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16. Abstract

This report is the fifth in a series of scientific reports used to guide the agency's development of a laboratory-based accelerated service life test for light vehicle tires (i.e. "tire aging test"). This paper focuses on the modulus results (akin to hardness) in the inter-belt wedge rubber component of the tire. The wedge compounds of five of the six tire models retrieved from service in Phoenix, AZ, were found to increase progressively in modulus with increasing amounts of service. However, one tire type (Type H light truck tires) decreased in modulus with increasing amounts of service. It has been reported in scientific literature that the rubber compounds in passenger tires tend to increase in modulus during service due to oxidation. However, when optional resins are added to the rubber compounds to promote adhesion and impart reinforcement, they form a network structure with elevated modulus values. This resin network structure is quickly broken down by mechanical strain during rolling service. At sufficiently high levels of resin content, this could lead to a net mechanical softening of the rubber compound during service despite the ongoing hardening effects of oxidation.

To validate this hypothesis, the resin content in wedge compounds of 24 different tire models was estimated by comparing their softening in double strain sweep testing to model compounds produced with known levels of resin. Bead apex rubber compounds from five tire models were also tested as a control since they were likely to contain high levels of resin. Of the six models collected in the NHTSA Phoenix study, only the wedge compound of Type H light truck tire model was estimated to contain a high level of resin. The wedges of twelve models, including four of the NHTSA Phoenix models, were estimated to contain low levels of resin. The wedges of the remaining eleven tire models were estimated to contain no resin. These results indicate that matching the modulus properties of wedge (and belt-coat) compounds of laboratory-aged tires to in-service tires will require a combination of both oxidative aging and mechanical strain.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

As a result of the TREAD Act of 2000, NHTSA initiated an effort to develop a laboratory-based accelerated service life test for light vehicle tires (herein referred to as a “tire aging test”). This paper focuses on the modulus results (akin to hardness) obtained for the rubber compound located between the steel belts at the belt edge, which is often referred to as the “wedge.” Modulus profile results of the wedge regions of the six tire models retrieved from on-vehicle service in Phoenix, AZ, were compared to new tires of each model. The wedge compounds of five of the six tire models were found to increase progressively in modulus with increasing amounts of service. However one tire type, the Type H light truck tires, decreased in modulus with increasing amounts of service. Accelerated oven aging of new tires of all six types generated uniform increases in the modulus of all tire types (including the Type H tires). However, accelerated roadwheel aging of new tires of all six types also replicated the decrease in wedge region modulus in the Type H tires. Since static oven aging was, by all other measures, the most effective and least expensive method of accelerated tire aging (when compared to two roadwheel aging methods) the inability of oven aging to match in-service modulus results was a concern.

It was believed that tire rubber compounds that contain an optional resin for promotion of adhesion and to impart reinforcement may cause the compounds to soften (reduce in modulus) when exposed to strain (elongation, shear, or compression) during rolling service or on a laboratory roadwheel. This may explain the modulus results of the Type H light truck tires. To validate this hypothesis, the resin content in belt-coat rubber compounds of the original six tire models retrieved by NHTSA in Phoenix, AZ, as well as 18 additional models were estimated by comparing their softening in double strain sweep testing. In this technique, the modulus of the compounds was measured before and after being subjected to strain. Model compounds that contained known levels of resin were measured, and the results used to estimate the probable resin content of the rubber compounds in the tires. Bead apex rubber compounds from five tire models were also tested as a control since they were likely to contain high levels of resin.

For tires of the six models collected from on-vehicle service in Phoenix, AZ, only the wedge of the Type H light truck tires produced much more mechanical softening than the other tires studied. The wedge in this tire was estimated to contain approximately 8 parts of resin per hundred parts rubber (8 phr). Type B, a small passenger tire, had relatively little softening, and was estimated to contain no resin. The remaining four passenger tire models produced intermediate levels of softening, and are estimated to contain 1-2 phr of resin. For the other 18 tire models, none of the other light truck wedge compounds were calculated to contain resin. One of the Michelin passenger tires and many of the Bridgestone, Continental, and Goodyear passenger tires were calculated to possibly contain resin (1-2 phr) in the wedge compound, with the Cooper, Sumitomo, and Toyo tires being unlikely to contain resin.

These results indicate that matching the modulus properties of wedge (and belt-coat) compounds of laboratory-aged tires to in-service tires will require a combination of both oxidative aging and mechanical strain. The mechanical strain could be induced prior to or following oven aging using moderate period of conditioning on a laboratory roadwheel, or may happen during the initial phases of a post-aging roadwheel test (however this would preclude matching the modulus properties of the aged tire to an in-service state prior to structural evaluation).

BACKGROUND

As a result of the TREAD Act of 2000, NHTSA initiated an effort to develop a laboratory-based accelerated service life test for light vehicle tires (herein referred to as a “tire aging test”). Part of the test development project included examining how tires change during service by measuring their material properties after varying lengths of service and accumulated mileages. Since the rate of degradation of tire rubber components increases with temperature, NHTSA expected that the “worst case” in-service tires in the US would be found in the hottest states. After weighing many considerations, Phoenix, Arizona was chosen as the tire collection site. Six models of tires were collected at traditional retail locations from on-vehicle use and were benchmarked against new copies of each tire model to quantify the rates of change during service. One of multiple measures used throughout the project to gauge the effectiveness of a tire-aging test was to compare the changes in modulus properties of the rubber compounds in the laboratory aged tires to tires which had been retrieved from on-vehicle service in Phoenix, AZ, as detailed in the NHTSA Tire Aging Development, Phase 1 report[1].

The rubber compound between the steel belts at the belt edge, or “wedge” compound, experiences the highest level of strain energy density during tire service, resulting in high localized temperatures. The wedge is an additional rubber component placed between the belt edges during tire building and is often comprised of the same rubber compound as the belt-coat. Integrity of the belt-edge region is critical in preventing tread separation failures (formally referred to as “tread and belt #2 detachments”). Modulus (akin to hardness) profile results of the wedge regions of the six tire models retrieved from on-vehicle service in Phoenix, AZ, were compared to new tires of each model. The wedge compounds of five of the six tire models were found to increase progressively in modulus (i.e., experienced hardening) with increasing amounts of service. However one tire type, the Type H light truck tires, decreased in modulus with increasing amounts of service. Accelerated oven aging of new tires of all six types generated uniform increases in the modulus of all tire types, including the Type H tires. However, accelerated roadwheel aging of new tires of all six types also replicated the decrease in wedge region modulus in the Type H tires. Since static oven aging was, by all other measures, the most effective and least expensive method of accelerated aging (when compared to the two roadwheel aging methods evaluated), the inability of oven aging to match in-service modulus results of tires from all manufacturers was a concern.

Scientific literature attributes the modulus changes observed in the wedge compound of passenger tires during service to a combination the opposing processes of oxidation, which results in hardening and embrittlement, and mechanical softening[2-4]. Oxidation generally leads to formation of crosslinks between the polymer chains and an increase in modulus. Mechanical shear strain, which is highest at the belt edges, generally leads to softening of the compound. The net result thereby would be a combination of the two effects. If the compound is particularly susceptible to mechanical softening, the modulus could decrease during service. If the compound is less susceptible to mechanical softening the modulus would increase during service, as oxidative hardening would dominate the modulus changes during service.

It is known that resin reinforced compounds are used in the tire industry for beltcoat, wedge and apex compounds[5-11]. Hoff, Evans, & Waddell (1996) reported a history of resin use in tire wire coat compounds:

> "Experimental results have shown that bonding systems containing HMMM *(hexamethoxymethylmelamine)* provide superior, i.e. higher pull-out adhesion and rubber coverages under aging conditions including heat-aging, humidity-aging and steam-aging when compared to HEXA (*hexamethylenetetramine*). Today's modern tire adhesion bonding system typically contains HMMM, a resorcinol or a prereacted resorcinol-formaldehyde component, and a precipitated silica. The optimized system might contain the following proportions:
>
> * HMMM - 3-6 phr;
>
> * Resorcinol - 2-3 phr or R/F resin 3-4 phr;
>
> * Silica - 10-15 phr
>
> Cyrez (*HMMM*)/resorcinol systems function primarily because they are polar and migrate to the high-energy wire interface and form a resin-rich layer on the brass of the wire surface. Thus, the resin system protects the steel cord from attack by moisture and oxygen, reduces dezincification, stabilizes the $[Cu_{(2-x)}]S$ interfacial linkage, and imparts both original and humidity-aged adhesion. Finally, resins increase rubber tear strength and pull-out adhesion."[11]

Reinforcing resins provide advantages, namely higher modulus and wire adhesion without the mixing and processing disadvantages from alternate routes to high modulus, such as extra sulfur and or reinforcing fillers (carbon black and/or silica). However, unlike a reinforcing filler network,[4, 12] the resin network structure is not reformed after being exposed to high levels of strain. Therefore compounds containing resins can be expected to have a higher degree of softening than those without resin. Initial testing indicates that a combination of both oxidative aging and mechanical stress are necessary to match the modulus of a laboratory-aged tire to a tire removed from on-vehicle service. The hypothesis is that mechanical stress is needed to break down the resin in the compound, as would happen in the initial service usage, in order to match statically oven-aged tires to the modulus properties of in-service tires. With no simple chemical test to detect the forms and amounts of resins in a tire compound, a dynamic mechanical analysis (DMA) of the compounds was selected in order to evaluate the hypothesis.

EXPERIMENTAL TECHNIQUES

<u>Tires</u>

The 24 tires were dissected to remove a slice of belt-package wedge compound (and bead apex compound from 5 tires) for DMA analysis by double strain sweep analysis. In this procedure the sample is first exposed to a strain sweep to break down the network structure. A subsequent strain sweep is used to analyze the modulus of the remaining network. The tires in this study covered a broad range of brands, types, sizes, and applications, as shown in Table 1.

Table 1. Original Six Phoenix Tire Models

Sample Number	Tires	Component	Tire Type	Plant Code	Tire Manufacturer	Tire Brand Name	Tire Model	Construction
ERTNB3-83-21	N1042	Wedge	B	AP	Michelin	BFGoodrich	Touring T/A SR4	Passenger
ERTNB2-27-23	N1094	Apex	B	AP	Michelin	BFGoodrich	Touring T/A SR4	Passenger
ERTNB3-83-4	N1542	Wedge	C	M6	Goodyear	Goodyear	Eagle GA	Passenger
ERTNB3-83-5	N1542	Apex	C	M6	Goodyear	Goodyear	Eagle GA	Passenger
ERTNB3-83-1	N1142	Wedge	D	B3	Michelin	Michelin	LTX M/S	Passenger
ERTNB3-83-2	N1142	Apex	D	B3	Michelin	Michelin	LTX M/S	Passenger
ERTNB3-83-23	N1372	Wedge	E	VN	Bridgestone	Firestone	Wilderness AT I	Passenger
ERTNB3-83-24	N1319	Apex	E	VN	Bridgestone	Firestone	Wilderness AT I	Passenger
ERTNB3-83-3	N1242	Wedge	H	PJ	Goodyear	Pathfinder [Discount Tire]	ATR A/S	Light Truck
ERTNB3-83-25	N1442	Wedge	L	A3	Continental	General	Grabber ST	Passenger
ERTNB3-83-26	N1442	Apex	L	A3	Continental	General	Grabber ST	Passenger

Table 2. Additional Test Tire Models

Sample Number	Tires	Component	Tire Type	Plant Code	Tire Manufacturer	Tire Brand Name	Tire Model	Construction
ERTNB3-83-27	N2028	Wedge	P2	UP	Cooper	Futura [Pep Boys]	Scrambler A/P (LT)	Light Truck
ERTNB3-83-10	N2056	Wedge	P3	UT	Cooper	Futura [Pep Boys]	Scrambler A/P (P-XL)	Passenger
ERTNB3-83-11	N2081	Wedge	U2	EU	Sumitomo	Dunlop	SP Sport 4000 DSST (Run Flat)	Passenger
ERTNB3-83-6	N2222	Wedge	B6	7X	Bridgestone	Bridgestone	DUELER H/T 689	Passenger
ERTNB3-83-28	N2249	Wedge	B7	VN	Bridgestone	Firestone	Wilderness AT I	Passenger
ERTNB3-83-12	N2286	Wedge	B8	0B	Bridgestone	Bridgestone	B450	Passenger
ERTNB3-83-7	N2344	Wedge	O2	PJ	Goodyear	Big O [Big O Tire]	Bigfoot A/T (LT265)	Light Truck
ERTNB3-83-8	N2371	Wedge	D2	PJ	Goodyear	Arizonian [Discount Tire]	Silver Edition	Passenger
ERTNB3-83-9	N2430	Wedge	D4	3D	Cooper	Dominator [Discount Tire]	Durango Radial A/T	Light Truck
ERTNB3-83-29	N2444	Wedge	C3	A3	Continental	Continental	Contitrac	Passenger
ERTNB3-83-30	N2487	Wedge	C5	AC	Continental	Continental	TouringContact AS	Passenger
ERTNB3-83-13	N2517	Wedge	B9	7X	Bridgestone	Bridgestone	Duravis M773 II	Light Truck
ERTNB3-83-14	N2542	Wedge	C7	A3	Continental	Continental	Contitrac TR	Passenger
ERTNB3-83-15	N2567	Wedge	C8	P5	Continental	General	Ameri G4S	Passenger
ERTNB3-83-16	N2592	Wedge	H3	T7	Hankook	Hankook	DynaPro AS	Light Truck
ERTNB3-83-17	N2617	Wedge	M10	B7	Michelin	Michelin	LTX A/S	Light Truck
ERTNB3-83-18	N2642	Wedge	S1	V4	Sumitomo	Sumitomo	HTR+	Passenger
ERTNB3-83-19	N2667	Wedge	T2	9T	Toyo	Toyo	800 Ultra	Passenger

Dynamic Mechanical Analysis (Strain Sweeps)

A Metravib DMA150 Dynamic Mechanical Analyzer was used to complete strain sweeps using tensile geometry. Strain sweeps were performed in tension from 0.05% to 51% strain (not dynamic strain amplitude) including 13 strains at evenly spaced logarithmic steps. The dynamic strain values are 0.093%, 0.17%, 0.31%, 0.56%, 1.0%, 1.8%, 3.1%, 5.5%, 9.7%, 17%, 29%, and 51%. The dynamic mechanical properties were measured at room temperature and 2 Hz.

RESULTS

Model Compound Analysis

Model beltcoat compounds were prepared and tested to examine the influence of different types and levels of reinforcement resins on the rate of modulus change. The resins are listed in Table 3. The model beltcoat compound recipes are listed in Table 4.

Table 3. List of Reinforcing Resins

Name	**Composition**
Control	No resin
Resin A	SRF-1501 + HMMM
Resin B	B-19-S + HMMM
Resin C	Elaztobond A250 + HMMM
Resin D	Resorcinol + HMMM
Resin E	Resorcinol + HEXA
SRF1501 is a resorcinol-formaldehyde novolak supplied by SI Group, Inc.	
B-19-S is a resorcinol-formaldehyde polymer manufactured by INDSPEC Chemical Corporation. Penacolite resin B-19-S is a low dusting, resorcinol, resorcinol-formaldehyde resin with a softening point of 100-114°C.	
Elaztobond A250 is a modified resorcinol-formaldehyde resin manufactured by SI Group, Inc.	
Resorcinol is manufactured by INDSPEC Chemical Corporation.	
HMMM is hexamethoxymethylmelamine manufactured by Cytec Industries, Inc.	
HEXA is hexamethylenetetramine.	

Table 4. Model Compound Formulations

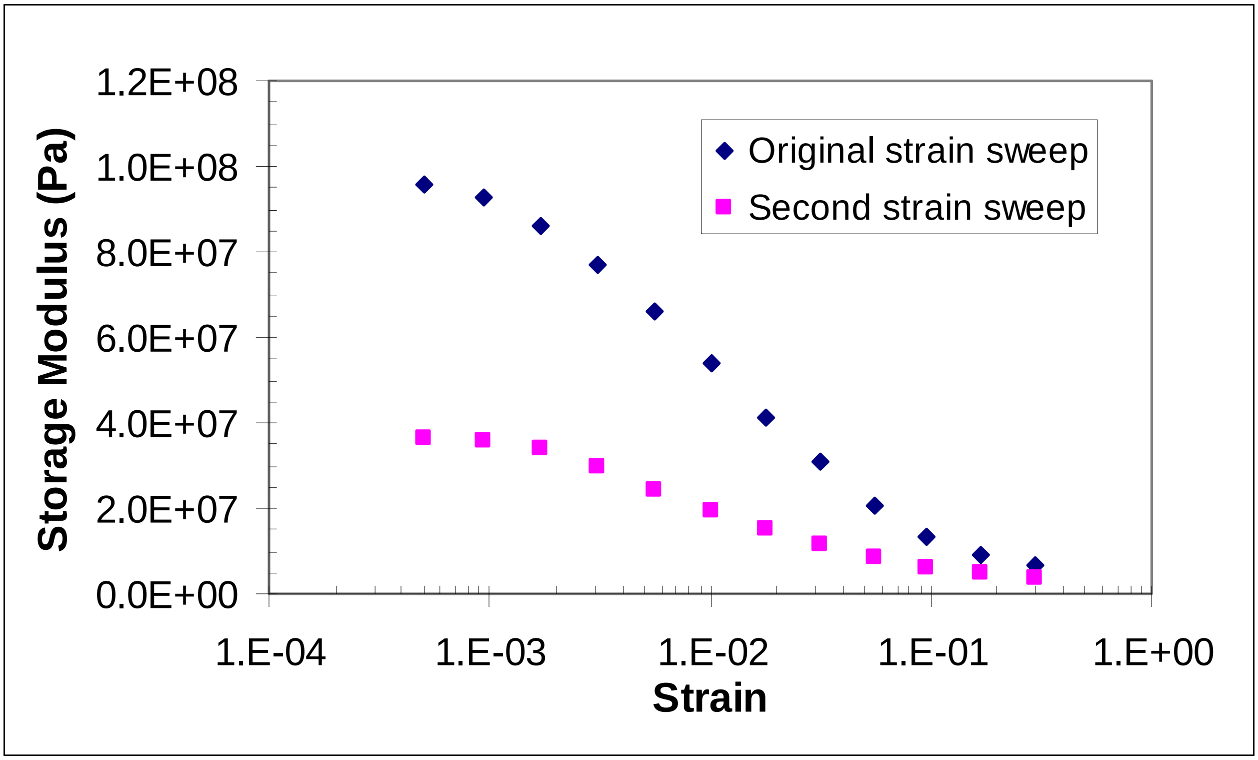
Sample Number ***ingredient***	**ERTNB3 -44-1** ***parts***	**ERTNB3 -44-5** ***parts***	**ERTNB3 -46-21** ***parts***	**ERTNB3 -54-3** ***parts***	**ERTNB3 -54-8** ***parts***	**ERTNB3 -69-1** ***parts***	**ERTNB3 -69-3** ***parts***	**ERTNB3 -74-2** ***parts***
Natural Rubber	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Filler	65.00	65.00	65.00	65.00	65.00	70.00	60.00	65.00
Antioxidant	1.75	1.75	1.75	1.75	1.75	0.75	0.75	1.75
Curatives	16.65	16.65	16.65	16.65	16.65	16.65	15.45	16.65
Oil	2.00	2.00	2.00	2.00	2.00	2.50	2.50	2.00
Resin A	7.00				28.00			
Resin B			11.00					
Resin C				7.00				
Resin D						7.00	4.80	
Resin E								2.65
Total	**192.40**	**185.40**	**196.40**	**192.40**	**213.40**	**196.90**	**183.50**	**188.05**

The softening resistance values of the model compounds were determined by a double strain sweep experiment (two strain sweeps performed consecutively) (Table 5 and Figure 1). The strain sweeps include thirteen strains in at equal logarithmic-based intervals. The percent softening was measured at the first twelve strains. The average of the twelve percent softening values was termed the average percent softening for the compound. The average storage modulus for the compound was the average of the twelve storage modulus values. The original average storage modulus and average percent softening values were used to rank order compounds and tire components.

Table 5. Storage Modulus as a Function of Strain (Original and Second Sweep) for ERTNB3-44-1

	Original Strain Sweep	Second Strain Sweep	Softening	Percent Softening
Dynamic Strain	E'o	E's	E'o-E's	E'o-E's/E'o
(Unitless)	(Pa)	(Pa)	(Pa)	(%)
0.000500	9.60E+07	3.63E+07	5.97E+07	62.2
0.000933	9.27E+07	3.58E+07	5.69E+07	61.4
0.00172	8.62E+07	3.38E+07	5.24E+07	60.8
0.00312	7.71E+07	2.95E+07	4.76E+07	61.7
0.00561	6.62E+07	2.43E+07	4.19E+07	63.3
0.0100	5.39E+07	1.95E+07	3.44E+07	63.9
0.0178	4.12E+07	1.53E+07	2.60E+07	63.0
0.0314	3.07E+07	1.17E+07	1.90E+07	61.9
0.0552	2.06E+07	8.73E+06	1.18E+07	57.6
0.0967	1.32E+07	6.29E+06	6.90E+06	52.3
0.169	9.11E+06	4.58E+06	4.53E+06	49.7
0.294	6.51E+06	3.58E+06	2.92E+06	44.9
Average	**4.94E+07**	**1.91E+07**	**3.03E+07**	**58.6**

Figure 1. Storage Modulus as a Function of Strain (Original and Second Sweep) for ERTNB3-44-1



The values for the average original storage modulus, average second sweep storage modulus, average softening, and average percent softening for the model compounds are shown in Table 6. The control compound is ERTNB3-44-5, which did not have a reinforcing resin. The resins increased compound modulus (Figure 2), except for the two compounds containing resin D. It is now suspected that compounds containing resin D were mixed in such a way that most of the resorcinol sublimed rather than becoming fixed in the compounds. Therefore results from the two compounds containing resin D were eliminated from the calibration of resin level. The effect of resin loading was also studied. Resin loading increased compound modulus; however, it also increased compound softening (Figure 3).

Table 6. Storage Modulus of Model Compound Formulations

Sample Number	Resin, phr	Resin Type	Average Original E'	Average Second E'	Average Softening	Average Percent Softening
ERTNB3-44-1	7	A	4.94E+07	1.91E+07	3.03E+07	58.6
ERTNB3-44-5	0	Control	2.05E+07	1.30E+07	7.53E+06	35.8
ERTNB3-46-21	11	B	2.84E+07	1.46E+07	1.38E+07	46.2
ERTNB3-54-3	7	C	3.07E+07	1.52E+07	1.54E+07	48.0
ERTNB3-54-8	28	A	1.57E+08	2.70E+07	1.30E+08	78.0
ERTNB3-69-1	7	D	1.52E+07	9.09E+06	6.16E+06	32.8
ERTNB3-69-3	4.8	D	1.19E+07	8.32E+06	3.55E+06	29.5
ERTNB3-74-2	2.65	E	3.12E+07	1.64E+07	1.48E+07	45.6

Figure 2. Effect of Resin Type on Storage Modulus

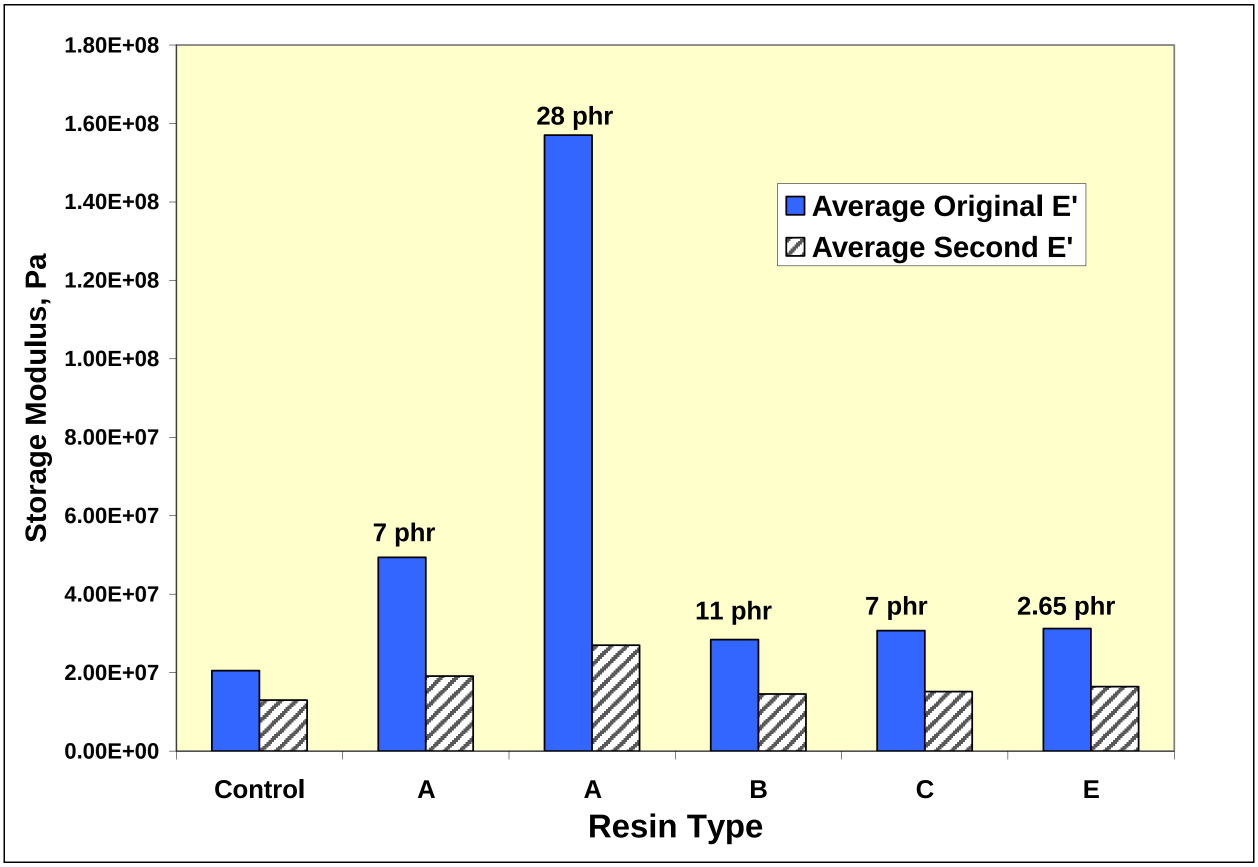


Figure 3. Effect of Resin Loading on Softening

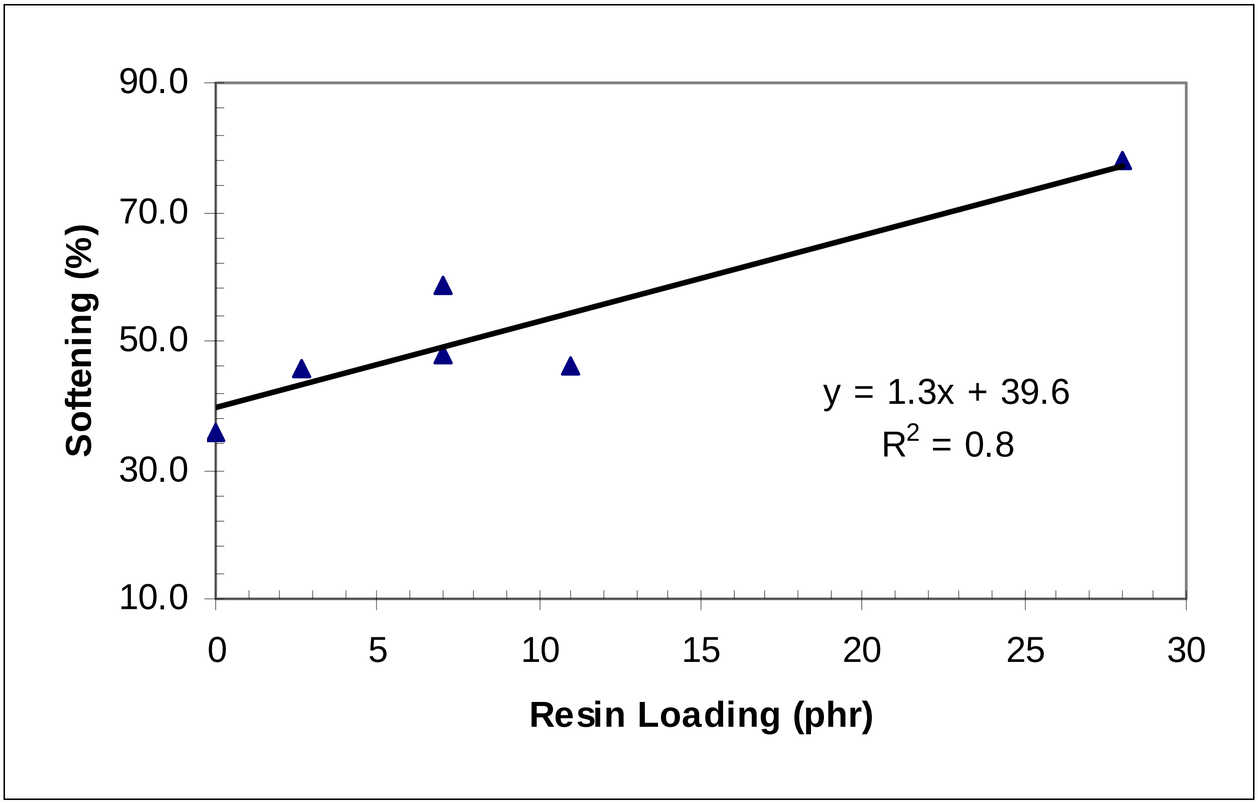


Figure 3 shows the percent softening, which appears to increase with increasing resin content of the compound. Nested analysis of the percent softening by resin type and phr yield the equations shown in Table 7, with an overall R^2 of 0.92. Thus, for resin B an increase of 0.77% in softening would correspond to 1 part of resin per hundred parts of rubber (1 phr). For resin E it would require a change of 2.98% to correspond to 1 phr of resin.

Table 7. Percent Softening Versus Resin Content, by Resin Type

Resin Type	Intercept	Change in Softening, % / phr Resin
A	37.71	1.53
B		0.77
C		1.47
E		2.98

Tire Bead Apex Compound Analysis

It is desirable for the apex rubber, which is usually at the center of the bead region, to have a high degree of stiffness (high modulus) as well as good adhesion to the steel bead bundle. Therefore high levels of reinforcing resins are often used in the apex compounds. The apex compound from five tire models were analyzed to serve as an upper limit on the dynamic mechanical analysis (Table 8).

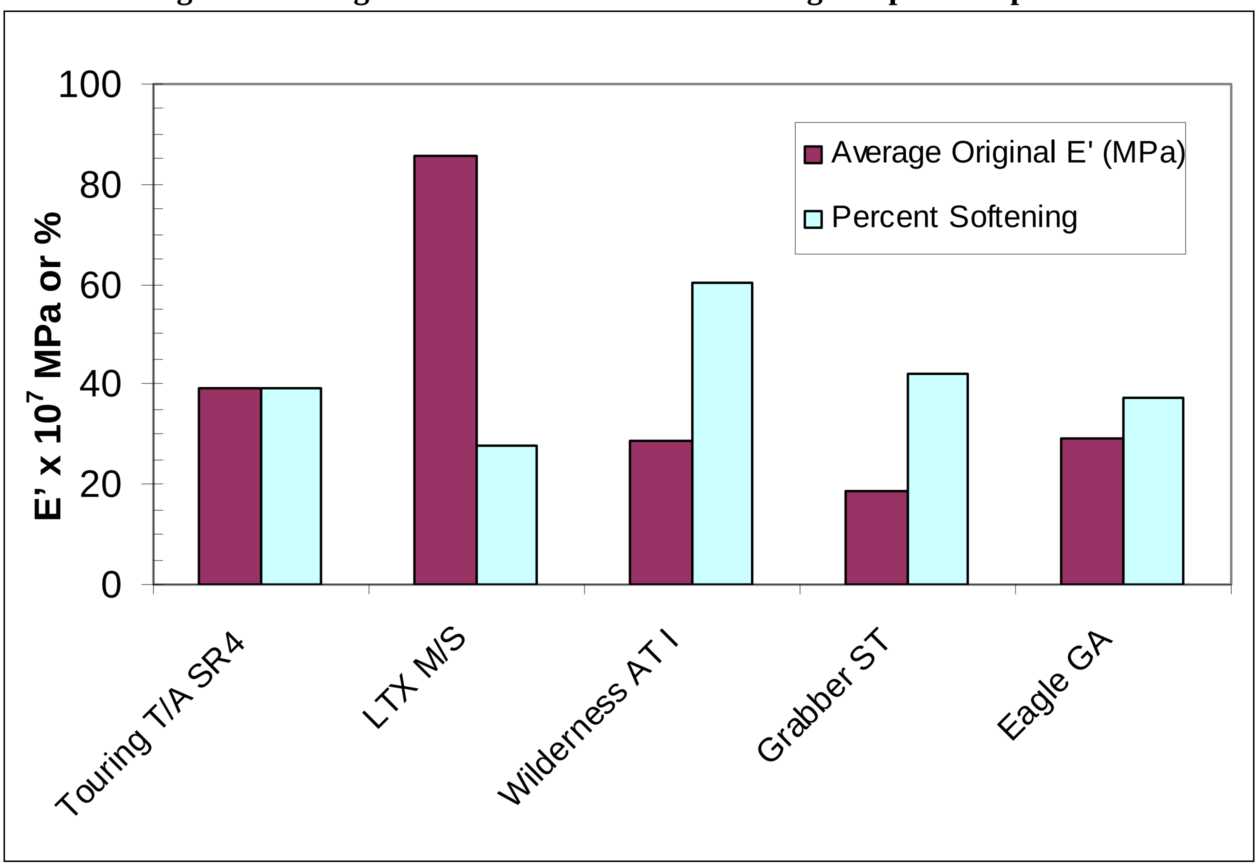
Table 8. Storage Modulus of Tire Apex Compounds

Tire Barcode	Tire Type	Tire Model	Average Original E'	Average Second E'	Average Softening	Average Percent Softening
N1094	B	Touring T/A SR4	3.91E+07	2.18E+07	1.46E+07	39.0*
N1142	D	LTX M/S	8.56E+07	6.17E+07	2.39E+07	27.7
N1319	E	Wilderness AT I	2.88E+07	1.07E+07	1.81E+07	60.3
N1442	L	Grabber ST	1.86E+07	1.07E+07	7.88E+06	42.0
N1542	C	Eagle GA	2.91E+07	1.81E+07	1.10E+07	37.4

* Calculations for N1094 apex were based on nine strain conditions in place of twelve because the sample broke at 20% strain.

The average storage modulus and average percent softening values for the five bead apex compounds were compared (Figure 4). The tire models included were the BF Goodrich Touring T/A SR4, Michelin LTX M/S, Firestone Wilderness AT I, General Grabber ST, and Goodyear Eagle GA. The Michelin apex had the highest average original modulus and the lowest average percent softening. The BF Goodrich was second highest in modulus. The BF Goodrich, Wilderness AT I, Grabber ST, and Eagle GA had higher softening than the LTX M/S, indicating possibly that they contained resin and may soften during service.

Figure 4. Storage Modulus and Percent Softening in Apex Compounds



Tire Wedge Compound Analysis

The softening resistance values of the tire wedge compound were determined (Table 9). The data was particularly useful in other areas of the project to understand modulus profile results in field tires.

Table 9. Storage Modulus of Tire Wedge Compounds

Tire Barcode	Tire Type	Average Original E'	Average Second E'	Average Softening	Average Percent Softening
Phoenix-Retrieved Tire Models					
N1042	B	1.03E+07	7.06E+06	3.24E+06	31.3
N1142	D	1.31E+07	7.90E+06	5.21E+06	39.1
N1242	H*	3.22E+07	1.62E+07	1.61E+07	49.4
N1372	E	1.68E+07	1.03E+07	6.55E+06	39.2
N1442	L	1.83E+07	1.07E+07	7.55E+06	41.0
N1542	C	1.74E+07	9.87E+06	7.57E+06	41.9
Additional Tire Models					
N2028	P2*	1.38E+07	8.82E+06	5.02E+06	36.1
N2056	P3	1.23E+07	7.61E+06	4.66E+06	37.9
N2081	U2	7.68E+06	5.55E+06	2.12E+06	26.5
N2222	B6	1.39E+07	8.30E+06	5.58E+06	39.3
N2249	B7	1.47E+07	8.85E+06	5.87E+06	39.7
N2286	B8	1.71E+07	9.78E+06	7.28E+06	41.7
N2344	O2*	2.77E+07	1.42E+07	1.35E+07	48.2
N2371	D2	1.26E+07	7.76E+06	4.81E+06	38.8
N2430	D4*	1.23E+07	7.91E+06	4.42E+06	35.9
N2444	C3	2.15E+07	1.19E+07	9.59E+06	44.2
N2487	C5	1.45E+07	9.75E+06	4.71E+06	32.1
N2517	B9*	1.13E+07	7.17E+06	4.17E+06	35.1
N2542	C7	1.71E+07	1.01E+07	6.97E+06	40.6
N2567	C8	1.30E+07	7.94E+06	5.04E+06	38.5
N2592	H3*	1.05E+07	7.25E+06	3.25E+06	30.3
N2617	M10*	1.39E+07	9.56E+06	4.34E+06	30.9
N2642	S1	1.11E+07	7.58E+06	3.53E+06	32.1
N2667	T2	1.35E+07	8.62E+06	4.87E+06	35.7

*Light truck tires.

The light truck wedge compounds were evaluated by manufacturer. The comparison included their average original modulus and percent softening values (Figure 5). The Goodyear Type H light truck tire wedge compound had the highest modulus and the highest softening. This indicated that it contained resin and may soften during service. The Cooper, Bridgestone, and Michelin light truck wedge compounds were similar in average original modulus and percent softening. The range of calculated resin amounts, using the equations shown in Table 7 are shown in Table 10. The wedge compounds of the Goodyear tires were calculated to contain approximately 8-phr resin, with a range of 3.5 to 15 phr, depending on resin type. None of the other light truck tire wedge compounds were calculated to contain resin.

Figure 5. Storage Modulus and Percent Softening in Light Truck Wedge Compounds

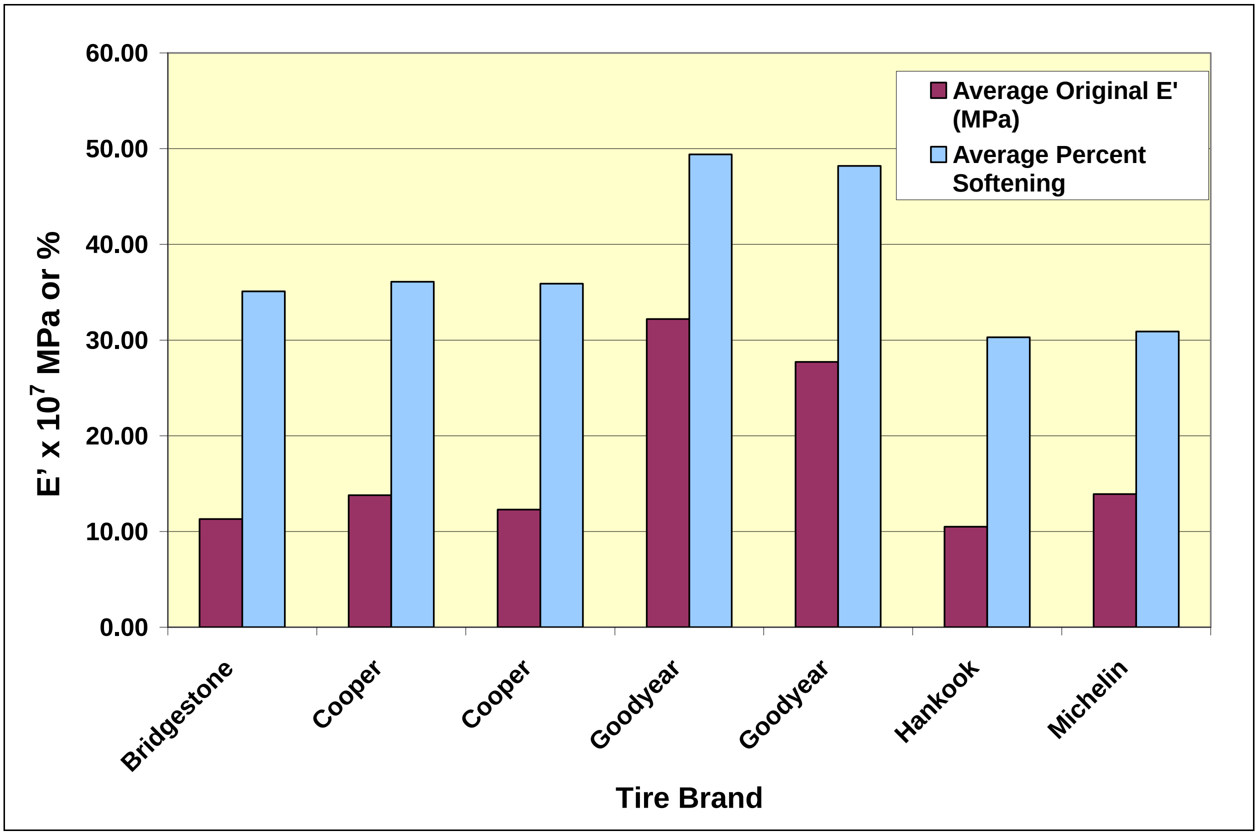


Table 10. Calculated Resin Content of Light Truck Wedge Compounds

Tire Barcode	Manufacturer	Calculated Resin, phr - Minimum	Calculated Resin, phr - Maximum	Calculated Resin, phr - Average	Average for Manufacturer
N1242[1]	Goodyear	3.9	15.1	8.7	8.25
N2344	Goodyear	3.5	13.6	7.8	
N2517	Bridgestone	≈ 0	≈ 0	≈ 0	≈ 0
N2430	Cooper	≈ 0	≈ 0	≈ 0	≈ 0
N2028	Cooper	≈ 0	≈ 0	≈ 0	
N2617	Michelin	≈ 0	≈ 0	≈ 0	≈ 0
N2592	Hankook	≈ 0	≈ 0	≈ 0	≈ 0

The passenger wedge compounds were analyzed by manufacturer. The calculated resin content is shown in Table 11. The comparison included their average original storage modulus and average percent softening (Figure 6). Most of the Continental wedge compounds, one of the Michelin wedge compounds, the Bridgestone compounds, and the Goodyear compounds had high modulus and high softening. This suggests that they possibly contained resin and would exhibit softening from service. The calculated resin content averaged approximately 2 phr. The Cooper, Sumitomo, Dunlop, and Toyo wedge compounds had low modulus and average to low softening, indicating they do not contain resin.

[1] Type H light truck tire in Phoenix Phase I study.

Figure 6. Storage Modulus and Percent Softening in Passenger Wedge Compounds

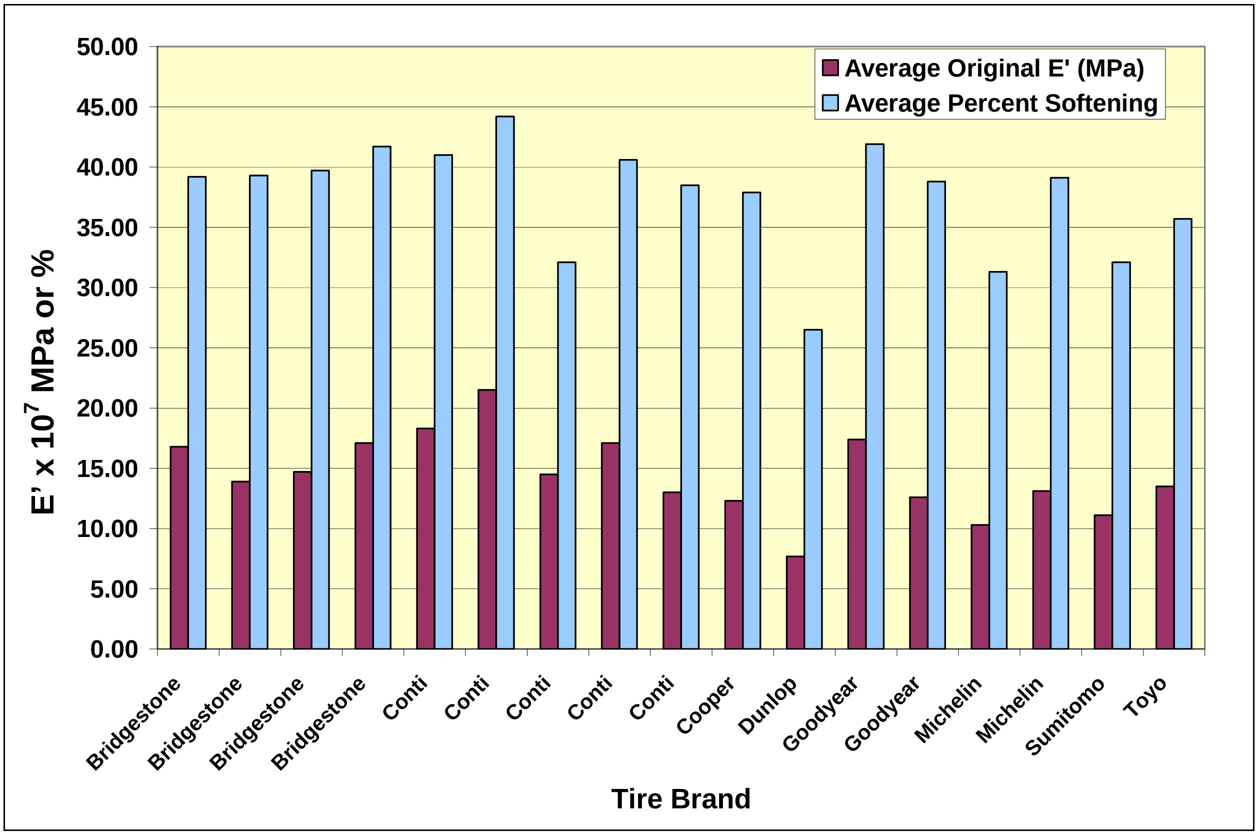


Table 11. Calculated Resin Content of Passenger Tire Wedge Compounds

Tire Barcode	Manufacturer	Calculated Resin, phr - Minimum	Calculated Resin, phr - Maximum	Calculated Resin, phr - Average	Average Resin phr for Manufacturer
N1142	Michelin[2]	0.5	1.8	1.0	≈ 0.5
N1042	Michelin[3]	≈ 0	≈ 0	≈ 0	
N1542	Goodyear[4]	1.4	5.4	3.1	1.9
N2371	Goodyear	0.4	1.4	0.8	
N2222	Bridgestone	0.5	2.1	1.2	1.7
N2286	Bridgestone	1.3	5.2	3.0	
N1372	Bridgestone[5]	0.5	1.9	1.1	
N2249	Bridgestone	0.7	2.6	1.5	
N2542	Continental	1.0	3.7	2.1	≈ 2.0
N2567	Continental	0.3	1.0	0.6	
N1442	Continental[6]	1.1	4.3	2.4	
N2444	Continental	2.2	8.4	4.8	
N2487	Continental	≈ 0	≈ 0	≈ 0	
N2056	Cooper	0.1	0.2	0.1	0.1
N2642	Sumitomo	≈ 0	≈ 0	≈ 0	≈ 0
N2081	Sumitomo*	≈ 0	≈ 0	≈ 0	
N2667	Toyo	≈ 0	≈ 0	≈ 0	≈ 0

* Dunlop-Sumitomo JV, Run-flat tire; manufactured by Sumitomo.

[2] Tire type D in Phoenix Phase I study
[3] Tire type B in Phoenix Phase I study
[4] Tire type C in Phoenix Phase I study
[5] Tire type E in Phoenix Phase I study
[6] Tire type L in Phoenix Phase I study

SUMMARY

All of the compounds experienced softening after experiencing strain of 51% in tension. The average softening for the model wedge compounds that did not contain resin was 37%. Model wedge compounds that contained resin softened up to 60% depending on resin type and level. The percent softening appeared to be a function of resin type and level, and the results of the regression analysis were used to estimate the percent resin that may be used in the compound.

Based on percent softening of the five bead apex compounds tested, the Bridgestone tire was the most likely to contain resin, the Michelin tire was the least likely, with the Continental, Goodyear, and B F Goodrich tires being intermediate. For the wedge compounds of the seven light truck tire models, the Goodyear tires were very likely to contain resin, with an estimated level of 8 phr. None of the other light truck wedge compounds were calculated to contain resin. For the wedge compounds of the seventeen passenger tire models, one of the Michelin passenger tires and many of the Bridgestone, Continental and Goodyear passenger tires were calculated to possibly contain resin (1-2 phr) in the wedge compound, with the Cooper, Dunlop, Sumitomo and Toyo tires being unlikely to contain resin.

The properties for the wedge compounds of the NHTSA Phase 1 tires are shown in Table 12. Tire Type B has a very low initial modulus and experiences very little mechanical softening. A laboratory-aging test developed for this tire would probably not require mechanical strain during aging to match the physical properties of the wedge compound. Tire Types C, D, E, and L have somewhat higher modulus values initially and show significantly more mechanical softening. It is evident that the Type H tire shows much more mechanical softening than the other tires studied. Even though the initial modulus was approximately double the modulus of the other tires, the loss in modulus was approximately three times as great after a strain sweep. This is consistent with the results seen in tires retrieved from service. These results indicate that to match the properties of wedge (and belt-coat) compounds of all laboratory-aged tires to in-service tires will require a combination of both oxidative aging and mechanical strain. The mechanical strain could be induced prior to or following oven aging using moderate period of conditioning on a laboratory roadwheel, or may happen during the initial phases of a post-aging roadwheel test (however this would preclude matching properties of the aged tire to an in-service state prior to structural evaluation). For tires with little or no resin content in its compounds, the strains imparted during a moderate roadwheel break-in would produce little effect other than to exercise the tire structure and compounds in a field-like manner.

Table 12. Estimated Resin Content of the Wedge Compound for NHTSA Phase 1 Tires

Tire Type	Initial Modulus (MPa)	Softening (MPa)	Softening (Percent)	Estimated Resin Content (phr)
B	10.3	3.24	31.3	0
C	17.4	7.57	41.9	3.1 ±1.7
D	13.1	5.21	39.1	1.0±0.7
E	16.8	6.55	39.2	1.1 ±0.8
H*	**32.2**	**18.10**	**49.4**	**8.2 ±5.0**
L	18.3	7.55	41.0	2.4 ±1.5

*Light truck tire.

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