

Asphalt-Rubber Interactions

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Three experiments were designed to evaluate the influence of increasing percentages of rubber (0, 10, 15, and 20 percent by weight of binder) and rubber type (passenger and industrial tires), pretreatment of rubber (none, tall oil pitch), and asphalt chemistry (Strategic Highway Research Program materials reference library asphalts AAD, AAG, AAF, and AAM) on asphalt-rubber interactions. Viscosity was measured by a Brookfield rotational viscometer; testing variability was also estimated. Untreated rubber was included to represent interaction characteristics representative of the wet process. Treated rubber was included as a way of stabilizing the rubber before use in the dry process. Results confirmed that rubber (either passenger or industrial tires) reacts more readily with a softer grade of asphalt from a given refinery. Pretreatment of passenger tire rubber with various percentages of tall oil pitch significantly reduces both the viscosity and the influence of aging. Pretreatment of industrial tire rubber appears to have a significant effect only when lighter grades of binder are used. The same rubber will react differently with various sources of the same grade of asphalt cement. This is a function of the molecular weight of the asphalt cement, which is related to solubility, and the viscosity of the binder at the storage temperature, which is related to the rate of penetration and swell.

The Intermodal Surface Transportation Efficiency Act, passed by Congress in 1992, requires states to use an increasing percentage of rubber in the construction of asphalt concrete pavements over the next 5 years. Crumb rubber has been added to asphalt concrete mixtures since the mid 1950s by various processes with mixed results. The most used and better established method uses the rubber as a polymer modification of the asphalt cement (i.e., wet process). Although this process generally produces pavements that have good performance, the cost of the binder is increased from one to two times, making this process an economically difficult choice. It is more appealing economically to use the crumb rubber as an aggregate substitute (i.e., dry process) that is added during mixing, but existing patents and unreliable results have hindered its use.

On behalf of the Minnesota Department of Transportation, the University of Minnesota is conducting an evaluation of both asphalt-rubber interactions and asphalt-rubber mixtures using the dry process. Experimentation with pretreating the rubber to reduce its demand for key asphalt components is also being investigated. This paper will cover only the asphalt-rubber interaction evaluation; the mixture testing was scheduled to be completed in the spring of 1993.

BACKGROUND

Two methods have been used to add crumb rubber to asphalt concrete mixtures. The most common method is referred to

as the wet process and adds the rubber to the binder. With sufficient time and heat, a partially polymer modified asphalt cement is achieved as the rubber is slowly depolymerized (1,p.203). When the wet process is used, a high degree of interaction between the asphalt and the rubber is desired to accelerate the depolymerization of the rubber particles (1). The second method, the dry process, uses the rubber as an aggregate replacement. Although some reaction of the rubber with the asphalt occurs, the primary goal of this approach is to provide solid elastomeric inclusions within the asphalt-aggregate matrix. These inclusions are thought to provide more rebound to the mixture under traffic loading. When the dry process is used, a stable, long-term reaction with the rubber is important.

It is desirable for the asphalt used in the wet process to contain a relatively high percentage of light fractions. This is usually achieved by either adding an extender oil or selecting a lower-viscosity grade binder (2). Both have the added advantage of compensating for the increased viscosity when the rubber is added as well as providing sufficient aromatics for rubber reaction without removing key asphalt components. Little work has been done in identifying key asphalt properties for the dry process.

Key rubber properties for either process include the rubber gradation (i.e., particle size) and rubber type (3). Finer gradations provide a higher surface area and hence are more reactive with the asphalt (3). Passenger and industrial tires are each manufactured with different types of rubber. Passenger tires are primarily a combination of synthetic rubber and natural rubber. Industrial tires are primarily natural rubber. Previous research has suggested that industrial tires produce a more stable and desirable reaction (4). Until the past decade, passenger tires were generally 20 percent natural rubber and 26 percent synthetic, whereas industrial tires were around 33 percent natural and 20 percent synthetic. These percentages change with manufacturer, tire type, and technological advances (4).

One of the most commonly used measures of asphalt-rubber interactions is the Brookfield viscosity measured at various times after the rubber has been added to the asphalt cement. This instrument is a type of rotational viscometer that immerses a disk-shaped spindle into a large volume of asphalt-rubber cement. Huff reported that viscosity first exhibits a peak after a short time, then it decreases. He noted that the desired reaction time is that required to achieve the peak viscosity (5).

The test procedure for determining the viscosity of asphalt-rubber binders recommended by Heitzman (4) is ASTM D2994. This method uses a Brookfield viscometer and a 1-pint sample of material to determine the viscosity at 90, 105, and 120°C with a No. 4, No. 4, and No. 2 spindle, respectively, 60 sec

after starting the viscometer. Heitzman modified the ASTM methodology when he recommended requirements for asphalt-rubber binder grades by setting a minimum of 1,000 and a maximum of 4,000 centipoise at 175°C (347°F), a No. 3 spindle, and 12 rpms (4).

A significant amount of research during the past 25 years in the rubber industry has been devoted to defining the physics of rubber and oil interactions. The following sections have been developed from documented research conducted in the rubber technology field.

Swelling

Most high molecular weight polymers (i.e., rubbers) can show signs of increased volume (i.e., swelling) when immersed in low molecular liquids, to varying degrees (1). Polymers that are soluble in water are called hydrophilic. When they are soluble in organic solvents, they are called hydrophobic.

Swelling is a diffusing—not a chemical—process that results from the liquid moving into the internal matrix of the polymer. Strong cross-links between the rubber chains prevent the liquid from completely surrounding the chains and provide a structure that will limit the distortion of the particle. As swelling increases, there is a corresponding degeneration of the polymer properties.

Just after a polymer is immersed in a liquid, the surface of the rubber has a high liquid concentration. As time progresses the liquid moves into the interior portion of the rubber. This movement is controlled by the molecular compatibility of the rubber and liquid, the length of time the rubber is immersed, and the viscosity of the liquid.

Thermodynamics of Swelling

Gibb's free energy of dilution, ΔG_1 , is defined as the change in the system resulting from the transfer of 1-unit quantity of liquid from the liquid phase into a large quantity of the mixture phase (6). This free energy should be 0 for a constant pressure with respect to the transfer of liquid, that is, when swelling has reached equilibrium, $\Delta G_1 = 0$. The total free energy of the dilution can be written as

$$\Delta G_1 = \Delta H - T\Delta S_1$$

where ΔH is the change in heat content and ΔS is the change in entropy of the system caused by the transfer of 1 mole of liquid from the liquid phase to a large quantity of the mixture.

The heat term, ΔH , which is indicative of the absorption of heat during mixing, is relatively small and positive in a natural rubber-benzene solvent solution. The small ΔH is associated with the lack of strong intermolecular forces (i.e., chemical reaction) (6). The much larger increase in entropy typically seen in this solution, when compared with the heat of mixing, is consistent with diffusion processes.

Compatibility

Unvulcanized rubber will dissolve and vulcanized rubber will swell quickly in a compatible liquid (1). Compatibility is de-

termined by comparing the solubility parameters of the individual components:

$$\delta = (\text{cohesive energy density})^{1/2} = \frac{\Delta H - RT}{M/\rho}$$

where

Δ = latent heat of vaporization,

R = gas constant,

T = absolute temperature,

M = molecular weight, and

ρ = density.

When there is no specific chemical interaction, and in the absence of crystallization, the rubber and liquid are compatible if their solubility parameters are equal. The solubility parameter for rubbers ranges from 7.6 for butyl to 9.9 for nitrile rubbers; the values for most rubbers are in the upper (around 9.0) limit of this range (5). For example, swelling is generally high for most rubber (except butyl) when immersed in chloroform ($\delta = 9.3$) or benzene ($\delta = 9.2$) and poor in acetone ($\delta = 10.0$) except for nitrile (1). It is the chemical nature of the liquid that defines the amount of liquid that will be absorbed.

Diffusion

The movement of a liquid through the rubber (i.e., penetration) is defined by (1)

$$P = \frac{M_t}{C_o A \sqrt{t}} = \frac{l}{\sqrt{t}}$$

where

P = penetration rate,

M_t = mass of liquid absorbed,

A = surface area,

t = time,

C_o = concentration of liquid (g/cm³) in the surface of the rubber, and

l = depth of swollen layer.

The rate of penetration is related to the diffusion coefficient by

$$D = \frac{1}{4} \pi P^2$$

where D is the diffusion coefficient and P is the penetration rate.

The length of time for penetration increases with the square of the depth of penetration. For example, it takes four times as long for a given liquid to penetrate throughout a particle with a diameter of 0.50 cm as it will for one with a diameter of 0.25 cm (1). These relationships confirm previous observations that finer rubber reacts more quickly with a given asphalt cement than coarser rubber gradations. Although the chemical nature of the liquid determines the equilibrium swell value, the viscosity of the liquid determines the rate of swell. The rate of swell increases as the viscosity of the liquid decreases.

EXPERIMENTAL APPROACH

The objectives of the asphalt-rubber interaction portion of this study were to evaluate the following:

- Testing variability,
- Effect of increasing percentages and type of rubber on viscosity,
- Effect of pretreating rubber on asphalt-rubber interactions, and
- Key asphalt cement components that define a highly reactive and a nonreactive asphalt.

To accomplish the above objectives, three experimental designs were developed. The first experiment includes four percentages of rubber (0, 10, 15, and 20 percent by weight of asphalt cement), one rubber gradation, two rubber sources (passenger and industrial tires), and two asphalt cement grades (85/100 and 120/150 pen grades).

Tall oil pitch, a by-product of pulp processing, was identified as a rubber pretreatment and is similar in chemistry to the light fractions of the asphalt. Tall oil pitch is currently used in asphalt-compatible areas such as rubber reclaiming tackifiers, limed pitch for asphalt tile, roofing compounds, oil well drilling fluid additives, and the manufacturing process for neoprene. Four levels of rubber pretreatment (0, 2, 5, and 10 percent of tall oil pitch by weight of rubber) were added to the variables in the first experiment, and the percentages of rubber were reduced to one level (20 percent) after a review of the results from the first experiment.

The third experiment required a wide range of asphalt cement chemistry to attempt to identify key asphalt components in the asphalt-rubber interactions. Four of the Strategic Highway Research Program (SHRP) materials reference library (MRL) asphalts were obtained for this purpose (7). The experimental design included the four asphalts, one percentage of rubber (20 percent), both rubber types, and two levels of pretreatment (0 and 5 percent tall oil pitch by weight of rubber).

MATERIALS

Binders

Two locally available binders, 85/100 and 120/150 penetration grade, were used for the first two experimental designs and were obtained from the Koch refinery in Inver Grove Heights, Minnesota. The physical properties of both asphalt cements are shown in Table 1.

The SHRP asphalt cements represent two performance pairs, AAD/AAG and AAF/AAM. The AAD and AAG are both AR-4000 grade binders from California Coastal and California Valley crude sources, respectively (8). Field performance notes indicate the AAD is susceptible to age hardening. The AAG had the crude treated with lime before distillation, its performance exhibits rutting and tenderness problems, and it tends to be temperature susceptible. The AAF and AAM are AC-20s from West Texas Sour and West Texas Intermediate Asphalt crude sources, respectively. Performance notes on the AAF binder indicate that it makes a moisture-sensitive mix, ages quickly, and, whereas it is a very aromatic asphalt with good polymer compatibility, it is not generally a well-performing asphalt. The AAM has a high molecular weight neutral phase with low temperature susceptibility and generally is a good performer. Selected physical properties reported by the SHRP MRL are shown in Table 1 (J. S. Moulthrop to R. Robertson, personal communication, 1990).

Rubber

Both the passenger and industrial tire crumb rubber (ambiently ground) were obtained from the Whirl Air, Inc. (Bab-bit, Minnesota) processing plant. The gradation consisted of 100 percent of the rubber particles passing the 2.38-mm (No. 8) sieve and 51, 19, 5, and <1 percent passing the 1.12-, 0.50-, 0.30-, and 0.15-mm (No. 16, 30, 50, and 100) sieves, respectively.

TABLE 1 Asphalt Cement Properties

Properties	Koch		AAD	AAG	AAF	AAM
Grade	120/150 Pen	85/100 Pen	AR 4000	AR 4000	AC 20	AC 20
Crude Source	Unknown	Unknown	California Coastal	California Valley	West Texas Sour	West Texas Intermed.
Viscosities: 60°C, Poise 135°C, cSt	908 259	1,588 362	1,055 309	1,862 243	1,872 327	1,992 569
Penetration, 0.1mm 25°C, 100g/5 sec	94	132	135	53	55	64
Component Analysis, % Asphaltenes (n-heptane) Asphaltenes (iso-octane) Polar Aromatics Naphthene Aromatics Saturates	Not Available	Not Available	23.0 3.4 41.3 25.1 8.6	5.8 3.3 51.2 32.5 8.5	14.1 3.1 38.3 37.7 9.6	3.9 NR 50.3 41.9 1.9

NR: Not reported

Tall Oil Pitch

Tall oil pitch was selected as a pretreatment for the rubber on the basis of its past history of use in asphalt-related industries, compatibility with the lighter fractions of the asphalt cement, and economic considerations. Tall oil pitch (DP-3) was provided by Union Camp Corporation of Jacksonville, Florida. Table 2 presents the properties reported by the supplier.

Rubber was pretreated by adding the required weight of tall oil pitch (percent by weight of rubber) to the bottom of a large, flat, stainless steel pan and then heating at 135°C (275°F) for 5 min. Crumb rubber was then added on top of the pitch and stirred until none of the pitch remained on the bottom of the pan. Occasionally, this required returning the pan (with rubber and pitch) to the oven for a few minutes and repeating the stirring process. Pretreated rubber was prepared at least 24 hr before use; it was stored in sealed plastic bags until used.

The percentages of tall oil pitch used in this study were selected on the basis of conversations with Whirlair, Inc., a firm that uses this product in the manufacture of rubber mats, and a modification of the aggregate test method for determining specific gravity of fines (ASTM C128). Briefly, batches of pretreated rubber were prepared with various percentages of tall oil pitch, and the material was poured into the cone and tamped. The optimum tall oil pitch pretreatment was defined as the percent at which the material just holds its shape. For the passenger tires, optimum was 5 percent. The 2 and 10 percentages were selected to represent values on both sides of the optimum. The same percent of tall oil pitch was used with the industrial tires so that the level of pretreatment would be consistent throughout the study.

TESTING

Test Methodology

Preliminary experimentation with the Brookfield viscometer identified several procedural problems with Heitzman's recommendations. First, the Brookfield model recommended by the manufacturer for testing asphalt cements is a model

HATDV, not an LVT as specified in ASTM D2994. The HATDV has preset choices of rotational speeds of 0.5, 1, 2.5, 5, 10, 20, 50, and 100 rpm; the specified 12 rpm was not available. Second, a single size spindle could not be used for all materials. Changing spindles was necessary to follow the manufacturer's recommendation for the percent of torque applied for a given spindle. This resulted in the use of a No. 1 spindle for the neat asphalt cements, and a No. 2, No. 3, and No. 4 spindle for the 10, 15, and 20 percent asphalt-rubber binders, respectively.

Temperature control was also a problem. No hot oil bath capable of reaching 175°C was available, so the use of various hot plates, heating mantles, and ovens was evaluated for maintaining test temperature. Temperature fluctuations occurred with all heating systems. At this point, advice from industry was sought. Conversations with various laboratory personnel involved with the manufacturing of asphalt-rubber binders resulted in the following testing procedures.

Procedure

The neat asphalt cements were heated in a 200°C (392°F) oven for 4 hr, approximately 400 g of asphalt was transferred to a 600-mL beaker, and the rubber was added and then thoroughly stirred. The tin foil-covered beaker was then returned to a 185°C (365°F) oven. Before testing, the beaker of asphalt-rubber was removed from the oven and stirred vigorously for 30 sec. The viscometer was set at 100 rpm and the spindle was lowered into the fluid for 1 min to allow the spindle to reach the test temperature. The viscometer motor was then stopped and the fluid was stirred briefly. The test was started at the 10 rpm speed and the first reading was taken at 10 sec. The rotational velocities were then increased incrementally to 20, 50, and 100 rpm; readings were taken 10 sec after each speed change. Viscosity and binder temperature were then determined at intervals of 0.5, 1, 1.5, 2, and 3 hr; a 24-hr measurement included in the first experiment was eliminated in subsequent testing because of time constraints.

Figure 1 shows typical trends seen throughout the testing; there is a slight tendency toward thixotropy at the higher rubber percentages. This is seen as a lower viscosity measured after the speed has been increased to 100 rpm and is then

TABLE 2 Tall Oil Properties

Property	Properties
Composition, %:	
Fatty Acids And Esterified Acids	46
Rosin Acids	20
Unsaponifiables	34
Acid Number	101
Saponification Number	0.6
Specific Gravity	1.03
Viscosities:	
60°C, cSt	3732
99°C, cSt	260
135°C, cSt	59
Flash Point, °C	216

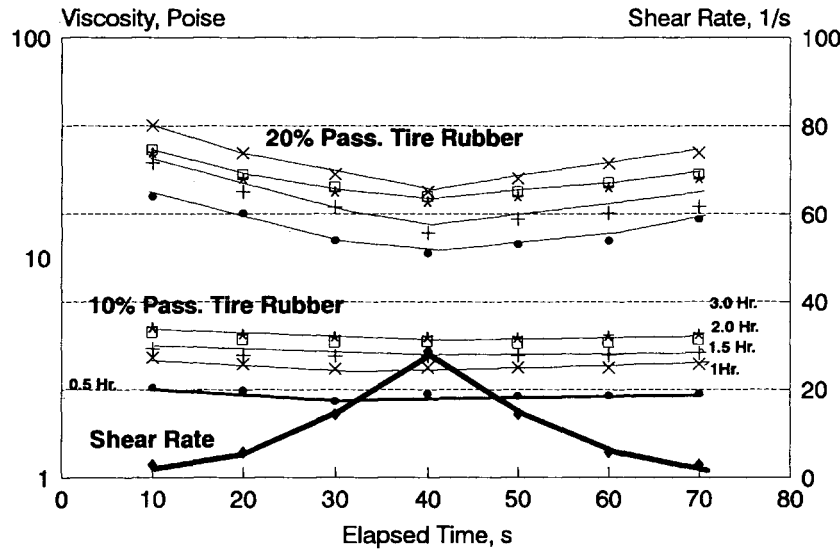


FIGURE 1 Investigation of thixotropy for modified binders.

decreased back to 10 rpm. Because of this phenomenon, the order and time between each shear rate change will influence the results obtained from this test (8). On the basis of these results, strict stirring and test times were used to obtain the data presented in this paper.

RESULTS AND DISCUSSION

Non-Newtonian Behavior

Figure 2 shows that the slope (i.e., flow index) of the shear stress to shear strain relationship becomes slightly flatter as the concentration of rubber is increased. The addition of rubber decreases the flow index from 1 for the control, to 0.95 for 10 percent, and to 0.65 for 20 percent passenger tire rubber [120/150 pen asphalt cement (3 hr)]. The flow index for a

given percentage and type of crumb rubber remained constant, regardless of storage time.

Testing Variability

Testing variability was a concern because of both the temperature drift noticed during testing and modifications to the ASTM D2994 method. Table 3 presents results obtained for replicate tests of 85/100 asphalt modified with 10, 15, and 20 percent of either passenger or industrial tire rubber. These results were obtained at least 2 months apart and represent both testing and material variability as a new sample of binder was obtained for the replicate. This table shows that the standard deviation appears to be magnitude dependent; a higher viscosity corresponds to a higher standard deviation. When this is the case, the coefficient of variation (CV) is used to

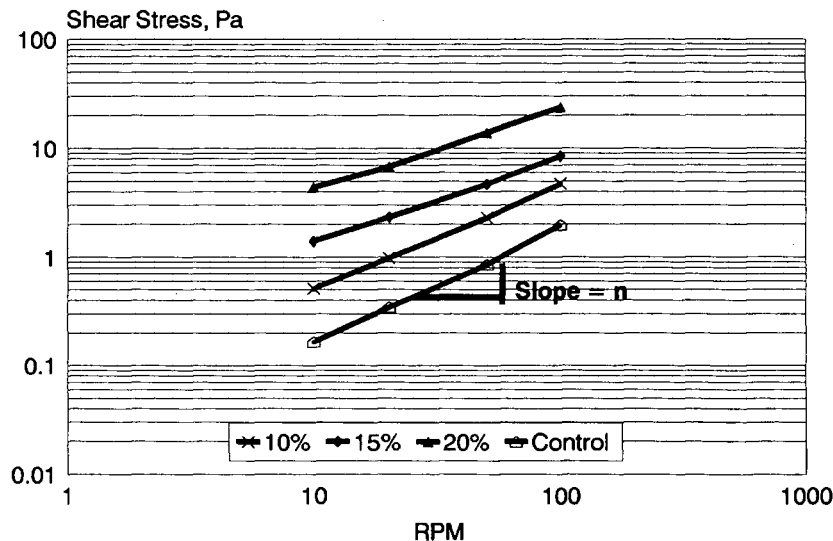


FIGURE 2 Definition of flow index.

TABLE 3 Estimate of Test Variability

Variable	Standard Deviation	Coefficient of Variation
Passenger Tires		
10%	0.352	11.27
15%	0.628	10.96
20%	1.50	9.02
Industrial Tires		
10%	0.338	12.58
15%	0.80	15.00
20%	1.64	15.95

express the test variability. The CV for the passenger and industrial tire mixtures are approximately 10 and 15 percent, respectively. These CVs compare favorably (considering the limited data base) with the standard vacuum viscosity measurements (ASTM D2171), with CVs of 7 and 10 percent for within- and between-laboratory results, respectively. On the basis of this evaluation of the test method, the modified testing procedure was adopted for the remainder of the study.

Effect of Concentration, Binder Grade, and Type of Rubber

Figure 3 shows that the viscosity increases with increasing percentage of crumb rubber, regardless of rubber type. Passenger tire crumb rubber produces a larger increase in viscosity for a given grade of binder and percentage of rubber than does the industrial tire rubber. Although these trends are consistent for both types of rubber, the magnitudes of the industrial tire-modified viscosities are consistently lower than those for the passenger tires. On the basis of the general

concept of greater compatibility being represented by increased viscosities, it would at first appear that passenger tires are more compatible with asphalt cements. However, it is most likely that the industrial tires with their higher percentage of natural rubbers have a greater tendency to dissolve, rather than swell, in asphalt cements. This would result in a more uniform, more quickly formed polymer network. It is acknowledged that this assumption should be evaluated using a more fundamental rheological approach such as parallel plate rheometry, but this work is beyond the scope of the current research program.

Effect of Aging on Viscosity

To evaluate the influence of storage time at elevated temperature on viscosity, a ratio of either the 24- or the 3-hr viscosity to the initial 30-min viscosity was calculated; all measurements were taken at the 50-rpm speed. This ratio will be referred to as an aging index and is a function of the heat hardening of the neat binder, chemistry changes in the neat

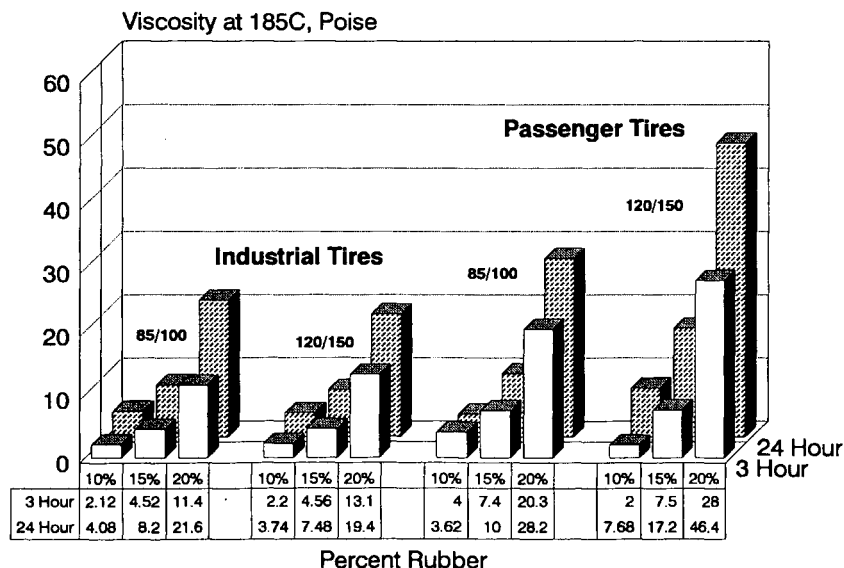


FIGURE 3 Influence of percent rubber, rubber type, and AC grade.

binder as the light ends are absorbed by the rubber, rubber swell, and the introduction of carbon black from the rubber into the mixture as the rubber structure is expanded. The plasticizers and softening agents (e.g., extender oils) used in the manufacture of rubber could also be a factor.

Figure 4 compares the aging indexes calculated for both the 3- and 24-hr test results. There is a general trend of increased aging as the percent of rubber is increased for the 3-hr index. The 24-hr aging indexes show a similar trend for the 85/100 pen asphalt binders. However, the 120/150 pen 24-hr indexes are uniform and higher than any of those seen for the 85/100 pen binders. This again agrees with the information presented in the background section: lower viscosities mean fast penetration, which in turn means faster swelling.

A comparison of the rubber types shows that the industrial tire binders have consistently lower aging indexes than passenger tire-modified binders. This difference is most evident when comparing the industrial tire aging indexes (<2.5) for 20 percent rubber and the 120/150 asphalt to the passenger tire-modified binders (>3.5). Again, this is most likely a result of the dissolution of industrial tires rather than swelling. This theory cannot be confirmed within the scope of this research but is offered as a probable hypothesis.

Effect of Pretreatment on Asphalt-Rubber Interactions

The reason for the pretreatment of the rubber was to inhibit or block the penetration of the asphalt cement components into the rubber. If the pretreatment was successful, this should be seen as a reduction in the viscosity increase. Even assuming that the tall oil could contaminate the asphalt cement, the viscosities of both the neat binder and the tall oil are less than 1 poise at the test temperature of 185°C; no discernable changes would be observed.

Figure 5 shows a general trend of decreasing viscosities with increasing percent of tall oil pitch pretreatment. The exception to this trend is a slight increase in viscosities for the 2 percent tall oil pitch pretreatment. This could indicate that low percentages of pretreatment (below optimum) help increase the asphalt-rubber interactions for either type of rubber. Viscosities are still consistently higher for the 120/150 pen asphalt when compared with the 85/100 pen asphalt binder; this agrees with trends seen in the previous section. Industrial tires still produce consistently lower viscosity binders than those prepared with passenger tire rubber.

In summary, these results indicate that penetrating either source of rubber with at least 5 percent of tall oil pitch would reduce the interactions between rubber and either grade of binder.

Effect of Asphalt Chemistry on Compatibility

Figure 6 shows that the AAD, AAG, and the AAF asphalt-rubber binders produce similar viscosities after 3 hr of aging (50 rpm) for a given type of rubber. This trend is also seen when either rubber is pretreated with 5 percent tall oil. The AAM asphalt-rubber binder viscosities are less than half of any of the other rubber-modified binders. Industrial rubber-modified binders produce consistently lower viscosities; again the AAM-modified asphalts produce viscosities less than half of the other modified binders. Pretreatment of either rubber with 5 percent tall oil consistently reduces the viscosities by about 8 percent of the nonpretreated rubber binders, again with the exception of AAM.

Figure 7 shows that although the viscosities for the AAD, AAG, and AAF are virtually identical at 3 hr, there are significant differences after extended aging. The AAG showed the greatest increase in viscosity followed by the AAF, AAD,

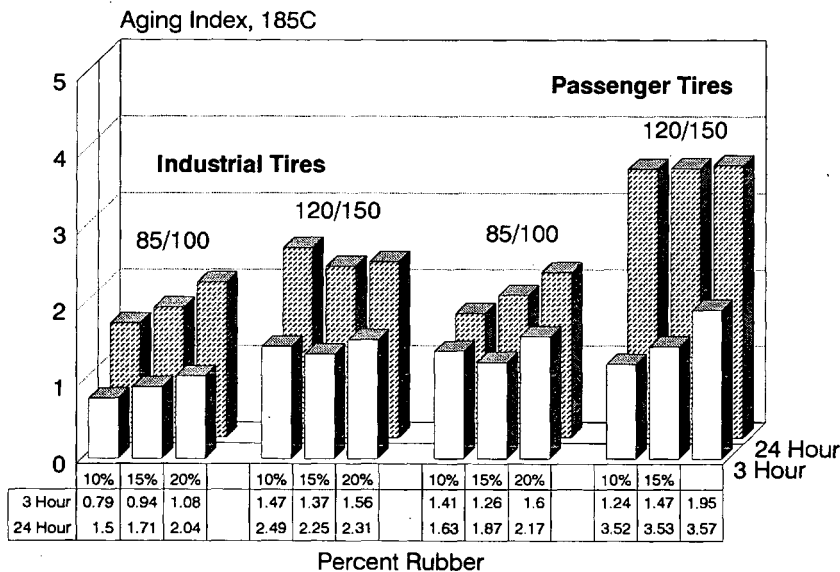


FIGURE 4 Influence of percent of industrial tire rubber.

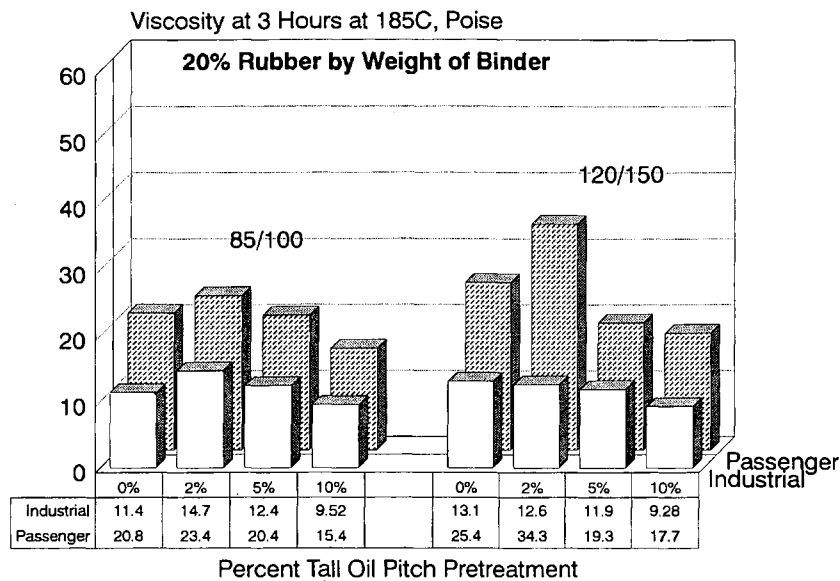


FIGURE 5 Changes in 3-hr viscosity with pretreatment of both passenger and industrial tire rubber.

and AAM. If the compatibility of AAD, AAG, and AAF with the rubber is assumed to be constant, the differences in the rate of viscosity increase should be caused by the rate of penetration and, hence, the viscosity of the binder. The viscosities of the neat binders at 185°C are 0.67, 0.88, and 0.84 poise for AAG, AAF, and AAD, respectively. These viscosities agree very well with the increased viscosities after aging. In addition, the viscosity of the neat AAM binder is 1.27 poise at 185°C; not only does the rubber appear to be

less soluble in this binder, but any solubility is impeded by the much higher viscosity at the aging temperature. Again, the pretreatment of the rubber inhibits the compatibility of the rubber and binders.

Because solubility is a function of molecular weight, there should be a relationship between the molecular weight (Table 1) of the binders and their compatibility with rubber. Figure 8 shows that as molecular weight increases, the compatibility decreases. The 11-poise viscosities for the AAM binder cor-

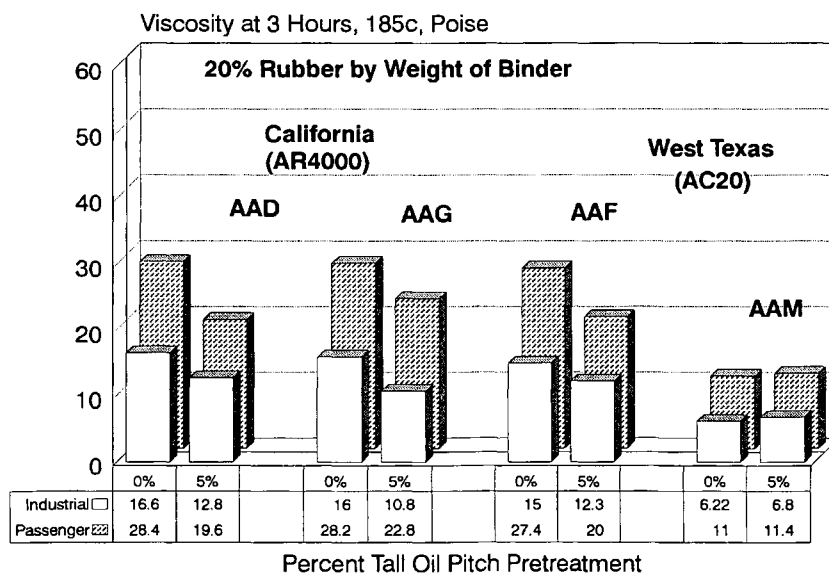


FIGURE 6 Changes in 3-hr viscosity with changes in crude source and pretreatment of rubber (SHRP asphalts).

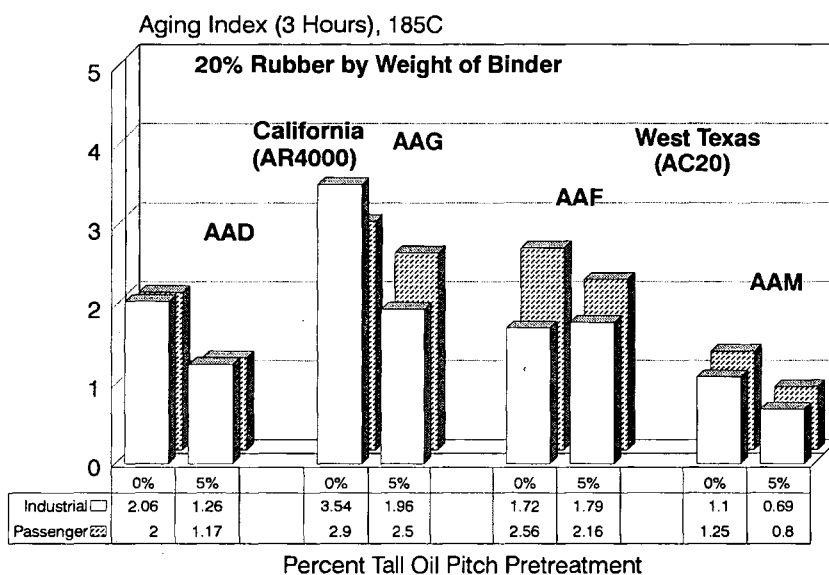


FIGURE 7 Changes in 3-hr aging index with changes in crude source and pretreatment of rubber (SHRP asphalts).

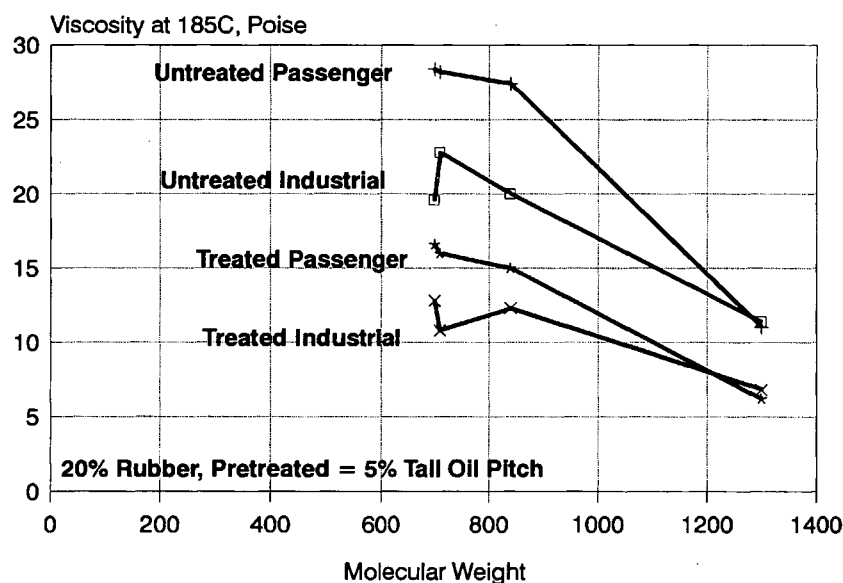


FIGURE 8 Relationship between molecular weight and viscosity of modified binders.

respond to a molecular weight of about 1,300. Molecular weights of less than 850 produce high viscosities for asphalts modified with 20 percent rubber. When the rubber is pretreated, the influence of asphalt cement molecular weight is decreased.

CONCLUSIONS

The following conclusions can be drawn from the data presented in this paper.

- Modifications to ASTM D2994 were necessary to use this test method with a wide range of asphalt-rubber binders.

Modifications include specific material handling procedures, shear rate sweeps at higher rotational speeds, and use of various-sized spindles.

- Asphalt-rubber binders prepared with industrial tires have viscosities that are more variable than binders prepared with passenger tire rubber. The coefficients of variation for this study were 10 and 15 percent for passenger and industrial tire-modified binders, respectively.

- Viscosities increase with increasing concentrations of rubber, regardless of the type of rubber.

- Non-Newtonian behavior of asphalt-rubber binders increases with increasing concentrations of rubber.

- A lower-viscosity neat asphalt increases the reaction of the rubber with the asphalt cement compared with a higher-viscosity asphalt from the same refinery.

- Industrial tire-modified binders consistently show less of a viscosity increase than passenger tire rubber. This is possibly because of the dissolution of the industrial tire rubber rather than its swelling in asphalt cements. Further, more fundamental work (i.e., parallel plate rheology) is needed to confirm this hypothesis.

- Pretreatment of rubber with tall oil pitch reduces the compatibility of the rubber and asphalt cement. The reduction in compatibility increases with increasing levels of pretreatment. A corresponding decrease in aging is seen.

- The asphalt-rubber interactions are a function of the molecular weight of the asphalt cement. Lower molecular weight cements are more interactive with crumb rubber.

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