slope to the central portion of the letter “S”. Strands have a *Z* (right-hand) lay if the spirals conform in direction of slope to the central portion of the letter “Z” (49). Lay lengths of the strands or cords, ranging from 2.5 to 25.0 mm, are chosen to hold the filaments together and yet obtain the smallest degree of fretting and the highest fatigue life during tire service. A spiral wrap of a single filament is applied to some large-diameter tire cords in order to increase the cord’s compression resistance and bending rigidity. However, this wrap decreases elasticity and increases fretting of cord during tire service.

The way the filament, strand, and spiral wrap are assembled, and the filament diameters used (usually in millimeters), determine the cord construction. The tire industry has adopted an ASTM wire nomenclature. The description of the construction follows the sequence of manufacturing of the cord, ie, starting with the innermost strand or filament and moving outward. A plus (+) sign separates each layer. If the filament diameters are the same in two or more components, the diameter is omitted for all but the last component. If a strand is a single filament, the numerical designation “1” is omitted. The full description of the construction is given by the following formula:

$$(N \times F) \times D + (N \times F) \times D + F \times D \qquad (1)$$

where N = number of strands, F = number of filaments, and D = nominal diameter of filaments, in mm (7, 49). The cords can be classified into (*1*) regular, (*2*) Lang’s lay, (*3*) open, (*4*) compact, and (*5*) high elongation. The most common cord is the regular cord in which the direction of lay in strands is opposite to direction of

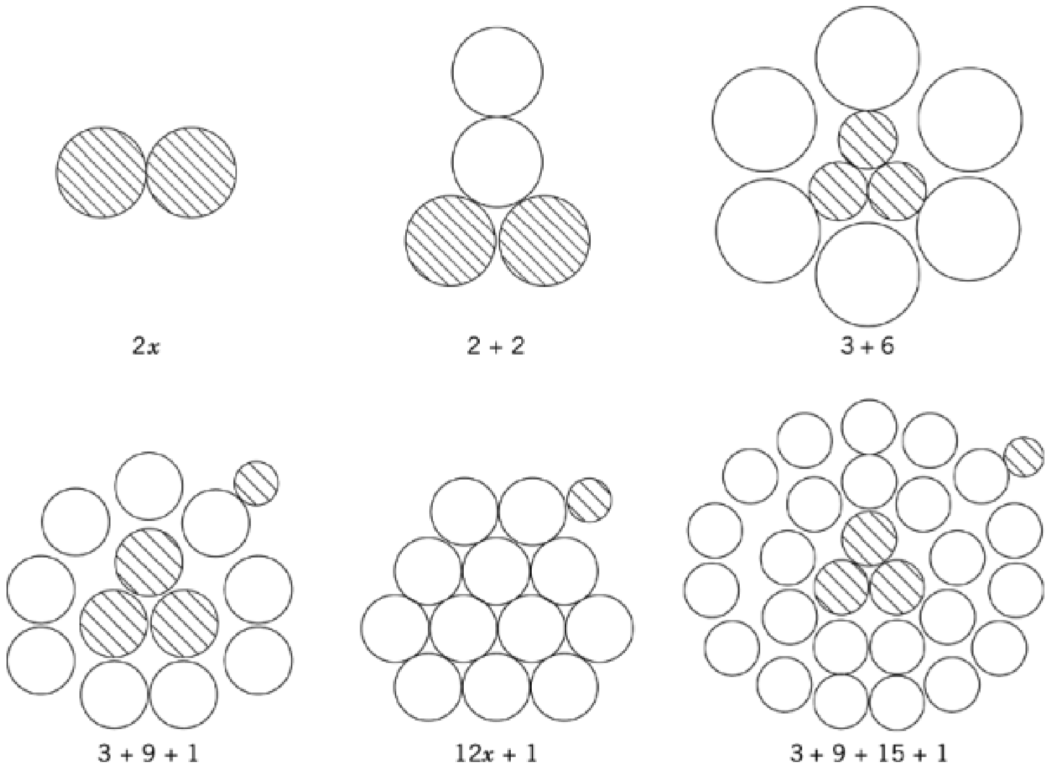

Fig. 3. Cross sections of cords used in tires where represent inner- and outermost strands (first and/or last number in description).

lay in closing the cord. Lang's lay cord is formed such that the direction of lay in the strands is the same as the direction of lay in closing the cord. Open cords are loosely twisted and movable relative to each other to enable rubber penetration into the cord (49, 50). Open cord can be also obtained by using preformed filaments. Compact cord is bunched so that the filaments have mainly linear contact with each other; rubber penetration can be promoted by using filaments of different diameters (49, 51). High elongation cord is a Lang's lay cord in which the strands are loosely associated and movable relative to each other, to allow the cord substantial stretchability under load (49). Examples of the various cords used in tires are shown in Figure 3.

11.3. Adhesion

A thin layer of brass coating on steel cord facilitates adhesion between the metal and rubber compound. The mechanism of rubber–brass adhesion has been the topic of much speculation and fundamental research. Advanced techniques such as auger electron spectroscopy (aes), electron spectroscopy for chemical analysis (esca), and scanning transmission electron microscopy (stem) have contributed to a better understanding of adhesion formation and degradation (52, 53). The interfacial reaction products, which consist of Cu_xS where x ranges from 1.8 to 2.0, depend on copper and ZnO content of the brass surface. There is a minimum critical thickness of Cu_xS for maximum adhesion as well as a maximum thickness above which adhesion begins to drop. In general, adhesion degradation is prevented by a lower copper content or thinner brass layer. Additional elements in copper–zinc alloy improve adhesion, especially aged adhesion. Additional elements under study include cobalt, nickel, and iron (46, 52–54).

11.4. Stress in a Cord

Twisting two or more filaments together to form a cord reduces the overall modulus and strength of the construction. The degree of the reduction depends on the individual filaments (55). If the lay length is significantly higher than the filament diameter, the stress is $\sigma_a = 4P/\mathrm{n}\pi d^2$, under axial loading, and $\sigma_b = Ed/D$ under bending load, where σ_a and σ_b are axial and bending stresses, respectively; P is axial load; n is the number of filaments in the cord; E is the modulus; d is the filament diameter; and D is the diameter of bending. The bending load equation shows that the smaller the filament, the lower the bending stress of the cord, resulting in increased bending fatigue life (48).

12. Cord Mechanics

12.1. Cord Elasticity

Tire cords, consisting of several yarns twisted together, are one-dimensional structural members. The cord properties depend on yarn filament properties and their geometrical organization (56). The filament itself possesses an internal structure at the microscopic level. The way in which cord properties are related to filament properties, geometries, and other variables is the subject of textile mechanics (21, 56). In application to tires, interest lies in cord properties obtained experimentally without relating to the microstructure in formulation of cord composite properties. Cords, as the reinforcing member of cord–rubber composite, have certain strength, modulus, and dimensional, thermal, and chemical stability properties. Cords may be characterized by linear relationship between stress and strain tensors as in the following:

$$\sigma_i = Q_{ij}\epsilon_j \quad \text{or} \quad \epsilon_i = S_{ij}\sigma_j i\ ,\ j = 1, 2 \ldots 6 \qquad (2)$$

where σ, ϵ, Q, and S are stress component, strain component, stiffness matrix, and compliant matrix, respectively. In general, cords are considered transversely isotropic materials, ie, in one plane, mechanical properties are equal in all directions. This application leads to five independent constraints that characterize cord, namely (*1*) extensional Young's modulus, (*2*) extensional Poisson's ratio, (*3*) transverse Young's modulus, (*4*) transverse Poisson's ratio, and (*5*) shear modulus. However, most applications of cord–rubber composite require only extensional Young's modulus, extensional Poisson's ratio, and shear modulus. The influence of transverse Young's modulus and transverse Poisson's ratio are negligible.

Cord materials such as nylon, polyester, and steel wire conventionally used in tires are twisted and therefore exhibit a nonlinear stress–strain relationship. The cord is twisted to provide reduced bending stiffness and achieve high fatigue performance for cord–rubber composite structure. The detrimental effect of cord twist is reduced tensile strength. Analytical studies on the deformation of twisted cords and steel wire cables are available (22, 56–59). The tensile modulus E_c of the twisted cord having diameter D and pitch p is expressed as follows (60):

$$E_c = \frac{E_f}{1 + \tan^2\theta} = \frac{E_f}{1 + \frac{\pi^2 D^2}{p^2}} \qquad (3)$$

where θ is the helix angle of the outermost filament and E_f is the filament modulus. The Young's modulus of twisted cord E_c decreases with increasing twist, whereas the Poisson's ratio v_c increases with increasing twist, according to equation 4 (60).

$$v_c = \frac{p^2}{\pi^2 D^2} \qquad (4)$$

Table 4. Values of Young's Modulus for Tire Cord[a]

Cord construction	Young's modulus, E_c, GPa[b]
belt ply	
$5 \times 1 \times 0.025$ mm steel	110
1670/2 Kevlar	25
1840/3 rayon	11
body ply	
1110/2 polyester	4.0
940/2 nylon	3.4

[a]Ref. 62.
[b]To convert GPa to psi, multiply by 145,000.

The cord fatigue phenomenon and effect of twist has been discussed (61). Values of Young's modulus of some belt and carcass cords used in passenger tires are given in Table 4 (62). Poisson's ratio υ_c of tire cords is often in excess of 0.5 due to twist; the higher the twist, the larger Poisson's ratio of cords.

12.2. Cord Viscoelasticity

Cords used in tires exhibit time-dependent viscoelastic property. Viscoelasticity means the loss of energy during stress–strain cycle. This loss of energy is dissipated in the form of heat which affects cord material properties and therefore tire performance. Viscoelastic behavior of tire cord contributes to the total power loss of the tire and therefore its rolling resistance. When a tire cord is subjected to sinusoidal strain of small amplitude, the resulting stress–strain curve is elliptical, exhibiting linearly viscoelastic characteristics, and the material properties are represented by real and imaginary moduli E' and E'', and tan δ the ratio E''/E'. The properties are dependent on temperature and frequency but independent of strain amplitude. However, all tire cords, including steel, exhibit nonlinearity, especially when the strain amplitude is relatively large, eg, tire cord operating under normal tire conditions (63). The stress–strain loop is no longer elliptical. Material properties in the nonlinear region are no longer represented by real and imaginary moduli, and the viscoelastic properties in this nonlinear region are characterized by effective dynamic modulus and mechanical loss. The most important aspect of viscoelasticity is that organic cord properties change as cords are processed for adhesive application through the dip unit. Here organic cord is subjected to tension under high temperature conditions; the organic cords in the new cured tires may have considerably different properties from that of cord pulled from used tires (64, 65). A typical hysteresis loop indicating nonlinear viscoelastic behavior of a tire cord is shown in Figure 4. Demonstrated approaches of designing tire cords for minimum mechanical loss are available (66).

12.3. Cord–Rubber Composite

The pneumatic tire is a commonly used fiber-reinforced rubber composite product that is subjected to severe punishment during the course of its life. The main characteristic of fiber-reinforced rubber composites is a low stiffness property ratio of rubber matrix to that of reinforcing cords. The geometrical and design complexities of tires, along with the heterogeneous, anisotropic material properties and complicated load application and distribution, necessitate better understanding of these composite properties. Such information is valuable for tire engineering application, analysis, and performance, as well as continuously increasing requirements for smooth ride, handling, and durability.

The characteristic features of a cord–rubber composite have produced the netting theory (67–70), the cord–inextensible theory (71–80), the classical lamination theory, and the three-dimensional theory (67, 81–83). From structural considerations, the fundamental element of cord–rubber composite is unidirectionally

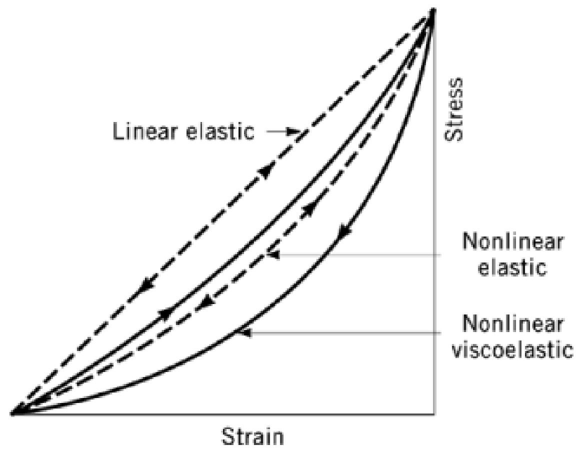

Fig. 4. Nonlinear elastic and viscoelastic response (66).

reinforced cord–rubber lamina as shown in Figure 5. From the principles of micromechanics and orthotropic elasticity laws, engineering constants of tire T cord composites in terms of constitutive material properties have been expressed (72–79, 84). The most commonly used Halpin-Tsai equations (75, 76) for cord–rubber single-ply lamina L are expressed in equation 5:

$$\begin{aligned} E_L &= E_c V_c + E_t V_t \\ E_\tau &= E_r \frac{(1+2V_c)}{(1-V_c)} \\ G_{LT} &= \frac{G_r[G_c + G_r + (G_c - G_r)V_c]}{[G_c + G_r - (G_c - G_r)V_c]} \\ V_L &= V_c V_c + V_r(1 - V_c) \\ V_T &= V_L \left[\frac{E_T}{E_L}\right] \end{aligned} \tag{5}$$

where V_c is the volume fraction of cord $(\pi r^2/t)$epi (r is the radius of cord, t is the thickness of ply, and epi is cords per inch of ply); V_r is the volume fraction of rubber; υ_c and υ_r are Poisson's ratio of cord and rubber, respectively; and G is shear modulus. It is important to realize that the Halpin-Tsai equations are valid only for small deformations. Attempts to predict effective elastic properties of orthotropic cord–rubber composites from the principle of virtual work have been made (85–87).

The direction of applied load in the cord rubber composite is not, in general, coincident with the principal axis of the system. The response of such a system is complicated by the development of shear strains due to off-axis loadings and therefore display complex behavior in terms of coupling between shear strain and normal stress, and normal strain and shear stress, resulting in generally orthotropic ply behaving as anisotropic lamina. The effect of cord angle on elastic constants for nylon cord–rubber lamina are shown in Figures 6 and 7 (88).

The tire is a system of laminated composites composed of numbers of orthotropic laminae. The elastic engineering properties of each ply vary due to material constituents, cord end count, cord angle, and rubber thickness. The stress–strain relations or engineering properties of laminated composites are complicated by the fact that the tensile load applications cause twisting, bending, and stretching. The derivative of in-plane and

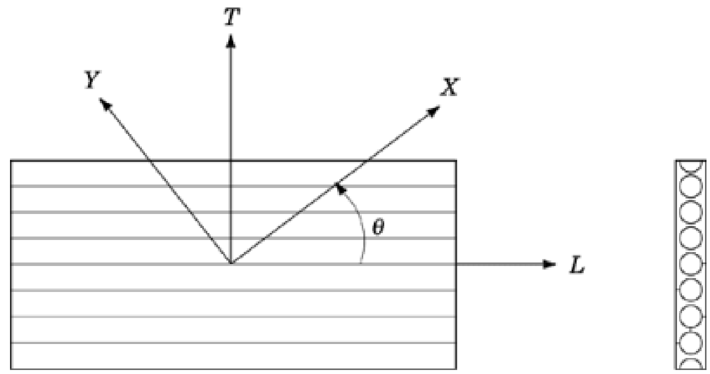

Fig. 5. Calendered unidirectionally reinforced single-ply cord–rubber lamina where θ is the helix angle, L is lamina, and T is tire.

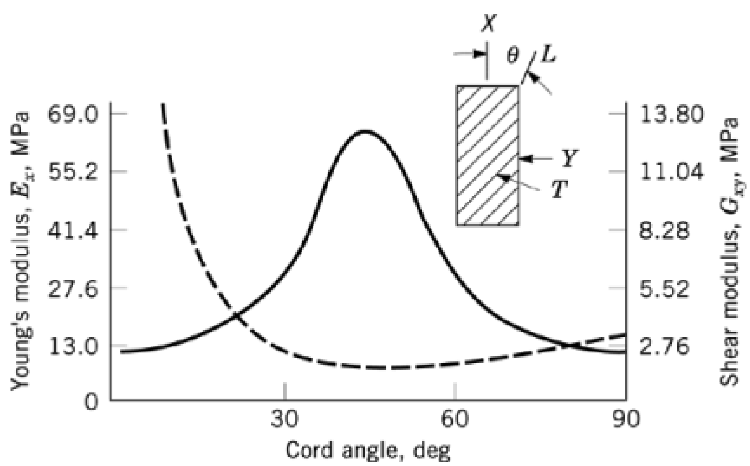

Fig. 6. Variation of Young's modulus (— — —) and shear modulus (—), with cord angle θ for one-ply nylon–rubber system (88).

out-of-plane displacements define stretching and bending strains, respectively. The mathematical formulations of stress–strain relations for laminated composites with application to tires have been discussed (83, 89), with some experimental verification.

Inter-ply shear is prominently featured in cord–rubber composite laminates, and may relate to delamination-induced failures. Studies utilizing experimental, analytical, and finite element tools, with specific application to tires, are significant in compliant cord–rubber composites (90–95).

13. Cord Impact on Tire Performance

The major load-bearing member of cord–rubber composites is the cord, which provides strength and many other critical properties essential for tire performance. Cords in plies form the structural backbone of the tire. The rubber plays the important but secondary role of transmitting load to the cords via shearing stresses at the cord–rubber interface. Other expected performance characteristics of the tire are due to design and

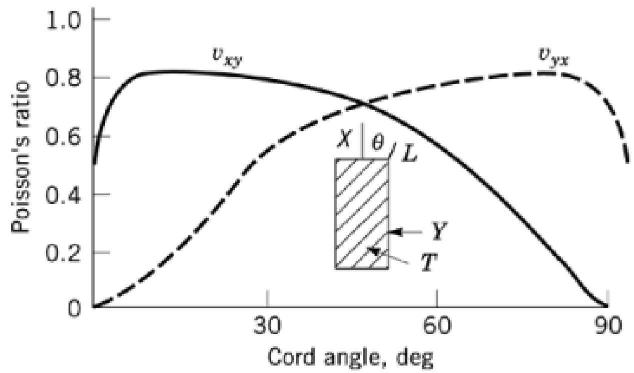

Fig. 7. Variation of Poisson's ratio, v, with cord angle θ for one-ply nylon–rubber system (88).

Table 5. Tire Performance Characteristics[a]

Tire performance and processibility	Knowledge of relationship: None	Poor	Fair	Good	Properties
burst strength				*	tensile, uniformity
bruise and cut resistance			*		high speed, hot tensile modulus, uniformity, toughness
endurance (separation resistance)			*		fatigue resistance, adhesion, ad-hesion degradation resistance in tire environment, dynamic properties (hysteresis), uniformity
for radial high speed			*		modulus, density
power loss		*			dynamic properties, density
tire size and shape			*		dimensional stability, modulus, creep
tire uniformity and flatspotting			*		dimensional stability (T_g), modulus, creep
tread wear			*		modulus
tire ride and handling		*			modulus, density
spring rate		*			modulus
noise		*			modulus, density
groove cracking resistance			*		creep
processibility			*		dimensional stability (T_g), hot creep and shrinkage, moisture regain, adhesion, environmen-tal degradation resistance, uniformity, stiffness, toughness, moisture swelling and shrink-age, compaction, tensile

[a]Ref. 96.

manufacturing processes. Table 5 (96) identifies several tire performance characteristics and how they are dependent on tire cord properties.

13.1. Burst Strength

The burst strength of the tire is derived from the cord strength and is related by equation 6 (97, 98):

$$\text{burst strength} = Nt_uK = \frac{\Pi P_b\left(r_c^2 - r_{\max}^2\right)}{\sin\alpha} \qquad (6)$$

where N is total number of cords in a tire, t_u is average ultimate tensile strength of cord, P_b is burst pressure, r_c is radius from the center of rotation to the crown of tire, r_{max} is radius from the center of rotation to the maximum section width of a tire, α is the crown angle between cord path and circumferential plane through the crown of a tire, and K is the efficiency factor which depends on the distribution of ultimate cord strength and is always less than one.

Tires are designed with a very high factor of safety, about six for radial medium truck tires and ten or higher for radial passenger tires. The reason for such a higher factor of safety is that the cord tensile strength is measured at 23°C and 55% relative humidity (ASTM D885-64). However, tires can reach short-term operating temperatures up to 150°C in some applications. At these temperatures some organic tire cord materials can degrade resulting in loss of strength $\leq$50% of room temperature value. Adding 10–20% degradation in cord strength during the life cycle of the tire, drops the effective tire strength to 150–200% of designed strength, which may be sufficient for burst but may fail to meet several important performance criterias. Therefore, selecting cords only on burst strength requirements may not be the most desirable approach for overall tire design.

13.2. Bruise Resistance

Bruise resistance of a rolling tire describes its ability to resist impact failure. Bruise resistance is tested by measuring the energy required to break a passenger tire under inflation at room temperature when a 19-mm diameter plunger is pushed through the crown at 51 mm/min crosshead speed (DOT test 49CFR571-109). The area under the load-deflection curve is measured as bruise energy. Bruise resistance should be measured at operating temperature conditions of the tire for an accurate prediction of cord contribution because its material properties exhibit different performance characteristics at elevated temperatures (97, 99, 100).

13.3. Tire Endurance

The interlaminar shear stress and deformation in the composite laminate of tire can produce delamination-induced failures, especially at the belt edges. The tire composite can be designed to minimize interlaminar shear stress through proper selection of cord properties, cord orientation, cord end count, and rubber properties. Another separation mechanism can involve cord–rubber adhesion. This adhesion depends on chemical and mechanical interaction between adhesive-treated cord–rubber surface. Another failure phenomenon is fatigue which is mostly observed on sidewall near the shoulder and bead regions due to high temperature and stresses (101–103). To some extent fatigue performance can be controlled through proper selection of cord material and twist.

High speed performance tires may generate enough heat to cause tread separation. At higher speeds, a tire can go into resonance (standing wave) which distorts the tire and results in shoulder growth and excessive heat buildup. The onset of resonance for a passenger radial tire generally begins at speeds of about 120 km/h. This onset speed can be raised through tire design changes such as shorter or stiffer sidewall or through lower belt weight by selecting lighter cord materials.

13.4. Cornering and Ride

The stiffness or modulus properties of cord–rubber composites used in tires strongly influence the ultimate performance of tires (104). The stiffness of the belt package primarily determines the cornering and ride characteristics of a radial passenger tire. The belt package in contact with the road is a fairly complex composite consisting of tire components including the innerliner, carcass, belts, and tread. The in-plane flexural rigidity of the belt package is the most important parameter controlling cornering, whereas out-of-plane flexural rigidity controls ride. Flexural rigidity, in turn, depends on the stiffness of the belt package. From the principles of composite mechanics, the circumferential modulus or stiffness per unit area in the hoop direction of a cord–rubber laminate with identical plies at equal and opposite cord angles is expressed as in equation 7 (62, 104):

$$E_x = E_c V_c \cos^4\theta + G_r (1 - V_c) - \frac{\left(E_c V_c \sin^2\theta \cos^2\theta + 2G_r (1 - V_c)^2\right)}{\left(E_c V_c \sin^4\theta + 4G_r (1 - V_c)\right)} \qquad (7)$$

where E_x is the circumferential belt modulus, θ is cord angle with respect to circumference, V_c is cord volume fraction, G_r is rubber shear modulus, and E_c is cord modulus in tension. Through the analysis of equation 6, it has been shown that, in order of importance, belt modulus depends on rubber modulus, cord angle, cord volume fraction, and cord modulus (62). However, equation 6 does not take into account the effect of additional stiffening due to internal pressure, double curvature of belt, and most importantly the presence of body ply or plies in tires, which can significantly affect overall stiffness. Again, cord properties play an important role in providing necessary stiffness for tire performances.

13.5. Treadwear

Treadwear is a complex physical–chemical process driven by the frictional energy developed at the interface between tread pattern elements and the pavement. The rate of wear is influenced by the loss modulus property of the tread compound, the microstructure (or abrasiveness) of the pavement, environmental conditions, and vehicle operation (105, 106). The wear of passenger tires occurs mainly during cornering maneuvers (104), where the tread center line distortion in the footprint impacts slippage of the tread rubber relative to road surface mainly in the region at the rear of the footprint. Belted radial tires experience less slippage than nonbelted tires in cornering. Even at straight driving, ie, at 0° slip angle, the footprint pressure distribution is much more uniform for radial belted than nonbelted constructions. This difference in performance has been explained by testing the tire footprint as a laminated anisotropic beam subjected to cornering force at the plane of footprint (83, 107). The Gough stiffness, S, which has been shown to correlate well with actual wear rate of tires (108), can be expressed as in equation 8:

$$S = \frac{E_x G_{xy}}{C_1 E_x + C_2 G_{xy}} \qquad (8)$$

where E_x and G_{xy} are circumferential and shear moduli of the cord–rubber laminate in the tread region (which depend on cord properties and tread package design), and C_1, C_2 are constants. However, it should be observed that the loss modulus of tread compound has been demonstrated as a single property to characterize compound wear characteristics. The loss modulus is dependent on the glass-transition temperature, T_g, the carbon black level and morphology, process oil content, and polymer microstructure properties. The proper use of these components opens up the possibility of developing compounds that can accurately characterize treadwear performance under selected environmental conditions.

13.6. Flatspotting

It is generally assumed that the tire cord is primarily responsible for flatspotting (109–114). The mechanism of flatspotting in tires is based on the viscoelastic behavior of tire cords. Tire cords such as nylon and polyester tend to shrink when heated above their glass-transition temperature, T_g, as in the case of a running tire. The cord strain in the footprint is much smaller than in other parts of the tire. When the tire stops rotating, the cord elements in the footprint cool to ambient temperature because they are under much less strain, and therefore shrink more than the cords in the remainder of tire which are in considerable tension due to inflation pressure.

When the tire starts to rotate again, persistence of this difference causes flatspot, which remains until the tire is reheated to a temperature at which the flatspot was introduced.

13.7. Power Loss on Tire Rolling Resistance

About 95% of rolling resistance or power loss is due to the viscoelastic loss of the tire. However, the relative contribution of cord and rubber to tire rolling resistance has been the subject of numerous studies (113–119). It is estimated that 20 to 40% of a tire's power loss is due to the behavior of cords in tires. Tires having carcass constructed with aramid cords have a lower rolling resistance than those constructed with steel cords (116). Similar findings are quoted for tires constructed with aramid and steel belts. Also, tire design, tire weight, cord deformation in tire, as well as dynamic properties of cords affect tire rolling resistance. There have been significant changes in tire construction and materials which have markedly reduced power loss, eg, change from bias to radial tire construction, use of higher inflation pressure, and improved rubber compounds, specifically tread compounds with better dynamic properties (120). However, the challenge is to understand the exact contribution of cord to tire power loss in radial tires and to develop cord material with properties that significantly reduce power loss.

14. Test Methods

Tire cords are characterized for their physical, adhesion, and fatigue properties for use in tires. These characterizations are conducted under normal and varying test conditions to predict their performance during tire operation. Various test methods used to characterize tire cords are described.

14.1. Standard Test Methods for Steel Tire Cord

ASTM standard D2969-92 includes test methods for steel cords that are specifically designed for use in the reinforcement of pneumatic tires. It describes test methods determining steel cord construction, break strength, elongation at break, modulus, flare, linear density, straightness, residual torsion, brass coating composition, and mass of steel cords.

14.2. Standard Test Method for Adhesion Between Steel Tire Cords and Rubber

Steel cords are vulcanized into a block of rubber and the force necessary to pull the cords linearly out of the rubber is measured as adhesive force. ASTM method D2229-93a can be used for evaluating rubber compound performance with respect to adhesion to steel cord. The property measured by this test method indicates whether the adhesion of the steel cord to the rubber is greater than the cohesion of the rubber, ie, complete rubber coverage of the steel cord or less than the cohesion of rubber (lack of rubber coverage).

14.3. Steel Cord Impact Test

A transverse impact test method for steel cords has been designed to determine the resistance to cutting (puncture resistance) when used as a tire belt reinforcement (121). The test is a modified charpy test, and the sample consists of a 3-mm diameter rubber cylinder reinforced in the center with a steel cord. The impact force and total amount of energy absorbed is measured. This test has demonstrated that high elongation cord possesses greater capacity to absorb energy compared with regular cord. This is one reason why high elongation cord constructions are used as a protection layer in truck and off-the-road tires.

14.4. Rotating Beam Fatigue Test for Steel Cords

The purpose of this test method is to evaluate steel cord for pure bending fatigue (121). The test sample consists of a 3-mm diameter rubber embedded with steel cord. Different bending stress levels are applied and the time to failure is recorded. The test stops at 1.44 million cycles. The fatigue limit is calculated from S–N (stress–number of cycles) curve.

14.5. Rotoflex Test for Steel Cords

The purpose of this test is to determine the bending fatigue limit as a function of pretension in the carcass cords of truck tires (121). The test sample consists of rubber strip 5 mm thick, 12 mm wide, and 450 mm long, reinforced with steel cord in the longitudinal direction. The dead weight determines the pretension in the cord, whereas the mold diameter determines the applied alternating bending stress in the filaments of the cord. Repeating the procedure for different pretensions leads to the determination of the Smith Goodman diagram, which reveals differences in cord construction from bending fatigue considerations.

14.6. Standard Test Methods for Tire Yarns, Cords, and Woven Fabrics

ASTM standard D885M-94 includes test methods for characterizing tire cord twist, break strength, elongation at break, modulus, tenacity, work-to-break, toughness, stiffness, growth, and dip pickup for industrial filament yarns made from organic base fibers, cords twisted from such yarns, and fabrics woven from these cords that are produced specifically for use in the manufacture of pneumatic tires. These test methods apply to nylon, polyester, rayon, and aramid yarns, tire cords, and woven fabrics.

14.7. Standard Test Method for Thermal Shrinkage of Yarn and Cord

ASTM test method D4974-89 is used for measuring thermal shrinkage of yarn and cords with linear density ranging from $20 - 700 \times 10^{-6}$ kg/m (20–700 tex) using the Testrite thermal shrinkage oven. A relaxed, conditioned specimen of yarn or cord is subjected to a tension of 4.4 ± 0.88 mN/tex to dry heat at a temperature of 177°C for two minutes. The percent shrinkage is read from a scale on the instrument.

14.8. Static Adhesion Tests for Organic-Based Yarns, Cords, and Fabrics

The most commonly used static adhesion tests are the H-test (ASTM D4776-88), U-test (ASTM D4777-88), T-test (122), I-test (123), and strip–peel test (ASTM D4393-85). These tests derive their name from the shape of the test specimen. In the H, U, and T tests, adhesion is reported by the force required to pull an embedded cord through and out of the rubber. The force of adhesion is affected by embedded length of cord, rate of loading, and temperature. In the I-test, both ends of an I-shaped test specimen are pulled. The force–deflection curve is recorded and adhesion is measured as the second peak force. The strip–peel adhesion test is used to determine peel adhesion force of reinforcing fabrics bonded to rubber compounds. This method is applicable to either woven or parallel cord textile structures.

14.9. Dynamic Adhesion for Organic-Based Yarns, Cords, and Fabrics

Adhesion gradually deteriorates with repeated deformation. Dynamic adhesion evaluation is characterized by number of cycles of deformation to reach limiting value. Various dynamic adhesion test methods have been developed based on the type of deformation. The two most commonly used methods are the Goodrich Disk Fatigue test (124) and the Dynamic Flex Strip Adhesion (ASTM D430-59). In the Goodrich Disk Fatigue test, samples can be subjected to both compression and extensional deformations. In the Dynamic Flex Strip

Adhesion test, a two-ply strip test piece is subjected to compressive fatigue by flexing it over a spindle. Adhesion is estimated by either comparison of strip adhesion before and after flexing or number of cycles for ply separations.

14.10. Fatigue Tests for Organic-Based Tire Cords

Tire cords experience large number of stress–strain cycles which lead to their degradation. There are a number of laboratory tests used to estimate fatigue life of tire cords (eg, ASTM D885-64). Some of the most commonly used test methods include the following. (*1*) In the Firestone Compression Flex test (ASTM D885-64) (125) the test specimen consists of two plies of cords in parallel plane, one ply of test cords and the other of steel cords. Compressive fatigue is produced by flexing the test piece over a spindle for a certain length of time. The test cords are then extracted and tested for retained strength. (*2*) In the Goodrich Disk Fatigue test (ASTMD885-64) (125, 126) the test specimen consists of a rectangular rubber block reinforced with cords parallel to a long axis. The test piece is firmly secured into the periphery of two canopied disks. Cords are subjected to simple longitudinal extension and compression during testing. Strength loss after a certain number of revolutions is used as a measure of fatigue life. (*3*) In the Mallory Tube Fatigue test (ASTM D885-64) (126, 127) the test sample consists of a hollow rubber cylinder in which cords are parallel to each other and parallel to the axis of the test cylinder and have certain ends per inch. The cords in the tube are subjected to alternate compression and tension. The number of revolutions until failure is the measure of fatigue resistance. (*4*) In the Dunlop Fatigue test a test specimen is an endless belt made up of five plies of cords in rubber at certain ends per inch. The second and fifth plies are comprised of cords that are to be tested. The test consists of running belt for a known time, then extracting cords from two test plies and measuring their retained strength.

15. Tire Cord Status

As a load-carrying member, the type of tire cord used for a specific tire depends on the use requirements. For example, the requirements for original vehicle fitment are more extensive than the replacement market. In addition, these requirements also vary with the type of vehicle, eg, passenger, light truck, or medium truck, vehicle design, and service expectations. One important consideration in selecting tire cord remains value to customer. Therefore, the total cost of tire from materials to conversion to customer delivery may play a significant role in the final preference for tire cord. It is therefore not surprising that volume usage of tire cord varies in different regions around the world. To some extent the preference for a tire cord is dictated by tire designs, ie, bias vs radial. Also, within the same design, the belt cord could be different than carcass cord due to different functionality in these components. The belt material for radial tires requires high stiffness/modulus vs carcass material requirements of flexibility and fatigue resistance for comfort and durability.

The automotive industry is becoming more global in nature due to various trade pacts and the free market economy push. An apparent change from globalization is tire design conversion from bias to radial. From a historical perspective, the transition from bias to radial led to relative change in the volume of tire cord material used in that market. For bias applications, nylon tire cord remains dominant, particularly in heavy tires with high load-carrying capacity. The use of nylon-6 vs nylon-6,6 follows the basic criteria: value to customer in that market, with the exeptions of the airplane and large earth-mover tires. In this tires, the wider temperature performance range for nylon-6,6, due to its higher melting temperature, may offer an advantage in certain applications. Polyester has also been used in bias tires (passenger and light trucks). For radial tires the choice of tire cord for belt application varies among glass, rayon, and steel. Fiber glass, once a dominant belt material in North America, has not made much headway in Europe and Japan, due to value glass provided in these regions vs steel, which remains the dominant belt material. Whereas polyester quickly became the choice for carcass material in passenger tires in North America and Japan, rayon and nylon continued to be used in

Europe and Asia. Value to the customer remains a significant factor in choice of tire cord in specific markets at specific times. In this respect, the total cost structure of tire cord material as influenced by nontire market requirements and also plays an important role in determining the intrinsic value to the customer.

Requirements for tire cord material will to some extent be driven by new vehicle trends. For example, the clean air emphasis in North America places lightweight vehicles and materials at a premium. For tire cord the fuel economy or rolling resistance provided by the cord–rubber composite may shift the pattern of usage. A common requirement for all types of tire cord surfaces is a high strength-to-weight ratio.

For steel cord, to meet the higher strength-to-weight ratio, continuous improvements have been made to increase steel cord strength, including steel composition, low levels of impurities, controlled nonmetallic inclusion, minimized segregation during metallurgical solidification processes, and minimum surface defects and decarbonization (128), in conjunction with an increase in the total amount of drawing.

A new approach for high strength organic fibers includes polymer compositions capable of forming in the liquid crystalline state (thermotropic and lyotropic). High modulus, high strength fibers from aromatic polyamides and aromatic copolyesters have been manufactured utilizing conventional dry-jet wet spinning or melt spinning technology (129).

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