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Fiber Properties Required for Tires

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Synopsis

Contrary to what the appearances would suggest, a pneumatic tire is basically an engineered textile object rather than a rubber one. The functional characteristics and performance of tires are chiefly determined by the properties of the textile fibers and by the way in which they are disposed in the tire structure. The specific roles of some of these properties (e.g., modulus, tensile strength, fatigue resistance, hysteresis) will be related to tire performance. Different tire constructions require a different balance of textile properties for optimum performance. Belted tires, and especially radial ply tires, present a different set of requirements for optimum textile fiber performance in tires. The nature of the differences are discussed.

The common pneumatic passenger car tire is an extremely complex, engineered object whose essential function and mode of operation is poorly understood by the people who use them. If we were to conduct a poll among the motoring public to determine the tire properties they consider important, we might very well end up with the list in Figure 1. This is a slightly contrived list, but I use it to make these points: (1) The properties cited relate to the rubber compounds in the tire, and in the minds of most of us a tire is thought of basically as a rubber object. (2) The list represents a set of secondary tire properties, all described as negative virtues, i.e., a good tire shouldn't wear out, shouldn't lose air, shouldn't crack, squeal, slip, etc.

But one cannot discern from such a list what the essential role of the tire on the vehicle is, what its positive virtues are. If, on the other hand, we were to ask an automotive engineer for his list of important tire properties, it would include the properties listed in Figure 2. It is noteworthy in that (1) the properties cited relate more strongly to the essential func-

SOME TIRE PROPERTIES
TREADWEAR
AIR HOLDING
CRACKING RESISTANCE
WEATHERING RESISTANCE
NOISE
SKID & TRACTION

Fig. 1.

SOME OTHER TIRE PROPERTIES
- CORNERING FORCE
- SELF ALIGNING TORQUE
- SPRING RATES
  - • VERTICAL
  - • LATERAL
- ENVELOPMENT
- RESPONSE

Fig. 2.

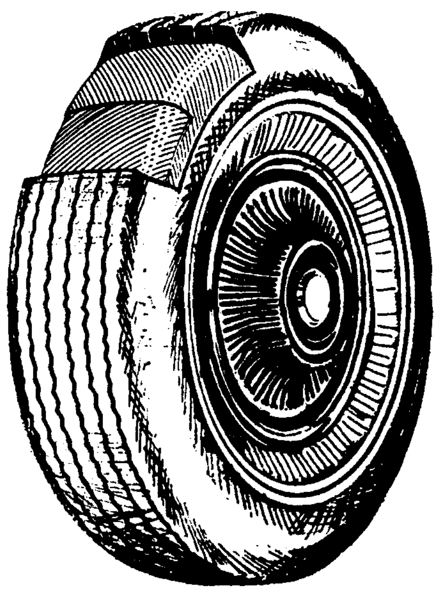

Fig. 3.

tion of the tire as the device responsible for all of the force transfer between the vehicle and the road, (2) The properties cited relate to the character of the tire as a textile object.

A pneumatic tire might most aptly be designated as neither a rubber nor a textile object, but the most important and perhaps the first technically significant object made out of a true composite. But for the moment I would prefer to have you view the tire as an organic structure with a structural skeleton of tire cords fleshed with rubber compounds (Fig. 3).

The essential performance characteristics of the tire are basically determined by the properties of the tire cords and their angular disposition within the tire. Viewed from a formal geometric viewpoint, our tire may exert or transfer force along the x, y, or z axis (Fig. 4), and these may readily identify with tractive (or braking) force, cornering force and vertical load.

In addition, we are interested in two of the related torques or moments (Fig. 5). One relates to the rolling resistance of the tire, and the other is the self-aligning force which is important to the steering characteristics of a vehicle. In all of these forces and moments, the textile properties have the dominant role.

One of the most simple manifestations of this general thesis lies in the relationship between the shape of the tire as molded and the shape of the inflated tire. In Figure 6 are depicted the different inflated cross sections of the carcass contour that would arise from a set of three tires, all cured in the same mold, but having the cord angle disposed at 90°, 45°, and 30°, respectively, with regard to the centerline of the tire. Cord paths in the

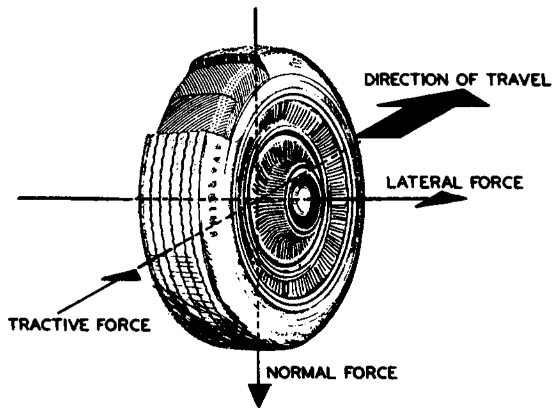

Fig. 4.

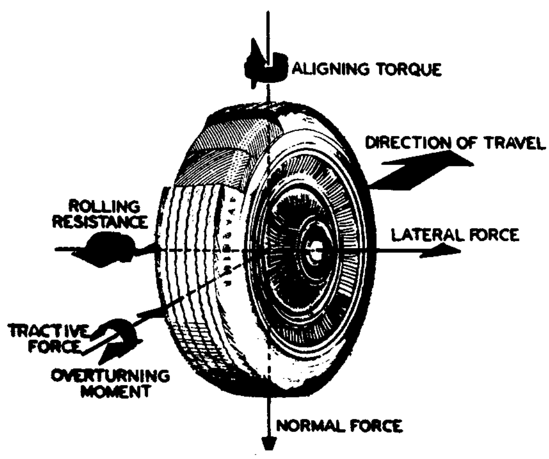

Fig. 5.

radial direction will produce a circular cross section, whereas, as the cord path is altered to the circumferential direction, the inflated shape becomes progressively wider and flatter (low profile).

If I have convinced you that a pneumatic tire is basically a textile object, let us now go on and develop some of the relations between the tire properties and the textile properties.

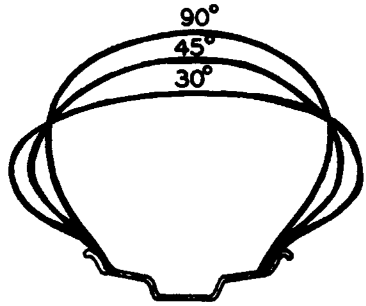

Fig. 6.

TENSILE STRENGTH

Tensile strength is perhaps the most obvious criterion of value for a tire cord. A tire must envelop minor asperities in the road. It must also on occasion attempt to envelop larger asperities like rocks, chuckholes, curbstones, etc., which produce large localized forces that can rupture the tire. Cord strength in a tire substantially in excess of that required to transfer force to the wheel is primarily put there for the purpose of resisting rupture. Figure 7 illustrates a rupturing device used in our test headquarters. The height of the hemispherical plunger is raised successively and the loaded wheel run over it until the impact is sufficient to rupture the tire. If this process is carried out in the laboratory by a slow application of force in a suitable apparatus, it is described as a plunger energy test, required by the D.O.T. Tire strength is a design criterion, and the strength level adopted by tire manufacturers will be one chosen to reduce the incidence of rupture failure to a very minor cause of failure.

Having once established an appropriate strength level, the tire engineer will seek to achieve it in as simple a structure as possible. In this endeavor tire engineers have been greatly assisted by the textile manufacturers. Within living memory we have progressed from tires made from cotton cord with a tensile strength of 1 gram per denier to high-strength rayons that started at 2 grams per denier and have improved to almost triple that

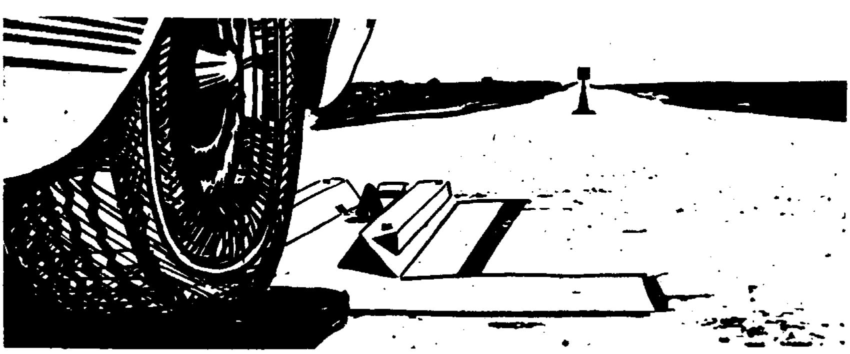

Fig. 7.

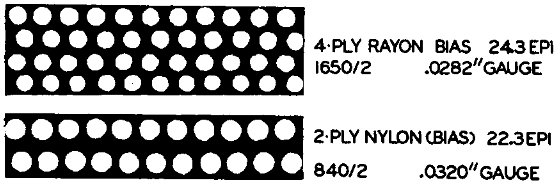

Fig. 8.

value. As well, we had first nylon and then polyester in the 8–10 grams per denier range, and we are now seeing novel new fibers with tensile strengths all the way up to 20 grams per denier.

These developments have permitted systematic reductions in the numbers of plies in tires and gauge reductions in the plies to the point where it is possible to provide ample carcass strength in a thin two-ply structure. As a matter of history, Figure 8 depicts carcass configurations of a four-ply rayon tire of some time ago vis-a-vis two-ply nylon tires of the same carcass strength.

It should be obvious from the foregoing that in any given textile system, improvements in tenacity without corresponding loss in other properties permit cost economies in manufacture in a fairly linear relation. Accordingly, tenacity is a major area of competition for fiber suppliers.

FATIGUE RESISTANCE

Perhaps the most critical performance requirement of a tire, historically, has been fatigue resistance. A passenger tire loaded with a normal load is deflected about 1 inch. These deflections are caused by bending of the sidewall. In Figure 9 I have attempted to trace the carcass line in a two-ply tire going from the undeflected state to full deflection. It is clear that the deflection strains are concentrated in one location in the tire buttress and in another up near the bead. These locations are the classical sites for fatigue failures in tires.

Reckoning the effective circumference of the tire at roughly 7 feet, it figures that in its life span it must endure about 50 megacycles of this stress cycle without substantial strength loss. Moreover, since the footprint area only subtends about one twelfth of the tire's circumference, at 70 mph the tire is undergoing this distortion at an effective rate of about 100 cps.

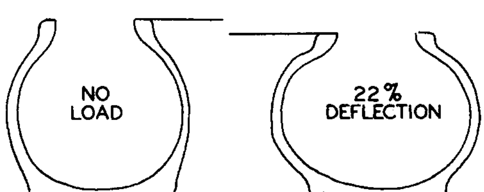

Fig. 9.

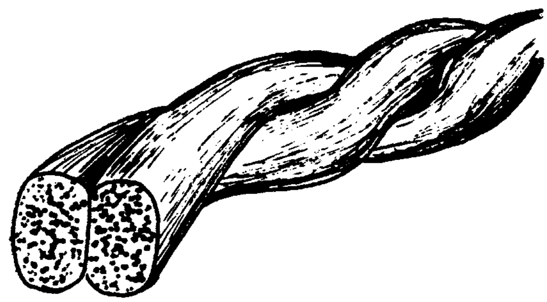

Fig. 10.

During such cycles, the measured stress along the axis of the cord may vary from +8 lb to −1 lb in the cord. The corresponding strain cycle might be +3 to −10%. The most basic disruptive stress is produced by the interaction of neighboring cords on each other with the net effect of snapping open the two or more cord plies within a cord to the distress of the peripheral filaments in the cord and to the adhesive bond to the rubber phase (Fig. 10).

Progressive deterioration of the tensile strength of the cord through filament damage on the cord periphery may reach the point where cord breakage occurs and ultimately tire failure due to what is referred to as cord fatigue. If we have failure of the adhesive bond between cord and rubber, localized buckling of the cord structure leads to failure.

A detailed discussion of cord fatigue is beyond the scope of this paper as well as the capabilities of its author. Obviously, the fatigue resistance depends importantly on the cord geometry and the various features of the cord construction that comprise the stock in trade of the textile engineer. But after the engineering optimums have been established, it is clear that the physics and morphology of the cord materials themselves establish the performance ceilings.

Insofar as fatigue resistance is concerned, there are strong familial patterns. Rayon, nylon, and polyester all owe their preeminent position as tire cord materials to their superior fatigue resistance, and yet there are characteristic differences to be found among them, and minor differences in test conditions may sometimes produce profound variations in their performance.

MODULUS

For good performance, we require the structural members of a tire to have great stiffness and rigidity in one plane of reference, but to be highly compliant in a different plane of reference. To obtain the requisite carcass stiffness to resist unwanted deformations, the modulus of the tire cord is important.

	MODULUS X 10^5 PSI
RAYON	16.0
POLYESTER	13.0
NYLON	7.0
GLASS	53.0
FIBER B	59.0
WIRE	179.0

Fig. 11.

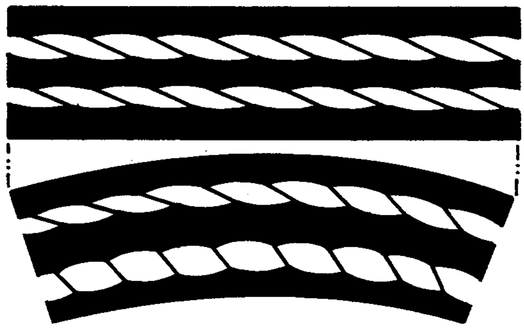

Fig. 12.

By tire cord modulus we mean modulus in tensile, and yet not Young's modulus, but rather the stress–strain relationship in the region of a cord loading of 5 lb/cord.

On Figure 11 are displayed the cord moduli of some typical tire cord materials as well as some pretenders. This reasonably illustrates the useful range of modulus preferred. Nylon lies at the low end of the spectrum, and the characteristic low modulus of nylon was viewed as a minor disadvantage, requiring alterations of carcass angle to permit sensibly the same dynamic tire properties as high-modulus fibers such as rayon and polyester.

If we were to compare tires from tire cords of different modulus, in otherwise identical tire constructions (rarely possible), we would find that higher cord modulus tires had better treadwear, better stability and better response in ride and handling, but tending toward inferior fatigue resistance.

For good treadwear resistance, we want maximum rigidity in the crown of the tire in both the lateral and fore-and-aft direction in the footprint area to minimize tread scrubbing. For fast cornering response and high cornering forces, we prefer stiffness and inextensibility in the sidewall wheel region of the tire where these forces are generated. Again we prefer high modulus cords.

On the other hand, in a multiple tire structure, high-modulus tire cords tend to be bad for fatigue. To make this plausible, let us consider a simple beam structure composed of two parallel cords imbedded in rubber. If now we are to deflect the beam (Fig. 12), it is clear that the outer cord is subject to an increase in stress. If its modulus is so high as to prevent stretching, then the inner cord is subject to a very damaging compression stress. If, on the other hand, the outer cord may stretch, the inner cord may continue to retain a tensile stress, although diminished.

In summary, then, our wishes would be to have the highest possible modulus in a tire cord consistent with adequate fatigue resistance.

The way in which the cord modulus is a determinant of the stress cycles in a tire is quite probably an important reason for the performance differences to be found in a tire versus a simple test piece in one or another kind of fatigue tester.

There is yet one more important reason why higher-modulus (low elongation) cords are preferred by tire engineers: they produce more uniform tires. As an industry, we are being seriously constrained to produce tires of improved dimensional uniformity. Low-modulus cords tend to magnify the effects produced by other nonuniformities in a tire and to produce unduly large dimensional variations from tire to tire.

HYSTERESIS

In their role of transferring forces between the vehicle and the road, the tires are sensitive to all of the road irregularities and transmit these forces as well. Some of them are perceived in the vehicle as vibrations or as noise.

Moreover, the tire itself, having significant mass, may be made to vibrate in a variety of modes with characteristic resonance frequencies. The excitation may be from being struck by road asperities, or in some cases the tire may be self-exciting. These vibrations also may be perceived inside the vehicle and can be a source of disturbance to the occupants. The extent to which these vibrations are successfully transmitted into the car depends partly upon the hysteretic behavior of the cords in the relevant frequency ranges.

From the standpoint of noise and vibrations, we would like tire carcasses to exhibit high hysteresis and excellent damping. However, the other side of that coin could be heat buildup in a tire.

One of the perpetually indeterminate topics of tire research is exactly how much of the heat buildup in a tire should be assigned to tire cord, or even to the whole tire carcass. Authorities differ widely. However, I believe there is fairly general agreement that the lower running temperatures of nylon tires, as well as their less desirable noise characteristics, alike relate to the very low hysteresis of nylon tire cord.

RUBBER ADHESION

A *sine qua non* for any tire cord is that it must be capable of being bonded firmly and permanently to the kinds of rubber compounds used in tire carcasses. Generally speaking, it is not feasible to bond tire cords directly to the rubber stocks. Instead, an intermediate bonding film is applied to the cord which bonds well both to the cord material and also to the carcass rubber.

Some fibers, by their chemical and physical natures, are more difficult to adhere to rubber than are others. For example, rayon and nylon are quite easily bonded to rubber by the application of a resorcinol–formaldehyde–rubber latex adhesive, commonly referred to as an RFL adhesive, to the cord. These adhesive compositions were not adequate, however, to bond polyester fiber to rubber, primarily because polyester is more chemically inert than either rayon or nylon. New or modified adhesive systems had to be developed before the fiber could be commercially used in tires. These may be "double dip" systems, in which an adhesive which will form a strong bond to the fiber is applied first to the cord, than a second adhesive is applied which will bond to the first adhesive and also to the rubber.

The adhesive bond must be of very high quality, particularly with regard to high frequency dynamic stress application and heat and chemical resistance.

In the overall behavior of a tire in transferring forces to and from the vehicle, it has been noted that the cords exercise the major role. Nonetheless, within the tire these forces must be transferred into the cords, and again must be transferred out the cords via stress transfer by the rubber. A superior dynamic adhesive bond is critical to this stress transfer process since the excellence of the adhesion will define the minimum safe cord length or cord area within which this stress transfer must occur.

It is obvious that as tire cords become progressively stronger and permit lower volume usage, the surface area available for bonding decreases exponentially. The problems of stress transfer are correspondingly intensified and the role of the cord adhesive becomes more critical. Accordingly, the development of an adequate cord adhesive system must precede even the basic evaluation of any potential new tire cord material.

The five properties we have just discussed above pretty much summarize the technically important properties for successful tire performance. All commercially useful materials meet them, but to different levels of excellence property to property, and each of the competitive textile materials combines these qualities in its own unique way. The tire designer is then faced with the problem of optimizing the individual blend of these properties into a tire. And it is apparent to the discerning customer that we have made tradeoffs to benefit tire performance.

Thus far, though, in our considerations we have been talking about a simple (so to speak) bias ply tire in which a single carcass material had simultaneously to satisfy all of the stringent performance requirements of the tire. The relatively few materials that have achieved commercial importance amply attest to the severely restrictive technical requirements.

But with the past few years there have been major technological changes in tires that markedly alter the requirements for commercially successful tire cords, and some redirection of textile development effort is appropriate. The tire technology I refer to is the development of belted tires, both bias ply and radial ply.

In Figure 13 are schematic diagrams of both types of belted tires. Formally speaking, a radial ply tire may be viewed as the special case of a

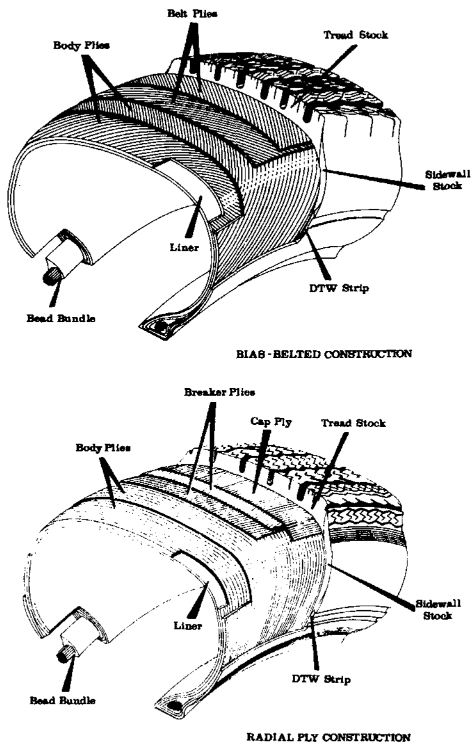

Fig. 13.

belted tire in which the carcass plies make a 90° angle with the circumferential plane of the tire.

The essential feature of the belted tire is that the belt constrain the carcass to assume a different shape than it wants to assume. Specifically, the belt forces the tire to have a smaller outer diameter (and circumference) than it would like to have, and a correspondingly wider cross section. Contrariwise, if the belt of a belted tire were to be removed, the tire would blow up to a larger outer diameter and a narrower cross section. The Italian word "cinturato" for cinch gives a better image of what is going on.

I find it convenient to view the belted tire as a tire within a tire. The belt, in the crown region of the tire, can be considered to be the carcass of a low-profile tire which contains within it the carcass of another tire which would like to assume a higher inflated diameter. In the crown region of the tire, the belt dominates the situation and sustains the inflation stress. This behavior is illustrated schematically in Figure 14. Out beyond the edges of the belt, the tire properties are those of the "inner" tire!

Belted tires can show very substantial improvements in treadwear resistance compared to unbelted tires. Moreover, in their basic dynamic properties they offer certain improvement potentialities for ride and handling characteristics that make them a preferred choice of vehicle suspension engineers.

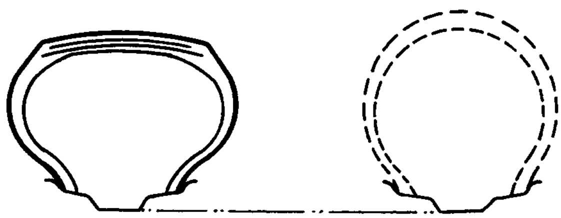

Fig. 14.

However, for the purpose of this discussion, the important thing we have done is to segregate the functional requirements of the tread region of the tire from those of the sidewall, and we are now at liberty to meet those requirements with two different textile materials if we wish. We have in this fashion secured some freedom from the conflicting material requirements of the crown of the tire and of the sidewall and can make a less restricted choice than we could when we required a single textile material to meet them all.

These changing requirements present new opportunities in textile development of tire cord textiles. Coincident with the commercialization of belted tires, both bias ply and radial tire, has been the commercialization of two new tire cord materials, and doubtless others will follow.

As we have noted earlier, in the crown of the tire we require high rupture resistance, good treadwear, and a high level of dimensional uniformity. These tire qualities relate to the tensile strength and the modulus of the tire cord material. On the other hand, the fatigue requirements in the crown of the tire are minimal—the major strain cycles occur in the sidewall. We are then permitted to choose textile materials with high tensile strength and high tensile modulus, but without the requirement of high fatigue resistance. Fiber glass cords and steel cords respond to this description, and both have assumed positions of importance as belt materials in belted tires.

Corresponding opportunities exist for a new carcass material, and it is to be noted that the requirements differ somewhat for a bias ply tire and a radial ply tire. The primary requirement for a bias ply carcass is fatigue resistance; a radial ply tire seems to be a lot less demanding in this respect and will tolerate textile cords that would be inadequate for a bias ply tire. Carcasses for both bias ply and radial ply belted tires alike demand textiles with modestly high modulus and excellent dimensional stability, but tensile strength is no longer a prime requisite since the rupture resistance may be independently secured in the belt. It would appear also that there exist opportunities for the development of a tire cord fiber with superior damping properties in the carcass.

One last property remains to be discussed: cut and puncture resistance. I think everyone will agree that the frequency of punctures and flats has declined steadily in recent years, with the advent successively of tubeless tires and belted tires. Nonetheless, punctures and massive cuts still represent the largest causes of tire failures, and inasmuch as air loss is involved, such failures can be seen to be safety related.

What is needed is a strongly cut and puncture-resistant tire construction. Wire cord would appear to have much promise in this respect, and this expectation may be responsible for the great current interest in wire belts. The newly announced Fiber B would also appear to have superior cut resistance to other conventional tire cords. Further developments along these lines would command much interest.