EFFECTS OF TREAD COMPOSITION ON WET SKID RESISTANCE OF PASSENGER TIRES

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The composition of the tread is an important factor in tire friction. In this paper, which surveys the state of the art, reported effects of composition variables on wet friction of tires are surveyed. Natural rubber and various synthetic rubbers of differing physical properties have been evaluated in a range of tread compounds differing also in extender oil and carbon black contents. The results show that compounds having high hysteresis also have higher coefficients of friction than low hysteresis compounds. The wet skid resistance of practical tread compounds can be varied by the choice of rubber or rubber blend, amount of extender oil and type of carbon black, listed in order of decreasing effectiveness. Rubbers with higher glass transition temperatures have better skid resistance than rubbers with low transition temperatures. Oil-extended rubbers are better than non-extended rubbers. High structure carbon blacks impart more skid resistance than low structure blacks. It is not practical, however, to pyramid all these effects exclusively for skid resistance since the resultant composition would not meet other criteria of acceptable tire performance including durability and treadwear. Rubbers which are best for skid resistance tend to be poorest for treadwear and vice versa. There are also practical limits for the kind and amounts of extender oil and carbon black that can be used. Modern tread compounds represent judicious choices of composition which satisfy various manufacturing and performance requirements including high skid resistance and good treadwear.

The skid resistance of an automobile during cornering, acceleration and deceleration depends importantly on the effective friction coefficient of the tire treads on the road surface. The friction coefficient of rubber tires on dry roads is generally high but on wet roads it can be dangerously low. Wet skid resistance is affected by many factors, including speed, road surface topology, water depth, tire design, tread pattern, state of wear and tread composition (1). Among these factors, the tread composition plays a relatively minor role (2). Nevertheless, the changes in wet friction that can result from changes in tread composition have considerable practical importance.

In this paper, the effects of tread composition on the wet friction of passenger tires and its relation to other tread properties and tire performance are reviewed. The relation of tread composition to skid resistance on icy roads is not included. However, it can be stated that some compositions which are superior on icy roads at temperatures well below freezing are inferior on wet roads, and vice versa. This reversal has been explained in terms of basic physical chemical principles (3).

Skid Resistance and Hysteresis

The ground work for much of the present understanding of wet rubber friction can be found in papers presented at the First International Conference on Skid Prevention (1958). Two items in particular are pertinent. First, the British Portable Skid Tester described then (4) is now commonly used in laboratories throughout the rubber industry to determine the coefficient of friction on typical road surfaces. Various workers have shown that the coefficients of friction measured by the PST correlate closely with stopping distances obtained from actual vehicle skid tests (5). The correlation between stopping distance rating and PST readings for a slippery road surface is illustrated in Figure 1. Second, the important notion advanced by Tabor (6) that a rubber compound having high hysteresis (low resilience) would have greater skid resistance than a rubber of low hysteresis (high resilience) has been well documented and, indeed, serves as a guiding principle in the development of tread compounds. The results in Figure 2 for blends of two synthetic rubbers (SBR and chlorobutyl) at constant hardness demonstrate the negative correlation of skid resistance rating and resilience (pendumum rebound) (7).

Wet skid resistance has been correlated not only with resilience but also with hardness, but the results in the literature are contradictory. Some investigations have shown that increasing hardness is detrimental to wet friction but others have shown increasing hardness to be beneficial.

In a study of ninety-nine rubber compositions, Bevilacqua (8) showed that their wet skid resis-

Figure 1. Agreement between Portable Skid Tester readings and stopping distance tests for different tread compositions on wet slippery asphalt.

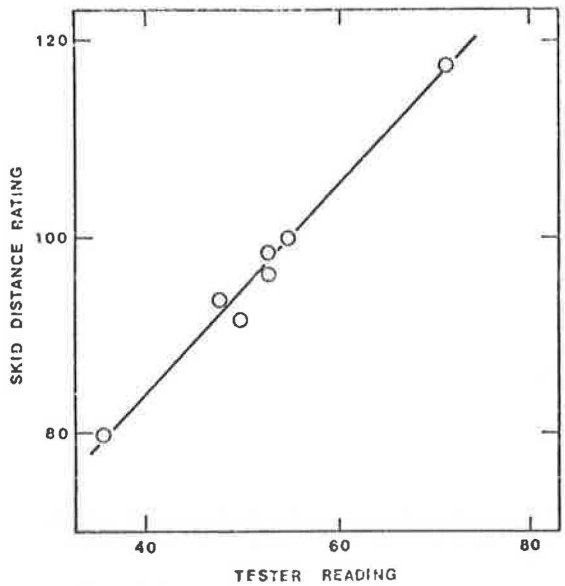
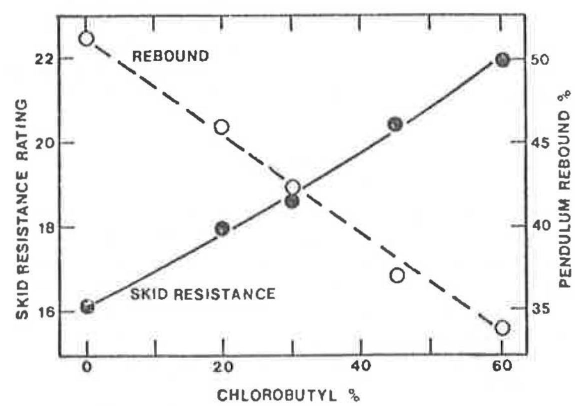


Figure 2. Illustration of the relation between wet skid resistance and resilience for blends of chlorobutyl with SBR.



tances as measured by the British Portable Skid Tester, could be well predicted by a linear regression equation with variable terms in resilience and hardness. Compounds included in this study were based on five different rubbers and various loadings of carbon black, oil and other conventional compounding ingredients to obtain compounds ranging from 8 to 75% resilience and from 21 to 80 in Shore A hardness. The compositions were chosen to provide orthogonality of resilience and hardness and many were outside the limits of practical tread compositions. At constant hardness, skid resistance decreased with increasing resilience and at constant resilience, skid resistance decreased with increasing hardness. It was concluded that wet skid resistance as measured by the British Portable Skid Tester, on a slippery road can be accurately predicted by a linear regression equation with terms for resilience and hardness.

For actual stopping-distance measurements on a smooth asphalt road, the following equation was derived (2):

$$\text{Skid distance (ft)} = 91.6 + 0.61\,R_o + 0.77\,D$$

$$r^2 = 0.99$$

where R_o indicates Bashore resilience (ASTM D-1054) at 0°C and D indicates hardness (Shore A durometer). The success of this equation in predicting skid distance is demonstrated in Table 1.

Table 1. Observed and calculated stopping distances on a wet asphalt road.

Rubber	Rebound 0°C	Hardness	Stopping Distance Calculated	Stopping Distance Observed
BR	62	62	177	180
NR/BR	46	57	162	163
EPDM	32	63	160	160
SBR/BR	33	55	155	158
SBR	34	52	152	151
Butyl	9	40	132	130

The foregoing results were obtained for sliding friction with wheels locked. Measurement first of the peak coefficient of friction and then the sliding coefficient has shown that tread resilience affects the peak coefficient even more than the sliding coefficient. This is evident in Maycock's results (10) which are shown in Table 2.

Table 2. Peak and slide braking force coefficients versus tread resilience.

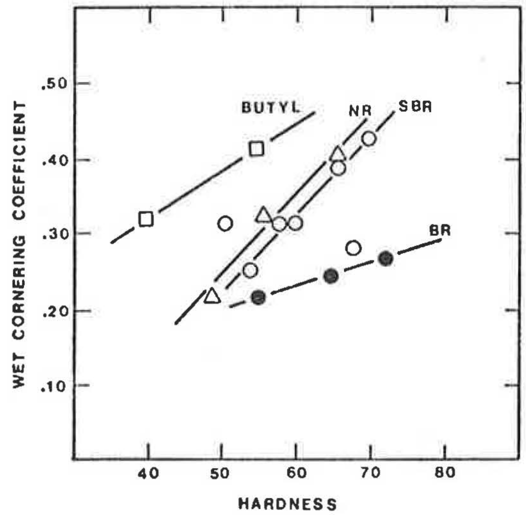
Rubber	Hardness	Resilience	Braking Force Coef. (40 mph) Peak	Braking Force Coef. (40 mph) Slide
Natural	67	48.5	0.63	0.45
Synthetic	67	28.0	0.77	0.51
High Styrene	67	23.5	0.82	0.50

Keller (7) also found for blends of two elastomers, styrene-butadiene rubber and chlorobutyl, that the peak coefficient was more strongly dependent on resilience than was the slide coefficient.

Veith (9) determined skid resistance in wet cornering tests for four different elastomers with widely different resilience. At a given hardness, the least resilient, butyl, had a much higher cornering coefficient than the most resilient elastomer, polybutadiene. Natural rubber and styrene-butadiene rubber were intermediate in both resilience and cornering coefficient. However, the cornering coefficient increased with increasing hardness for all four rubbers as shown in Figure 3.

It is concluded that low resilience (high hysteresis) is beneficial for wet skid resistance but the effect of hardness depends on conditions. Softer treads are better in straight stopping

Figure 3. Effects of hardness and type of rubber on wet cornering coefficient.



tests but harder treads are better in resisting skids during cornering.

Tread Compositions

Tire treads of current commercial passenger tires have compositions generally in the range shown in Table 3.

Table 3. Passenger tire tread recipe.

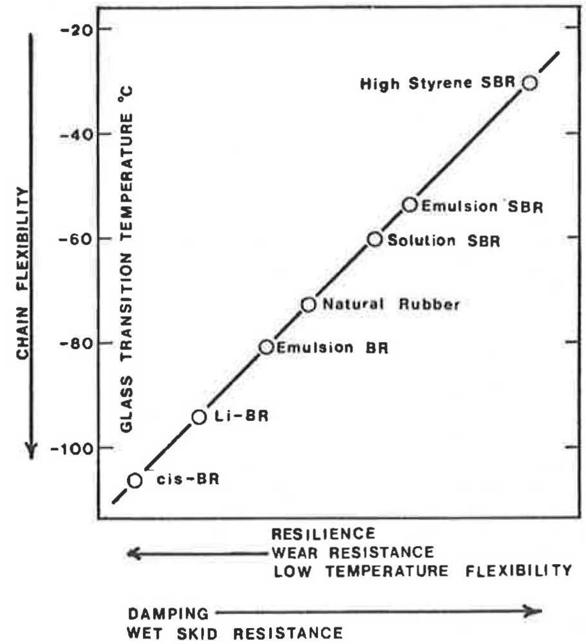
	By Weight
Rubber	100
Reinforcing Filler	60 - 90
Extender Oil	25 - 60
Antidegradants	1 - 3
Curatives	5 - 10

The components that principally affect wet skid resistance are the rubber, the oil and the reinforcing filler, listed in order of decreasing importance. The antidegradants, which preserve the rubber against the deteriorating effects of light, oxygen and ozone during service, do not affect skid resistance. Variations of the curatives can affect hysteresis but not significantly in the range required for maximum strength and abrasion resistance.

Types of Rubber and Their Properties

Many types of rubber have been evaluated for tire performance and ranked for both wet skid resistance and wear resistance. It has been found that each rubber can be characterized by its glass transition temperature (T_g) which correlates, qualitatively at least, with several properties of practical importance (11). The glass transition temperature is the temperature below which a rubber becomes very hard and brittle. Different elastomers have different glass transition temperatures. It has been observed that with decreasing glass transition temperature, there is an increase in the abrasion resistance, the resilience, the low-temperature flexibility and the diffusion rate but a decrease in the damping capacity or hysteresis and the friction coefficient. The qualitative ordering of different rubbers with respect to these different properties is portrayed graphically in Figure 4.

Figure 4. Rubbers classified according to glass transition temperature.



The fact that when measured under similar test conditions, the wet friction coefficients of different rubbers always rank them according to their glass transition temperatures, has been explained in terms of the fundamental principles of viscoelasticity (1). The relation of the wet friction coefficient and T_g is a consequence of the hysteretic nature of wet friction, as proposed by Tabor (3). Hysteresis is at a maximum slightly above T_g and decreases with increasing temperature as shown in Figure 5. Since elastomers suitable for use in tire treads have T_g values well below normal outdoor temperatures, hysteresis and wet friction are generally higher for those elastomers with higher T_g and lower for elastomers with very low T_g. Since the hysteresis depends on the interval between the test temperature and the glass transition temperature, a correlation is generally obtained between the skid resistance rating of different rubber compounds and simple hysteresis measurements, like rebound.

The glass transition temperature of hydrocarbon rubbers suitable for tires in terms of vulcanization, processing qualities and cost can be varied from about -30°C to -108°C by the choice of monomeric starting materials and polymerization conditions. Commercially acceptable compromises between skid resistance and other properties, especially wear, limit the practical range to about -55° to -75°C. This range includes not only emulsion SBR (23% styrene), low vinyl solution

Figure 5. Damping factor (tan δ) as a function of temperature for BR and SBR tread stocks.

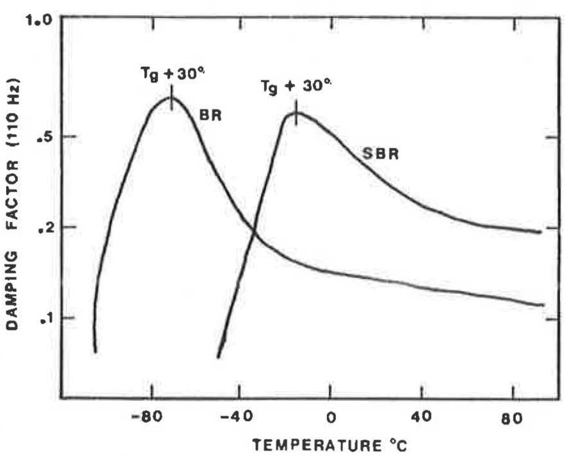
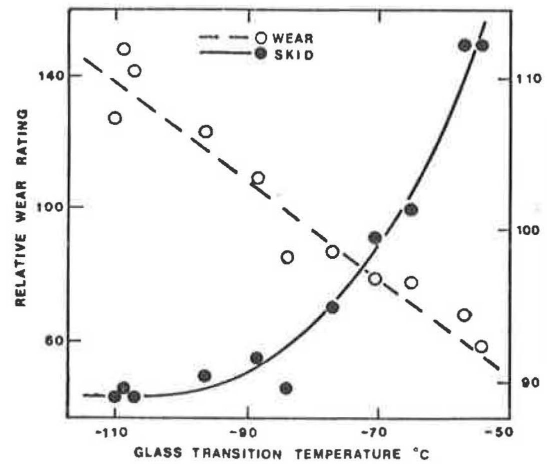


Figure 6. Illustration of the relation of wet skid resistance (solid line) and wear resistance (broken line) to the glass transition temperatures of different rubbers.



SBR, medium vinyl polybutadiene and various blends containing cis-polybutadiene but also natural and synthetic polyisoprene.

Effects of Tread Composition Changes

The obvious way to make a tread with high wet skid resistance is to use a rubber that has high hysteresis such as a 40% styrene SBR. As shown in Table 4, such a tread has superior wet skid resistance but poor wear (12). Reducing the styrene content reduces the glass transition temperature, raises the resilience, reduces wet skid resistance and improves wear.

Table 4. Effect of styrene content on T_g, abrasion resistance and skid resistance.

Polymer	% Styrene	T_g	Rebound 0°C	Wet Skid, Concrete	Abrasion Resistance
BR	0	-105	42	76	240
6:4 SBR:BR	14	- 76	26	94	122
SBR 1500	23.5	- 56	12	100	100
Solution SBR	25	- 50	10	102	97
SBR 1516	40	- 30	6	111	76

For styrene-butadiene copolymers, the properties are also dependent on the microstructure; i.e. the relative fraction of cis, trans and vinyl groups in the butadiene portion of the molecule. The wear resistance and wet skid resistance as a function of the glass transition temperature are shown in Figure 6 for a number of rubbers differing in cis, trans, vinyl and styrene content (13).

Butyl rubber has much higher hysteresis than the butadiene and isoprene rubbers with similar glass transition temperatures. Butyl tires have excellent wet skid resistance but poor wear resistance and high rolling resistance. The rolling resistance is especially high in cold weather because the hysteresis of butyl is strongly dependent on temperature.

Butyl rubber cannot be blended with the butadiene and isoprene rubbers because of vulcanization incompatibility. However, chlorobutyl which has the same hysteretic properties as butyl has been blended with SBR to make tread compounds suitable for testing in tires. The results of tests on blends of SBR and chlorobutyl showed that as the proportion of chlorobutyl increased, the resilience decreased, the skid resistance increased and the wear resistance decreased (7).

In general, the choice of rubber used in the tread compound largely determines the resilience which correlates well with both skid and wear resistance. Treads with high resilience have good wear but poor skid resistance.

Another major component of a tire tread is the reinforcing filler which, at present, is almost all carbon black. Many non-black fillers have been tested without successfully improving the skid resistance but generally reducing the wear resistance. The effects of carbon black on tread performance are dependent on the types and the concentration used. Hysteresis and wet skid resistance increase as the amount of black is increased, but at high levels of black, wear resistance decreases. The effects of carbon black on rubber properties are related to two major black properties - ultimate fineness and structure. Finer particle size and higher structure tend to increase the hysteresis, hardness and strength of rubber, but if the particle size is too small, effective dispersion cannot be obtained by conventional mixing methods. Beyond a loading of about 50 parts by weight of carbon black it is necessary for processing reasons to add some extender oil. Therefore, carbon black loading and the amount of extender oil are usually covaried. The addition of extender oil also raises hysteresis. The hysteresis increases as the proportions of carbon black and oil are increased because the volume fraction of elastic material in the total compound is decreased.

The amount of oil that can be added is limited because the strength of very highly extended rubber compounds diminishes, abrasion resistance decreases and tire building properties deteriorate.

However, it is possible to maintain good properties in the range of 40 to 50 parts by weight of oil with 70 to 75 parts of carbon black, and much higher loadings have been evaluated in tires.

The type of extender oil also affects hysteresis and wet skid resistance. The hysteresis is generally higher for extender oils of higher molecular weight (14). Table 5 shows the tire test results in which the oil type was varied in a synthetic rubber tread (2).

Table 5. Effect of oil T_g on wear and wet skid resistance.

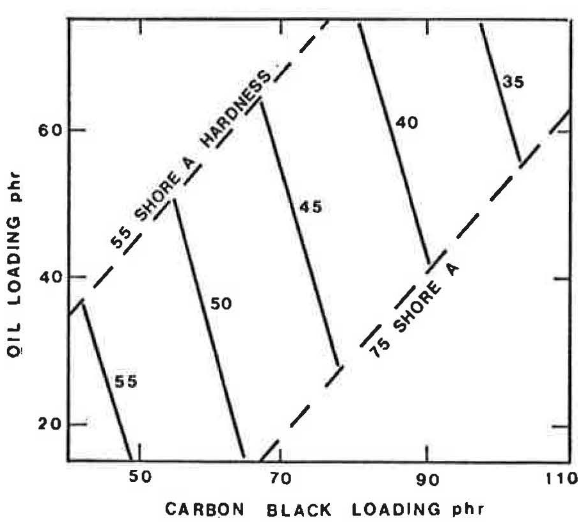
Oil	Sundex 790*	Dutrex 985+	Dutrex 998+
Oil T_g	- 52	- 33	- 2
Compound T_g	- 73	- 66	- 56
Rebound, 32°F	27	22	17
Hardness	55	56	57
Tensile Strength	2600	2650	2450
Wet Skid Resistance	100	104	108
Wear Resistance	100	86	77

*Sun Oil Co.
+Shell Oil Co.

Wet skid resistance increased as the hysteresis increased, but the wear resistance decreased.

When oil and carbon black loadings are increased simultaneously, the rebound decreases as shown in Figure 7 (15). This figure shows that

Figure 7. Rebound as a function of oil and carbon black loadings.



the hardness also changes when the oil and carbon black loadings are varied.

Figure 8 shows how the wet skid resistance can change with variations in oil and black loadings, and Figure 9 shows the corresponding changes in treadwear (15). Figures 7, 8, and 9 represent data obtained for a particular type of high structure carbon black in a synthetic rubber tread stock. Published plots for different kinds of carbon black differ mainly in the dependence of treadwear on loading. Superposition of wear and skid plots of this type provides a convenient means for the tire compounder to select compositions that have a desired balance of properties.

Figure 8. Wet skid resistance as a function of oil and carbon black loadings.

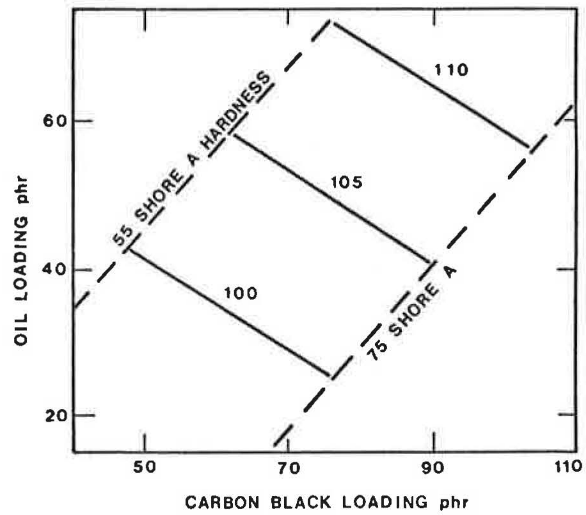
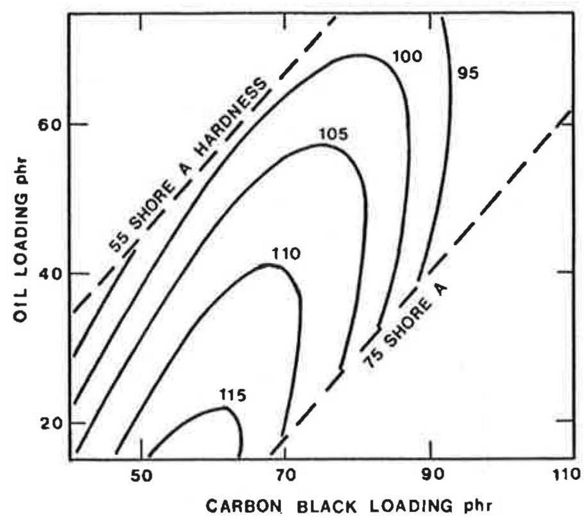
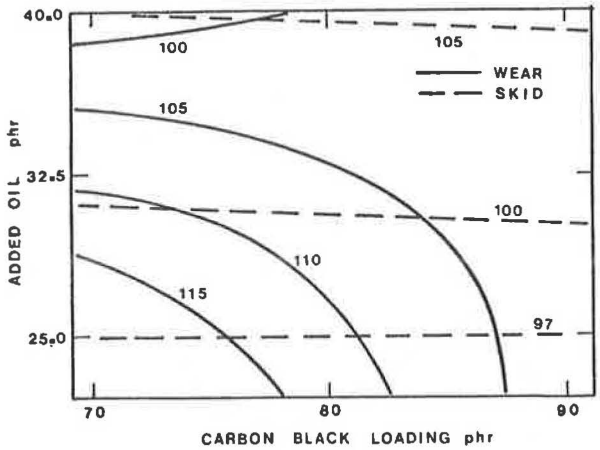


Figure 9. Treadwear index as a function of oil and carbon black loadings.



Effects of oil loading and carbon black type on skid and wear properties of 70% SBR, 30% cis-polybutadiene treads on different wet road surfaces were reported by Scott et al (16). Although the effects were minor relative to those resulting from variations in tread design and speed, they were considered to be significant. A low loading of a high structure carbon black and high loading of oil imparted the most skid resistance. Tread wear resistance was best with low loadings of oil and medium structure carbon black. Either equivalent skid resistance with improved tread wear or improved skid resistance with equivalent tread wear was reported to be achievable as illustrated in Figure 10.

Figure 10. Effects of oil and black loadings on the overall tread wear index and the relative skid resistance on wet asphalt.



Summary

In the testing of passenger tires on wet roads, the best skid resistance is associated with treads having high hysteresis and poor wear resistance. However, the best wear resistance is associated with treads having low hysteresis and poor wet skid resistance. This results in a serious problem for the tread compounder who must strive to make long-wearing tires with a safe level of wet skid resistance, but it does not mean that high levels of wear and wet skid resistance are mutually exclusive. The type of rubber or blend of rubbers, the type and amount of extender oil and the type and amount of carbon black are the principal factors that can be varied exclusive of design and construction features to obtain an excellent balance of performance properties.

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