USE OF DEVULCANIZED TIRE RUBBER/PLASTIC MODIFIED ASPHALT CEMENT IN HOT-MIX ASPHALT

FINAL REPORT FOR PHASE I

Submitted to

Ben Franklin Technology Center of Southeastern Pennsylvania

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Submitted to
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by
Hussain U. Bahia
and
Robert M. Davies

Pennsylvania Transportation Institute
The Pennsylvania State University
Research Office Building
University Park, PA 16802-4710

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EXECUTIVE SUMMARY

In this study, the effects of the crumb rubber modifiers (CRM’s) manufactured by different processes on the performance-related properties of selected asphalt cement binders were evaluated. The study focused on crumb rubbers manufactured by three different processes from whole passenger tires with a maximum particle size of 1.00 mm. Four asphalts that vary significantly in their physical and chemical properties and that are used widely in the United States and Canada were included in the study. The properties measured included the performance-related properties selected by the recently completed Strategic Highway Research Program (SHRP). The properties included the rheological, failure, and aging properties that reflect the contribution of asphalt binder to resistance to the major distress modes of asphaltic pavements. The response variables were measured at different combinations of asphalt source, rubber type, and test temperature.

The main objective of the study was to evaluate the crumb-rubber-based composite manufactured by Tyreplex Corporation and to assess its value as a modifier for paving-grade asphalt cements. To achieve this objective, state-of-the-art technology developed recently by SHRP for characterization of asphalt cements was used. Also, the effects of the Tyreplex composite on the properties of selected asphalt were compared to the effects of other crumb rubber modifiers currently used.

The study included several phases designed to quantify the effects of different factors on the changes that the CRM will impart on asphalt cements; to study the storage stability of the crumb rubber modified binders and identify differences in stability of properties of the different binders; and to quantify the effect of crumb rubber content on the change in important properties.

The analysis of the results indicates that the crumb-rubber-based composite produced by Tyreplex can be used to enhance certain asphalt cement properties for better resistance to critical pavement distress. The composite results in effects that are comparable to other crumb rubber modifiers commonly used as asphalt modifiers. The product is found to retain its initial effects on asphalts and does not change when stored at high temperatures. This
stability of effects is a property that is important for paving applications. The stability of the Tyreplex product is unique when compared to the stability of the effects of other CRM products included in this study.
CHAPTER 1
BACKGROUND

1.1 Introduction

Crumb rubber is derived from used vehicular tires after removing the fiber and steel and producing a particulate material by shredding or grinding. Crumb rubber has been used for a wide variety of industrial applications (1). In the early 1960’s, pavement engineers in the United States started experimenting with the use of crumb rubber as a modifier to asphalt cement used in pavement applications (2). Different approaches were used to incorporate crumb rubber modifier (CRM) in road-paving materials. In general, these approaches are at the present time classified as the dry method and the wet method (3). The wet method involves dispersing the CRM particles into the asphalt cement to produce what is called asphalt rubber (AR), which in turn is used to produce hot-mix asphalt concrete. The dry process involves mixing the CRM with the aggregate before introducing the asphalt cement to the mixture.

Although the use of asphalt rubbers for paving applications is not new, and although there are now a number of paving contractors specialized in AR, only a few studies have been reported on how these binders differ from unmodified binders in general and how the rubber particles change the properties of the base asphalt cements used in their production (4,5,6). Furthermore, these few reports were for the most part based on conventional types of binder testing with limited scopes. The asphalt rubber industry is now expanding, in particular following the mandate of recycling used tires included in the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. The mandate in many ways created a significant dispute about the usefulness of using CRM in asphalt pavements, about whether there are enough data to support the technical soundness of the mandate, and about what is the most efficient approach to satisfy the mandate.
The one point upon which all parties involved are in agreement is the fact that scientific research on the effect of CRM on asphalt binder properties is sparse, and that there are no established procedures for the successful use of CRM in the asphalt pavement industry. This fact has resulted in a confusion on the part of the pavement industry and state agencies as to what type of CRM to use, how to use it, how to construct it, and whether or not the added cost is justified. In November of 1990, there were more than 30 producers of CRM, and the number since then is increasing rapidly. Production of CRM can vary significantly and result in CRM that will affect the asphalt binder or mixtures in vastly different manners. The few studies reported about CRM have already shown that the method by which CRM is produced has significant consequences on the properties of asphalt rubbers. There are now emerging technologies by which CRM properties can be altered or customized to meet application-specific requirements. There are also additives that can be used with CRM asphalts to further improve their performance.

This report summarizes the result of a research project that was initiated to assist the Tyreplex corporation of Pennsylvania to develop a specialized crumb rubber product that can be used effectively as an asphalt modifier. Tyreplex corporation uses a novel process to produce crumb rubber particles from wasted vehicular tires, commingled wasted plastics, and a compatilizer. The report includes five chapters and covers the results of a detailed experimental plan to evaluate the effects of CRM produced by Tyreplex corporation on rheological, failure, and aging characteristics of a set of selected asphalts that are commonly used in the United States. The report also includes a comparison of the effects of Tyreplex product with other crumb rubbers commonly used as asphalt modifiers.

This research study has been funded by a grant from The Ben Franklin Technology Center, Tyreplex corporation, and the Pennsylvania State University. The study started in January 1993 and was completed in January 1994. The project was renewed in 1994 to enter a second phase that will take the laboratory results into a full-scale field experiment to validate the results and further develop guidelines for use in paving applications.
1.1.1 Importance of the Highway Paving Market

In the United States in 1990, there was a total of approximately 4 million miles of roads; 2.4 million of these were paved with asphalt or concrete. The rest were surfaced with gravel, stone, or soil (1.3 million miles). A lesser amount were unsurfaced (0.4 million miles). Of the 2.4 million paved miles, 96 percent (almost 2.2 million miles) had asphalt surfaces. More than 95 percent of the 2.2 trillion annual vehicle-miles of travel occurred on the paved surface roads.

The amount of HMA produced and placed in the United States has been estimated at more than 500 million tons annually for the past few years. It is valued at approximately $10.5 billion. Our nation’s highway expenditures were estimated at $35 billion in capital expenditures and $20 billion in maintenance expenditures for 1990. Although capital expenditures have decreased by approximately 1.7 percent (in terms of constant dollars) compared to 1970, our maintenance expenditures have increased by approximately 5.5 percent in constant 1970 dollars. Highway trust fund authorizations, as indicated by the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 for fiscal year 1994, include $1.8 billion in new interstate construction, $2.9 billion in interstate maintenance, and $1.3 billion in demonstration projects, research programs, and other studies. Annual travel on the nation’s highways grew about 54 percent during the 1960’s, another 38 percent in the 1970’s, and another 41 percent in 1980’s. Highway travel by Americans, expressed as vehicle-miles of travel per capita (VMT), reached 8,560 miles, which far exceeds highway travel by citizens of other major countries like Japan (3,021 VMT), Germany (4,474 VMT), the United Kingdom (6,934 VMT), and France (4,659 VMT).

The above numbers demonstrate the importance of the asphalt industry and its vital role in our nation’s well being. The challenge to this significant sector of the construction materials industry is to provide long-lasting material that contributes to superior performing pavements. The engineering community, during the past 40 years, has managed to define the critical needs for the achievements of this objective. The distress and failure mechanisms of pavements are fairly well understood by pavement engineers. The design and quality control requirements of paving materials have been well researched during the last decade and have
entered into implementation stages in many areas. Research has shown that asphalt modifiers can be effectively used to produce superior paving materials that combine low cost and better performance. Asphalts modified with crumb rubbers have been used successfully in many areas of this country. Contractors specialized in asphalt rubbers have been the first to offer warranties on performance of their products in the paving industry.

1.1.2 Asphalt Production and Modification

To understand the need for asphalt modifiers, and the market potential for such modifiers, an understanding of the process by which asphalts are produced is necessary. The main source of asphalt for paving applications is crude petroleum of the type with a high specific gravity. Depending on the type of refining process and the source of crude, the asphalt yield from crude petroleums can vary between 10 to 60 percent. The chemical constitution of an asphalt and, in consequence, its properties are largely decided by crude origin, although some modification of these properties can be achieved by refinery processing.

Asphalt production, however, is not one of the main profit generation processes in the refining industry. Most refineries in the U.S. deal with asphalt as a by-product of crude fractionating. Production of better performing asphalts is not considered as one of the common strategies in the planning of refining practices. Throughout the years, these facts have left pavement engineers with the challenge of selecting suitable asphalt for their specific application conditions, which include climate, traffic, and pavement structure. When, as in many instances, the produced asphalt does not perform, modification of the asphalt using additives has served as one of the cost-effective engineering solutions. Modification of asphalts has increased steadily within the last decade because it provides the versatility of the properties needed to build better performing roads. Asphalt modification is expected to continue increasing in the future because of the economical barriers involved with improving asphalts through refining processes, and because of the logistical difficulties of using crudes that naturally produce better performing asphalts.
1.1.3 The Visco Elastic Nature of Asphalt Binders

The successful modification of asphalt binders, using crumb rubbers or other modifiers, should start by a good understanding of the properties of the base asphalt binders. Asphalt binders are viscoelastic materials with a mechanical response that is highly sensitive to temperature and the time of loading. At any combination of time and temperature, viscoelastic behavior within the linear range has to be characterized by at least two properties: the total resistance to deformation and the relative distribution of that resistance between an elastic part and a viscous part. Although there are many methods of characterizing viscoelastic properties, dynamic (oscillatory) testing is the best technique that can represent the uniqueness of the behavior of this class of materials. In the shear loading mode, the complex modulus \(G''\) and the phase angle \(\delta\) are measured. \(G''\) represents the total resistance to deformation under load, while the \(\delta\) represents the relative distribution of this total response between an in-phase component and an out-of-phase component. The in-phase component is an elastic component and can be related directly to energy stored in the sample for every loading cycle, while the out-of-phase component represents the viscous component and can be related directly to energy lost, per cycle, in permanent flow, or damage. The relative distribution of these components is a function of composition of the material, loading time or frequency, and temperature.

Rheological properties can be represented either by the variation of \(G''\) and \(\delta\) as a function of frequency at a constant temperature (commonly referred to as a master curve) or by the variation of \(G''\) and \(\delta\) with temperature at a selected frequency or loading time, commonly called isochronal curve. Although time and temperature dependency can be related using a temperature-frequency shift function, for practical purposes it is much easier to present data with respect to one of the variables. Figure 1.1 depicts typical rheological properties of an AC-40 and an AC-5 asphalt binder at a wide range of temperatures and frequencies. Figure 1.1a is a master curve at 25 °C, and figure 1.1b is an isochronal curve at 10 rad/s.

There are some common characteristics of the rheological behavior of asphalts that can be seen in the typical plots of figure 1.1:
Figure 1.1. Typical rheological master curves of asphalt binders. 
(a) frequency effects at 25 °C, and (b) temperature effects at 10 rad/s.
• At low temperatures or high frequencies, both asphalts tend to approach a limiting value of $G'$ of approximately 1.0 GPa and a limiting value of $\delta$ of 0.0 degrees. The 1.0 GPa reflects the rigidity of the carbon hydrogen bonds as the asphalts reach their minimum thermodynamic equilibrium volume. The 0.0 value of $\delta$ represents the completely elastic nature of the asphalts at these temperatures.

• As the temperature increases or as the frequency decreases, $G'$ decreases continuously while $\delta$ increases continuously. The first reflects a decrease in resistance to deformation (softening), while the second reflects a decrease in elasticity or stored energy. The rate of change is, however, dependent on the composition of the asphalt. Some will show a very rapid decline with temperature or frequency; others will show gradual change. Asphalts within this range may show significantly different combinations of $G'$ and $\delta$.

• At high temperatures, the $\delta$ values approach 90° for all asphalts, which reflect the approach to complete viscous behavior or complete dissipation of energy in viscous flow. The $G'$ values, however, vary significantly, reflecting the different consistency properties (viscosity) of the asphalts.

From the above description of asphalt properties, it is clear that without the distinction between types of asphalt response in terms of total resistance to deformation ($G'$) and relative elasticity ($\delta$), and without measuring properties at the temperature or loading frequency ranges that correspond to pavement climatic and loading conditions, selection of asphalt binders for better performing pavements is not possible.

1.1.4 Asphalt Properties and Pavement Performance

Figure 1.2 is an isochronal plot that depicts rheological properties of both an asphalt in its unaged condition and one after aging in the field, under a moderate climate, for approximately 16 years. To relate to pavement performance, the plot can be divided into four temperature zones. At temperatures above 100 °C, mixing and construction take place and, thus, the binder consistency needs to be controlled. At temperatures above 100 °C, most asphalt binders behave like Newtonian fluids whose response is totally viscous.
Figure 1.2. Main pavement distress modes as related to rheological properties of binders before and after field aging.
Therefore, a measure of viscosity is sufficient to represent the workability of the asphalt during mixing and construction of Hot Mix Asphalt (HMA).

At temperatures in the range of 45 °C to 85 °C, typical of highest pavement in-service temperatures, the main distress mechanism is rutting, and, therefore, the $G'$ and $\delta$ need to be measured. A measure of viscosity alone cannot be sufficient since viscosity measurements are done on the assumption that asphalt response has only a viscous component. For rutting resistance, a high $G'$ value is favorable because it represents higher total resistance to deformation. A lower $\delta$ is favorable because it reflects a more elastic (recoverable) component of the total deformation.

Within the intermediate temperature zone, asphalts are generally harder and more elastic than at higher temperatures. The prevailing failure mode at these temperatures is fatigue damage, which is caused by repeated cycles of loading at levels lower than the static strength of a material. For visco elastic materials, like asphalt binders, both $G'$ and $\delta$ play a role in damage caused by fatigue. They are both important because during every cycle of loading, the damage is dependent on how much strain or stress is developed by the cyclic load and how much of that deformation can be recovered or dissipated. A softer and more elastic material will be more favorable to resist fatigue damage, because the stress developed for a given deformation is lower and the asphalt will be more capable to recover to its pre-loading condition. Similar to rutting, a single measure of hardness or viscosity cannot be sufficient to select better performing asphalts with respect to fatigue resistance. Rutting and fatigue damage are both functions of the frequency of loading, and, therefore, the rate of loading of pavement under traffic needs to be simulated in measurement to get a reliable estimate of binder contribution to pavement performance.

The fourth and last temperature area is the low-temperature zone at which thermal cracking is the prevailing failure mode. Thermal cracking results from thermal stresses generated by pavement shrinkage as a result of thermal cooling. During thermal cooling, asphalt stiffness increases continuously and thus results in higher stresses for a given shrinkage strain. Simultaneously, thermal stresses relax due to the visco elastic flow of the binder. To reliably predict binder contribution to cracking, both the stiffness of a binder and its rate of relaxation need to be evaluated. The stiffness of the binder is directly proportional
to $G'$, and the rate of relaxation is directly related to $\delta$. A lower stiffness and higher rate of relaxation is favorable for resistance to thermal cracking. As with other temperature zones, a single measure of the stiffness or viscosity of the binder is not sufficient to select better binders that will resist cracking at the lowest pavement temperatures.

The above discussion of the relation between asphalt binder properties and pavement performance is further complicated by the aging phenomenon. Asphalts are hydrocarbon materials that oxidize when in contact with oxygen from the environment. This oxidation process changes the rheological and failure properties of the asphalt. As shown in figure 1.2, the rheological master curve becomes flatter with aging, which indicates higher $G'$ values and smaller $\delta$ values at all temperatures. These changes translate in less sensitivity of $G'$ and $\delta$ to temperatures or loading frequency and a more elastic component (lower $\delta$). Significant oxidation effects usually appear after considerable service life. Increased $G'$ values and lower $\delta$ values are favorable changes with respect to rutting performance, but they are unfavorable for thermal cracking performance. For fatigue cracking, the increase in $G'$ is not favorable, while the decreased $\delta$ is mostly favorable, depending on the type of pavement and mode of fatigue damage.

1.1.5 SHRP New Proposed Measures and Specification for Binders

The properties that are proposed for the new SHRP binder specification were derived and selected by addressing each type of pavement failure, understanding the failure mechanism, understanding the contribution of the binder to resistance of that failure, and selecting the required measure that will best reflect that contribution of the binder. The new binder specification is based on climatic conditions; the criteria that a binder has to meet does not change, but the temperature at which the property is measured depends on the specific field climate and on the failure mode being considered.

Three failure modes were identified as critical pavement distress modes in which the binder plays an important role: rutting, fatigue cracking, and thermal cracking. Oxidative aging and physical hardening were considered as durability factors that result in changes in
the properties of binders and, thus, affect performance. Four types of tests were selected (see figure 1.3):

- The rotational viscometer to measure flow properties at temperatures that mimic temperatures at which pumping and mixing of binders takes place.
- The dynamic shear rheometer to measure properties at temperatures that mimic high and intermediate pavement temperatures and to mimic loading rates typical of traffic loadings.
- The bending beam rheometer test to measure properties at lowest pavement temperatures and to mimic loading conditions that result from thermal cooling.
- The direct tension test to measure failure properties at lowest pavement temperatures and to mimic loading that results from thermal cooling.

To simulate aging, the Rolling Thin Film Oven (RTFO) was selected to simulate aging that occurs during the mixing, transport, and construction of pavements. To simulate long-term oxidative aging that occurs during the service life of pavements, the Pressure Aging Vessel (PAV) was introduced by SHRP. The PAV is expected to simulate aging of binders in pavements after 8 to 12 years of service at different field temperatures.

The test methods are used to measure properties and grade asphalts according to a standard specification system as shown in figure 1.4. User agencies will use the new SHRP specifications to specify requirements for asphalt properties that should be used in their regions. These requirements are expected to ensure quality of asphalts and thus better pavements.

1.1.6 ISTEA and the Utilization of Crumb Rubber in Asphalt Pavements

The Environmental Protection Agency (EPA) estimates that the present size of the scrap tire problem is 2 to 3 billion tires. Each year our nation discards approximately 285 million tires out of which 188 million are added to stockpiles, landfills, or illegal dumps across the country. The environmental risks linked to the presence of scrap tire stockpiles as
Figure 1.3. The new SHRP asphalt binder test methods.
## AASHTO Performance Graded Binder Specification (MP1)

<table>
<thead>
<tr>
<th>Performance Grade</th>
<th>PG-52</th>
<th>PG-58</th>
<th>PG-64</th>
<th>PG-70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average 7-day Maximum Pavement Design Temperature, °C</td>
<td>&lt;52</td>
<td>&lt;58</td>
<td>&lt;64</td>
<td>&lt;70</td>
</tr>
</tbody>
</table>

**Flash Point Temp. T44 Minimum °C**

**Vacuum, ASTM D 4402:**
- Maximum, 3 Pa (3000 eP), Test Temp. °C

**Dynamic Shear, TP5:**
- G'at 6 °C, Minimum, 1.00 kPa, Test Temp @ 10 rad/sec, °C

**Rolling Thin Film Oven (T240) or Thin Film Oven (T179) Residue**

**Mass Loss, Maximum, %**

**Dynamic Shear, TP5:**
- G'at 6 °C, Maximum, 2.20 kPa, Test Temp @ 10 rad/sec, °C

<table>
<thead>
<tr>
<th>Physical Hardening</th>
<th>90</th>
<th>100</th>
<th>100</th>
<th>100 (100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creep Stiffness, TP1, f</td>
<td>0 -6</td>
<td>-12</td>
<td>-18</td>
<td>-24</td>
</tr>
<tr>
<td>Direct Tension, TP3, f</td>
<td>0 -6</td>
<td>-12</td>
<td>-18</td>
<td>-24</td>
</tr>
</tbody>
</table>

**Notes:**
- a. Pavement temperatures can be estimated from air temperatures using an algorithm contained in the SUPERPAVE software program or may be provided by the specifying agency, or by following the procedures as outlined in PPA.
- b. This requirement may be waived at the discretion of the specifying agency if the supplier warrants that the asphalt binder can be adequately pumped and stored at temperatures that meet all applicable safety standards.
- c. For quality control of unmodified asphalt cement production, measurement of the viscosity of the original asphalt cement may be substituted for dynamic shear measurements of G'at 6 °C at test temperature where the asphalt is a Newtonian fluid. Any suitable standard means of viscosity measurement may be used, including capillary or rotational viscometry (AASHTO T 201 or T 202).
- d. The PAV aging temperature is based on simulated climatic conditions and is one of three temperatures 90 °C, 100 °C or 110 °C. The PAV aging temperature is 110 °C for PG 64 and above, except in desert climates, where it is 110 °C.
- e. Physical Hardening - TP 1 is performed on a set of asphalt at 6 °C and 6 °C above the minimum performance temperature. The 24-hour stiffness and m-value are reported for information purposes only.
- f. If the creep stiffness is below 300 MPa, the direct tension test is not required. If the creep stiffness between 300 and 600 MPa the direct tension strain requirement can be used in lieu of the creep stiffness requirement. The m-value requirement must be satisfied in both cases.

Figure 1.4. SHRP performance graded asphalt binder specifications.
well as a number of recent, well-publicized tire stockpiles initiated legislative action at the state and national level. At the beginning of 1991, 44 states had drafted, introduced, regulated, or enacted laws to control the scrap tire problem. Starting in 1990, a number of bills were introduced in Congress to address the scrap tire problem. The most relevant to the highway community is the ISTEA of 1991, which was enacted in December of 1991. The act specifically addresses the use of Crumb Rubber Modifiers (CRM) in Section 1038, "Use of Recycled Paving Material." The three primary requirements of this section as they relate to CRM are:

1. Relax federal regulations to permit state and local agencies to use CRM.
2. Study the performance, recycling, and environmental aspects of CRM.

The minimum CRM utilization requirements specify that the contract bid quantities of asphalt pavements awarded in the states during a fiscal year and financed in whole or part by any assistance pursuant to Title 23, United States Code, shall be 5 percent by 1994, 10 percent by 1995, 15 percent by 1996, and 20 percent by 1997.

The use of CRM in asphalt paving is not a new concept, and it did not develop as a solution to an environmental problem. The development of natural rubber in asphalt was in fact introduced in the early 1840's. The use of scrap tires in its current form started in the early 1960's and has continuously increased since then. In 1991, there were 33 suppliers of CRM in the United States. The effects of CRM on asphalt binder properties have been examined in a large number of studies using different testing and characterization techniques. The results reported to date indicate that the interaction between asphalts and rubbers is a function of asphalt composition, rubber composition and morphology, and rubber concentration. The results also indicate that more research is needed to establish guidelines for use of this material both at the design level and the application level.
1.1.7 Asphalt Modification Strategies and Targets

The successful modification of asphalt binders should be engineered to improve one or more of the basic properties and should focus on dealing with one or more of the pavement distress modes. The basic properties that should be targeted in modification may cover a long list, among which the most important are listed below. The material response parameters that are proposed by SHRP to measure each of these properties are also mentioned.

- **Rigidity**: Defined as total resistance to deformation which can be measured by complex moduli like $G'$ under dynamic loading or by creep stiffness, like $S(t)$, under quasi-static loading. Higher rigidity is favorable at high temperatures or low loading rates to resist rutting while lower rigidity is favorable at intermediate- and low-temperatures to resist fatigue or thermal cracking.

- **Elasticity**: Defined as recovery of deformation by storing energy applied. It can be measured either by the phase angle ($\delta$) or by the logarithmic creep rate ($m$). To resist rutting and fatigue damage more elasticity is required. To resist thermal cracking, less elasticity and more ability of relaxing stress by flow is required.

- **Brittleness**: Failure at low strains is the best definition of brittleness. To improve resistance for fatigue and thermal cracking, brittleness should be reduced by enhancing strain tolerance or ductility.

- **Durability**: Oxidative aging, physical hardening, and volatilization are key durability properties. Resistance to all of these durability changes is favorable.

A modifier can be selected to improve one or more of these main properties. Also, different modifiers that affect different properties can be combined to improve several properties.

1.1.8 Production of Crumb Rubber Modifiers

Early as well as recent research clearly indicates that the process by which crumb rubber is produced plays a major role in defining the type of interaction between asphalt and
rubber. Rubber production may include several variables among which the most important are the rubber source (raw material), size reduction technique, and additives used. Rubber sources include whole passenger tires, whole truck tires, tread peel, and buffings. Although all of these sources have certain potential for becoming a major source of CRM, whole passenger tires can be considered as having the highest potential because of the economical disadvantage of re-treading them and the larger quantities being disposed compared to other sources. Using only passenger tires to produce CRM—although this reduces the variability in CRM properties—does not ensure constancy of chemical composition. CRM should therefore be chemically analyzed to define its composition. The several constituents that are defined by ASTM standards include acetone extracts, ash, carbon black, rubber hydrocarbons, natural rubber, and moisture. In addition, different CRM contain different contents of steel wire residue and fiber residue. All of these constituents may have varying effects on the performance of the CRM binder. Table 1.1, published by one of the major CRM producers, gives a reasonable estimate of the chemical composition of whole tire rubber.

Size reduction technique is an important factor in defining effects of CRM on asphalt properties. Active work at Penn State using the new SHRP binder tests, and previous work using more conventional tests, indicates that there exist significant differences between CRM effects on rheological and failure properties. The different CRMs react differently and show differences in the kinetics of their reactions. Among the widely used methods for reduction of CRM are the following:

- Ambient grinding (1/4" to 40 mesh)
- Ambient Granulating (1/4" to 30 mesh)
- Cryogenic Grinding (1/4" to 100 mesh)
- Wet grinding (40 mesh to 100 mesh)
- Mechanical extrusion (1/4" to 40 mesh)

Each of these methods produces rubber particles with different size distribution, shape, and surface texture. The importance of these particle characteristics stems from the
Table 1.1. Chemical composition for whole tire rubber.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mean, %</th>
<th>Std Dev, %</th>
<th>Min, %</th>
<th>Max, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>acetone extract</td>
<td>15.1</td>
<td>1.33</td>
<td>13.1</td>
<td>17.5</td>
</tr>
<tr>
<td>ash</td>
<td>5.0</td>
<td>0.60</td>
<td>4.0</td>
<td>6.1</td>
</tr>
<tr>
<td>carbon black</td>
<td>32.0</td>
<td>1.03</td>
<td>30.5</td>
<td>33.2</td>
</tr>
<tr>
<td>rubber hydrocarbon</td>
<td>47.9</td>
<td>1.33</td>
<td>44.9</td>
<td>49.7</td>
</tr>
</tbody>
</table>

Source: Baker Rubber, Inc.
fact that the asphalt-rubber interaction is a physico-chemical process that includes physical diffusion as well as chemical reaction that results in establishing a complex interface zone at the surface of particles. Therefore, as size distribution, shape, and texture changes, the surface area accessible to the asphalt changes, resulting in different bulk properties of the total mixture. The surface area also affects the rate of reaction and the amount of asphalt components that diffuse into the rubber.

In addition to the effect of size distribution on surface area and thus the reaction kinetics with the asphalt, size distribution has an important economical role. The smaller the maximum size, the higher the cost of the CRM. CRM manufacturers will be consulted to establish the cost-size relation and select the levels for this factor to include cost of production as an indirect controlled variable. This is an important factor since one of the major concerns of using CRM is the cost of modified binders.

The other variable related to CRM type is additives. Extender oils, powders, and other modifiers are currently being used as a supplement for CRM. Each of these additives will have a certain function and may result in enhancement of the properties at specific conditions. The cost effectiveness of these additives are not well known, and there are a number of emerging technologies in the area of CRM additives.

The novel method used by the Tyreplex Corporation is unique in many aspects. The process combines pulverized scrap vehicular tires with commingled waste plastics to produce a specialized CRM. An additive is also added to produce a homogenous mixture of rubber and plastic and to facilitate extrusion of the CRM at elevated temperatures. The Tyreplex product was initially intended for manufacturing of conventional products such as trash cans, low-pressure pipes, industrial containers, recycling bins, and road safety cones. Realizing the importance of the paving market, the company decided to explore the use of the composite material as a modifier for asphalt binder. Different variations of the composite material can be produced by varying the amount of plastic combined with the rubber. Two different rubber/plastic ratios were examined in this study.
1.2 Objectives of the Research Project

The research project was planned to be a 12-month undertaking to focus on evaluating the effects of the rubber-plastic composite produced by the Tyreplex Corporation on the properties of selected asphalt cements. Technical assistance to the Tyreplex Corporation was also to be provided in order to further develop their product and make it suitable for use as an asphalt modifier.

The evaluation of the product was to be accomplished by quantifying its effects on basic rheological, failure, and aging properties of asphalt binders using state-of-the-art test methods and concepts. In addition, the evaluation was to include comparing the product’s effects with the effects of other crumb rubbers currently used in asphalt modification.

Three primary objectives were defined for the project.

1. Determine the effect of the addition of crumb rubber modifier (CRM) produced by Tyreplex corporation on performance-related properties of selected asphalt cements.
2. Compare the effects of the CRM produced by Tyreplex with the effects of other CRM products commonly used for paving applications.
3. Establish guidelines for selecting CRM content for asphalt binders.

The evaluation was performed using the new binder testing methods and aging procedures developed for the Strategic Highway Research Program (SHRP). The following sections give details of the experimental design, materials, and testing techniques used in the study.

1.3 Experimental Design and Techniques

The scope of the study included several controlled factors that were selected after careful study of the existing literature on CRM in paving applications and after contacts with producers of crumb rubbers, asphalt rubber contractors, and experts. Five main controlled
factors were selected: CRM type, the asphalt binder source, concentration of rubber, time of reaction, and the oxidative aging condition. Response variables included the critical properties that are related to pavement performance as selected by the SHRP program.

1.3.1 Controlled Variables

Several levels from each of the controlled variables were selected to include important levels that are related to field applications of CRM.

1. Rubber Type
   a. Ambient Shredding
   b. Cryogenic Grinding
   c. Tyreplex Process (Two plastic to rubber ratios)
      Total: 2

2. Asphalt Binder Source
   a. Lloydminster
   b. West Texas Sour
   c. California Valley
   d. West Texas Intermediate
   Total: 4

3. Proportion Concentration
   a. 80% Asphalt - 20% Rubber
   b. 85% Asphalt - 15% Rubber
   c. 90% Asphalt - 10% Rubber
   d. 95% Asphalt - 5% Rubber
   e. 100% Asphalt - 0% Rubber
   Total: 5

4. Time of Reaction
   a. 1 hour
   b. 24 hour
   Total: 2
5. Oxidative Aging

a. unaged  
b. TFOT & PAV aged  
<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total: 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Four rubber types were included in the study. Two were produced by Tyreplex with different rubber to plastic ratios. The factor of rubber to plastic ratio was included in the study because it has important impact on the final cost of the CRM composite produced by Tyreplex. The ratios included were 70/30 and 90/10 (rubber/plastic). The ratios were selected based on feasibility of production and experience of the Tyreplex Corporation technical staff with the extrusion process. The study was to include more ratios in case results indicated that the rubber to plastic ratio is an important factor. The other CRM’s used included ambient shredded CRM and cryogenic grinded CRM. These were used as the control rubbers to which the effects of Tyreplex CRM’s will be compared. These two particular CRM’s were selected to represent the materials that have been used widely and have the potential for dominating the pavement market for CRM. The four rubbers were similar in size distribution and have a maximum particle size of 1 mm. All rubbers were produced from whole passenger-car tires.

The study also included the use of four asphalts. The asphalts were selected to cover a wide range in compositional properties. The asphalts varied in their asphaltene content, aromatic content, average molecular weight, and in their rheological and failure properties. The asphalts included 2 AC-10 grade asphalts, an AR-2000, and a 200/300 pen asphalt. The chemical and physical characteristics of the asphalts selected can be seen in Table 1.2. Different asphalts were used because earlier research has suggested that changes due to the addition of rubber to asphalt binders were asphalt-specific. No additives were used in producing the asphalt rubbers.

The rubber content, measured in terms of rubber to total binder by weight, included four contents (5%, 10%, 15%, and 20%) in addition to testing the unmodified asphalt (0.0 percent rubber). These contents were selected to include the rubber concentrations that are
Table 1.2. Properties of selected asphalts.

<table>
<thead>
<tr>
<th>Grade:</th>
<th>Asphalt Type</th>
<th>200/300</th>
<th>AR - 2000</th>
<th>AC - 10</th>
<th>AC - 10</th>
<th>SHRP PG:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td></td>
<td>46-34</td>
</tr>
<tr>
<td>% Asphaltene</td>
<td>16.2</td>
<td>5</td>
<td>13</td>
<td>4.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% P. Aromatics</td>
<td>36</td>
<td>51</td>
<td>38.7</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% N. Aromatics</td>
<td>35.1</td>
<td>35.3</td>
<td>34.6</td>
<td>41.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Saturates</td>
<td>11.4</td>
<td>6.6</td>
<td>11.9</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
commonly used in practice. The objective was to attempt to establish guidelines that assist pavement engineers in selecting suitable rubber contents for different applications.

The time of reaction was included in the study to evaluate the storage stability of the different crumb rubbers during high-temperature storage. Storage stability has important consequences on the paving application of CRM. The consistency of the asphalt rubber has to remain within certain limits so that effective mixing with aggregates and effective compaction of the asphalt rubber concrete mixture can be achieved. Several previous studies have indicated that certain combinations of asphalt and rubbers show sudden and rapid reactions that result in an excessive decrease in the workability of asphalt rubbers. The levels of this factor were selected at one hour and 24 hours to optimize testing time and to relate to field practices. The mixing of the asphalt rubber was done by using a high-shear laboratory mixer under constant temperature conditions. The mixing was done in one-quarter containers that were maintained at a temperature of 160 °C ± 5°C. The temperature was controlled by using an electrical heating mantle. The mixing continued for one hour after which the samples were split into two portions. One portion was used for testing the initial (1-hour) properties and the other was transferred to an oven maintained at the same temperature of the mixing (160 °C). The sample portion was left in the oven for an additional 23 hours with intermittent mixing. The sample was then tested to measure the properties after storage (24-hour properties).

The last factor studied was the aging condition of the binders. Since aging characteristics are an important factor affecting the contribution of asphalt binders to pavement performance, all binders including the base asphalts were tested without aging and after aging with the procedures recommended by SHRP. The main focus was placed on the two extreme conditions: unaged and aged with the combined TFOT and PAV procedures.

The experimental design did not include a full factorial for all factor levels. Instead, a partial factorial design was followed by selecting certain combinations to optimize resources and concentrate on important factors. For each combination of factors, response variables were measured using four testing systems as recommended by SHRP. The response variables were selected to be indicators of performance-related properties as defined by SHRP results.
1.3.2 Response Variables

A brief description of the response variables, the testing systems used to measure them, and the testing conditions used follows.

- **Rotational Viscosity**: Rotational viscometer was used to evaluate the change in consistency of the binders before and after mixing the different rubbers with the selected asphalts. The viscometer was also used to evaluate the storage stability of the asphalt rubbers. The testing was done with a Brookfield viscometer at three different temperatures (135 °C, 160 °C, and 185 °C) using one type of spindle (SC4-27) at a constant speed of 20 rpm. The objective was to evaluate the changes in consistency of the binders at temperatures in the range of mixing and construction temperatures.

- **Dynamic Shear Rheometer**: The dynamic shear rheometer is used to measure two rheological parameters: G* and sin δ. These parameters were selected by SHRP researchers to describe the rheological behavior of binders. They are used in this study to measure the effect of CRM on the values of these parameters for the base asphalts within the range of maximum and intermediate pavement temperatures. The measurements were done in a temperature range of 5 °C to 75 °C. These temperatures cover the temperature ranges used in the current SHRP binder specifications.

- **Flexural Creep and Failure Properties**: At low pavement temperatures, SHRP recommendations include using the bending beam rheometer and the direct tension device for evaluating creep and failure characteristics. The bending beam rheometer is used to measure creep stiffness, S(t), and the logarithmic creep rate, m(t), at different loading times. The direct tension test is used to measure the strain at failure, εf, under a constant rate of deformation of 1.0 mm/min. In this project, the bending beam rheometer and the direct tension test were used to measure the responses at several temperatures ranging between -30 °C and 0 °C. The objective is to evaluate the influence of rubbers on low-temperature asphalt properties.

- **Aging Characteristics**: The Thin Film Oven (TFOT) and the Pressure Aging Vessel (PAV) were used to investigate the aging behavior of asphalts before and after mixing with the different rubbers. For evaluating the aging characteristics, the dynamic shear rheometer was used at intermediate pavement temperatures, and the bending beam rheometer and the direct tension test were used at low-pavement temperatures. The TFOT aging was done according to the ASTM
standard method (D1754), and the PAV aging was done according to SHRP recommendations at 100°C.

1.4 Testing Accomplished

The laboratory testing was divided into three phases, each designed to achieve certain objectives of the project. The three phases are as follows.

1.4.1 Phase 1: Effect of Tyreplex Rubber Type and Time of Reaction

The primary focus of this phase was to evaluate the effects of the CRM produced by the Tyreplex Corporation on rheological and failure properties of the selected asphalts in the unaged condition. The properties of different asphalt-rubber mixtures were evaluated after 1 hour of mixing and after an additional 23 hours of high-temperature storage. Table 1.3 represents a testing matrix that shows the combination of factors studied in this phase. All mixtures tested in this phase contained 15 percent CRM by weight of the total binder.

1.4.2 Phase 2: Effect of the CRM Content on Asphalt Properties

A study of the effect of rubber concentration in the asphalt rubber is required to determine if the interaction between the CRM’s and the binders is influenced by the concentration. It is also required to give guidelines as to what concentration will give optimum properties in the field. Table 1.4 summarizes the work done in Phase 2. The Tyreplex rubber with a rubber/plastic ratio of 70/30 was chosen based on the results from Phase 1. The two control CRM’s were also tested. The mixes included two asphalts, A and B, that were each mixed with three rubbers at four different concentrations: 80/20, 85/15, 90/10, and 95/5. These two asphalts were selected because they showed the most significant changes in properties when mixed with the Tyreplex rubbers. They also vary significantly in their physical and chemical properties. Time of reaction was not considered as a factor in
Table 1.3. Mixture matrix for phase 1.

<table>
<thead>
<tr>
<th>R/P Ratio (Type)</th>
<th>Time of Reaction: 1 hour</th>
<th></th>
<th>Time of Reaction: 24 hours</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Asphalt Binder Type</td>
<td>A</td>
<td>B</td>
<td>F</td>
</tr>
<tr>
<td>70/30 Tyrplex</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>50/10 Tyrplex</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ambient (control)</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryogenic (control)</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neat Asphalt</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

NOTE: ALL MIXES CONTAIN A RUBBER-ASPHALT RATIO OF 15%

Testing Within Each Cell:
1. HIGH TEMPERATURE RHEOLOGY - DSR-25
2. LOW TEMPERATURE RHEOLOGY - DSR-3
3. BENDING BEAM RHEOMETER - BBR
4. DIRECT TENSION TEST - DTT
5. BROOKFIELD TEST
Table 1.4. Mixture matrix for phase 2.

<table>
<thead>
<tr>
<th>A/R Ratio</th>
<th>CRUMB RUBBER TYPE: Tyrplex TP7-3</th>
<th>CRUMB RUBBER TYPE: Ambient Shredded (AS)</th>
<th>CRUMB RUBBER TYPE: Cryogenic Grinded (CG)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80/20</td>
<td>85/15</td>
<td>90/10</td>
</tr>
<tr>
<td>%</td>
<td>A</td>
<td>B</td>
<td>F</td>
</tr>
<tr>
<td>80/20</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>85/15</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>90/10</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>95/5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Testing Within Each Cell:

1. HIGH TEMPERATURE RHEOLOGY - DSR-25
2. LOW TEMPERATURE RHEOLOGY - DSR-8
3. BENDING BEAM RHEOMETER - BBR
4. DIRECT TENSION TEST - DTT
5. BROOKFIELD TEST

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this phase. The testing scheme for this phase included measuring the response variables at high, intermediate, and low pavement temperatures as discussed in the previous section.

1.4.3 Phase 3: Aging Characteristics As Measured by the TFOT and the PAV

The main focus of this phase was to quantify the effects of the CRM's on the aging characteristics of the base asphalts. Table 1.5 shows the testing matrix that was used in this phase. The two Tyreplex rubbers mixed with all four rubbers were included in addition to the other rubbers mixed with only asphalt A and B. All mixtures were produced at 15 percent rubber content. The mixtures in addition to the base asphalts were tested after aging in the TFOT followed by the PAV procedure. The testing included rheological properties at high and intermediate temperatures, using the dynamic shear rheometer, the creep properties at low pavement temperatures, and failure properties at low pavement temperatures. The test results were compared with those of the unaged specimens tested in phase 1. Only the 1-hour mixing samples were used.
Table 1.5. Mixture matrix for phase 3.

<table>
<thead>
<tr>
<th>Rubber Type:</th>
<th>A/R Ratio</th>
<th>Asphalt Binder Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A/R %</td>
<td>A</td>
</tr>
<tr>
<td>Base Asphalt</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Tyrplex TP7-3</td>
<td>85/15</td>
<td>X</td>
</tr>
<tr>
<td>Tyrplex TP9-1</td>
<td>85/15</td>
<td>X</td>
</tr>
<tr>
<td>Ambient (AS)</td>
<td>85/15</td>
<td>X</td>
</tr>
<tr>
<td>Cryogenic (CG)</td>
<td>85/15</td>
<td>X</td>
</tr>
</tbody>
</table>

Testing Within Each Cell:
1. HIGH TEMPERATURE RHEOLOGY - DSR-25
2. LOW TEMPERATURE RHEOLOGY - DSR-8
3. BENDING BEAM RHEOMETER - BBR
4. DIRECT TENSION TEST - DTT
5. BROOKFIELD TEST
CHAPTER 2
EFFECT OF CRM TYPE ON ASPHALT MECHANICAL PROPERTIES

The effect of adding different crumb rubbers on the mechanical properties of the asphalt binders was evaluated in the first phase of the project. As described in the experiment design section of chapter one, two Tyreplex rubbers were used, one with a rubber/plastic ratio of 9/1 (TP9-1) and another with a rubber/plastic ratio of 7/3 (TP7-3). Two other rubbers (called the control rubbers) were also used. The two control rubbers included a cryogenic grinded (CG) crumb rubber and an ambient shredded (AS) crumb rubber. The evaluation methodology consisted mainly of comparing the properties of the base asphalt before and after the addition of the different rubbers. The crumb rubber concentration was held constant at 15 percent by the total weight of the modified asphalt binder. The results and findings of Phase 1 are discussed in this chapter.

2.1 High-Temperature Consistency and Thermal Stability

A major concern in using any form of asphaltic concrete is whether it can be mixed and placed effectively. The asphalt binder is the main component that controls the workability of asphalt concrete mixtures. It is therefore necessary for the binder to be soft (workable) enough so that it can be pumped and mixed with aggregates efficiently, and such that the mixture can be compacted effectively after laydown in the field. Viscosity of binders at high temperature is the engineering measure used to evaluate workability at mixing and construction temperatures. Viscosity, which is simply defined as the resistance to flow, is not a property that reflects pavement performance directly; nevertheless, it has major consequences on performance because a poorly constructed or compacted pavement layer will not perform properly. To ensure workability of binders, the new SHRP specifications require that the viscosity at 135 °C be less than 3 Pa-s.
Measuring the viscosities of asphalts modified with CRM is critical because all CRM's are known to increase the viscosity of the base asphalt. CRM's tend to retain their particulate nature within the mixture because of their high melting points. They act, therefore, as fillers increasing the resistance to flow. In addition to the filler effects, several studies have shown that there exists a reaction between the asphalt and certain rubbers that results in swelling of the rubber particles. This swelling phenomenon results in further increases in viscosity beyond the filling effect. These studies have also shown that this phenomenon is both time and temperature dependent. In this phase of the study, the initial effects of CRM's as well as the post-reaction effects were evaluated. The following sections summarize the analysis of the data collected for the high-temperature consistency properties.

2.1.1 Initial Properties

The properties after the CRM was initially mixed into the asphalt were examined first. The mixing time was held constant at one hour at approximately 160 °C. The initial mixtures are referred to here as the one-hour unaged mixtures. The rubbers produced by Tyreplex (TP7-3 and TP9-1) were mixed with four asphalts, while the control rubbers were mixed with only two asphalts that were observed to be most reactive with the Tyreplex rubbers. Figures 2.1 and 2.2 show the viscosity increase due to the addition of the four crumb rubbers for asphalts A and B respectively. Figures 2.3 and 2.4 compare the effects of only the two Tyreplex rubbers on the remaining two asphalts (F and M). Although attempts were made to measures viscosities at three different temperatures (135 °C, 160 °C, and 185 °C), measurements at 185 °C were difficult to obtain for certain combinations of asphalts and rubbers because of the reaction within the testing time. The reactions were particularly significant for rubbers AS and CG with asphalt B. The figures, therefore, show the results for only two temperatures: 135 °C and 160 °C. As can be seen in the figures, there is a significant increase in viscosity at both temperatures for all rubber-asphalt combinations. Figures 2.1 and 2.2 indicate that the increase is greater for the control rubbers, AS and CG, than that of the Tyreplex rubbers (TP9-1 and TP7-3) at both temperatures. The effect of both Tyreplex rubbers was observed to be very similar, which indicates that the
Figure 2.1. Effect of CRM type on the viscosity of asphalt A.
Figure 2.2. Effect of CRM type on viscosity of asphalt B.
Figure 2.3. Effect of CRM type on viscosity of asphalt F.
Figure 2.4. Effect of CRM type on viscosity of asphalt M.
rubber/plastic ratio is not of any importance with regard to high-temperature viscosity. The figures also indicate that the AS and CG rubbers have relatively similar effects with the CG rubber, showing a slightly higher effects. Figures 2.3 and 2.4 confirm the observation that both Tyreplex rubbers have similar effects. They indicate, however, that the effect is significantly dependent on the asphalt source. The highest effects can be seen with asphalt F, while the lowest can be seen with asphalt M. It is interesting to note here that asphalt M has the highest aromatic content (see table 1.1), while asphalt F has a much lower aromatic content. Although the scope of experiment does not allow drawing a solid conclusion, there is certainly a trend that indicates less effects of rubbers with increased aromatic content. This trend can be observed when comparing the data for asphalts A and B in figures 2.1 and 2.2.

The above analysis indicates that the influence of rubber on the viscosity of the base rubber is not only rubber-specific but also asphalt-specific. The analysis also indicates that there is some interaction effect between asphalt type and rubber type as the relative degree of effect is reversed when different asphalts are compared. In relation to the SHRP specification viscosity limit of 3 Pa-s, all asphalt-rubber combinations tested after 1 hour of mixing meet this requirement. The Tyreplex rubbers consistently had lower viscosity readings, suggesting that they are more favorable with respect to the increase in viscosity.

2.1.2 Properties After Storage

To evaluate the storage stability of the modified asphalts, viscosities of all the mixtures were evaluated after long-term storage at high temperatures. The 1-hour mixtures were placed in an oven at 160 °C for a period of 23 hours and mixed at intermittent intervals to provide agitation that keeps rubbers dispersed uniformly in binder. These mixtures are referred to here as the 24-hour unaged mixtures. The viscosity values for the 24-hour mixtures are shown, in a similar fashion to those of the 1-hour mixtures, in figures 2.5 to 2.8. Once again, the data collected at 135 °C and 160 °C are shown. In comparison to the 1-hour mixing measurements shown in figures 2.1 to 2.2, it can be seen that there are significant increases after storage in all cases, including the base asphalt. The Tyreplex
Figure 2.5. Effect of CRM type on the viscosity after storage on asphalt A.
Figure 2.6. Effect of CRM type on the viscosity after storage on asphalt B.
Figure 2.7. Viscosity ratios showing relative change in viscosity after 23-hour storage for asphalts A and M.
Figure 2.8. Effect of CRM type on the viscosity after storage on asphalts M and F.
rubbers, however, show a relatively small change from the 1-hour readings, while the
cryogenic (CG) and ambient (AS) crumb rubbers show much higher changes, particularly
with asphalt B. The small changes in the base asphalts and in the Tyreplex rubbers’
mixtures can be related mainly to the aging of the binders due to storage at high
temperatures. The changes for AS and CG rubbers, however, cannot be attributed to only
aging, and this indicates that certain type of reaction is taking place. To evaluate the
changes on relative bases, figure 2.7 depicts the ratios of viscosity after mixing and storage
compared to the viscosity of the base asphalt for the one-hour and the 24-hour mixtures. By
taking the ratio, the effect of the aging of the binder can be normalized. The figure indicates
the significance of the reaction taking place during the storage, and also indicates the stability
of properties of the Tyreplex rubbers. In relation to the limits recommended by SHRP, the
increase shown in figures 2.5 and 2.6 is so significant for the AS and CG rubbers that they
no longer meet the SHRP specifications limit of 3 Pa-s. The TP9-1 and TP7-3 rubbers,
however, remain within the specification limits for both asphalts. Figure 2.8 depicts the
results of the Tyreplex rubbers for the remaining two asphalts at two temperatures. The
results shown confirm the stability of these two rubbers and further indicate that the
rubber/plastic ratio does not play an important role in the storage stability of the modified
asphalts.

The analysis of the viscosity measurements after storage at high-temperatures leads to
important findings. The most important finding is related to the stability of the Tyreplex
rubber mixtures compared to the other rubbers. Excessive rubber reactions that lead to
unacceptable levels of viscosities of asphalts modified with CRM is one of the main problems
that engineers are faced with in the field. The results of this experiment indicate that the
Tyreplex process of producing CRM may offer a solution to this problem. The analysis of
the measurements also indicates that the effect of storage is more pronounced at 160 °C than
at 135 °C for all asphalt-rubber combinations, especially with asphalt B. This finding leads
us to believe that the effects of reaction, which has been described to result in a swelling
phenomenon, are a function of the temperature and type of testing: the higher the test
temperature, the higher the effect on mechanical properties. Finally, the analysis shows that
within the time limits that may very well be experienced during construction in the field, an

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asphalt modified with CRM may change its properties to such a limit that it will not need workability requirements. It is imperative that asphalts modified with crumb rubbers be tested for their storage stability. The analysis in this section indicates that in the area of storage stability, although a function of rubber type and asphalt type, the effect of rubber type is more prominent.

2.1.3 Continuous Measuring Results

The results of the high-temperature storage stability were very important for this study because they indicated that the Tyreplex rubbers have a special stability characteristic that makes them very favorable from an application point of view. To further examine this characteristic and ensure that it is not an experimental artifact, an experiment was initiated in which viscosity of mixtures was continuously monitored in the rotational viscometer while providing continuous agitation in the viscometer. The measurements were done at a constant temperature of 160 °C for an extended period of time that exceeded 7 hours. Viscosity readings were continuously recorded throughout the storage period using a strip chart recorder. The viscosity traces were digitized later and plotted versus time at 15-minute intervals, as can be seen in figures 2.9 and 2.10. The figures depict the viscosity values for the four crumb rubbers combined with unaged asphalts A and B respectively. Figure 2.9 indicates that while mixtures made with Tyreplex rubbers remained stable throughout the test, mixtures made with AS and CG showed a continuous increase with time that amounted to more than 60 percent within 400 minutes at 160 °C. Figure 2.10 depicts the results for mixtures made with asphalt B. Once again, the mixtures made with the Tyreplex rubbers remained consistent, while those made with the CG and AS rubber increased continuously, with some sudden dramatic increase for rubber AS. After approximately 120 minutes at 160°C, the viscosity of the AS-modified asphalt B increased dramatically to values that are an order of magnitude higher than the initial values. There is obviously some sort of reaction that takes place between the AS rubber and asphalt B. It is, however, not simple to explain why this reaction is so sudden. To determine if such an increase was an experimental artifact, the test was replicated twice on the same asphalt-rubber combination.
Figure 2.9. Effect of storage on the viscosity of CRM modified asphalt A.
Figure 2.10. Effect of storage on the viscosity of CRM modified asphalt B.
The results are shown in figure 2.11, which depicts the same sudden change that was observed in the first test. This reassures the possibility that a sudden reaction is taking place and that the measurements are a true reflection of the material characteristics.

The results of the storage stability confirms that Tyreplex rubbers can be considered unique in their storage stability characteristics when compared to the other two rubbers used in this study. This finding should, however, be qualified with the fact that the scope of the study included four asphalts and that the storage was done only at a temperature of 160°C. The results also shows an interesting phenomenon of sudden reaction between certain types of rubbers and asphalts. This phenomenon would certainly need further evaluation and research, which is beyond the scope of this project.

2.1.4 Findings

The analysis, of data collected in this part of the study indicates that the mechanisms by which the CRM’s affect the high-temperature consistency of asphalt binders are rather complicated. The analysis of the results that represent testing of three types of CRM mixed with four asphalts tested at two temperatures have resulted in the following findings:

1. The effect of CRM’s on viscosity of asphalt binders is both rubber-type and asphalt-source specific. Although the experiment is limited in scope, its results indicate that rubber type is more important than the asphalt source, and that there is only a small interaction between these two factors.

2. The effect of additional CRM’s, irrespective of rubber type or asphalt source, is a significant increase in viscosity at all temperatures. On relative bases, the increase is found to be higher at higher temperatures.

3. The increase in viscosity was higher for the control CRM’s (AS and CG) than the Tyreplex CRM’s (TP7-3 and TP9-1). The Tyreplex rubbers showed similar results, which indicate that the ratio of rubber to plastic is not an important factor. Also, the AS and CG rubbers showed similar effects, which indicate that despite the difference in morphology of these CRM’s, the initial (short-time storage) effects on viscosity is not an important factor.
Figure 2.11. Viscosity vs. time for ambient modified asphalt B.
4. The effect of storage at high temperatures revealed very important findings: the Tyreplex rubbers showed no important increases in viscosity after the 23-hour storage period, while the control rubbers AS and CG showed significant changes due to storage. The stability of Tyreplex rubbers and the reactivity of the other rubbers were confirmed by continuous monitoring of the viscosity in a rotational viscometer.

5. The reaction of the AS and CG rubbers were found to be different for the two asphalts. This raises questions about the mechanism that is responsible for the interaction, and indicates that more research is needed to fully understand the cause of the sudden increase in viscosity that was observed with certain asphalt-rubber combination.

2.2 Rheological Properties at High and Intermediate Pavement Temperatures

One of the primary distresses of a flexible pavement is that of rutting. Rutting is a surface distortion that can be caused by consolidation of one or more of the pavement layers. The asphaltic pavement layer itself can contribute to rutting because of its low resistance to deformation and its reduced elasticity. Rutting is particularly critical when pavements are exposed to high temperatures, under heavy axle load, or have a cyclic loading pattern. High pavement temperatures recommended in the latest version of the SHRP specifications ranged between 46 °C and 82 °C. For this study, testing was done at temperatures ranging between 45 °C and 75 °C, to cover the high pavement temperature range.

The other primary distress mechanism of flexible pavements is fatigue cracking. Fatigue cracking is caused by repeated deformation of the thin pavement layers under traffic loading. It is particularly critical at intermediate pavement temperatures because of the high resistance to deformation under cyclic loading and its reduced elasticity. Intermediate pavement temperatures recommended in the SHRP specifications range between 7 °C and 34 °C. For this study, testing was done at temperatures ranging between 5 °C and 35 °C to represent the intermediate temperature range.

The dynamic shear rheometer (DSR) was used to measure two primary SHRP parameters: the complex shear modulus (G*) and the phase angle (δ). The first (G') relates to the total resistance to deformation of a material under dynamic loading. As G' is
increased, the binder’s resistance to deformation is also increased. The other parameter ($\delta$) relates to the elasticity (storage of energy) during each loading cycle. A lower value of $\delta$ indicates that there is a smaller loss of energy during the loading cycle, which results in a greater elastic response of the binder. An asphalt with a greater elastic response will perform better at high and intermediate pavement temperatures. In the SHRP specifications, the parameter of $G^*/\sin \delta$ ($1/J''$) is recommended to measure the contribution of the binder to resistance of pavement rutting. An increase in the value of $1/J''$ indicates a greater resistance of the binder to rutting, especially at high pavement temperatures. The parameter of $G^* \sin \delta$ ($G''$) is recommended to measure the contribution of the binder to resistance to fatigue cracking of the pavement. An increase in the value of the loss modulus ($G''$) is not favorable in relation to fatigue performance. The following sections will discuss the analysis of data collected to evaluate the effect of CRM on asphalt properties at high and intermediate temperatures.

2.2.1 Performance-Related Properties at Selected Frequencies

To examine the changes in properties related to pavement performance, temperature isochronal plots of SHRP parameters at selected frequencies were constructed. The first set of curves, figures 2.12 and 2.13, depict $G^*$ at 10 rad/s (1.5 Hz) as a function of temperature. Figure 2.12 shows isochronal curves for the base asphalt A before and after mixing with the four CRMs at 10 rad/s. The 10 rad/s was selected according to SHRP recommendations which consider this frequency to represent the rate of loading of trucks moving at a speed of approximately 55 mph. Figure 2.13 depicts similar plots for asphalt B.

Figure 2.12 indicates that, for asphalt A, the addition of the rubber modifier to the base asphalt results in higher values of the complex modulus ($G^*$) at all temperatures. The relative increase is higher at higher temperatures and amounts to an average change of an order of magnitude (10 folds) at the highest test temperature of 75 °C. As mentioned earlier, the increase in $G^*$ indicates an increase in the total resistance to deformation, which is very favorable for rutting resistance. At intermediate temperatures, the increase is not favorable, since resistance to fatigue cracking favors a lower resistance to deformation (lower
Figure 2.12. Effect of CRM type on shear response of asphalt A.
Figure 2.13. Effect of CRM type on shear response of asphalt B.
The plots, however, indicate that the relative increase is less as the temperature is decreased. Examining figure 2.13, the same type of change can be seen at the high temperature region. At low temperatures, the asphalt is showing lower $G'$ values after mixing with the four rubbers compared to the un-modified asphalt. Figure 2.13 shows that the isochronal curve for the base asphalt B intersects the modified curves between the values of 18 °C and 28 °C, which corresponds to $G''$ values of 350 and 1900 kPa. For asphalt A, no such intersection could be observed even at temperatures as low as 5 °C and $G''$ values of 1800 kPa.

Another important observation, that can be seen in both figures, is the variation in the behavior of the individual asphalt-rubbers. The curves for the different rubbers intersect each other at different temperatures ranging between 25 °C and 45 °C, depending on the asphalt type and the rubber type. With respect to relative increase and temperature dependency, however, the ranking of the different rubbers is consistent for both asphalts; the AS rubber is showing the largest increase at high temperatures and the least sensitivity to temperature. The CG rubber is the next in both these characteristics, while the two Tyreplex rubbers are showing the smallest change at high temperatures and the most sensitivity to temperature, all compared to the base asphalt. The large change at high temperatures and the lower sensitivity to temperatures are both favorable changes. Although not ranked favorably with respect to other rubbers, the relative changes of the two Tyreplex rubbers with respect to the base asphalt are still very favorable.

The phase angle ($\delta$) isochronal curves for the asphalt rubbers, at a frequency of 10 rad/s expressed in terms of the parameter "$\sin\delta$", are shown in figures 2.14 and 2.15. This parameter is used here because it is recommended by SHRP to relate to the energy dissipation concept, and is a reflection of the relative elasticity of a binder. $\sin\delta$ is inversely proportional to the elasticity of the binder (energy stored per loading cycle). Both figures show a general decrease in the value of $\sin\delta$ for the modified binders from that of the base binder. This decrease occurs throughout the temperature range to varying levels depending on temperature and the rubber type. The reactive decrease ranges between no change at high temperatures for the CG and the Tyreplex rubbers to a maximum of approximately 30 percent for rubber AS at the same temperature. The AS rubber shows a significant decrease
Figure 2.14. Effect of CRM type on phase angle of asphalt A.
Figure 2.15. Effect of CRM type on phase angle of asphalt B.
for both asphalts. The changes observed for the AS rubber confirm earlier findings that the ambient shredded rubbers, because of these morphology enhances the elasticity more than other rubbers, particularly at high temperatures. The changes in elasticity, however, are by far less than the changes observed for $G^*$ values. The increased elastic response, resulting from lower $\sin \delta$, is generally favorable at both high and intermediate pavement temperatures.

2.2.2 Effects on SHRP Specification Parameters

The SHRP specification parameters for high and intermediate temperature analysis are $G^*/\sin \delta \ (1/\eta'')$ for rutting performance and $G^* \sin \delta \ (G'')$ for fatigue cracking performance. Figures 2.16 to 2.19 depict bar charts reflecting $1/\eta''$ values at the high temperatures for the base asphalt and each of the asphalt rubbers at a 15% concentration. The values were measured after 1 hour of mixing at $160 \degree C \pm 5 \degree C$. It can be seen that the values vary depending on the asphalt rubber type, the base asphalt type, and the temperature.

Several observations can be made from examining figures 2.16 to 2.19. The relative change in $1/\eta''$ between the unmodified asphalt and the asphalt rubbers generally increases as the temperature rises. This suggests a relatively higher increase due to the modification as the temperature rises, which is favorable since the contribution to rutting resistance is more critical at elevated temperatures. To evaluate the relative change in $1/\eta''$, table 2.1 lists the values of the ratios of modified base asphalt properties for all combinations shown in figures 2.16 to 2.19. The ratios vary between a low value of 2.5 to a high value of 29.5. The ratio depends on the asphalt type, the rubber type, and the temperature of the test. With respect to the rubber type, the AS rubber in general shows more effects than the other rubbers, followed by the CG rubber, and then by the two Tyreplex rubbers, which have relatively similar effects. The Tyreplex rubber with the higher plastic content (TP7-3) shows slightly higher ratios than the Tyreplex rubber with the lower plastic content (TP9-1) consistently for all asphalt-temperature combinations. With respect to the asphalt type, asphalt A shows the highest ratios followed by F, B, and M, which shows the lowest ratios. With respect to the temperature, the CG and Tyreplex rubbers show no significant increase in ratios with
Figure 2.16. Effect of CRM type on $1/J''$ for asphalt A.
Figure 2.17. Effect of CRM type on asphalt B.
Figure 2.18. Effect of CRM type on asphalt F.
Figure 2.19. Effect of CRM type on asphalt M.
Table 2.1. Ratio of 1/J" (modified asphalt (15%)/base asphalt).

<table>
<thead>
<tr>
<th>SAMPLE I.D.</th>
<th>TEMPERATURE:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>45C</td>
</tr>
<tr>
<td>Asphalt A</td>
<td>1.</td>
</tr>
<tr>
<td>AS/A-2 1hr U</td>
<td>8.4</td>
</tr>
<tr>
<td>CG/A-2 1hr U</td>
<td>8.6</td>
</tr>
<tr>
<td>TP9-1/A-2 1hr U</td>
<td>5.3</td>
</tr>
<tr>
<td>TP7-3/A-2 1hr U</td>
<td>7.5</td>
</tr>
<tr>
<td>Asphalt B</td>
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<tr>
<td>AS/B-2 1hr U</td>
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</tr>
<tr>
<td>CG/B-2 1hr U</td>
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</tr>
<tr>
<td>TP9-1/B-2 1hr U</td>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>TP7-3/M-2 1hr U</td>
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temperature, which suggests that the $1/J''$ temperature profile does not change significantly. There is significant increase in ratios with temperature, however, for AS rubber.

Considering the intermediate pavement temperatures, the loss modulus ($G''$) is another important parameter selected by SHRP to control the contribution of binder to fatigue cracking resistance. A decrease in the loss modulus is an indication of a decrease in the energy dissipated per cycle, which indicates less fatigue damage, and is, therefore, considered favorable. Figures 2.20 to 2.23 show the values of $G''$ at the intermediate temperature range for all four unaged asphalts modified with each rubber at a concentration of 15%. The values were measured at a frequency of 10 rad/s, which is the frequency selected for the SHRP specifications. From examining the figures, it can be seen that the effect of rubber modification is mixed, with both an increase and a decrease in $G''$ values, depending on the temperature, asphalt, and rubber combination. Table 2.2 gives a summary of ratios of $G''$ values for the measurements shown in figures 2.20 to 2.23. The ratios vary between a low of 0.49 to a high of 5.81. The ratios are consistently decreasing with lower temperatures. On average, the ratios are higher for asphalt A, followed by F, M, and B which shows the lowest ratios. With respect to the rubber type, AS rubber is giving the lowest ratios, followed by CG rubber, TP9-1 rubber, and then the TP7-3 rubber which shows the highest ratios. For $G''$ ratios, the two Tyreplex rubbers do not show similar results particularly with asphalts F and B. The TP9-1 shows consistently lower values, which is more favorable. The effects of the rubbers on $G''$ as indicated by the ratios is much smaller than the effects on $1/J''$. This can be explained by examining figures 2.12 to 2.15. These figures show that at lower temperatures the increase in $G^*$ is less and than at high temperatures. Also, the decrease in $\sin\delta$ is greater at lower temperatures than at high temperatures.

2.2.3 Effect of High-Temperature Storage on Rheological Properties

The effect of high-temperature storage on the complex shear modulus and phase angle was studied by examining $1/J''$ values for one of the Tyreplex rubbers (TP7-3) and the AS and CG rubbers. The other Tyreplex rubber was not included because it did not show any
Figure 2.20. Effect of CRM type on $G''$ for asphalt A.
Figure 2.21. Effect of CRM type on $G''$ for asphalt B.
Figure 2.22. Effect of CRM type on G'' for asphalt F.
Figure 2.23. Effect of CRM type on $G''$ for asphalt M.
Table 2.2. Ratio of G" (modified asphalt (15%)/base asphalt)

<table>
<thead>
<tr>
<th>SAMPLE I.D.:</th>
<th>TEMPERATURE:</th>
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<tbody>
<tr>
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<tr>
<td>TP7-3 / A-2 1hr U</td>
<td>1.7</td>
</tr>
<tr>
<td>Asphalt B</td>
<td>1</td>
</tr>
<tr>
<td>AS / B-2 1hr U</td>
<td>.5</td>
</tr>
<tr>
<td>CG / B-2 1hr U</td>
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</tr>
<tr>
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<td>.6</td>
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<tr>
<td>TP7-3 / B-2 1hr U</td>
<td>.6</td>
</tr>
<tr>
<td>Asphalt F</td>
<td>1</td>
</tr>
<tr>
<td>TP9-1 / F-2 1hr U</td>
<td>.8</td>
</tr>
<tr>
<td>TP7-3 / F-2 1hr U</td>
<td>.9</td>
</tr>
<tr>
<td>Asphalt M</td>
<td>1</td>
</tr>
<tr>
<td>TP9-1 / M-2 1hr U</td>
<td>.7</td>
</tr>
<tr>
<td>TP7-3 / M-2 1hr U</td>
<td>.8</td>
</tr>
</tbody>
</table>
changes in viscosity values after storage and during the continuous viscosity testing experiment (see sections 2.1.2 and 2.1.3). The same asphalt-rubber mixtures from the 1-hour testing samples were placed in an oven at a controlled temperature of 160 °C ± 2 °C and mixed intermittently for a period of 23 hours to simulate high temperature storage conditions. The mixtures were contained in one-quart cans and covered with aluminum foil throughout the storage period to minimize aging. The 24-hour mixtures were then tested using the dynamic shear rheometer with a 25 mm plate size at a temperature range of 45 °C to 75 °C. Figures 2.24 and 2.25 depict bar charts showing the ratio of 1/J" for asphalts A and B respectively after one hour mixing and after the additional 23-hour storage. Both figures reveal that the ratios after 23-hour storage did not show any significant increase. On the contrary, at certain combinations of temperature, rubber, and asphalt, a decrease in the ratio is observed. This finding is in contradiction with the large increase in the rotational viscosity at high temperatures discussed earlier. The ratios in both figures clearly show that the swelling-reaction phenomenon that results in increased viscosities at high temperatures does not have a similar effect at temperatures in the range of maximum pavement temperatures. With regard to the decrease in ratios and the values of 1/J", the only explanation that can be offered is that there might be some degradation of the rubber occurring during the storage period or the reaction is reaching a maximum after which the 1/J" values start dropping. The possibility of degradation is, however, not very likely to occur because tire rubbers are known to be stable at even much higher temperatures. The possibility of a peak in reaction kinetics is, on the other hand, more likely. Such behavior has been reported before in previous studies. The findings from this part of the study are very significant in terms of paving applications. They indicate that the swelling-reaction mechanism, which has been reported in many studies as one of the main concerns with respect to using CRM's, is only a high-temperature phenomenon. This finding leads us to believe that there are no real benefits in reacting rubbers with asphalts, as they will not give any enhancement of properties at pavement temperatures. The experiment conducted here is by no means comprehensive in nature; the reaction with a larger number of asphalts and at different temperatures needs to be studied.
Figure 2.24. Ratio of $1/J''$ values (24hr/1hr unaged) for asphalt A.
Figure 2.25. Ratio of $1/J''$ values (24hr/1hr unaged) for asphalt B.
2.2.4 Findings

The above observations suggest that the addition of crumb rubber modifiers to asphalts results consistently in a significant increase in values of $1/J''$ of the base asphalts. The increase, measured in terms of ratio of $1/J''$ of the modified asphalt to the base asphalt, ranged between 2.50 and 29.5, depending on the asphalt source, the rubber type, and the temperature of measurement. This effect is considered very favorable for the improvement of rutting resistance of pavements, especially at the high end of the pavement temperature spectrum. The results clearly indicate that the effect of the addition of rubber is asphalt-specific and also rubber-specific. The effect for most asphalt-rubber combinations is more pronounced at higher temperatures.

For asphalts A and B, the AS and CG rubbers have consistently produced higher values of $1/J''$ than the Tyreplex rubbers. The TP7-3 has resulted in higher $1/J''$ values than that of the TP9-1 for all temperatures. The differences between the Tyreplex rubbers, however, were generally minor compared to the differences with the other rubbers, and they were generally similar for the four asphalts. The one exception was asphalt A at low temperatures (45 and 55°C), which showed significant changes between the Tyreplex rubber compared to the other rubbers. The overall analysis, however, indicates that the content of plastic in the Tyreplex rubbers is not an important factor with respect to the properties of binders at high pavement temperatures. The results also indicate that the AS and CG rubbers are more effective in increasing the values of $1/J''$ than the two Tyreplex rubbers.

For all rubbers, the results indicate that the primary changes in the values of $1/J''$ come mainly from significant increase in rigidity as measured by $G^*$ values. The changes in $\sin \delta$, which were consistently negative, are not important and play only a minor role in reducing $1/J''$. This can be seen from examining figures 2.12 to 2.15.

For the loss modulus ($G''$), which is related to contribution of binder to resistance to fatigue cracking, the results indicate that the addition of the crumb rubbers can result in an increase or a decrease of the $G''$ value depending on the asphalt properties, the rubber type, and the test temperature. The data indicate, however, that the effect is more dependent on asphalt properties than the other factors. A reduction in values of $G''$ is more favorable with
respect to the contribution of binders to fatigue cracking resistance. On average, the AS and CG rubbers are more effective in reducing the $G''$ values than the Tyreplex rubbers. The Tyreplex rubbers are still showing improvements when compared to the base asphalt, particularly at low temperatures (5 and 15 °C) where the asphalts show $G''$ in the range of 5000 kPa, which is the limit recommended by SHRP.

The data for the 24-hour stored binders suggest no significant increase in $1/G''$ for any of the rubbers. The Tyreplex rubber (TP7-3) and the AS and CG rubbers did not show a significant change with any of the asphalts after 23 hours of storage. The AS and CG rubbers, which showed significant change in viscosity at higher temperatures (135 °C to 180 °C), behaved similar to the TP7-3 and did not show any significant changes in the values of $1/G''$.

At certain asphalt-rubber-temperature combinations, a decrease in the ratios is observed. This behavior does not agree with earlier findings that show a significant increase in rotational viscosity when exposed to high temperatures (see figures 2.1, 2.2, 2.5, and 2.6). This suggests that the swelling or reaction that takes place at high temperatures (135 °C to 185 °C) does not have an effect on the rheological properties within the range of pavement temperatures. The reduction may be related to the kinetics of the asphalt-rubber reaction and the fact that in some cases a peak in the reaction takes place after which a reduction in consistency or rigidity is observed.

2.3 Rheological and Failure Properties at Low Pavement Temperatures

One of the main pavement distress mechanisms within the low-temperature region is thermal cracking. Thermal cracking of asphaltic pavements results from build-up of thermal stresses due to the restraint of volume shrinkage of the surface layer during cooling cycles.

The low-temperature characterization for this study was conducted using the bending beam rheometer (BBR) and the direct tension test device (DTT). The BBR is used to measure two response variables: creep stiffness, $S(t)$, and the logarithmic creep rate, $m(t)$. The first, is related to the amount of thermal stresses that may result in a pavement during a
cooling cycle, and \(m(t)\) is related to the ability of the binder to relax these stresses by flow. The BBR measurements were determined at various temperatures ranging between \(-30\, ^\circ C\) and \(0\, ^\circ C\). With regard to thermal cracking, a lower value of \(S(t)\) and a higher value of \(m(t)\) are preferred, because a lower \(S(t)\) value indicates lower thermal stress build-up, and a higher \(m(t)\) indicates a faster rate of relaxation of stresses.

The \(S(t)\) and \(m(t)\) parameters, however, are only indicators of pre-failure properties. They do not give any indication of the failure characteristics of binders, particularly modified binders. Therefore, the direct tension test is used for direct measurements of failure properties. The primary property measured by the DTT is the strain at failure. This measurement relates to the binder capability to stretch under load, and it is a good indicator of the brittleness of the binder at low temperatures. A higher strain at failure is preferred because this indicates a high strain tolerance of the binder, which can improve resistance of pavements to cracking.

2.3.1 Effect on Creep Response at Minimum Pavement Temperatures

Creep response measured using the BBR was characterized for the four different rubbers mixed with only the four asphalts. For rubbers AS and CG, the data collected included only asphalts A and B, which were chosen because they represent the two extremes in low-temperature properties among the four asphalts. The base and modified binders were tested at temperatures varying between \(-30\, ^\circ C\) and \(0\, ^\circ C\), depending on the asphalt tested. Figures 2.26 to 2.31 depict values for both creep stiffness \(S(t)\) and the logarithmic creep rate \(m(t)\) for the four modified asphalts along with the base asphalt. The data shown represent the response measured at a loading time of 60 seconds, which is used in the current SHRP specifications. SHRP specifications recommend a maximum value of 300 MPa for \(S(60)\) and a minimum value of 0.300 for \(m(60)\). A common temperature of \(-20\, ^\circ C\) was selected so that the data could be directly compared and also to capture the limiting range of 300 MPa.

Examining figures 2.26 to 2.28, it can be seen that for both asphalts, the addition of the crumb rubber modifier generally reduces the stiffness value. The reduction for asphalt A, which has a relatively low value of stiffness (51 MPa), is only minor. The reduction for
Figure 2.26. Effect of rubber type on creep stiffness of asphalt A.
Figure 2.27. Effect of rubber type on creep stiffness of asphalt B.
Figure 2.28. Effect of rubber type on creep stiffness of asphalts F & M.
Figure 2.29. Effect of rubber type on creep rate of asphalt A.
Figure 2.30. Effect of rubber type on creep rate of asphalt B.
Figure 2.31. Effect of rubber type on creep rate of asphalts F & M.
asphalt B, however, is much more significant and amounts to more than 400 MPa, which is more than a 50 percent reduction in the S(60) for this asphalt which is 720 MPa. The same level of reduction can be seen for asphalts F and M with the Tyreplex rubbers. This reduction is favorable with respect to the binder contribution to resistance of pavement cracking. For each asphalt, the reduction for all modifiers was relatively the same, indicating that the rubber type is not an important factor with respect to the reduction. Figure 2.26 also depicts the changes in S(60) for the four rubbers at -30 °C for asphalt A. The figure shows a significant reduction similar to the other asphalts. The effect is, therefore, not only asphalt-type specific, but also temperature dependent. The reduction is more at a lower temperature or higher stiffness value. The Tyreplex TP7-3 rubber resulted in the least reduction in creep stiffness; in the case of asphalt A, it actually increased the stiffness slightly above that of the original base asphalt at -20 °C.

Figures 2.29 to 2.31 show the change in m(60) for the same specimens shown in figures 2.26 to 2.28. Although the changes in m(60) values vary among the asphalts and the rubbers, there is a general trend indicating that the effect of rubbers is very small on this property. For asphalt A, the control rubbers reduced the creep rate, while the Tyreplex rubbers slightly increased or showed no significant reduction to the m(60) value of the base asphalt. In the case of asphalt B, the AS and TP9-1 modifiers slightly increased the value of m(60), while the CG and TP7-3 rubbers showed a slight decrease. A reduction in m(60) is not favorable, since m(t) is an indicator of the rate at which a binder can relax thermal stresses when cooled at a certain rate. The changes produced in all cases are not significant, and, therefore, it is unlikely that rubber type is an important factor with regard to changes in the logarithmic creep rate values.

2.3.2 Effect on Failure Properties

In the SHRP specifications, the strain at failure as measured by the direct tension device using a deformation rate of 1mm/min is used to reflect the propensity of binders to brittle failure. A minimum limit of 1 percent is recommended in the current specification. Figures 2.32 and 2.33 depict the strain at failure values for asphalts A and B for the four
Figure 2.32. Effect of CRM type on strain at failure of asphalt A.
Figure 2.33. Effect of CRM type on strain at failure of asphalt B.
rubber modifiers together with the base asphalt. The temperature for each set of data was selected so that the strain at failure for the base asphalt was close to the 1 percent limit. A temperature of -20 °C was selected for asphalt A, and a temperature of -10 °C was selected for asphalt B.

From data shown in these figures, it can be seen that the percent strain at failure increases significantly as a result of the addition of any of the crumb rubber modifiers. Although asphalts were tested at different temperatures, it appears that the rubbers are more effective in increasing the strain at failure of asphalt A than of asphalt B. The rubber type does not appear to have a major role in the changes of asphalt A, but it does appear to play an important role for asphalt B. This observation indicates that the changes are asphalt-rubber combination specific for the unaged condition.

2.3.3 Effect of Storage at High Temperatures

The effect of high temperature storage on the creep response and failure properties of the modified binders was examined in a similar fashion to the high and intermediate pavement temperature properties. The changes in creep stiffness after 24-hour storage are shown in figures 2.34 to 2.36. For asphalt A, figure 2.34 shows that the creep stiffness values remain approximately constant despite the storage at high temperatures. For asphalt B, the modified binders show some decrease in the stiffness values except for the Tyreplex rubber, which remains unchanged. For asphalts F and M with the Tyreplex rubber, figure 2.36 indicates that the storage results have a slight increase in S(60).

The changes in S(60) values for the Tyreplex rubber with any of the asphalts are all within the range of 10 percent of the initial (1-hour mixture) values. They are, therefore, not very important and can be considered within the range of experimental variations. The reduction for the other rubbers, however, is significant, particularly for asphalt B. The reduction is 30 percent for the AS rubber and 40 percent for the CG rubber, both with asphalt B. With the limited scope of the experiment, it is not possible to offer a good explanation for this phenomenon. The type of interaction that these rubbers undergo with the few asphalts selected is certainly complex in nature. The only finding to be noted here is
Figure 2.34. Effect of high temperature storage on $S(t)$ of asphalt A.
Figure 2.35. Effect of high temperature storage on S(t) of asphalt B.
Figure 2.36. Effect of high temperature storage on $S(t)$ of asphalts F & M.
that the interaction is asphalt- and rubber-specific and that the time of storage can result in significant changes for the AS and CG rubbers. For the Tyreplex rubber, however, the storage time does not appear to be of any importance, which confirms the stable character of the rubber with respect to the low temperature properties.

Figures 2.37 to 2.39 summarize the changes that occur in the logarithmic creep rate after the high-temperature storage. For asphalt A, despite the relative decrease in $S(60)$ for rubbers AS and CG, no change in the $m(60)$ values for any of the rubbers could be observed. For asphalt B, however, an increase in $m(60)$ could be observed for the AS and CG rubbers, while a slight decrease was observed for the Tyreplex rubber. These changes are in agreement with the changes observed for $S(60)$, considering that for all asphalt binders a decrease in $S(60)$ is usually accompanied by an increase in $m(60)$ values.

The general conclusion that can be drawn from an analysis of the results related to the effect of storage on creep response is that the effects can be important for some asphalt-rubber combinations, and that the effects are more pronounced at lower temperatures, or higher $S(60)$ values. The other important finding with regard to the Tyreplex rubber is the observation that the effect of storage was relatively minor for all four asphalt and temperature combinations. This observation confirms the stable character of this rubber with respect to high-temperature storage.

Figures 2.40 and 2.41 depict the changes measured for strain at failure due to high-temperature storage for two of the asphalts. For asphalt A, all mixtures show minimal changes with storage, which is in agreement with the results of the creep response shown in figures 2.34 and 2.35. Mixtures made with asphalt B show the same trend, except for rubber CG. The 24-hour data show significant increase in failure strain compared to the 1-hour data. The mixtures made with the AS and Tyreplex rubber do not show any changes. It is not known why the mixture with the CG rubber shows an increase in strain. The general trend, however, is that the low-temperature properties, including creep and failure properties, are not significantly affected by the high-temperature storage.
Figure 2.37. Effect of high temperature storage on m(t) of asphalt A.
Figure 2.38. Effect of high temperature storage on m(t) of asphalt B.
Figure 2.39. Effect of high temperature storage on m(t) of asphalts F & M.
Figure 2.40. Effect of high temperature storage on strain of modified asphalt A.
Figure 2.41. Effect of high temperature storage on strain of modified asphalt B.
2.3.4 Findings

The results of the evaluation of the effect of CRM's on low-temperature properties lead to a number of important findings. In general, the results indicate that the incorporation of rubber modifiers are beneficial with respect to the expected contribution of binders to low-temperature pavement performance. A general decrease in creep stiffness values, $S(60)$, has been observed for almost all combinations of rubbers, asphalts, and temperatures. These decreases amounted to more than 50 percent for certain combinations. The effect on the logarithmic creep rate, $m(t)$, was much smaller than the effect of $S(60)$. For some combinations, a reduction in $m(60)$ was observed which, although small in magnitude, is not favorable. The values of strain at failure were increased in all cases. In some cases the increase was by a significant margin of approximately an order of magnitude.

The enhancement of low-temperature properties were found similar for the four rubbers, which indicates that the type of rubber does not play a major role at low temperatures. The enhancement was, however, found to depend on asphalt type and the temperature of test. These two factors (asphalt type and temperature) cannot be considered independent, because response at different temperatures is a function of asphalt properties. The general trend found is that the higher the stiffness value (or the lower the test temperature), the more the effect of the rubbers.

The effects of CRM's on low-temperature properties are found to be significantly smaller than the effects observed for the high and intermediate temperature properties.

The study of failure properties for the modified asphalts was limited in scope compared to the other properties. The reason for this was the continuous modification of the testing system that was occurring during the time this experiment was conducted. The limited data collected, however, confirm that enhancement in low-temperature properties is the general trend resulting from the addition of the crumb rubber modifiers, produced by Tyreplex as well as others. The improvements in failure strain, however, should not be exaggerated, since the strain at failure of asphalts is very sensitive to temperatures, as indicated in previous studies.
Trends concerning the effects of high-temperature storage on low-temperature properties are a complex phenomenon. For certain combinations of asphalts and rubbers, significant changes were observed. Reductions in $S(60)$, which are a favorable change, were measured at approximately 40 percent for some combinations. The effects of storage were highly asphalt- and rubber-specific. For the Tyreplex rubber used in the study (TP7-3), no significant changes could be observed. This finding again reinforces the earlier findings with respect to the stability of this product during high-temperature storage.

Finally, it is important to realize that the findings within this section, as within this entire chapter, are based on testing binders in the unaged (tank) condition. Another important part of this study is the effect of CRM's on the aging characteristics of the asphalts, which relates to the behavior of the binder after it has been placed in the field and subjected to the effects of aging during its service life.
CHAPTER 3

EFFECT OF CRM TYPE ON AGING CHARACTERISTICS OF ASPHALT BINDER

The previous chapter discussed the effects of the crumb rubber modifiers on the unaged binders. The findings lead to the overall conclusion that the addition of the rubber modifiers did generally improve the rheological properties of the binder. One of the important characteristics of asphalt binders, which has important consequences on their contribution to pavement performance, is their aging performance.

Aging is known to be asphalt-specific; some asphalts are observed to age faster and become harder than others. This fact resulted in the need to characterize the aging performance of the different asphalts so that the resistance to aging is taken into account when selecting asphalts and predicting performance of asphalt pavements. Aging of asphalts in the field is known to occur in two different stages. The first stage is during mixing and lay-down operations, during which asphalts are exposed to rapid oxidation and volatilization resulting from the high temperatures and the large surface area of the heated aggregates. The second stage is a much slower process that occurs during the in-service life of the pavement when the oxygen in the environment percolates in the asphalt mixture and reacts with the asphalt binder. During the first stage, the loss of volatiles, particularly for certain asphalts, is a major factor that leads to hardening. During the second stage, the volatilization is minimal and therefore oxidation is known to be the main hardening mechanism.

As part of the SHRP research efforts, an investigation of the oxidative aging phenomenon of asphalts was carried out. One of the main objectives was to develop a lab-aging procedure that can simulate, in an accelerated fashion, the aging occurring in the field. This procedure was to be used to predict the propensity of an asphalt to oxidative aging during the design pavement life and hence be used for specification and quality control of binders. SHRP researchers elected to use either the thin film oven test (TFOT), as described by the ASTM standard method D1754, or the rolling thin film oven test (RTFO), as
described by the standard method D2872, as tests that could effectively simulate the aging that takes place during the mixing and lay-down operations. Therefore, the new aging procedure that would simulate only the in-service aging is done on the residue from either of these tests. For the aging happening during the long-term in-service conditions, the researchers developed a new test procedure called the Pressure Aging Vessel (PAV). The procedure is not totally new; it is based on previous works that were done during the past 40 years, and it is similar in many aspects to a current procedure used to evaluate the oxidation resistance of different types of polymers and plastics.

For this project, it was essential to see if the rubber modifiers had any influence on the aging characteristics of the base asphalts. The effect of the addition of CRM’s on the aging characteristics of the asphalt binder was examined by conducting laboratory aging and comparing the changes in mechanical properties of the rubber modified asphalts with the changes of the base (unmodified) asphalts due to that aging. The aging was done using the standard TFOT procedure (ASTM D1754) and the new SHRP PAV procedure. The variables included in this phase remained the same as those of phase 1. Two Tyreplex rubbers were used, TP9-1 and TP7-3; the ambient shredded (AS) and cryogenic grinded (CG) rubbers served as control rubbers. The four base asphalts also remained the same with the rubber content held constant at 15 percent by the total weight of the asphalt-rubber mixture. The same testing scheme that was used in Phase 1 of the project was again used in Phase 2. The analysis of results and the findings of Phase 2 are discussed in this chapter.

3.1 Effect on TFOT Properties

The Thin Filmed Oven Test (TFOT) is conducted at a temperature of 163°C for 5.25 hours and is designed to simulate the aging that is taking place during mixing and construction operations in the field. Following the mixing of the CRM with asphalts, each of the asphalt-rubber mixtures was subjected to the TFOT according to ASTM standard procedure D1754. After the aging, the mass loss and the rheological properties at test temperatures in the range of maximum pavement temperatures were measured.
3.1.1 Mass Loss

Mass loss is an indicator of the relative volatility of asphalt binders. Mass changes in the TFOT procedure combines the effect of both, the loss of volatiles as well as the gain in weight due to oxidation. Although mass loss is not a property that is directly related to pavement performance, the current specifications for asphalt binders as well as the proposed SHRP specifications place limits on the change in mass of a binder. Table 3.1 is a summary of the mass loss measured for the different asphalt-rubber combinations (the data are also shown in figure 3.1). The data in the table indicate that the rubbers result in higher mass loss values for all four asphalts. The relative increase is, however, dependent on the asphalt type. For example, while the change for asphalt A was only minor, the change in mass loss for asphalt B was more than double for all rubbers. The mass loss is also a function of the rubber type; the Tyreplex rubbers show higher mass loss values than the AS and CG rubbers for both asphalts. Replicate measurements for the mass loss is not available to assess the significance of the differences between the rubbers. Based on reported variability of the TFOT results, it can be stated that the addition of the rubbers resulted in important increases in mass loss values. With respect to the limits required in the new SHRP specifications (maximum of 1 percent), the increases are still well below that limit. Therefore, the increases, although important, are not considered excessive with respect to any standards for any of the rubbers including the Tyreplex rubbers.

In summary, the mass loss measurements indicate that the rubbers increase the mass loss; they show that the change is highly asphalt-specific and that the Tyreplex rubbers have slightly higher mass loss values. These findings raise some questions concerning the nature of interaction between rubbers and asphalts. The mass loss should decrease if the swelling/interaction phenomenon, which is used to explain the interaction between the rubber particle and the base asphalt, is to hold true. This phenomenon is hypothesized to be the result of the migration of the softer components (light ends) from the asphalt to the rubber, which should produce a decrease in the mass loss. It appears that the rubbers are selectively absorbing certain components of the asphalt, a process that leaves other volatile components more free to escape during the long-term aging in the TFOT procedure.
Table 3.1. Summary of mass change.

<table>
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<td>-0.464</td>
</tr>
<tr>
<td>AS/Asphalt A</td>
<td>-0.488</td>
</tr>
<tr>
<td>CG/Asphalt A</td>
<td>-0.489</td>
</tr>
<tr>
<td>TP9-1/Asphalt A</td>
<td>-0.83</td>
</tr>
<tr>
<td>TP7-3/Asphalt A</td>
<td>-0.538</td>
</tr>
<tr>
<td>Asphalt B</td>
<td>-0.071</td>
</tr>
<tr>
<td>AS/Asphalt B</td>
<td>-0.17</td>
</tr>
<tr>
<td>CG/Asphalt B</td>
<td>-0.174</td>
</tr>
<tr>
<td>TP9-1/Asphalt B</td>
<td>-0.511</td>
</tr>
<tr>
<td>TP7-3/Asphalt B</td>
<td>-0.238</td>
</tr>
<tr>
<td>Asphalt F</td>
<td>-0.276</td>
</tr>
<tr>
<td>TP9-1/Asphalt F</td>
<td>-0.666</td>
</tr>
<tr>
<td>TP7-3/Asphalt F</td>
<td>-0.412</td>
</tr>
<tr>
<td>Asphalt M</td>
<td>0.083</td>
</tr>
<tr>
<td>TP9-1/Asphalt M</td>
<td>-0.37</td>
</tr>
<tr>
<td>TP7-3/Asphalt M</td>
<td>-0.12</td>
</tr>
</tbody>
</table>
Figure 3.1. Effect of different rubber type on TFOT aging of asphalts.
3.1.2 Rheological Properties

The effect of the TFOT on the rheological properties of the rubber-modified binders was examined by testing the samples within the temperature range of 45 °C to 75 °C. The testing was done using the dynamic shear rheometer to measure the complex shear modulus \((G^*)\) and the phase angle \((\delta)\). The analysis of the results was done using the parameter \(G^*/\sin\delta (1/J'')\), since it is the parameter selected by SHRP to measure properties of binders in relation to pavement rutting. To measure aging caused by the TFOT, the ratios of \(1/J''\) before and after aging were calculated and compared for the different asphalt-rubber mixtures. The TFOT aging was done using the 1-hour mixed samples.

Figures 3.2 to 3.5 depict these \(1/J''\) ratios for the four asphalts modified with the different crumb rubbers. Figure 3.2 indicates that for asphalt A the ratios of \(1/J''\) vary within a relatively narrow range of 1.7 to 2.6 for all combinations of rubbers and temperatures. The ratios are similar to the base asphalt ratios, and they do not change significantly with the test temperature. With regard to rubber type, the AS rubber shows the smallest ratios while the TP9-1 shows the largest ratios. For asphalt B, the ratios also vary within a narrow range, but they are on average smaller than the ratios for asphalt A. The ranking of the rubbers is different from asphalt A, and there appears to be more dependency on the temperature. For asphalts F and M, the ratios, shown only for the Tyreplex rubbers, are within the same range as the other asphalts and indicate that rubber TP9-1 consistently shows higher ratios than the TP7-1 rubber.

The ratios shown in figures 3.2 to 3.5 are all within acceptable, normal limits known for paving-grade asphalt binders. The results indicate that the rubbers do not appear to significantly change the TFOT-aging characteristics of the base asphalts. This result is interesting because it was expected that during the aging in the TFOT at 163 °C, the reaction between asphalt and rubbers would proceed and certain changes in aging characteristics would be observed. Knowing that for the AS and CG rubbers the reaction must have proceeded, the results discussed in this section confirm that the reaction does not affect rheological properties at maximum pavement temperatures.
Figure 3.2. Ratio of $1/L''$ values (TFOT/1hr unaged) for asphalt A.
Figure 3.3. Ratio of $1/J''$ values (TFOT/1hr unaged) for asphalt B.
Figure 3.4. Ratio of $1/J''$ values (TFOT/1hr unaged) for asphalt F.
Figure 3.5. Ratio of $1/l''$ values (TFOT/1hr unaged) for asphalt M.
3.2 Effects on Aging in the PAV

The second type of aging, long-term aging, which includes mainly oxidation with minimal volatilization, is simulated by using the Pressure Aging Vessel (PAV) procedure as developed for the SHRP specifications. This procedure involves aging the asphalt specimens of a given film thickness in a pressure vessel for 20 hours at temperatures ranging between 90 °C and 110 °C. The procedure presumably represents 5 to 10 years of pavement aging in the field. Although the PAV development did not include a validating procedure for modified binders, such as asphalts modified with CRM, it was assumed in this experiment that the procedure was valid and could represent field aging of the tested asphalts.

The PAV procedure was used to age binders that were aged already in the TFOT. Following the PAV aging, which was done at 100 °C for 20 hours under 2.07 MPa pressure, the aged binders were tested using the dynamic shear rheometer, bending beam rheometer, and the direct tension test device. Rheological properties were measured at intermediate and low pavement temperatures. The failure properties were measured only at low-pavement temperatures. The following sections discuss the results of the PAV-aging experiment and compares the effects of the different rubbers.

3.2.1 Rheological Properties at Intermediate Pavement Temperatures

The effect that the crumb rubber modifiers have on the aging characteristics of asphalts as measured by PAV aging, at intermediate pavement temperatures, was determined by analyzing changes in the parameter $G''$. The testing was conducted using the DSR within a temperature range of 5 °C to 35 °C. The data are plotted in terms of ratios or relative change between the PAV residue and the 1-hour mixed material.

The $G''$ values were used to calculate the ratio of $G''$ of the PAV residue to $G''$ of the unaged binder. The ratios for each of the four asphalts are shown in figures 3.6 to 3.9. The bar charts in these figures indicate that for all combinations of asphalt, rubber, and temperature, the addition of the rubbers results in smaller aging ratios. The one exception that can be seen is asphalt F with the TP9-1 rubber (figure 3.8) which gives a slightly higher
Figure 3.6. Ratio of $G''$ values (PAV/1 hr) for asphalt A.
Figure 3.7. Ratio of $G''$ values (PAV/1 hr) for asphalt B.
Figure 3.8. Ratio of $G''$ values (PAV/1 hr) for asphalt F.
Figure 3.9. Ratio of $G''$ values (PAV/1 hr) for asphalt M.
ratio than the base asphalt. The decrease in the ratio is certainly a favorable change since it indicates that the rubbers result in less hardening due to aging. The results shown also indicate that the ratios for any binder (modified or base) increase with temperature consistently. This trend is expected from the nature of change of rheological properties due to oxidative aging. The trend indicates that the rubbers do not alter the nature of change of rheological properties due to oxidative aging; they only reduce the magnitude of aging. The relative change in ratios is observed to be highly asphalt- and rubber-specific. The data in figure 3.7 for asphalt B show a reduction in aging ratios from a value of 8 for the base asphalt to a value of 1.2 for the same asphalt after mixing with the CG rubber. In figures 3.8 and 3.9, however, the rubbers do not show effects of the same significance for asphalt A and B. The Tyreplex rubbers (TP7-3 and TP9-1) show similar effects for all asphalts. Their effect is somewhat different from the CG rubber, which shows the lowest values for asphalts A and B, and from the AS rubber, which still shows lower values than the Tyreplex rubbers.

The differences between effects of the different rubbers are significant only at higher temperatures (25 °C and 35 °C). At 5 °C and 15°C, where the G" values are more critical with respect to pavement performance, the rubbers essentially show the same effects. It can, therefore, be concluded that the change in aging characteristics due to CRM addition within the range of critical properties is similar for the different rubbers. The effect within the region of critical values is, however, highly asphalt-specific. Hardening of asphalts A and B is more reduced by the addition of the rubber compared to asphalts F and M.

3.2.2 Low Pavement Temperatures

The low-temperature SHRP parameters of creep response and creep rate were measured using the bending beam rheometer (BBR) for the PAV-aged asphalts A and B. These asphalts were chosen because they represent extremes in physical and chemical properties. The measurements used to evaluate aging were the creep stiffness and logarithmic creep rate at 60 seconds of loading time, S(60) and m(60) respectively. Also the strain at failure at selected temperatures was used. These measurements represent the control parameters used in the SHRP specifications for low-temperature thermal cracking. The
effect of the rubbers on aging was studied by comparing the effects of the rubbers before and after the PAV aging.

The creep stiffness $S(t)$ values are shown in figures 3.10 and 3.11 for asphalts A and B respectively. The data for asphalt A depict an increase in the value of creep stiffness ranging from 367 MPa to 491 MPa for the base asphalt. For the CRM-modified binders, the relative increase in $S(60)$ values is significantly lower and is similar for the different rubbers. Figure 3.11 for asphalt B shows a similar trend. The figure, however, shows some variation among the rubbers with the Tyreplex rubbers, showing higher values. Figures 3.12 and 3.13 depict the $m(60)$ values for the same asphalts. Similar to the effects observed for the unaged condition (section 2.3), the influence of rubbers on $m(60)$ values is very small. In fact, for the PAV-aged condition, the changes in $m(60)$ values are even smaller and tend to shift to the positive direction as shown in figure 3.13. With regard to the role of rubber type and asphalt type, the data collected show small variations that do not warrant any significant comments about the importance of these factors.

3.2.3 Failure Properties After PAV Aging

Failure strain of the PAV-aged samples was measured using the direct tension device at temperatures ranging between -30 °C and 0 °C. Similar to tests conducted for the unaged binders, the SHRP standard deformation rate of 1mm/min was used for all tests. Results from testing are shown in figures 3.14 and 3.15 for asphalts A and B respectively. Three rubbers along with the base asphalt were tested at various temperatures, depending on their properties such that the measurements be in the range of 1 percent strain. The 1 percent strain is the limit used in the SHRP specification to reflect transition from brittle to ductile failure. The values are shown at the temperature which captured the 1 percent strain.

Figure 3.14 indicates that there is a general reduction in value of failure strain after aging for the base- and the rubber-modified asphalts. The rubber-modified asphalts, however, show relatively higher reductions than the base asphalt. Despite the reduction, the modified asphalts still show higher values of strain compared to the base asphalt. Since the degree of reduction is relatively the same among the rubbers, there is little speculation that
Figure 3.10. Effect of PAV on creep stiffness of modified asphalt A.
Figure 3.11. Effect of PAV on creep stiffness of modified asphalt B.
Figure 3.12. Effect of PAV of creep rate of modified asphalt A.
Figure 3.13. Effect of PAV on creep rate of modified asphalt B.
Figure 3.14. Effect of PAV on strain at failure of modified asphalt A.
Figure 3.15. Effect of PAV on strain at failure of modified asphalt B.
rubber type has an influence on the amount of decrease. In the case of asphalt B, figure 3.15 also depicts a reduction in strain values after aging. The data in the figure, however, show less reduction due to PAV aging with the exception of the AS rubber. The AS rubber decreased at a greater rate and fell into range with the other rubber types. The modified asphalts still maintained a higher value of strain over the base asphalt B in the aged condition. The data suggest that the ratio of improvement of the modified asphalts over the base asphalt for asphalt B remains the same if not slightly increased for the aged condition.

3.3 Findings

Based on the analysis discussed in this chapter, several findings can be stated with regard to the effect of the addition of CRM on aging characteristics of asphalt cements.

The TFOT-aging results indicate that all rubbers result in a significant increase in mass loss of the asphalts as measured by the standard ASTM method (D1754). The TFOT results, however, indicate that these significant changes in mass loss are not accompanied by significant changes in rheological properties at high pavement temperatures. The discrepancy between effects on mass loss and rheological properties is not simple to explain. The increased mass loss also raises some questions with respect to the nature of the interaction between asphalts and rubbers at elevated temperatures. This observation could not be further investigated within this project, but it should be considered in future research.

The effect of rubbers on aging characteristics in the PAV indicated several trends. At intermediate pavement temperatures, aging measured in terms of changes in G" values, a significant reduction in hardening is observed for many asphalt-rubber combinations. This change is favorable for paving applications and is expected to contribute to better resistance to fatigue cracking. Although there are some differences in the effects of rubbers on hardening at relatively high testing temperatures, within the range of critical G" values, the rubbers show generally the same effect. The effects were, however, clearly asphalt-specific.

At low pavement temperatures, the creep and failure measurements confirmed the trend that there are some benefits that can be gained from CRM addition with respect to the aging of asphalts. The PAV-aged samples show more reduction in creep stiffness values
(S(t)) compared to the unaged samples. The slight reduction in m(60) values observed for the unaged samples is reduced further after PAV aging, and in some cases it turns into an increase in m(60). No significant differences between the effects of the different rubbers could be observed. For the failure strain values, the increase in failure strain is less after PAV aging compared to the unaged samples. The failure strain values are still, however, higher than the base asphalt values after PAV aging. The general conclusion that can be drawn from the aging study is that crumb rubbers can produce significant favorable changes in the aging characteristics of certain asphalts.
CHAPTER 4

GUIDELINES FOR SELECTING CRM CONCENTRATION

Similar to other modifiers, the effect of CRM on the mechanical properties of the modified binder will depend on the concentration of the CRM in the binder. For this study, four different concentrations were used for each asphalt-rubber combination. The concentrations, measured in terms of the weight of CRM to weight of the total asphalt rubber, varied between 5 percent and 20 percent at 5 percent increments. These concentrations were selected based on a review of the published literature, personal communications with asphalt rubber producers, and exploratory experiments done in the laboratory. For each concentration, the modified asphalt was fully characterized at high, intermediate, and low temperatures. The objective of this phase of the study was to establish guidelines for selecting CRM concentration to meet specific requirements defined by the user. The requirements can be defined in terms of property values at selected climatic conditions that reflect the pavement application conditions. The results and findings of the CRM concentration experiment are discussed in this chapter.

4.1 High Temperature Consistency

The consistency at the mixing and compaction temperatures is the measure used to evaluate the workability of asphalt binders. SHRP researchers selected a maximum limit of 3.0 Pa·s to ensure workability of the binder. Two objectives were defined for this experiment: (1) quantify the role of CRM content on workability within the practical, reasonable limits used in the field, and (2) evaluate the interaction between the content and type of rubber in their effects on workability. Only 1-hour mixtures were tested for this experiment, and the tests were conducted at three temperatures (135 °C, 160 °C, and 185 °C). All tests were performed using the same shear rate, spindle size, and thermal history. Figures 4.1 and 4.2 depict bar charts for rubber TP7-3 mixed with asphalts A and B,
Figure 4.1. Effect of asphalt/rubber ratio on rotational viscosity of asphalt A.
Figure 4.2. Effect of asphalt/rubber ratio on rotational viscosity of asphalt B.
respectively, at four different percentages. The results indicate that viscosity is continuously increasing with rubber content at all three temperatures. The increase for both asphalts is very significant compared to the neat asphalts, and it is also very significant at the different rubber ratios. For example, the increase in viscosity between the 5 percent and the 20 percent rubber content is in the order of 10 folds or more at any combination of asphalt and temperature. The bar charts in figures 4.1 and 4.2 also indicate that the effect of rubber content is not linear and that it is possibly a function of the temperature. Figures 4.3 and 4.4 provide some insight into the nature of the effect; plotting viscosity as a function of rubber content confirms that the effect of the rubber content is not linear, and it clearly shows that the effect of rubber content is a function of the temperature. Plotting the viscosity on a logarithmic scale, as shown in figures 4.5 and 4.6, indicates that the relation cannot be linearized by using the logarithmic transformation, but it shows that the relation is similar for the different temperatures. The same trends were observed for the other two rubbers (AS and CG) with either of the asphalts. Figures 4.7 and 4.8 depict the results for the three rubbers at two temperatures. The results for rubbers AS and CG, although fitting the same trend at lower rubber contents, deviate at higher contents where some measurements are missing. The measurements for these two rubbers where difficult to collect at 20 percent concentration because of their reaction with the asphalts during the measurements. Variability between the replicates were high, and for some systems measurements would not be stabilized. Figures 4.7 and 4.8, however, show that within the limit of 15 percent rubber, effects of the three rubbers are similar.

The modeling of the effect of the rubber such that viscosity can be estimated from only a few measurements is useful for the selection of rubber contents and for predicting mixing, production, and construction temperatures. The model can be developed only for the TP7-3 rubber produced by Tyreplex, because it was the only stable rubber that good measurements could be collected. A third-order polynomial was selected as the general form of the model because the relation between logarithm of viscosity and rubber content was cubic in nature as shown in figures 4.5 and 4.6. The form of the model is shown in equation 4.1, which is fitted for asphalt A at 135 °C.
Figure 4.3. Viscosity-rubber content profiles at different temperatures for asphalt A mixed with rubber TP7-3 for 1 hr.
Figure 4.4. Viscosity-rubber content profiles at different temperatures for asphalt B after one-hour mixing.
Figure 4.5. Viscosity-rubber content profiles at different temperatures for asphalt A mixed with rubber TP7-3 for 1 hr.
Figure 4.6. Viscosity-rubber content profiles at different temperatures for asphalt B mixed with rubber TP7-3 for 1 hr.
Figure 4.7. Viscosity-rubber content profiles at different temperatures for asphalt A mixed with 3 rubbers for 1 hr.
Figure 4.8. Viscosity-rubber content profiles at different temperatures for asphalt B mixed with 3 rubbers for 1 hr.
Log (Vis) = 2.287 + 0.0223(RC) + 0.0032(RC)^2 - 0.000002(RC)^3

The R² for this model is 0.996 and the standard error of log (Vis) estimate is 0.0345. The same level of goodness of fit was observed for the other temperatures and with the other asphalt. To generalize the model, however, the temperature effect has to be included in the model because the regression coefficients were significantly different for the different temperatures. Furthermore, the base-asphalt effect has to be included in a generalized model; different asphalts will have different viscosities. To account for both of these factors, the viscosity ratios (called here normalized viscosities, VR) can be used. The normalized viscosities calculated by the ratio of viscosity of asphalt rubber to the viscosity of the neat asphalts were calculated at all temperatures. Figure 4.9 depicts the normalized viscosities, plotted on a logarithmic scale, versus rubber content for both asphalts. The figure shows that the normalization reduced the effect of the temperature significantly. The figure also indicates that a lower-order polynomial might give a good fit for the data. A first-order, second-order, and a third-order polynomial were fitted to examine the level of goodness of fit for each polynomial. The statistical analysis for the models is shown in table 4.1. The analysis first included the rubber content (RC) as the only independent variable. As shown in the table, first-order, second-order, and third-order polynomial were used, and each gave a different set of values for the statistical indicators. Although the R² values are comparable for the models, the standard error of estimate is relatively high. The second-order polynomial was found to be a good model because going to the third order did not result in a significant improvement in either the power of estimation (as indicated by the standard error of the Y estimate) the goodness of fit (as indicated by the adjusted R²). Evaluating the predicted and measured values, however, indicated that neglecting the temperature effects is not acceptable, despite the fact that a viscosity ratio is used. A final model was selected that includes the RC, the RC², and the temperature as the main factors. The standard error of estimate is significantly reduced, and the R² is slightly increased. Figure 4.10 shows the comparison between measured and predicted viscosity values for the two asphalts modified by the Tyreplex rubber at different temperatures. As indicated in the figure, the predicted and measured values show excellent correlation, and the scatter is relatively small.
Figure 4.9. Viscosity ratio versus rubber content at different temperatures for asphalt A after mixing with TP7-3 for 1 hr.
Figure 4.10. Measured versus predicted viscosity values for asphalts A and B mixed with TP7-3 for 1 hr.
Table 4.1. Statistical models for estimation of viscosity of CRM-modified asphalts.

<table>
<thead>
<tr>
<th>Model</th>
<th>Std. Error of Y est</th>
<th>Std. Error of Coefficient</th>
<th>R² adjusted</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>log</strong> (VR) = 0.0698 (RC)</td>
<td>0.1609</td>
<td>0.0024</td>
<td>0.921</td>
</tr>
<tr>
<td>log(VR) = 0.0377 (RC) + 0.0019 (RC)^2</td>
<td>0.1287</td>
<td>0.00794</td>
<td>0.950</td>
</tr>
<tr>
<td>log(RV) = 0.0086 (RC) + 0.0064 (RC)^2 - 0.000154 (RC)^3</td>
<td>0.1259</td>
<td>0.02091</td>
<td>0.952</td>
</tr>
<tr>
<td>For Viscosity Estimation</td>
<td>0.990</td>
<td>0.00089</td>
<td>0.970</td>
</tr>
<tr>
<td>log(VR) = -0.6699 + 0.00406 (T) + 0.0412 (RC) + 0.001794 (RC)^2</td>
<td>9.716</td>
<td>0.0090</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

VR = Viscosity Ratio of rubberized to neat asphalt
RC = Rubber Content in percentage
T = Temperature, °C

The other topic that needs to be addressed is the effect of different rubber contents on the viscosity-temperature profiles. Figures 4.11 and 4.12 depict viscosity values, plotted on a logarithmic scale, as a function of temperature for asphalts A and B before and after the addition of the Tyreplex rubber TP7-3. The figure shows that the relation between the logarithm of viscosity and temperature remains linear for all CRM contents. Figure 4.13 depicts a plot similar to figure 4.11 but includes different rubbers at three contents of 5, 10, and 15 percent. The figure indicates that at low rubber contents (5 percent), all rubbers show the same effect and the same viscosity temperature profile. As the rubber content increases, however, the viscosity-temperature profiles start to deviate and show significant differences related to rubber type. The same trend was observed for the other asphalt included in the study. Comparing the effect of the three rubbers, the TP7-3 rubber produced
Figure 4.11. Viscosity-temperature profiles for different rubber content for asphalt A after one-hour mixing.
Figure 4.12. Viscosity-temperature profiles for different rubber contents for asphalt B after one-hour mixing.
Figure 4.13. Viscosity-temperature profile for three rubbers mixed with asphalt A at three contents.
by Tyreplex consistently shows the least increase in viscosity compared to the ambient shredded rubber (AS) and the cryogenic grinded rubber (CG), which show the largest increase in viscosity.

The analysis of the rotational viscosity data indicates that there is a significant interaction between rubber content and temperature; a relative increase in viscosity for asphalt A and rubber TP7-3, for example, ranges between 23 at 135 °C to approximately 40 at 185 °C for the rubber content of 20 percent. The temperature effects can, however, be normalized by expressing the effect of the rubber in terms of the ratio of viscosity of the rubberized asphalt to the neat asphalt. A simple regression model was developed to estimate the viscosity ratio, using the rubber content as the only independent variable. The model was developed using only two asphalts that are different in their chemical and physical properties. The statistical analysis indicates that the asphalt type was not an important factor and therefore was not included in the regression model. The analysis also indicates that there is a significant interaction between the rubber content and rubber type as shown in figure 4.13. The interaction is more pronounced at higher contents. In relation to the limit recommended by SHRP (maximum of 3.0 Pa-s at 135 °C), it can be concluded that the 20 percent rubber content will not meet the requirement for both asphalts for all rubber types. All other combinations of rubber type and content will meet the requirement. In addition, visual evaluation of the asphalt rubber mixes at 20 percent indicate that they are of spongy nature and are expected to be difficult to handle for pavement applications.

4.2 Rheological Properties at High Pavement Temperatures

As discussed in earlier chapters, the parameter selected by SHRP to indicate binder contribution to resistance of pavement to rutting is $G'/\sin\phi$, which is equivalent to the inverse of the creep compliance $(1/J)$. CRM modifiers are known to be very effective in improving the properties at high pavement temperatures by increasing the value of $G'$ and by decreasing the value of $\sin\phi$. The effect of the content of the rubber and the type of the rubber has not been well investigated. One of the objectives of this study was to evaluate the effect of these factors with two of the selected asphalts and try to develop a model that can be used to
estimate effects that would assist in the design of modification without the need for extensive testing.

Figures 4.14 and 4.15 depict bar charts for $1/J''$ values for asphalts A and B mixed with different percentages of rubber TP7-3. The results shown indicate that $1/J''$ is a continuous increasing function of the rubber content. On a relative basis, the effect is more pronounced at higher temperatures. It also appears that the increase in $1/J''$ is not a linear function of the rubber content. Figure 4.16 shows the same results plotted as a function of rubber content for different temperatures and confirms these trends. To linearize the relation between $1/J''$ and the rubber content several transformations were tried. The logarithmic transformation of the parameter $1/J''$ was found to give the best fit as shown in figure 4.17. The excellent fit was also observed for most of the other rubber-asphalt combinations.

Although the relation is simplified by becoming a linear function of the rubber content, the effects of three other factors (temperature, asphalt type, and rubber type) need to be considered. The temperature was clearly an important factor as it changes the starting value (neat asphalt) of $1/J''$. The asphalt type is also important and it is actually expected to have some interaction with temperature, because asphalts vary in both their values of $1/J''$ as well as the sensitivity to temperature. To investigate the effects, a general linear model was used with successive elimination of factors to evaluate the goodness of fit using the different factors. The results for the Tyreplex rubber are listed in table 4.2. The statistical analysis indicates that the best estimation model includes all three factors (rubber content, temperature, and asphalt content). The $R^2$ value of this model is 0.97, which indicates that an interaction term between any two of these factors is not important. Eliminating the asphalt type as a factor reduced the $R^2$ value to 0.932 and increased the standard error of estimate from 0.1234 to 0.1861, a change that can be considered important. Although the $R^2$ value is high, since the experiment included only two asphalts, it is not recommended that this factor be removed from the model. Eliminating the temperature as a factor resulted in a very low $R^2$ value of 0.252, which is not acceptable.

The analysis of a model for the Tyreplex rubber was a first step to look at a more general model that represents all rubbers. Table 4.3 lists the statistical analysis of the models used to estimate $1/J''$ from the independent variables included in the experiment. The
Figure 4.14. Effect of rubber content on $1/1''$ of TP7-3 modified asphalt A.
Figure 4.15. Effect of 5% rubber concentration on $1/J''$ of asphalt B.
Figure 4.16. Variation of $1/J''$ with rubber content at different temperatures for asphalt A mixed with rubber TP7-3.
Figure 4.17. Variation of $1/J''$ with rubber content at different temperatures for asphalt A mixed with rubber TP7-3.
Table 4.2. Statistical models for estimation of $1/J''$ for asphalts modified with Tyreplex rubber only.

<table>
<thead>
<tr>
<th>Model</th>
<th>Std. Error of Y est</th>
<th>Std. Error of Coefficient</th>
<th>$R^2$ adjusted</th>
</tr>
</thead>
</table>
| For TP7-3 rubber:  
  $\log(1/J'') = 5.5118 + 0.0520 \ (RC)$  
  $- 0.0515 \ (Temp) + 0.2707 \ (AC)$  
  $0.1234$ | $0.0028$ | $0.0017$ | $0.0390$ | $0.970$ |
| For TP7-3 rubber:  
  $\log(1/J'') = 5.9179 + 0.0520 \ (RC)$  
  $- 0.0515 \ (Temp)$  
  $0.1861$ | $0.00416$ | $0.00263$ | $0.932$ |
| For TP7-3 rubber:  
  $\log(1/J'') = 2.8276 + 0.0520 \ (RC)$  
  $0.6187$ | $0.01383$ | $0.252$ |

RC = Rubber Content in percentage (0, 5, 10, 20 percent)  
Temp = Temperature of testing (45, 55, 65, 75 °C)  
AC = Asphalt type (1, 2)  

Table 4.3. Statistical models for estimation of $1/J''$ for all three rubbers.

<table>
<thead>
<tr>
<th>Model</th>
<th>Std. Error of Y est</th>
<th>Std. Error of Coefficient</th>
<th>$R^2$ adjusted</th>
</tr>
</thead>
</table>
| For all rubbers:  
  $\log(1/J'') = 5.5095 + 0.0586 \ (RC)$  
  $- 0.0504 \ (Temp) + 0.2032 \ (AC) - 0.00488 \ (RT)$  
  $0.1573$ | $0.0020$ | $0.0013$ | $0.0287$ | $0.0176$ | $0.953$ |
| For all rubbers:  
  $\log(1/J'') = 5.4500 + 0.0586 \ (RC)$  
  $- 0.0504 \ (Temp) + 0.2032 \ (AC)$  
  $0.1567$ | $0.0020$ | $0.0013$ | $0.0286$ | $0.953$ |
| For all rubbers:  
  $\log(1/J'') = 5.8142 + 0.0585 \ (RC)$  
  $- 0.0504 \ (Temp) - 0.0049 \ (RT)$  
  $0.1876$ | $0.0024$ | $0.0015$ | $0.0210$ | $0.933$ |
| For all rubbers:  
  $\log(1/J'') = 5.805 + 0.0586 \ (RC)$  
  $- 0.0504 \ (Temp)$  
  $0.1869$ | $0.0024$ | $0.0015$ | $0.934$ |

RC = Rubber Content in percentage (0, 5, 10, 20 percent)  
Temp = Temperature of testing (45, 55, 65, 75 °C)  
AC = Asphalt type (1, 2)  
RT = Rubber Type (1, 2, 3)
first model included the rubber content, the temperature, and the asphalt type. The $R^2$ value is 0.953 and the standard error of the estimate is 0.1567. All factors are found significant as can be seen from the standard error of coefficients.

Another model that was considered included the rubber content, temperature, and the rubber type. This model had a slightly lower $R^2$ and a higher standard error of estimate. In addition, the value of the standard error of coefficient for the rubber-type content does not indicate that this factor is of importance. The last model considered included only two factors (rubber content and temperature). The $R^2$ for this model was higher than the model with the rubber type (0.934) as well as the standard error of estimate (0.1869). This result indicates that the rubber type is certainly not an important factor. It also indicates that for the two asphalts tested, the effect of asphalt type does not appear to be important. It is, however, expected that as other asphalts with more significant differences in their rheological properties are used, more important effects of the asphalt type will be observed. It is, therefore, recommended that asphalt type be kept as a factor in the model. No interaction terms seem to be important as the standard error of estimates and the $R^2$ indicate a high level of goodness of fit. The correlation between measured values of $1/J''$ and predicted values using the selected model are shown in figure 4.18.

The analysis of the results related to $1/J''$ at high pavement temperatures indicates some very interesting trends. The linear relation between the increase in $1/J''$ and the rubber content, which was observed to be valid for all combinations of rubber and asphalt, indicates that the effect of rubbers is simple and can be reliably predicted using linear models. The simplicity is also seen in the absence of significant interactions between the important factors that were found to be rubber content, temperature, and asphalt type.

### 4.3 Rheological Properties at Intermediate Pavement Temperatures

The mode of distress that prevails at intermediate pavement temperatures is fatigue cracking. To improve the contribution of binders to resistance to fatigue cracking, SHRP recommends a maximum value for the parameter $G^\ast\sin\phi$, which is the equivalent to $G''$ known in rheology as the loss modulus. The effect of the addition of rubber on $G''$ of
Figure 4.18. Comparison of measured and predicted values of $1/J''$ for asphalts A and B with 3 rubbers.
asphalts was shown in previous chapters to depend on the type of the asphalt. It was also shown to be marginal at a concentration of 15 percent. The objective of this part of the experiment was to quantify the effect of the different rubber contents and try to develop a statistical model to estimate the effects as a function of rubber content as well as other factors.

Figures 4.19 and 4.20 depict sets of bar charts that represent the change in $G''$ values for asphalts A and B at four temperatures ranging between 5 °C and 35 °C. The figures, which shows results for rubber TP7-3, indicate that the effect is highly asphalt-specific. For asphalt A, which is a relatively soft asphalt with low values of $G''$, the rubber consistently increased the value of $G''$ at all temperatures and for all rubber contents, except for the rubber content of 5 percent. For asphalt B, however, the rubber was either resulting in a similar or a lower value. Plotting $G''$ versus rubber content, as shown in figure 4.21, indicates that similar to the parameter $1/J''$ at high pavement temperatures, $G''$ as a function of rubber content can be linearized by a logarithmic transformation of $G''$. For asphalt A, $G''$ is an increasing function of rubber content at all temperatures. For asphalt B (figure 4.22), the relation changes from a positive slope to a negative slope as the temperature decreases. In other words, at temperatures of 15 °C and 5 °C, $G''$ is a decreasing function of rubber content. This behavior can be explained by considering the difference in stiffness of the rubber and the asphalt. It appears that at a certain temperature the asphalt stiffness becomes larger than the stiffness of the rubber, and thus a drop in $G''$ values is observed as rubber content increases. The trends shown in figures 4.21 and 4.22 were observed for the other two rubbers.

As with other properties, a general linear model approach was used to fit the data for the different rubbers at different temperatures. Table 4.4 lists the statistical analyses for the final selected models. The first includes all factor studies: rubber content, temperature, asphalt type, and rubber type. The model fit is very good with an $R^2$ value of 0.947 and a standard error of estimate of 0.1987. The last factor (rubber type) did not show a significant effect when the raw data were compared. To examine whether it is of any significance for the model, it was dropped as shown in the second model in table 4.4. The $R^2$ value did not decrease, but the standard error of estimate increased by a small margin. The model is
Figure 4.19. Effect of rubber content on $G''$ of TP7-3 modified asphalt A.
Figure 4.20. Effect of rubber content on $G''$ of TP7-3 modified asphalt B.
Figure 4.21. Change in $G''$ as a function of rubber content for asphalt A mixed with rubber CG.
Figure 4.22. Change in $G''$ as a function of rubber content for asphalt B mixed with rubber CG.
therefore considered very acceptable. To further examine the possibility of eliminating other 
factors, the asphalt type was removed from the model as shown in the third model, but a low 
$R^2$ of 0.764 was obtained, which is not acceptable. The model recommended is therefore the 
second model with three main effects (rubber content, temperature, and asphalt type). The 
statistical analyses indicate that no interaction terms are necessary for the model. 
The model can therefore be used by measuring the $G''$ value of the neat asphalt at a certain 
temperature (between 5°C and 45°C) and substituting in the equation to find the value of 
constant terms, which will include the term with the asphalt type.

Table 4.4. Statistical models for estimation of $G''$ for all three rubbers.

<table>
<thead>
<tr>
<th>Model</th>
<th>Std. Error of $Y_{est}$</th>
<th>Std. Error of Coefficient</th>
<th>$R^2$ adjusted</th>
</tr>
</thead>
</table>
| For all rubbers: 
   $\log(G'\prime) = 5.4744 + 0.01548 (RC)$ 
   $-0.06685 (Temp) + 0.7272 (AC) + 0.0528 (RT)$ | 0.1987 | 0.00323 | 0.947 |
| For all rubbers: 
   $\log(G'\prime) = 5.8144 + 0.0178 (RC)$ 
   $-0.0669 (Temp) + 0.7272 (AC)$ | 0.2037 | 0.00316 | 0.945 |
| For all rubbers: 
   $\log(G'\prime) = 6.9052 + 0.01782 (RC)$ 
   $-0.06685 (Temp)$ | 0.4210 | 0.00323 | 0.764 |

RC = Rubber Content in percentage (0, 5, 10, 20 percent) 
Temp = Temperature of testing (45, 55, 65, 75°C) 
AC = Asphalt type (1, 2) 
RT = Rubber Type (1, 2) 

Similar to the properties at high pavement temperatures, the analysis of the parameter 
$G''$ ($G''\sin\phi$) measured at intermediate pavement temperatures (5°C to 45°C) indicates that the 
effect of rubbers on the asphalts' response is simple in nature. The relation between the 
logarithm of $G''$ and rubber content was found to be linear and dependent on the temperature.
and asphalt source. The effects of the three factors were found to be independent. This independence was observed from the lack of a need for interaction terms between the variables to get a good statistical fit of the measurements.

4.4 Rheological and Failure Properties at Low Pavement Temperatures

The mode of distress that prevails at low pavement temperatures is thermal cracking. To improve the contribution of binders to resistance to thermal cracking, SHRP recommends a maximum value for the parameter $S(t)$, a minimum value for $m(t)$, and a minimum value for failure strain. The effect of the addition of rubber on these parameters for asphalts was shown in previous chapters to depend on the type of the asphalt and test temperature. It was also shown to be relatively small at a rubber concentration of 15 percent. The objective of this part of the experiment was to quantify the effect of different rubber contents on the change in these parameters. Unlike properties at higher temperatures, there was no intention of developing statistical models to estimate the effects as a function of rubber content as well as other factors. The reason for this lies in the difficulty of conducting testing at multiple temperatures, which entails the need for using new specimens at each temperature and the fact that the effect is relatively small compared to other properties. Testing, however, was conducted for two asphalts at multiple rubber contents at only selected temperatures to establish the nature of the rubber-content effect.

Figures 4.23 and figure 4.24 depict a set of bar charts that represent the change in $S(t)$ and $m(t)$ values for asphalt B at -18 °C, respectively. The figures, which show results for only rubber TP7-3, indicate that the effect is a continuous reduction in $S(t)$ accompanied by variable small changes in $m(t)$ values. This trend is also observed for other rubbers as shown in figure 4.25. The data shown in figure 4.25 indicate that the change in $S(60)$ is not linear within the low range of rubber content, but it becomes so at the higher contents. The data also indicate that the rubbers have similar effects for this asphalt. Figure 4.26 shows the variation in $m(60)$ values with rubber content for the 3 rubbers with asphalt B. The data confirms the finding that the rubbers have only a minor effect on $m(60)$ values. The similarity of effects of the different rubbers on $S(60)$ values does not appear to be true for all
Figure 4.23. Effect of rubber content on $S(t)$ of TP7-3 modified asphalt B.
Figure 4.24. Effect of rubber content on m(t) of TP7-3 modified asphalt B.
Figure 4.25. Change in $S(60)$ as a function of rubber content for asphalt B mixed with different rubbers.
Figure 4.26. Change in m(60) as a function of rubber content for asphalt B mixed with different rubbers.
asphalts. Figure 4.27 depicts the variation in $S(60)$ with rubber content for asphalt A. As shown in the figure, although the trend of decreasing $S(60)$ values with rubber content is still shown, there are significant differences between the effects of rubbers. The trends shown in figures 4.25 and 4.27 indicate that a model for predicting the effects of rubber content on $S(60)$ should include the rubber type and asphalt source as the main effects as well as an interaction term for these two factors. The model is not expected to be a linear model. For $m(60)$, the results of this study have clearly indicated that this material property is not sensitive to rubber addition nor to rubber content.

4.5 Findings

The effect of rubber content on properties at the construction and mixing temperatures and at critical pavement temperatures was evaluated within the range of 5 to 20 percent rubber by weight of total binder. The results indicated that critical properties change in a simple fashion with rubber content. Statistical modeling was used to represent the changes in properties as a function of rubber content using general linear models. The statistical analysis of the models and the evaluation of the trends lead to the following findings:

- The effect of rubber content on viscosity is exponential in nature; viscosity increases rapidly at higher rubber contents. A second-order polynomial is found to give a good prediction of the viscosity ratio of the asphalt rubber to the base asphalt as a function of rubber content. The prediction equation also includes a temperature term to take into account the variation in relation with temperature.

- The addition of the rubber did not affect the linearity of the relation between the logarithm of viscosity and temperature usually observed for neat asphalts.

- The effect of rubber content on the parameter $1/J''$ within the range of high pavement temperatures was also found simple. Using the logarithmic transformation of $1/J''$ results in a linear relation with rubber content. Statistical modeling indicates that the prediction equation in terms of $\log(1/J'')$ should include temperature and asphalt source as main effects. Rubber type is not found to be an important factor. Also, no interaction terms are found necessary for good prediction. The variation of $\log(1/J'')$ with rubber content has a positive derivative, which indicates that $1/J''$ increases exponentially with rubber content.
Figure 4.27. Change in $S(60)$ as a function of rubber content for asphalt A mixed with different rubbers.
• The effect of rubber content on $G''$ values was also found to be simple. Similar to the parameter $1/J''$, the effect was linearized by using the logarithmic transformation of $G''$ values. The best fit model includes rubber content, temperature, and asphalt source as the main effects. Neither rubber content nor any interaction was found necessary to give a good prediction of the $G''$ values. The relation between $\log(G'')$ and rubber content was not found to have a positive derivative consistently. Depending on asphalt type and temperature, the derivative changes from positive to negative as $G''$ values increase and/or temperature decreases.

• The effect of rubber content on creep properties is not found to be as simple as other properties. Stiffness values, although they show simple relation to rubber content, are not consistent for all combinations of asphalt and rubber. The effect on m(60) values is observed to be very small. No statistical modeling is done for the low-temperature creep properties because of the limited data collected.
CHAPTER 5

SUMMARY OF FINDINGS

In this study, the effects of crumb rubber modifiers manufactured by different processes on the performance-related properties of selected asphalt cement binders were evaluated. The study focused on crumb rubbers manufactured by three different processes from whole-passenger tires with a maximum particle size of 1.00 mm. Four asphalts that vary significantly in their physical and chemical properties, and that are used widely in the United States and Canada, were included in the study. The properties measured included the performance-related properties selected by the recently completed Strategic Highway Research Program (SHRP). The properties included the rheological, failure, and aging properties, which reflect the contribution of asphalt binder to resistance to the major distress modes of asphaltic pavements. The response variables were measured at different combinations of asphalt source, rubber type, and test temperature. The main objective was to quantify the effects of different factors on the changes that the CRM will impart on asphalt cements. The study also evaluated the storage stability of the crumb rubber modified binders and identified differences in the stability of important properties of these binders. The final part of the study addressed the effect of rubber content on the change in important properties and established some guidelines for estimating the rubber content required to achieve certain properties. The following sections give a summary of the important findings for the different topics covered in the study.

5.1 Effect of CRM on Consistency at High Temperatures

Although not a property that affects pavement performance directly, consistency at high temperatures is important to ensure that the binder can be pumped and mixed with aggregates and that the total mixture can be placed and compacted properly. The results of
this study, which included measurements in the range of 135 °C to 185 °C, led to the following findings:

- The addition of crumb rubbers results in significant increase in viscosity at temperatures in the range of mixing and construction temperatures in the field. The increase measured varied between a minimum of 5-fold and a maximum of 20-fold after one hour of mixing at 160°C.

- The addition of CRM results in a change in the viscosity-temperature profile. For all asphalt-rubber combinations, the relative increase is observed to be greater at higher temperatures.

- The effects of CRM were observed to be dependent on the asphalt source and also on the rubber type. Within the scope of this experiment, the rubber type appears to be more important than the asphalt source. Also, no significant interactions between these two factors could be observed.

- The increase caused by the Tyreplex rubbers (TP7-3 and TP9-1) was observed to be less than the increase caused by the ambient shredded (AS) and the cryogenic grinded (CG) crumb rubbers. The AS and CG rubbers showed similar effects despite the difference in their manufacturing processes.

- The increase in viscosity is not favorable with respect to paving applications. The Tyreplex rubbers can, therefore, be considered more favorable than the other rubbers evaluated in the study with regard to changes in viscosity at mixing and construction temperatures.

5.2 Effect of CRM on Performance-Related Properties at High Pavement Temperatures

The dynamic shear rheometer was used to measure the rheological properties of the base and the CRM-modified binders. The parameter selected for evaluating the effects of CRM on properties at high pavement temperatures is \( G'/\sin \delta \ (1/J'') \). This parameter was developed by SHRP researchers and is included as a control property in the new SHRP binder specifications. It is an estimate of the relative contribution of binder to resistance to rutting of pavements. It combines the total resistance to deformations (\( G' \)) and the relative elasticity of the binder (\( \sin \delta \)). A higher value is more favorable, as it indicates a more rigid and/or more elastic binder. The analysis of results leads to the following findings:
• Addition of CRM results in a consistent increase in the values of $G'$ and a consistent decrease in $\sin\delta$ values for all asphalts. The net effect was, therefore, a significant increase in values of $1/J''$. The relative increase ranges between a ratio of 3 and 30, depending on asphalt source, rubber type, and test temperature.

• The temperature dependency of $1/J''$ changes as a result of the addition of CRM. The relative increase is greater at higher temperatures.

• The asphalt source and the rubber both play an important role in the magnitude of effects. The AS and CG rubbers have consistently resulted in higher increases than the Tyreplex rubbers TP7-1 and TP9-1. The AS rubber showed the highest increases. The Tyreplex rubbers, which showed the lowest increases, have similar effects at all temperatures.

• The main change in properties is observed to be an increase in $G'$. The changes in $\sin\delta$ values were generally minor in magnitude. This indicates that the main effect of CRM is an increase in rigidity, with only a minor increase in elasticity.

• The increase in $1/J''$ is favorable with respect to paving applications. Although Tyreplex rubbers show a significant increase in $1/J''$ values compared to the base asphalts, their effectiveness in improving this property is less than that of the other rubbers evaluated in this study.

5.3 Effect of CRM on Performance-Related Properties at Intermediate Pavement Temperatures

The dynamic shear rheometer was also used to measure the rheological properties at intermediate pavement temperatures. The parameter selected for evaluating the effects of CRM on properties at intermediate pavement temperatures was $G'/\sin\delta$ ($G''$). This parameter was developed by SHRP researchers and is included as a control property in the new SHRP binder specifications. It is an estimate of the relative contribution of binder to resistance to fatigue cracking of pavements. Similar to $1/J''$, it combines the total resistance to deformations ($G'$) and the relative elasticity of the binder ($\sin\delta$). A lower value is more favorable as it indicates a more flexible and/or more elastic binder. The analysis of results leads to the following findings:
The addition of CRM may result in an increase or decrease in the value of $G''$, depending on asphalt source, rubber type, and temperature. Ratios of $G''$ for modified-to-base asphalt for the binders tested in this study ranged between 0.5 and 6.0, with greater ratios at higher temperatures and/or softer asphalts.

The relative changes appear to be more dependent on asphalt source ($G''$ value of base asphalt) rather than the rubber type. The AS and CG rubbers show smaller ratios compared to the Tyreplex rubbers. The AS and CG rubbers show similar effects at all combinations of asphalt and temperature, and the Tyreplex rubbers show similar effects at these combinations.

Similar to the changes at high pavement temperatures, the main change at intermediate pavement temperatures was observed to be caused by changes in $G''$ values. The changes in $\sin \delta$ values can be considered only minor.

The general effect of the addition of CRM on intermediate temperature properties can be considered small but favorable with respect to changes in $G''$ values, which is an indicator of binder contribution to fatigue cracking.

The Tyreplex rubbers, although showed favorable effects on some asphalts at critical levels of $G''$ values, their effects were generally less favorable than the effects of other rubbers included in the study.

5.4 Effect of CRM on Performance-Related Properties at Low Pavement Temperatures

The bending beam rheometer and the direct tension test device were used to measure the creep and failure properties at low pavement temperatures. The bending beam was used to measure the creep stiffness, $S(t)$, and the logarithmic creep rate, $m(t)$, to evaluate the effects of CRM on pre-failure properties at temperatures ranging between -30 °C and 0 °C. The direct tension test was used to measure failure strain within the same temperature range. These three parameters were developed by SHRP researchers and are included as control properties in the new SHRP binder specifications. They represent an estimate of the relative contribution of binder to resistance to thermal cracking of pavements. The parameter $S(t)$ is an indicator of the potential for build up of thermal stresses in pavements during a cooling cycle, and $m(t)$ is a measure of the relative ability of a binder to relax thermal stresses by flow during a cooling cycle. The failure strain is a measure of the ability of the binder to stretch without cracking; it is a measure of the strain tolerance of the binder. A lower value
of $S(t)$ and a higher value of $m(t)$ are more favorable as they indicate less thermal stress build up and faster relaxation during a given cooling cycle. A higher value of failure strain is favorable as it indicates a more strain-tolerant binder. The analysis of results related to these parameters leads to the following findings:

- The addition of CRM results in reduced stiffness values at all combinations of asphalt source, rubber type, and temperature. The reduction, measured in terms of percentage of $S(60)$ of the base asphalt, ranges between a few percent and 55 percent. The reduction is observed to be more at lower temperatures and/or higher stiffness values.

- The addition of CRM does not result in any important effects on values of the logarithmic creep rate, $m(60)$. The general trend is a slight decrease in $m(t)$ values for most of the combinations of asphalts and rubbers.

- The effects of the different rubbers were observed to be similar in magnitude. The reductions in $S(60)$ were, however, more pronounced at higher values of $S(60)$ of the base asphalts. The effects on different asphalts at a given $S(60)$ value are very similar. This finding indicates that there is no interaction effect between rubber and asphalt type; the rubber is mainly acting as a flexible filler at low testing temperatures.

- The addition of CRM results in an increase in the value of failure strain for all asphalt-rubber combinations. The limited data collected indicate that the rubber type does not play a major role in the effects of CRM. Some asphalt effects were observed. Due to the inherent variability of the test, however, no definitive trend could be observed.

- The reduction in stiffness and the increase in failure strain are favorable changes with respect to pavement resistance to cracking. Since all rubbers showed similar effects on asphalt properties, the Tyreplex rubbers are considered, in general, equally favorable to other rubbers.

5.5 Effects of CRM Addition on the Aging Characteristics at Intermediate and Low Pavement Temperatures

The aging characteristics were studied using the Thin Film Oven Test (TFOT) and the Pressure Aging Vessel (PAV). The first was conducted according to the ASTM standard method (D1754) and the latter was conducted according to the SHRP recommended
procedure at 100 °C. The TFOT is used to simulate the aging during mixing, transport, and construction stages in the field, while the PAV is assumed to represent the aging that takes place in the field during in-service conditions. The mass change and the changes in important rheological and failure properties were used as aging indicators. The analysis of the results leads to the following findings:

- The addition of CRM results in increased values of mass loss measured according to the standard TFOT procedure. This trend is observed for all asphalt-rubber combinations at different magnitudes. The increase in mass loss is highly asphalt- and rubber-specific. The AS and CG rubbers appear similar in their effects, which are smaller than the effects of the two Tyreplex rubbers. The increase in mass loss, although significant compared to the base asphalts, is still within acceptable limits (maximum of 0.666) for all tested binders.

- The addition of CRM does not appear to alter the change in rheological properties due to the TFOT aging procedure. The relative change in $1/J''$ after TFOT aging does not change significantly as a result of the addition of rubbers. This indicates that although the amount of volatilization is significantly changing, the relative hardening is not being affected.

- Changes in aging characteristics due to the addition of CRM, measured after aging in the PAV, were observed to be significant and favorable. The relative increase in the values of $G''$ due to PAV aging is significantly reduced as a result of CRM addition. Aging ratios in terms of $G''$ of PAV-aged values to unaged values are consistently lower, and they are reduced in the range from a few percent to more than 80 percent.

- Reduction in hardening due to PAV aging was also observed to be significant in the creep stiffness measurements, $S(60)$ and $m(60)$. For most of the modified binders, the relative increase in $S(60)$ and the relative decrease in $m(60)$, due to PAV aging, were much smaller after addition of the CRM. The failure strain values after PAV aging remained higher for the rubber-modified binders compared to the base asphalts.

- Although the data collected are limited in scope, reduction in hardening after PAV aging appears to depend on asphalt type, rubber type, and the interaction of these two factors. On the average, the Tyreplex rubbers showed effects comparable to other rubbers. They can, therefore, be considered equally favorable with regard to reduction in hardening.
5.6 Storage Stability of CRM-Modified Binders

One of the important problems associated with the modification of asphalts is the stability of the modified properties, particularly during storage at elevated temperatures. In practice, due to difficulties of tight control of construction schedules, asphalt binders have to be stored for long periods of time before or after mixing with aggregates. One of the known behaviors of crumb rubber modifiers is their reaction with asphalts, which is a time- and temperature-dependent phenomenon that may result in significant increases in consistency. This study evaluated the effect of high-temperature storage on properties by storing samples after 1 hour of mixing for an addition 23 hours at 160 °C. The analysis of results of the storage stability study leads to the following findings:

- High-temperature storage results in significant changes in the viscosity values of the rubber-modified binders. The changes were observed to be a continuous increase in viscosity for most asphalt-rubber combinations.

- The changes due to storage were observed to be highly rubber-specific. The AS and CG rubbers showed significant changes with all asphalts. The Tyreplex rubbers, however, were observed to be stable, and they did not show any additional change in properties due to storage.

- The Tyreplex rubbers were shown to be stable with all four asphalts during storage without agitation and during storage with continuous agitation. This characteristic, which was found to be unique to the Tyreplex rubbers, is believed to be of significant importance for the application of CRM in asphalt modification. It appears that the stability of these rubbers is the result of the manufacturing process used by Tyreplex.

- The effects of storage on rheological and failure properties within the range of pavement temperatures were observed to be negligible. The effects on $G'/\sin\delta$ at all testing temperatures were found to be very small, not indicating any trend. This finding was observed for all asphalt-rubber combinations, even for the modified binders that showed a significant increase in viscosity at high temperatures.
5.7 Selection of Rubber Contents

The study included evaluation of the rubber content on performance-related properties of asphalt cements. The rubber content for each of the studied crumb rubbers was varied between 5 and 20 percent at 5 percent intervals. Statistical models were used to model the effects of the different rubbers on viscosity at high temperatures, the $1/J''$ at high pavement temperatures, and the $G''$ at intermediate pavement temperatures. The models selected are listed in table 5.1. These models were based on the testing of limited numbers of asphalts with limited number of rubbers. They should, therefore, be used with caution for estimating effects of other rubbers with other asphalts.

Table 5.1. Statistical models for estimation of viscosity of CRM-modified asphalts.

<table>
<thead>
<tr>
<th>Model</th>
<th>Std. Error of $Y$ est</th>
<th>Std. Error of Coefficient</th>
<th>$R^2$ Adjusted</th>
</tr>
</thead>
<tbody>
<tr>
<td>For Viscosity Estimation</td>
<td>0.0990</td>
<td>0.00089</td>
<td>0.970</td>
</tr>
<tr>
<td>$\log(VR) = -0.6699 + 0.00406$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T + 0.0412(RC) + 0.001794(RC)^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>For $1/J''$ Estimation</td>
<td>0.1567</td>
<td>0.0020</td>
<td>0.953</td>
</tr>
<tr>
<td>$\log(1/J'') = 5.45 + 0.0586(RC)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$- 0.0504(T) + 0.2032(AC)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>For $G''$ Estimation</td>
<td>0.2037</td>
<td>0.7272</td>
<td>0.945</td>
</tr>
<tr>
<td>$\log(G'') = 5.8144 + 0.0178(RC)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$- 0.0669(T) + 0.7272(AC)$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$VR =$ Viscosity Ratio of rubberized to neat asphalt  
$RC =$ Rubber Content in percentage  
$T =$ Test temperature  
$AC =$ Asphalt source (indicator variable)
5.8 Tyreplex Rubbers Compared to Other Rubbers Used in the Study

Tyreplex rubbers are considered unique in their nature because they are produced by a special extrusion process and two additives are used to change the properties of the raw crumb rubber material. In this study, rigorous evaluation of these rubbers in comparison to other crumb-rubber modifiers, used commonly in paving applications, has been accomplished. The products of Tyreplex were found to have some advantages and some disadvantages compared to the other rubbers.

5.8.1 Advantages of Tyreplex Products

The main advantage of the Tyreplex products observed in this study was their stability during high-temperature storage. The stability was observed during storage with only intermittent mixing for 23 hours as well as during storage with continuous agitation in a rotational viscometer. The stability was observed with all four asphalts tested, which were selected to cover the range of chemical and physical properties of asphalts used in the United States and Canada. The reason for stability is hypothesized to be the novel process by which the rubber particles are produced. The process appears to result in a saturation of the raw crumb rubber bonds and a significant reduction in the active sites on the surface of the rubber particles. The additives used in the process (which were not researched in this study) along with the thermal and mechanical treatment yielded a more stable crumb rubber that improves significantly the potential for utilizing crumb rubber in paving applications.

5.8.2 Disadvantages of the Tyreplex Rubbers

Because Tyreplex rubbers are more stable, they do not interact with asphalts to the same extent as other rubbers. At high pavement temperatures, where increases in $G'/\sin\phi$ are favorable, the AS and CG rubbers show a better enhancement of properties compared to the Tyreplex rubbers. The Tyreplex rubbers, however, still show significant enhancement compared to the base asphalt. At intermediate temperatures, the same trend can be observed.
be observed. The relative difference between the Tyreplex rubbers and the other rubbers is less when compared to the properties at high pavement temperatures. At low pavement temperatures, the Tyreplex rubbers can practically be considered equal to the other rubbers. These disadvantages of the Tyreplex rubbers are believed to be the direct consequence of their stable characteristics and lower reactivity with asphalts.

5.9 Conclusions

The objective of this study was to evaluate the CRM produced by Tyreplex Corporation as an additive for asphalt cements used in highway paving applications. The results of this study indicate that the CRM produced by Tyreplex can be used to enhance certain asphalt cement properties for better contribution to resistance of critical pavement distress mode. The product results in effects comparable to other CRM commonly used as asphalt modifiers. The product is found to retain its initial effects on asphalts and not change when stored at high temperatures. This stability of effects is a property that is important for paving applications. The stability of the Tyreplex product is unique when compared to stability of the effects of other CRM products included in this study.

5.10 Recommendations for Further Studies

The following are suggestions for future research identified from the research completed in this study.

- The interaction of the AS and CG rubbers with certain asphalts was observed to be of an uncommon nature. It is believed that additional research is needed to reveal the nature of this interaction. It is clear from this study and many previous studies that the research community does not fully understand the mechanism by which the interaction between these two materials (CRM and asphalt) takes place.
• For the Tyreplex rubbers, it is very important that the research efforts extend to include the effect of these stable rubbers on the performance-related properties of asphalt-concrete mixtures. A mixture design procedure is necessary for the successful utilization of the CRM in pavements. Although significant enhancement can be observed in the binder properties, the evaluation of changes in asphalt rubber-aggregate properties is needed.
REFERENCES


Dear Dr. Hicks, Assoc. Dean of Research and Graduate Studies

Tyreplex Corporation is a producer of a unique novel crumb rubber modifier (CRM) from scrap vehicular tires. The process used in the manufacture of this material provides for useful properties not found in other crumb rubber as well as being extremely cost effective. (Sample enclosed)

The Pennsylvania State University Transportation Department has conducted a comprehensive research study of the Tyreplex product. This research has been funded in part by the Ben Franklin Technology Center. A copy of the research study is enclosed.

The Tyreplex Corporation would like to suggest that its product be included in the Research Project being conducted for the Federal Highway Administration. The Corporation believes its product can resolve many of the problems associated with the use of conventional crumb rubber.

May we hear from you regarding this matter.

Very truly yours,

John Kuc, Sr., President
TYREPLEX CORPORATION

cc: Mr. Michael Smith