

A tailor-made polymer for tyre applications

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Following the development of a road surface with the optimum micro- and macrotexture levels, a new wet grip/rolling resistance philosophy has been developed, based on measuring the dynamic properties of tread compounds in the laboratory under conditions approaching those existing at the tyre/road surface interface under both rolling and wet sliding conditions. The results obtained using conventional polymers indicate that if the generally accepted wet grip/rolling resistance relation for tyre tread compounds was to be broken whilst maintaining acceptable tread life, it would be necessary to develop a new 'tailor-made' polymer. The new wet grip/rolling resistance philosophy has enabled a new polymer to be developed which breaks with convention and significantly reduces the rolling resistance of tyres and improves wet grip whilst maintaining acceptable tread life. This development is the most significant advance in tyre polymer design/technology for 25 years and could be the forerunner of a new generation of relatively high 1,2 butadiene content, solution styrene-butadiene copolymers designed to reduce the rolling resistance of tyres (fuel consumption) whilst improving wet grip (safety).

Keywords Macrotecture; microtexture; wave propagation; micro-hysteresis; polymer; fuel economy; grip

INTRODUCTION

In today's environment, two important tyre requirements are rolling resistance (fuel consumption) and wet grip (safety). It is important to understand the part the tyre plays in the total fuel consumption of a passenger car. For a medium-sized family car running at a constant 80 km h^{-1} , an approximate analysis of the energy losses¹ is shown in Figure 1.

The amount of energy absorbed by the tyre represents approximately 6.6% of the total energy content of the fuel. For a family car running at a constant 80 km h^{-1} , a reduction of 4% in tyre losses as exhibited by the rolling resistance, results in approximately a 1% fuel saving. The simplest approach adopted to reduce the tyre rolling resistance is to increase the inflation pressure. Figure 2 shows how, for a radial ply tyre, increasing the inflation pressure reduces the rolling resistance of the tyre². However, increasing the inflation pressure generally results in inferior ride/comfort properties which today are significant factors for the majority of vehicle manufacturers.

Considering modifications to the tyre itself, the losses due to aerodynamic drag and the interaction at the tyre/road surface under constant speed conditions are small. Therefore, any major contribution to reductions in fuel consumption which can be brought about by the tyre will result from reductions in the hysteresis losses within the tyre combined with weight reductions.

Research³ has indicated that both the casing and belt reinforcement materials currently available have little effect on the tyre rolling resistance. Therefore, the hysteresis losses will most probably be reduced by modifying

one or more of the following aspects: (a) the sectional profile of the tyre; (b) the tread pattern design; and (c) the tread compound.

If the tyre rolling resistance is related to heat generation in the tyre, it has been shown⁴ that for a radial steel belted car tyre the energy losses in the tyre can be apportioned as follows:

Tread band	34%
Buttress region	33%
Sidewalls	11%
Clinch region	22%

Therefore, it can be seen that reducing the tread component to rolling resistance would be significant in

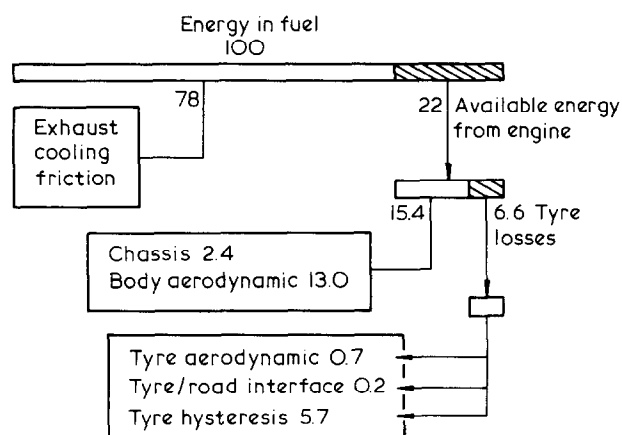


Figure 1 Apportioning of energy losses for a medium sized saloon car travelling at a constant 80 km h^{-1}

reducing the total rolling resistance of the tyre. Unfortunately, existing theories for tread compound development suggest that reducing rolling resistance must be accompanied by a fall-off in wet grip performance if modifications to the tread compound is the major reason for obtaining the reduced rolling resistance.

EXISTING THEORIES

There are two generally accepted wet grip theories used when considering the tread compound component:

- (a) As the rebound resilience of the tread compound decreases, the wet grip performance improves⁵;
- (b) Assuming a polymer can be used in a tread compound, as the glass transition temperature increases, the wet grip performance improves⁶.

Using conventional polymers, Figures 3-5 show the relation between wet grip and tread compound resilience, wet grip and tread polymer glass transition temperature and tread compound resilience and tread polymer glass transition temperature. The wet grip results were obtained on the Variable Speed Internal Drum Machine situated at the University of Birmingham⁷, the resilience results were obtained on the Dunlop Pendulum at 50°C and the glass transition temperatures were obtained by differential scanning calorimetry.

It has previously been shown⁸ that the tread component to the rolling resistance of the tyre is a function of loss modulus (E'') and loss modulus divided by the complex modulus squared (E''/E'^2), i.e.

Tread bending component $\propto E''$
 General tread compression component $\propto E''/E'^2$

Therefore, it was important to establish how E'' and E''/E'^2 relate to the tread compound resilience and hence to wet grip. Figures 6 and 7 show the relation between resilience and E'' and E''/E'^2 , respectively.

The results indicate, based on Tabor's theory, that as the wet grip improves, rolling resistance or temperature generation must increase and this was verified by the results shown in Figure 8. Thus, there are three major

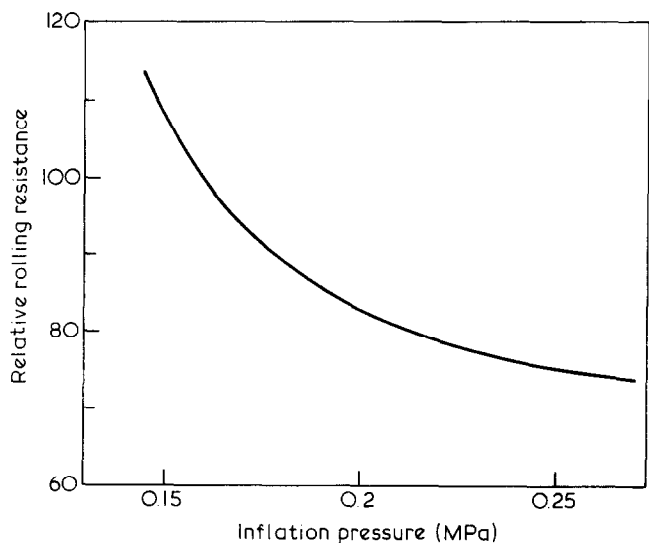


Figure 2 Effect of tyre inflation pressure on the tyre rolling resistance

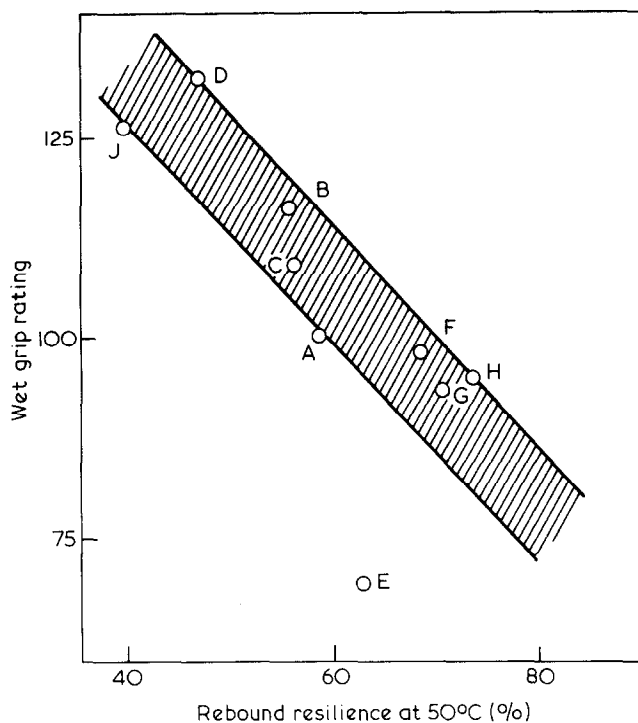


Figure 3 Wet grip/resilience relationship for conventional polymers. A, styrene-butadiene copolymer (23% styrene content); B, oil extended styrene-butadiene copolymer (23% styrene content); C, styrene-butadiene copolymer (30% styrene content); D, oil extended styrene-butadiene copolymer (40% styrene content); E, polybutadiene; F, low *cis*-polyisoprene; G, high *cis*-polyisoprene; H, natural rubber; J, butyl rubber

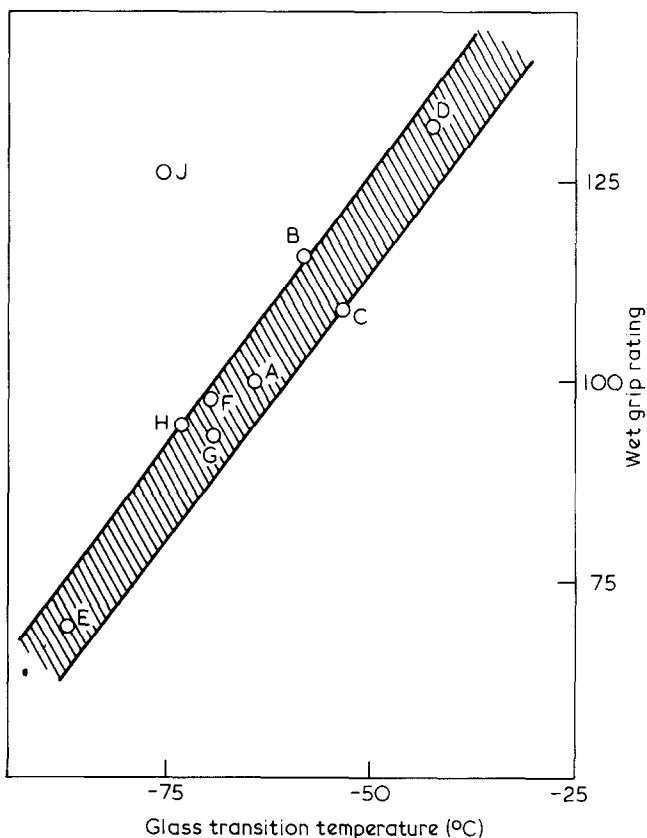


Figure 4 Wet grip/glass transition temperature relationship for conventional polymers. Notation as Figure 3

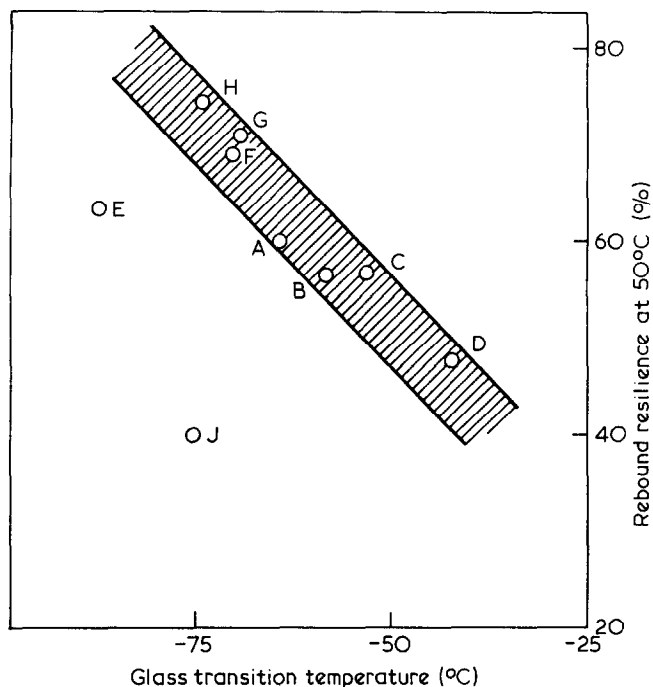


Figure 5 Resilience/glass transition temperature relationship for conventional polymers. Notation as Figure 3

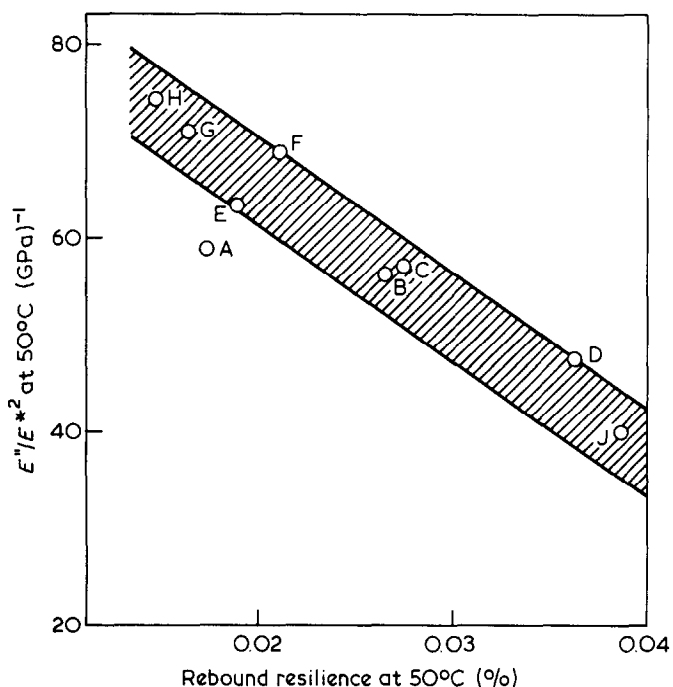


Figure 7 E''/E^{*2} /resilience relationship for conventional polymers. Notation as Figure 3

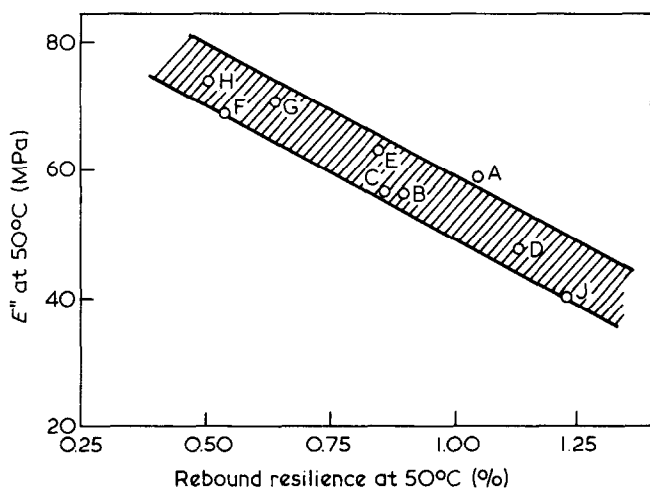


Figure 6 E'' /resilience relationship for conventional polymers. Notation as Figure 3

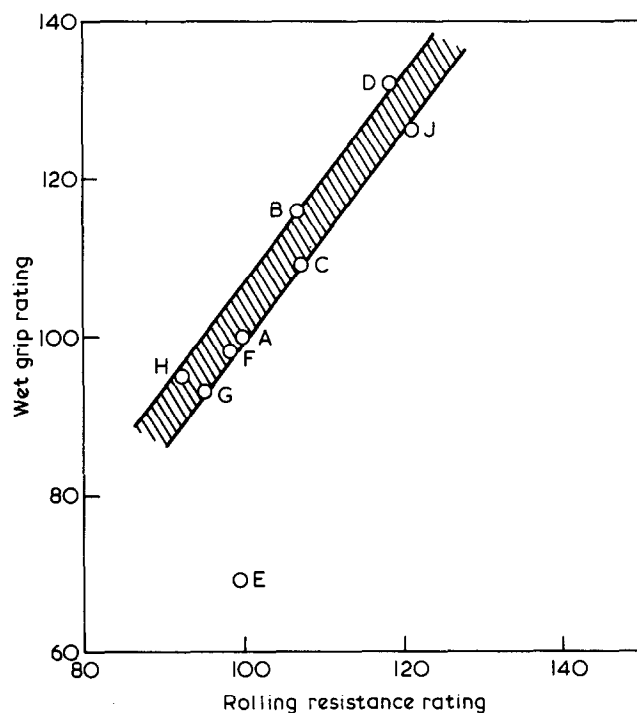


Figure 8 Wet grip/rolling resistance relationship for conventional polymers. Notation as Figure 3

conclusions which result from the two existing theories:

(a) The performance of the majority of conventional tread polymers can be explained;

(b) The performance of Butyl rubber cannot be satisfactorily explained;

(c) Tread compounds and polymers developed to improve wet grip must inherently possess higher rolling resistance characteristics and hence increase fuel consumption.

It is evident that a major breakthrough would be achieved if a new tread polymer could be developed which gave a significant reduction in the rolling resistance of the tyre whilst improving the wet grip performance without sacrificing the existing abrasion properties.

NEW WET GRIP/ROLLING RESISTANCE PHILOSOPHY

It was essential to improve understanding of the interaction taking place at the tyre/road surface interface. A considerable amount of research has been carried out over the last fourteen years^{9,10}. This resulted in the optimum road surface textural characteristics on both the

micro and macro scales being specified¹¹:

Microtexture levels— $10\text{--}100 \times 10^{-6}$ m
 Macrottexture levels—Aggregate particle size 6–12 mm.
 Inter particle spacing 1–4 mm
 Absolute texture depth 1–3 mm
 (dependent on aggregate size)

Using these road surface characteristics enabled a new wet grip/rolling resistance philosophy to be developed which considers both wet grip and rolling resistance. The new philosophy is based on the principle of measuring the dynamic properties of tread compounds in the laboratory under conditions approaching those existing at the tyre/road surface interface under both rolling and wet sliding conditions, i.e.

Rolling conditions (rolling resistance)
 →relatively low frequency (up to 120 Hz)
 →relatively low temperature ($\approx 50^\circ\text{C}$ for passenger car tyres)

Sliding conditions (wet grip)
 →relatively high frequency (50 kHz–1 MHz)
 →relatively high temperature (100–150°C)

Determination of the important properties

Rolling resistance—tread component. The total tread contribution to rolling resistance is given by:

$$R_t = R_b + R_c + R_{tm} \quad (1)$$

but

$$R_c = R_{Gtc} + R_{Mc} + R_{mc} \quad (2)$$

therefore

$$R_t = R_b + R_{Gtc} + R_{Mc} + R_{mc} + R_{tm} \quad (3)$$

Now

$$R_b \propto \text{loss modulus} \quad (\text{Collins } et al.^8)$$

$$R_{Gtc} \propto \frac{\text{loss modulus}}{(\text{complex modulus})^2} \quad (\text{Collins } et al.^8)$$

$$R_{Mc} \propto \frac{\text{loss modulus}}{(\text{complex modulus})^2} \quad (\text{Bond}^{12})$$

$$R_{Mc} \propto \text{aggregate size} \quad (\text{Bond}^{12})$$

$$R_{mc} \propto \frac{\text{loss modulus}}{(\text{complex modulus})^2} \quad (\text{Bond}^{12})$$

$$R_{mc} \propto \text{microtexture level} \quad (\text{Bond}^{12})$$

Thus, the important tread compound parameters relating to rolling resistance are:

$$\text{loss modulus and } \frac{\text{loss modulus}}{(\text{complex modulus})^2}$$

measured at the appropriate frequencies and temperatures.

Wet grip—sliding conditions (simplified account). The total frictional force generated at the tyre/road surface

interface under wet sliding conditions approximates to:

$$F_t \approx F_a + F_{mh} + F_{Bh} \quad (4)$$

Transposing the force components in equation (4) into power consumption terms, equation (4) becomes

$$\dot{E}_t \approx \dot{E}_a + \dot{E}_{mh} + \dot{E}_{Bh} \quad (5)$$

It has been shown previously¹² that the bulk hysteresis component (E_{Bh}) contributes up to only 1% of the total energy absorbed at the tyre/road interface under sliding conditions. Therefore, the bulk hysteresis component can be neglected and hence equation (5) becomes:

$$\dot{E}_t \approx \dot{E}_a + \dot{E}_{mh} \quad (6)$$

but $\dot{E}_a \propto \text{Loss factor}$ (Bulgin *et al.*⁶)
 $\dot{E}_{mh} \propto \text{Loss factor}$ (Bond¹²)

Thus the important tread compound parameter relating to wet grip is the loss factor measured at the appropriate frequencies and temperatures.

Overall tread compound requirements

To develop a tread compound with reduced rolling resistance and improved wet grip characteristics, it is essential to have relatively low power consumption (low loss) under rolling conditions and relatively high power consumption (high loss) under wet braking conditions, i.e.

Rolling conditions: Low values of loss modulus and loss modulus/(complex modulus)² measured at relatively low frequencies and temperatures. Typical machines used for obtaining the results are the Rotary Power Loss Machine¹³ and the Dynamic Response Apparatus¹⁴.

Wet grip—sliding: High values of loss factor and hence micro-hysteresis power consumption at relatively high frequencies and temperatures. The machine used for obtaining the results was a piece of high frequency test equipment developed specifically for this purpose¹⁰.

Breakthrough relative to studies of the day

The inclusion of the micro-hysteresis power consumption term in the wet grip study was the major breakthrough by considering the micro-hysteresis energy component to depend on wave propagation and not to depend on mechanical vibrations in the contact patch. The high frequency deformation (50 kHz–1 MHz) generated at the tyre/road surface interface due to the road surface microtexture ($10\text{--}100 \times 10^{-6}$ m) results in both dilatational and distortion waves being transmitted into the tread rubber. Under wet sliding conditions, the interface temperature ranging from 100 to 150°C, it can be assumed that Poisson's ratio for the tread compound lies between 0.45 and 0.50 and hence G is less than 3% of K . Therefore, for simplicity, it is assumed that dilatational waves are transmitted through the tread perpendicular to the tyre/road surface interface, the energy transmitted by the wave propagation being absorbed by the hysteretic properties of the tread compound in the form of heat generation. Therefore, the important compound parameters involved are:

$$\text{Elastic modulus} = K' + \frac{4}{3}G'$$

and

$$\text{Loss factor} = \frac{K'' + \frac{4}{3}G''}{K' + \frac{4}{3}G'}$$

Consider that the waves transmitted into the tread are generated by small cylindrical pistons of cross section a_{ms} and radius r_{ms} with a displacement amplitude equivalent to the microtexture level (ξ_0) and n elements per unit area of contact. The pressure amplitude falls off as the wave travels through the tread perpendicular to the tyre/road surface interface (x direction) as follows^{10,15}:

$$P = 2\rho_t v_t U_0 \exp(-\alpha_t x) \sin \frac{k}{2}(\sqrt{x^2 + r_{ms}^2} - x) \quad (7)$$

but the maximum velocity of displacement (U_0) is given by:

$$U_0 = \omega \xi_0 = 2\pi f_{ms} \xi_0 \quad (8)$$

and

$$k = \frac{\omega}{v_t} = \frac{2\pi f_{ms}}{v_t} \quad (9)$$

The microhysteresis energy absorbed due to the microtexture deformation perpendicular to the tyre/road surface interface at a distance x within the tread and elemental thickness δx will be given by¹⁰:

$$\delta \dot{E}_{mh} = \frac{A n a_{ms} \alpha_t}{\rho_t v_t} \cdot P^2 \delta x \quad (10)$$

Also it has been shown that¹⁰:

$$\alpha_t = \frac{\pi f_{ms}}{v_t} \cdot (\text{Loss Factor}) \quad (11)$$

Therefore, from equations (7)–(11) inclusive and integrating over the full tread thickness (h), the total micro-hysteresis energy absorbed by the tread at the tyre/road surface interface will be given by:

$$\dot{E}_{mh} = 16\pi^3 A n a_{ms}^2 f_{ms}^3 \xi_0^2 (\text{Loss Factor}) L \quad (12)$$

$$L = \int_0^h (\exp(-2\alpha_t x)) \sin^2 \left(\left(\frac{\pi f_{ms}}{v_t} \right) (\sqrt{x^2 + r_{ms}^2} - x) \right) dx \quad (13)$$

$$\alpha_t = \frac{\pi f_{ms}}{v_t} (\text{Loss Factor}) \quad (14)$$

Figure 9 shows the relation between wet grip rating and micro-hysteresis power consumption obtained for the conventional polymers detailed in Figures 3–5. The wet grip ratings were obtained on the Variable Speed Internal Drum Machine fitted with a surface having the optimum micro- and macrottexture levels (see earlier) and using model 2.25–8 cross-ply tyres. The micro-hysteresis power consumption figures were calculated from equations (12)–(14) using the surface microtexture and tyre details taken from the wet grip investigation together with the wave velocity and loss factor values obtained on the High Frequency Test Equipment¹⁰ at a temperature of 100°C.

It is evident that the trend shows that as the micro-hysteresis power consumption increases, the wet grip performance improves. The Butyl polymer appears to be

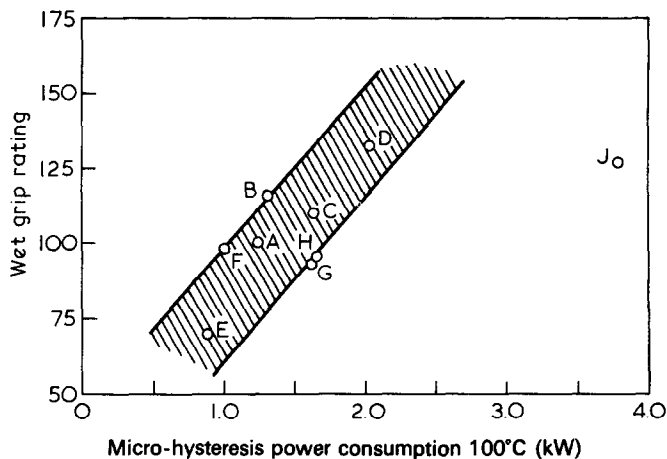


Figure 9 Wet grip/micro-hysteresis power consumption relationship for conventional polymers. Notation as Figure 3

an anomaly in terms of the high micro-hysteresis power consumption when compared to the overall level of wet grip performance. This anomaly was previously discussed by Bond¹² and an explanation suggested in terms of a reduced number of adhesion bonds per unit area of contact at the tyre/road surface interface when compared with other conventional polymers.

NEW POLYMER DEVELOPMENT

A considerable amount of work was carried out using blends of conventional polymers. Two conclusions were made:

(a) Tread compounds can only be developed to reduce either the rolling resistance of the tyre without sacrificing wet grip or improve wet grip without increasing rolling resistance at the expense of severe reductions in abrasion resistance.

(b) Tread compounds cannot be developed which both reduce rolling resistance and improve wet grip whilst maintaining present day levels of abrasion resistance.

Therefore, from the tread compound point of view, the only successful approach to reducing rolling resistance and improving wet grip whilst maintaining abrasion resistance would be to develop a new 'tailor-made' polymer which meets the parameters outlined in the new wet grip/rolling resistance philosophy, i.e.

Rolling conditions: Low values of loss modulus (E'') and loss modulus divided by complex modulus squared (E''/E'^2) measured at relatively low frequencies (say up to 120 Hz) and relatively low temperatures (for passenger cars of the order of 50°C).

Wet sliding conditions: High values of loss factor ($(K'' + \frac{4}{3}G'')/(K' + \frac{4}{3}G')$) measured at relatively high frequencies (in the range 50 kHz–1 MHz) and relatively high temperatures (in the range 100–150°C).

The principal problem was to establish how a polymer could be 'tailor-made' to reduce rolling resistance yet improve wet grip.

Consider a polymer to be made up of two components:

Component 1: The element of the polymer structure which determines its low frequency or rolling resistance characteristics.

Component 2: The element of polymer structure which determines its high frequency/high temperature or wet sliding characteristics.

If a new polymer could be developed, it was essential to include two further constraints on the approach to be adopted if it was to be a practical proposition:

(a) The development would be based on existing monomers used by polymer manufacturers in producing polymers for tyre applications.

(b) Any new polymer developed had to be processable on existing manufacturing equipment used throughout the tyre industry.

The initial work was carried out on the laboratory scale using polymers made up from butadiene and styrene monomers. The first objective was to produce a polymer which met the dynamic property requirements discussed earlier. The result¹⁶ was a copolymer which was produced using the solution copolymerization technique of placing the styrene and butadiene monomers into a non-polar solvent, together with diethylene glycol dimethylether as the structure modifier and heated to 50°C. The polymerization reaction was then initiated using a lithiumhydrocarbon compound. The styrene-butadiene copolymer produced had a 23% bound styrene content, 70% 1,2 butadiene content, a weight average molecular weight (M_w) of 450 000 and a number average molecular weight (M_n) of 260 000. The molecular weights were obtained using gel permeation chromatography, the instrument being calibrated using polystyrene standards. Three of the major characteristics of this polymer (DP1) were:

(a) The fundamental characteristic of the polymer was the glass transition temperature of -34°C as measured by differential scanning calorimetry.

(b) When compounded in a simple test formulation (100/50/0, polymer/N375 carbon black/free oil), the resilience of the compound, as measured on the Dunlop Pendulum at 50°C, was relatively high at 66.3%.

(c) The micro-hysteresis power consumption of the simple test compound at 100°C was relatively high at 3.0 kW.

It can be seen that the polymer (DP1) was inherently a high wet grip polymer (relatively high glass transition temperature) which, when used in a simple test formulation, exhibited a relatively high resilience giving potentially low rolling resistance characteristics.

The laboratory results obtained for wet grip and rolling resistance when compared to conventional polymers are shown in Figure 10.

The most serious difficulty which arose with DP1 was the compound mixing. The compound was mixed in the laboratory with great difficulty and however good the 'in-tyre' performance properties, it would not be possible to process the polymer on existing manufacturing equipment. Similarly, difficulties would be encountered when attempting to manufacture DP1 on a large scale. Therefore, at the present time, DP1 would not be a practical proposition. To overcome the laboratory difficulties encountered, DP1 was modified to DP2 by halving the 1,2 butadiene content. The wet grip/rolling resistance relation is shown in Figure 10. Again the polymer had a relatively high glass transition temperature (-46°C), relatively high rebound resilience at 50°C (66.9%) and a relatively high micro-hysteresis power consumption at 100°C (2.56 kW).

Having developed a new polymer (DP2) on a laboratory scale which showed a significant advance on existing commercially available polymers in terms of the rolling resistance/wet grip balance, it was essential to

verify the results on full-size tyres. The polymer used for the initial full-size tyre tests (PB1) was produced in a 'pilot plant' used for manufacturing larger quantities of experimental polymers. The results are shown in Figure 11 where the new polymer is compared to two conventional

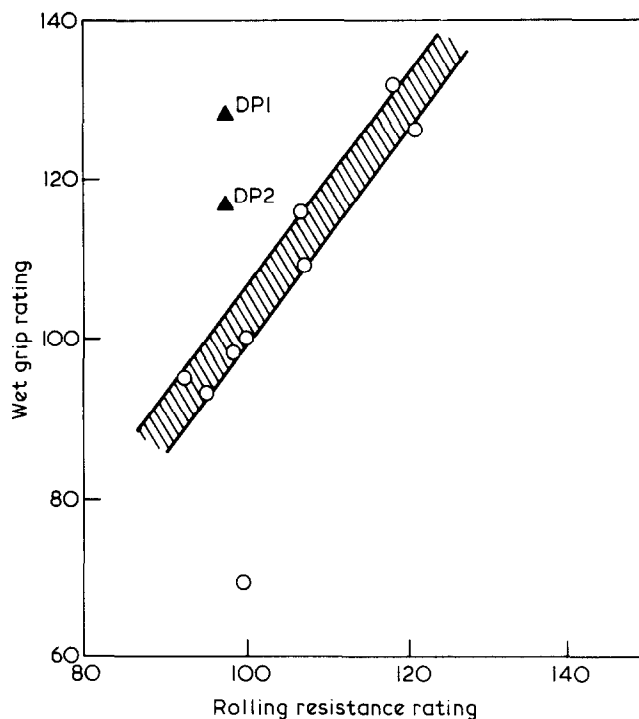


Figure 10 Wet grip/rolling resistance relationship obtained for the new laboratory scale polymers, DP1 and DP2, compared to the conventional polymers previously illustrated

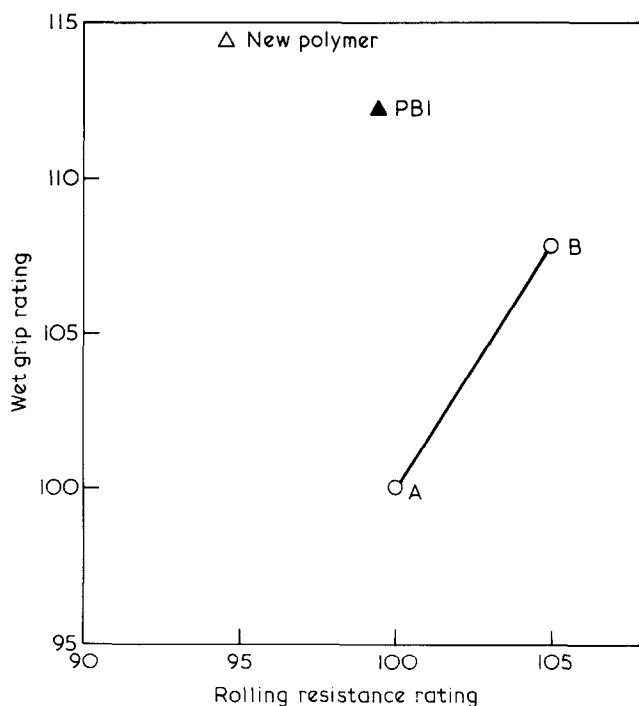


Figure 11 Wet grip/rolling resistance relationship obtained using 155 SR13 steel belted radial ply tyres for the pilot batch of polymer, PB1, and the New Polymer compared to two conventional polymers. A, styrene-butadiene copolymer (23% styrene content); B, oil extended styrene-butadiene copolymer (23% styrene content)

styrene-butadiene copolymers, an emulsion styrene-butadiene copolymer (23% styrene content) and an oil extended styrene-butadiene copolymer (23% styrene content).

Having verified the laboratory scale results on full-size tyres, the 'pilot' production level for the new polymer was then increased to commercial production levels. The results for the commercial polymer (New Polymer) are also shown in Figure 11 and it is evident that the move from the 'pilot' scale to the commercial scale polymer production levels has resulted in a further improvement in tyre performance.

The wet grip and rolling resistance investigation was carried out using 155 SR 13 steel belted radial ply tyres. The wet grip results were obtained on the Internal Drum Machine situated at the University of Karlsruhe. The wet grip ratings were taken as the mean of the peak and sliding friction values together with the peak cornering force generated over five speeds (60, 80, 100, 120 and 140 km h⁻¹) and five water depths (0.2, 0.5, 1.0, 2.0 and 3.0 mm). The rolling resistance ratings were obtained on the Tyre Dynamics Machine situated in Dunlop's Tyre Research Department¹⁷. The rolling resistance ratings were taken as the mean of the coefficients obtained at constant load over four speeds (20, 40, 60 and 80 km h⁻¹) and corrected to an ambient temperature of 22°C.

The new polymer characteristics compared to the well established emulsion styrene-butadiene copolymer (S-1502) are shown in Table 1.

To complete the comparison of the new polymer with emulsion styrene-butadiene copolymer, Table 2 compares the general compound and vulcanizate properties obtained in the laboratory and Table 3, the compound, vulcanizate, wet grip and rolling resistance properties obtained from the simplest test formulation used to evaluate the wet grip and rolling resistance performance of equivalent 155 SR 13 steel belted radial ply tyres, the only difference being the polymer in the tread compound.

NEW POLYMER—PRACTICAL APPLICATION

Processability

Full scale processing trials have been carried out in tyre factories to allow the processing characteristics of the new polymer to be assessed on various types of equipment in the areas of: mixing; extrusion (hot and cold feed); tyre building; and moulding.

The results have shown that the new polymer can be processed on existing equipment.

Table 1 Polymer characteristics

	New polymer	S-1502
Stabilizer	Non-staining hindered phenol	
Styrene content (wt%)	23.5	23.5
Cis content (%)	20	10
Trans content (%)	30	75
1,2 Butadiene content (%)	50	15
Molecular weight \bar{M}_n	250 000	110 000
\bar{M}_w	500 000	550 000
Density	0.93	0.93
Glass transition temperature, d.s.c. (°C)	-40	-55

Table 2 Laboratory formulation, compound and vulcanizate properties

	New polymer	S-1502
<i>Formulation</i> (pphr)		
Polymer	100.0	100.0
N-339 carbon black	45.0	45.0
Zinc oxide	5.0	5.0
Stearic acid	3.0	3.0
Santoflex 13	1.0	1.0
Santoflex 77	1.0	1.0
Santocure MOR	1.0	1.0
Sulphur	2.0	2.0
	158.0	158.0
Mooney viscosity, M_L (1 + 4), 100°C	80	65
<i>Vulcanizate</i>		
Tensile strength (MPa)	22	24
Modulus at 300% elongation (MPa)	13	14
Elongation at break (%)	425	400
Hardness, Shore A	61	62
Tear strength, angle (kN m ⁻¹)	50	52
Resilience, Lüpke Pendulum at 23°C (%)	42	52
Heat build-up (over 38°C) (°C)	34	33

Table 3 Tread formulation, compound vulcanizate wet grip and rolling resistance properties

	New polymer	S-1502
<i>Formulation</i> (pphr)		
Polymer	100.00	100.00
Zinc oxide	2.50	2.50
Stearic acid	1.00	1.00
75% BLE	2.00	2.00
N-375 carbon black	50.00	50.00
Sulphur	1.75	1.75
CBS	1.00	1.00
	158.25	158.25
<i>Vulcanizate</i>		
Tensile strength (MPa)	21.6	25.2
Modulus at 300% elongation (MPa)	14.3	14.2
Elongation at break (%)	390	430
Hardness (IRHD)	72.3	69.2
Resilience, Zwick at 50°C (%)	29.9	32.8
E' at 50°C (MPa)	7.65	7.46
E'' at 50°C (MPa)	1.008	1.138
E''/E* ² at 50°C (MPa) ⁻¹	0.0169	0.0200
<i>Tyre properties</i>		
Wet grip rating	114	100
Rolling resistance rating	94	100

Tyre performance

Extensive test programmes have been carried out comparing the performance of equivalent tyres with the exception of the tread compound, some tread compounds containing the new polymer, others using existing practical tread compounds. The closely controlled test programmes included: wet grip; rolling resistance; fuel consumption; temperature generation; structural performance; high speed performance; and tread wear.

The results have shown that tread compounds using the new polymer when compared to practical tread com-

pounds used at the present time, produce the following improvements in tyre performance:

- Reduce rolling resistance (−13%)
- Reduce fuel consumption (−2.7%)
- Improve wet grip (+5%)
- Reduce tread operating temperature
- Improve durability
- Maintain acceptable tread life

CONCLUSIONS

Over the past 25 years, the two accepted theories used for the development of improved wet grip tyre tread compounds, i.e. reducing the tread compound resilience improves the wet grip performance; and increasing the tread polymer glass transition temperature improves the wet grip performance, means that improving wet grip (safety) by improving the wet grip performance of the tread compound must inherently increase the tread component to the rolling resistance of the tyre and hence the overall rolling resistance of the tyre.

A new wet grip/rolling resistance philosophy has been developed, based on measuring the dynamic properties of the tread compound in the laboratory under the conditions approaching those existing at the tyre/road surface interface under both rolling and wet sliding conditions.

The requirements are:

Rolling conditions: Low values of loss modulus (E'') and loss modulus divided by complex modulus squared ($E''/E^*{}^2$) measured at relatively low frequencies (up to 120 Hz) and relatively low temperatures (for passenger cars of the order of 50°C).

Wet sliding conditions: High values of loss factor measured at relatively high frequencies (in the range 50 kHz–1 MHz) and relatively high temperatures (in the range 100–150°C).

The wet grip/rolling resistance philosophy has enabled a new polymer to be developed which contradicts established practices insofar as it allows the tyre rolling resistance to be reduced whilst improving the wet grip performance, the only difference between the tyres being the tread compound. This new polymer development represents the most significant advance in tyre polymer design/technology for 25 years and could be the forerunner of a new generation of relatively high 1,2 butadiene content styrene–butadiene copolymers.

NOMENCLATURE

a_{ms}	Surface area of particle contact on the microtexture scale
f_{ms}	Deformation frequency on the microtexture scale under sliding conditions
h	Tread thickness
n	Number of microtexture elements per unit area
r_{ms}	Radius of actual particle contact area on the microtexture scale
v_t	Wave velocity
x	Distance into tread perpendicular to the tyre/road surface interface
A	Area of contact
\dot{E}_a	Rate of energy absorption due to the tread adhesion component under sliding conditions

\dot{E}_{mh}	Rate of energy absorption due to the tread micro-hysteresis component under sliding conditions
\dot{E}_t	Rate of energy absorption due to the total tread component under sliding conditions
F_a	Frictional force due to the tread adhesion component under sliding conditions
F_{mh}	Frictional force due to the tread micro-hysteresis component under sliding conditions
F_t	Total frictional force due to the tread component under sliding conditions
F_{Bh}	Frictional force due to the tread bulk-hysteresis component under sliding conditions $\leq 1\%$ (Bond ^{1,2})
G' and G''	Shear elastic and loss moduli
K' and K''	Bulk elastic and loss moduli
P	Pressure amplitude
R_b	Tread bending component to rolling resistance
R_c	Total tread compression component to rolling resistance
R_t	Total tread component to rolling resistance
R_{tm}	Tread movement component to rolling resistance (assumed small for a well designed tyre)
R_{mc}	Road surface microtexture tread compression component to rolling resistance
R_{Gtc}	General tread compression component to rolling resistance
R_{Mc}	Road surface macrotexture tread compression component to rolling resistance
U_0	Maximum velocity of displacement
ξ_0	Maximum displacement on the microtexture scale
ρ_t	Tread compound density
ω	Angular velocity

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