

Research Report
for
Research Project T9902-09
"Rubber-Asphalt Study"

**A REVIEW OF CRUMB-RUBBER MODIFIED
ASPHALT CONCRETE TECHNOLOGY**

by

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DISCLAIMER

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ABSTRACT

This study presents an analysis of the characteristics of crumb-rubber modified (CRM) asphalt pavements. It is comprised of a state-of-the-art literature review of asphalt pavement materials with CRM included in the binder (wet process) or as part of the aggregate (dry process). In addition to the literature review, testing was conducted with a Brookfield viscometer to determine the curing properties of the CRM and asphalt mixes using different percentages of CRM and various grades of asphalt.

Blending of crumb rubber and asphalt cement has been practiced for years. The reaction that takes place between rubber particles and asphalt binder is not chemical in nature, but rather a diffusion process that includes the physical absorption of aromatic oils from the asphalt cement into the polymer chains, which are the key components of natural and synthetic rubber in CRM. Each group of polymer chains affects particular characteristics of the modified binder.

Papers reviewed indicate CRM softens and swells as it reacts with asphalt cement. The presence of CRM in asphalt produces a thicker binder, which increases aging and oxidation resistance. The presence of carbon black in CRM improves binder durability. The blending and reaction of the asphalt-rubber reduces temperature susceptibility causing more uniform fatigue characteristics of modified asphalt concrete over operating temperatures. The reduced temperature susceptibility increases rutting resistance in higher temperatures and thermal cracking resistance in lower temperatures.

Applications of CRM paving materials have been met with various degrees of success. The failures generally result from inexperience with CRM technology in project selection, design engineering, and construction decisions. Existing quality control and quality assurance methods have not been developed enough to ensure desired binder properties in the field.

Brookfield viscometer testing indicated that the viscosity of the modified blend increases as the amount of aromatic oils, which lubricates the binder, decreases. Results also indicated that as the percentage of rubber increased, the effects of the rubber on the viscosity increased significantly. A binder with 18% CRM had a viscosity of approximately 12 times that of the unmodified binder. In the mixes utilizing larger quantities of CRM, such as the mixes with 18% CRM, there is also a near-linear increase in viscosity with time when maintaining blending temperatures. This indicates that minimal mixing times are desired in order to control the degree of viscosity modification and obtain a workable mix.

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CHAPTER 1

INTRODUCTION

1.1 History

Over 240 million waste passenger car tires and 45 million waste truck tires accumulate annually in the United States (Heitzman, 1992). Of these 285 million tires, 33 million are retreaded, 22 million are resold, 42 million have other alternative uses, and 188 million go to stockpiles, landfills, or illegal dumps. The Environmental Protection Agency (EPA) estimates the present scrap tire problem amounts to approximately 2 to 3 billion tires.

A strong interest in developing alternative uses for scrap tires came about in the mid-1980's after a number of major scrap tire stockpile fires. These fires generated air pollutants, oils, soot, and other materials that caused air, water and soil contamination. In addition, tire piles present a potential haven for the breeding of mosquitoes and habitats for many vermin. Since the late 1980's, the use of scrap tire rubber in asphalt cement has been suggested as a potential partial solution to this environmental solid waste problem. The use of scrap tire rubber as an additive for asphalt concrete has been evolving over the past 25 years. The use of scrap tire rubber in asphalt paving may enhance pavement performance characteristics as well as contribute to the environmental rehabilitation of controlling the amount of waste tires in stockpiles. Waste tire rubber has also been used as a lightweight road fill, pavement sub-base, artificial reef and breakwater, retaining wall, crash barrier, erosion control, a source of energy, and so on.

Using scrap tire rubber in asphalt paving applications can no longer be ignored. Section 1038 of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 specifically addresses the study and utilization of scrap tire rubber by the highway industry. ISTEA requires states to use an increasing percentage of rubber in the construction of asphalt concrete pavements over the next five years. Its use is to begin in 1994 at 5% crumb-rubber of the total federal-dollar tonnage of asphalt concrete pavements being built, and it is to be increased 5% each year thereafter until a maximum mandatory 20% is achieved in 1997.

State agencies requested an extension on this mandate to allow time for further research to determine if current technology can utilize scrap tire rubber in paving applications in a cost-effective fashion. Environmental concerns of recycling the CRM pavements are also to be addressed. An extension was granted for one year to allow state agencies to further study the effects of recycling rubber tires in asphalt. This pushed the mandate date to 1995, but the original 10% crumb-rubber required for 1995 is still in effect. A second year extension was passed by Congress, which starts the mandate in 1996 with a 15% crumb-rubber requirement. Legislative action continues at present, involving various efforts ranging from further postponing to altogether repealing Section 1038 of the 1991 ISTEA.

1.2 Background

Crumb rubber is identified as a modifier because its presence affects the properties of the asphalt concrete. The principle source of raw material for crumb rubber modified asphalt (CRM) is tire rubber, which is a composite of natural rubber, synthetic rubber, and

carbon black. Natural rubber provides the elastic properties, while the synthetic rubber improves the thermal stability properties of the compound. The addition of carbon black improves the binder's durability.

During processing, one half of each tire is usually wasted, therefore, two to six tires are needed per metric ton of asphalt. If two to five million metric tons of CRM asphalt were to be used in construction in one year, over ten million tires would be used.

Scrap tires are shredded into 20x 20 cm pieces or smaller in order to produce a product that is easy to handle. The shredding of the tires also improves the quality of the material because the dirt and other contaminants on the tire surface are removed. Another product that can be used as CRM is called buffing waste. Buffing waste is a high quality scrap rubber by-product of the conditioning of tires in preparation for retreading. This by-product is a small thread-like material that is in high demand because it lacks contaminants. Talc is then added (not to exceed 4% by weight of the rubber) to the rubber to reduce its tendency to stick together.

Granulated CRM is defined as the product sized 2.0 to 9.5 mm in diameter while the ground CRM is 425 microns to 4.74 mm in diameter. The material cost for CRM is \$0.20 - \$0.35 / kg CRM plus shipping for coarse and medium particles (> 425 microns), and \$0.55 / kg CRM plus shipping for fine ground particles.

There are basically two methods for incorporating CRM into asphalt concrete. The first method is called the *wet process* which is defined as the blending of crumb rubber with asphalt cement before mixing the binder with the aggregate. This modified binder is commonly referred to as *asphalt rubber*. Such applications include crack sealants, surface treatments, and hot mix asphalt (HMA) mixes. The second method is called the *dry*

process which is defined as the blending of crumb rubber with the aggregate before the mix is charged with asphalt binder. The primary function of the crumb rubber is to replace a portion of the aggregate in the asphalt concrete. This modified mix is commonly referred to as *rubber modified hot mix*.

1.3 Viability Issues

Cost effectiveness is one of the main issues regarding the use of crumb rubber in asphalt cements. Pavement performance is a key component in determining the cost-effectiveness of CRM asphalt concretes. The cost of the processed crumb rubber material increases as the particle size decreases. This makes it desirable to find applications which could benefit from the physical properties of the material, while minimizing the required amount of size reduction.

A second concern in using these modified mixes is the ability to recycle the asphalt paving materials. Answers must be given as to whether or not recycling these products is environmentally safe, and if these materials are recycled in paving applications, can they perform cost-effectively.

CHAPTER 2

OBJECTIVES

The main objective of this study is to conduct a critical review of the literature available on rubber-modified asphalt concretes. The focus of the review is on the following:

- 1) Nature of the reaction between the asphalt cement binder and the crumb-rubber.
- 2) Interrelation between the aggregate gradation, the crumb rubber gradation and the characteristics of the asphalt cement binder. Emphasis will be placed on the advantages and disadvantages of dense-graded, gap-graded and open-graded aggregate gradations in relation to the different types of rubber-binder used.
- 3) Issue of aging and the observed increase in temperature susceptibility of the rubber-modified asphalt concretes with time.
- 4) Function of additives/extenders in improving the performance characteristics of rubber-modified asphalt concretes.
- 5) Reasons why certain rubber-modified processes result in sub-standard performances while others perform well under particular site conditions.

This report will document the rubber-modified technology aspects critical to implementing this technology in meeting the upcoming federal requirements.

The secondary objective is to determine the curing properties of CRM asphalt and the sensitivity of the viscosity measurements of CRM asphalt by conducting numerous viscosity tests with a Brookfield viscometer.

CHAPTER 3

LITERATURE REVIEW

The following is a comprehensive review of various state-of-the-art reports researching the effects of the addition of crumb rubber in asphalt cements and asphalt concretes.

3.1 Shuler, 1986

This study was conducted for and funded by the U.S. Department of Transportation, Federal Highway Administration. It discusses the structural properties of asphalt-rubber paving mixes. This paper evaluated the field performance for six types of paving materials containing ground tire rubber. These paving materials include:

- Asphalt-rubber seal coats - ARSC,
- Asphalt-rubber interlayers,
- Asphalt-rubber concretes - ARC (wet process; dense-graded),
- Asphalt-rubber friction courses - ARFC (wet process; open-graded),
- Asphalt concrete rubber filled - ACRF (dry process; dense-graded), and
- Friction course rubber filled - FCRF (dry process; open-graded).

The 219 test sections evaluated for this study were constructed between 1977 and 1984.

Sites were selected based on the quality of preconstruction data available, quality of experiment design, variety of application types, climate, and access to the site.

Performance was evaluated in terms of quantity and severity of distresses such as:

- Rutting,
- Raveling,
- Flushing,
- Corrugations,
- Alligator cracking,
- Longitudinal cracking,
- Transverse cracking, and
- Patching.

Evaluations were based on the relative performance of adjacent control sections. The wide variety of projects made comparison between project locations impractical since the traffic, climate, and construction techniques were different on all of the projects. An improvement rating system was developed, whereas a positive rating indicated an improvement over the available control sections, and a negative rating indicated a decrease in pavement performance from control sections. The rating scale range was from -3 to +3.

Figure 3.1 shows, graphically, the relative performance of each treatment type relative to control sections. The following observations can be made from the graphs in this figure:

- An almost normal distribution of performance exists for interlayers with the average being just below zero,
- Performance leans toward the negative side for asphalt-rubber seal coats and friction course-rubber filled systems,

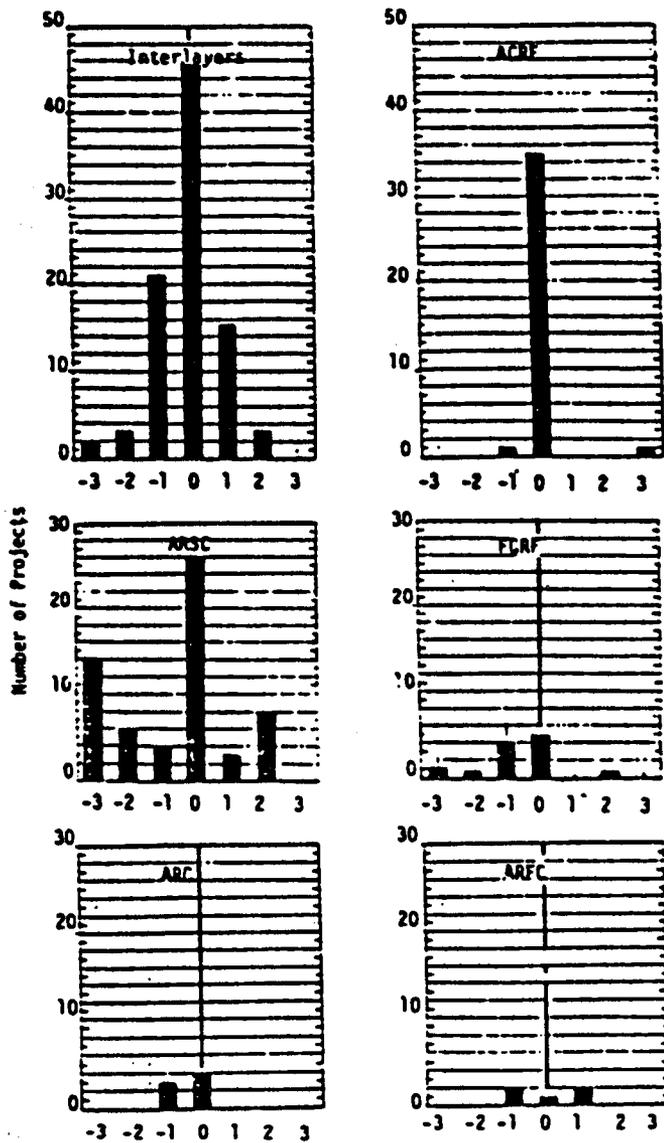


Figure 3.1: Performance of projects by application type (After Shuler, 1986)

- Performance leans toward the positive side for asphalt concrete-rubber filled systems, and
- Performance comparisons for asphalt-rubber concrete and asphalt-rubber friction course applications are inconclusive due to the lack of projects of these

types, however, performance is typically comparable or slightly worse when compared to unmodified mixes for both types of projects.

It may be noted that many of the asphalt-rubber seal coats with negative performance were constructed before 1979. The unsatisfactory performance of these sections can be explained by the lack of experience in the early stages of the development of asphalt-rubber technology. Also, pre-blending became standard CRM practice after 1979 because it improves the workability of the asphalt-rubber.

Indications of negative performance for many interlayers do not appear to be related to the asphalt-rubber material properties, but rather to inappropriate construction practices or design selection. It was discovered that interlayers are ineffective in reducing reflection cracking in asphalt concrete overlays on jointed Portland concrete, or where transverse cracks in asphalt concrete are at intervals of 15 feet or less.

Indications of negative performance for asphalt-rubber seal coats do not appear to be related to material characteristics, but rather to the construction practices. Flushing is the primary cause for unsatisfactory performance of asphalt-rubber seal coats. This type of distress occurs due to inappropriate proportioning of the binder and aggregate, which is further complicated by volume changes of the binder due to blending. When sections displaying flushing are removed from the statistical analysis, a shift from negative to positive performance is noted for the asphalt-rubber seal coats. If these seal coats had been designed to eliminate flushing, the resulting overall performance of asphalt-rubber seal coats may have been significantly better than corresponding control sections.

The performance of asphalt concrete rubber filled systems was superior when compared to control sections. The majority of projects indicating improved performance contained finely ground rubber at 1% of the total mix weight. On the other hand, projects with higher percentages of rubber indicated similar or worse performance than the control sections.

There were not enough applications of the FCRF, ARC, and ARFC to conclusively decide whether performance was improved in these test sections. Performance of the few projects evaluated indicated comparable results to control sections. Certain applications of friction course rubber filled systems appeared to perform significantly worse than others. Two mixes containing 2.5% fine ground rubber of the total mix weight failed significantly earlier than sections containing no crumb rubber.

Comparisons of performance between test and control sections were not conclusive due to inherent variations in construction procedures, traffic conditions, environment conditions, etc.

Asphalt-rubber binders appeared to provide significant improvement in performance when used in place of conventional binders, which resulted in marginal performance. The asphalt-rubber binder used in this study had considerably higher viscosity, fracture toughness, and tensile strength than the control binder. These differences in properties seem to be reflected in differences between marginal control section performance and the performance of the experimental mixes. This observation, however, is non-conclusive since there was no objective definition of "marginal" and "adequate" performance of the conventional binders.

3.2 Chehovits, 1989

The following study was conducted for the National Seminar on Asphalt-Rubber. The National Seminar on Asphalt-Rubber was co-sponsored by the Asphalt Rubber Producers Group and the Federal Highway Administration. The purpose of this seminar was to provide an update on the new technology in the use of asphalt-rubber and to educate people in the application of this technology. It discusses the design considerations for hot-mix asphalt-rubber concrete paving materials. Research studies have shown that asphalt-rubber materials have significantly modified physical properties when compared to conventional asphalt cement. These modifications include increased high temperature modulus, increased viscosity, increased toughness, increased elasticity, reduced temperature susceptibility, and reduced age hardening.

The interaction which occurs between asphalt and recycled rubber is dependent on the physical and chemical properties of asphalt, the physical and chemical properties of rubber, the mixing time and temperature, the mixing conditions (high shear or low shear rates), and the use of additives. The following is a summary of design considerations in designing a CRM mix:

- Asphalt cement - stiffness and temperature susceptibility influence the high temperature and low temperature performance of the asphalt-rubber. The chemical make-up of the asphalt influences the degree of interaction, which occurs between the asphalt and the rubber. Larger amounts of aromatic compounds tend to dissolve and interact with rubber to a greater degree than asphalts with lower aromatic contents.

- **Rubber** - particle size, shape, surface texture, contaminant presence, and chemical composition (i.e., hydrocarbon content, type of rubber polymer, plasticizer content, and reinforcement type and content - carbon black) influence properties of the asphalt-rubber.
- **Time and temperature** - increased mixing time results in larger interaction effects, while increased temperatures result in faster interaction.
- **Mixing conditions** - production mixing systems are designed to ensure uniform wetting and suspension of the rubber particles in the asphalt. It is important that lab mixing procedures do not subject the asphalt-rubber to excessive amounts of shear which could quicken the rubber devulcanization process.
- **Additives** - extender oils can be used to soften the material for improved low temperature performance and for improving the degree of interaction between the asphalt and rubber. Adhesion agents commonly used in asphalt paving can be used to improve film stripping resistance. Solvents, which are used in asphalt-rubber chip seal applications, must not be used in hot-mix applications.

Each of the factors listed above must be considered when developing an asphalt-rubber formulation for a specific use.

3.3 Roberts et al, 1989

This report is the result of a project sponsored by the Florida Department of Transportation and conducted by the staff of the National Center for Asphalt Technology

at Auburn University. It presents a state-of-the-art literature review of CRM asphalt technology for both the wet process and the dry process. No field or laboratory testing was conducted.

Many of the conventional asphalt cement tests, such as the capillary viscometer, cannot be used to evaluate asphalt-rubber blends because of the swelling of the rubber particles, and the varying characteristics of the blend with mixing time. The repeatability of the tests, which can be performed on CRM asphalt, depends on the uniformity of the samples. The discrete nature of the rubber results in considerable variation in sample consistency.

Viscosity of an asphalt-rubber blend is affected by the time and temperature used to combine the asphalt and rubber. This must be carefully controlled to achieve consistent results. The viscosity of asphalt-rubber increases as mixing temperature and time increase beyond the time required to complete the initial reaction between the liquid asphalt and the solid tire rubber. The initial asphalt-rubber reaction is not well understood, but it appears to be due to a chemical and physical "exchange" between the asphalt and rubber particles; whereby the rubber swells causing an increase in viscosity. This is shown in Figure 3.2, which is from an earlier report by Shuler (1986). The reaction is considered complete when the viscosity of the blend becomes relatively constant. Referring to Figure 3.2, it appears that the reaction is complete and the viscosity has stabilized after approximately 90 minutes. Other papers reviewed by this study indicated that enhanced pavement performance is obtained when the asphalt-rubber mix is used as soon as possible after blending.

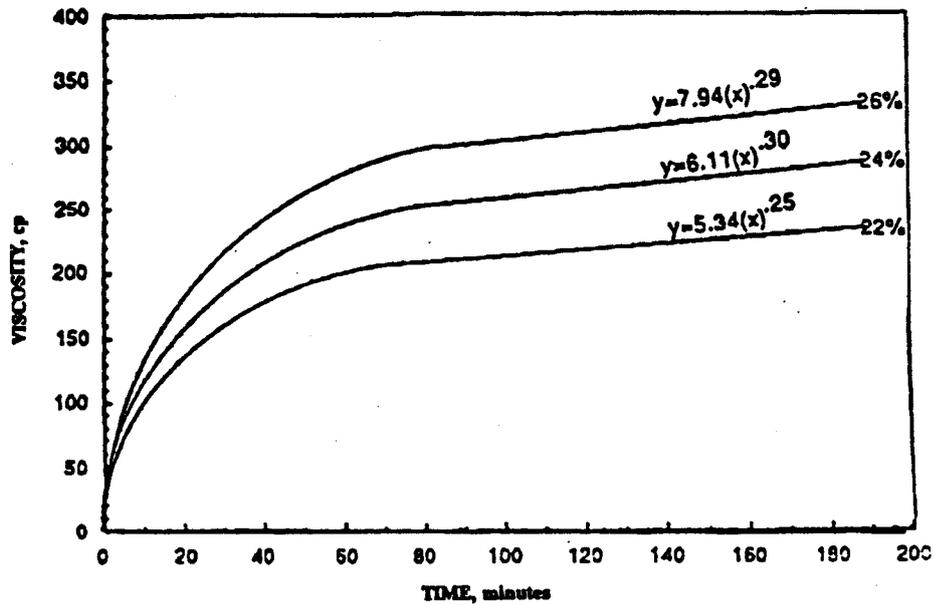


Figure 3.2: Effect of Digestion Time on Viscosity of Asphalt-Rubber (After Shuler, 1985).

Viscosity can also be controlled by diluting a binder with aromatic extender oils during the asphalt and rubber blending operation. Another way to lower the viscosity is to use a lower viscosity grade asphalt instead of an extender oil, but this results in permanent viscosity reduction. The viscosity of CRM asphalt is increased as temperature and time are increased beyond the time required to produce the initial reaction between liquid asphalt and crumb rubber.

The gradation used with CRM modified binders should be more open than those for conventional binders to allow room for the extra thickness of the binder film due to swelling. Binder drain down may occur when the open-graded friction coarse is stored at high temperatures.

A mix containing 3.5% coarse CRM exhibited a resilient modulus of 75% of that of a conventional mix. A mix containing 3.5% coarse CRM plus 2% fine CRM exhibited a resilient modulus of 160% of that of a conventional mix. Therefore, it appears that the presence of fine CRM results in a higher average resilient modulus. A similar laboratory study conducted by the Alaska Department of Transportation showed that in tests using 3% rubber with 8% AC 5 asphalt binder, the resilient modulus increased by an average of 22.6% over conventional mixes when using coarser ground rubber, and an average increase of 59.0% when using very fine ground rubber.

When rubber particles are added into HMA, the fatigue life is significantly improved in the laboratory. This improvement may not be fully realized in the field due to external factors, such as seasonal weather and traffic flow changes. In conclusion, rubber-modified mixes show superior fatigue resistance when compared to conventional mixes in the laboratory. For hotter temperatures, asphalt-rubber (i.e., wet process) binders have better fatigue resistance than rubber-modified (i.e., dry process). It should be noted that the fatigue resistance of both types of modified mixes is better than conventional dense-graded HMA mixes.

At higher temperatures, the higher resilient modulus of the asphalt-rubber mix results in a lower tensile strain for a given stress level. This lower strain in conjunction with the higher fatigue life make the asphalt-rubber mixes perform better than the rubber-modified mixes in warmer environments. Both of these modified mixes are better than the conventional asphalt concretes.

With the information and data available, the rutting performance, creep and permanent deformation characteristics of CRM mixes can be estimated and compared to that of conventional mixes. At higher temperatures, the rubber modified mixes exhibit higher strain under creep loading, which indicates that under slow moving or stopped vehicles, the CRM mixes experience a greater amount of rutting than conventional mixes. It is indicated, however, that dense grading of the aggregate and fine rubber gradation may improve their resistance. Comparing permanent compressive strain versus time data shows that deformation is larger in CRM asphalt pavements under creep load as compared to repeated loading. This indicates that CRM asphalt pavements deform more than conventional mixes under slow or stopped traffic while deforming less under high speed traffic.

The use of fine rubber could significantly reduce the drain-down of asphalt off the aggregate prior to placement allowing an increased binder content. An increase in binder content should reduce asphalt aging and improve durability. At the same time, this mix may be heated to higher temperatures. Rubber may also benefit the asphalt by making the asphalt more viscous, providing more ductility at low temperatures, enhancing the adhesive characteristics, and increasing elasticity, flexibility, and toughness.

The technology for the wet process is well established, the equipment is developed and available, and field performance indicates that the presence of rubber in such mixes produces beneficial effects. As a result, this study recommends the use of the wet process rather than the dry process.

3.4 Heitzman, 1991

This report, conducted on behalf of the Federal Highway Administration - Department of Transportation and presented at the 1992 Transportation Research Board Meeting, offered a comprehensive overview of the terminology, processes, products, and applications of crumb rubber additive technology. No laboratory or field tests were conducted for this report.

The reaction that takes place when crumb rubber is added to asphalt cement is the absorption of aromatic oils from the asphalt cement into the polymer chains, which are the key component of the natural and synthetic rubbers in crumb rubber. As the crumb rubber reacts with the asphalt cement, it softens and swells. This reaction is influenced by the blending temperature, the blending time, the mixing energy, the size and texture of the CRM, and the aromatic nature of the asphalt cement.

The modified binder exhibits enhanced binder properties such as a flattened temperature/viscosity curve, which indicates a reduction in the temperature susceptibility of the binder. These enhancements in binder properties, which can be measured in a laboratory, indicate better performance of the paving material in the field. The modified binder properties may mitigate:

- thermal cracking,
- rutting,
- chip retention,
- reflective cracking, and
- aging.

Since the modified mixes need additional binder, there is a possibility of flushing/bleeding and tracking as well as an increase in cost. All of these characteristics depend on the compatibility of the CRM and asphalt cement.

Rubber aggregate may influence pavement performance characteristics such as reflective cracking and ice debonding. Like the modified binder, there is an added cost as well as a possibility of ravelling. In the dry process, compatibility between the rubber and asphalt is not as important as in the wet process, because the reaction between the CRM and binder does not play a significant role in developing performance enhancement.

The gap-graded mix design concept is intended to maximize the asphalt rubber content of the mix. This mix is designed to combine the elastic properties of asphalt rubber with the stability of coarse aggregate contact. An open-graded mix is similar in design to conventional methods, the only difference being the use of asphalt rubber. To determine binder content, the thicker binder film must be taken into account.

The performance criteria and the cost-effectiveness of rubber-modified asphalt mixes vary. Therefore, site-specific performance data must be obtained for conducting a cost-effectiveness evaluation of this technology. Studies have concluded that laboratory tests using CRM mixes do not correlate well with observed field performance. This means that laboratory results used to predict pavement performance may not accurately reflect field performance. Therefore, laboratory results should not be used exclusively for predicting performance.

3.5 Ahmed et al, 1992

This paper is a summary of a master's thesis from Purdue University which was presented at the 1992 Transportation Research Board. It discusses the use of waste materials in highway construction by obtaining information from a review of published literature. The following information is a general overview of CRM pavement history. No laboratory or field experiments were conducted or discussed for this paper.

The experience of using CRM asphalt paving products across the United States was studied to establish the basic causes of observed failures. With few exceptions, the failures and successes had been random with no definite explanations for this unusual behavior. Pavements with the same percentage of CRM used in a similar product, under similar climatic environments demonstrated different behavior, whereas one failed within a short period of time, while the other performed much better than control sections. Many of these failures may be the result of poor design or quality control during construction. To date, there is no definite answer to this question.

The asphalt paving products which contain CRM are generally acceptable from an environmental point of view. Some concerns have been expressed over increased air pollution as a result of adding CRM to the asphalt concrete, and some are concerned with the requirement of elevated temperatures during mixing.

Benefits of using various rubber-modified hot-mix surfacing includes increased flexibility, higher viscosity, increase in toughness, increase in elasticity, greater resistance to aging, reduction in reflective and thermal cracking, greater resistance to studded tire wear, increased skid resistance, ice removal by elastic deformation of the rubber granules

under traffic loading and vehicle generated wind, suppression of pavement tire noise, and recycling of used rubber tires. It should be noted that each type of rubber-modified hot-mix surface does not produce all of the above mentioned advantages, but a mix can be chosen that can help eliminate existing problems which cannot be solved by a conventional mix.

3.6 Estakhri, et al, 1992

This paper was published in the 1992 Transportation Research Record No. 1339, was funded by the Texas Department of Transportation (TXDOT), and was conducted by the Texas Transportation Institute. It described the TXDOT experience with asphalt rubber. The availability of crumb rubber produced from scrap tires, and the cost-effectiveness of asphalt rubber was also analyzed in comparison to conventional paving materials on the basis of existing information. No laboratory testing was conducted for this paper.

A number of test sections were constructed by TXDOT to determine the performance of rubber modified asphalt pavements. Two projects which describe the range of performance TXDOT has experienced using the wet CRM process are as follows:

- a rubber modified asphalt concrete project in McAllen was considered disastrous with the roadway raveling severely. A chip seal was required three months after initial construction.
- a dense-graded overlay in Tyler was considered very successful with the CRM

roadway currently performing well.

TXDOT is interested in constructing more CRM hot mix asphalt pavements utilizing the wet process. Asphalt-rubber use has been very limited in Texas for construction of hot mix asphalt concrete, therefore it was concluded that more field test sites are needed to thoroughly analyze the effects of CRM asphalts in environments similar to Texas. No true determination of the cost-effectiveness of CRM hot mix asphalt pavements can be conclusively made until all of the test projects constructed have been in service for a considerable number of years.

3.7 Heitzman, 1992

This report, conducted on behalf of the Federal Highway Administration - Department of Transportation, offered a comprehensive overview of the terminology, processes, products, and applications of crumb rubber modifier (CRM) technology. It is a continuation of the paper presented at the 1992 Transportation Research Board Meeting (Heitzman, 1991). No laboratory or field tests were conducted for this report.

The first method for including CRM in asphalt concrete is the wet process, where the rubber is added to the binder before being mixed with the aggregate. The interaction which takes place when CRM and asphalt cement are blended together is defined as the asphalt-rubber reaction. This reaction is influenced by the blending temperature, the mixing time, and the mechanical energy input. These parameters can be adjusted to achieve the desired product. The reaction (e.g., polymer swell) is not of chemical nature, but rather the physical absorption of aromatic oils from the asphalt cement into the

polymer chains, which are the key components of the natural and synthetic rubber in CRM. The natural rubber polymers are more reactive with asphalt than the synthetic polymers. Each group of polymer chains affects particular characteristics into the modified binder.

As the CRM reacts with the asphalt cement, it softens and swells. The reacted particles become tacky and develop adhesive properties. A fully reacted particle can swell three to five times its original volume. As the CRM and asphalt cement react, the viscosity of the blend increases, while the amount of aromatic oils available for lubricating the binder decreases. The swelling and adhesive characteristics also add to the increased viscosity. An asphalt cement increases its viscosity by a factor of ten with the addition of 15% CRM at 135 °C.

The rate of reaction can be increased for higher CRM surface area and mixing temperature. The specified reaction time should be the minimum time required to stabilize the binder viscosity. The mechanical mixing energy used can significantly alter the characteristics of the binder (i.e., high energy shear mixing cannot be done with coarse CRM). In addition, CRM flattens the temperature versus viscosity curve which results in the reduction of the binder's susceptibility to temperature. Most of the binder's viscosity modification occurs at higher temperatures. The shift in low temperature properties can be accomplished by adding extender oil to the standard asphalt cement in addition to the CRM.

The ability of CRM to enhance the properties of the binder depends on the compatibility between the asphalt cement and the CRM. The modified binder properties

may affect aging. One of the components of CRM is carbon black. The addition of carbon black improves the binder's durability. These binders are also more viscous and tend to retain thicker binder films on the aggregate, which delays the effect of oxidation. Table 3.1 shows the effects of crumb rubber modifier on binder properties using AC 20 asphalt and #16 sieve nominal maximum size rubber. This data shows that a binder containing 21% rubber has a viscosity 100 times that of the unmodified binder at 350°F.

Modifying the asphalt binder with CRM requires an increase in the binder content. The increase in the binder content and the cost associated with a CRM modified binder substantially increases the unit cost of the asphalt concrete. Clearly, to justify this cost requires an equally substantial improvement in pavement performance.

The modified binder properties influence performance characteristics of the pavement in the following ways:

- increases thermal cracking resistance,
- decreases permanent deformation,
- increases reflective cracking resistance,
- increases aging and oxidation resistance, and
- increases chip retention.

Negative performance characteristics of the pavement caused by the modified binder may include:

- increases bleeding and flushing potential, and
- increases tracking potential until the binder has cooled and the surface oxidizes.

Table 3.1:
The effect of crumb rubber modifier on binder properties (After Heitzman, 1992)

Binder Property	Percent Rubber (by weight of binder)						
	0	6	9	12	15	18	21
Viscosity at 176 °C (cp) (350 °F)	60	550	800	900	1500	2500	6000
Cone Penetration at 25 °C (77 °F)	48	40	43	44	40	30	27
Resilience at 25 °C (77 °F)	-1	-1	12	19	23	40	47
Softening Point °C (°F)	50 122	52 126	58 136	60 140	61 142	63 146	72 162

NOTES: Asphalt is AC-20, rubber is a 1.18-millimeter (No. 16) sieve nominal maximum size.
Interaction (reaction) period is 90 minutes at 175 °C (350 °F).

The other method for including CRM in asphalt concrete is the dry process where rubber replaces certain aggregate sizes and is mixed with the binder and aggregate simultaneously. By using coarse granulated CRM and by limiting the blending time and temperature, the CRM can keep its original properties. This limited blending time allows the surface of the rubber to react with the asphalt cement, but does not allow sufficient time for the asphalt to penetrate into the rubber particle which would bond the two materials together.

The mix design must take into account the difference in the material specific gravities. The specific gravity of CRM is approximately 1.15, while the specific gravity of

the aggregate is generally around 2.65. Therefore, the weight of CRM on any sieve must be adjusted by a factor of approximately 2.3 in order to achieve a compatible sieve gradation.

Compatibility between the chemistry of the rubber and binder is not an issue when the CRM is used as a rubber aggregate, nor is there a substantial reaction between the asphalt cement and the CRM affecting the performance characteristics of rubber aggregate hot mix. On the other hand, the cost of CRM is significantly higher than the aggregate being displaced. The binder content has to be increased to compensate for the rubber/asphalt reaction that occurs on the surface of the CRM. This increased binder content also increases the cost of the mix. Another factor that results in increased cost is the handling and proportioning of the aggregate and rubber to fit the prescribed gradation of the mix. This total increase in the cost of the paving material should be balanced by an equal or better increase in the performance, in order to make this technology financially viable.

The rubber aggregate affects the performance characteristics of the pavement in the following ways:

- increases reflective cracking resistance,
- decreases ice retention on the pavement surface, and
- increases the potential for surface ravelling.

When considering dense-graded mixes, the characteristics of the modified binder alter the laboratory properties of the mixes which should be considered in design. The mixing and compaction temperatures should be increased to better reflect the proposed

field conditions. Combined with the elasticity of the binder and the higher viscosity of asphalt rubber, a thicker binder film is deposited on the aggregate surface.

This increase in the designed binder content is proportional to the amount of CRM added to the binder. For example, if a conventional dense-graded mix that required 5% binder was modified with 20% CRM, then the modified mix would use 6% binder ($5 \times 1.2 = 6$). An increase in the aggregate VMA is required to maintain the desired air void content because of the thicker binder film.

Gap-graded mixes are designed to enhance stability through coarse aggregate interlock. The current designs for gap-graded mixes are to maximize the asphalt rubber content of the mix. This combines the stability of coarse aggregate contact with the elastic properties of asphalt rubber.

PlusRide II is a tradename for a modified gap-graded, dry process CRM mix. The only property used to establish the asphalt content is the percent air voids, with 2%-4% being the target. CRM content is 3% by weight of the total mix, and the asphalt binder content ranges from 7.5% to 9%. PlusRide II hot mix asphalt is designed to increase the stability of the gap-graded aggregate matrix with the elastic properties of CRM. The coarse CRM acts as aggregate, while the fine CRM reacts with the asphalt cement to modify binder properties. This mix is sensitive to the variation in material quality and content since the role of the CRM in the PlusRide II process is to act partially as a fine aggregate that fills some of the gaps in the aggregate gradation, and partially to react with the binder improving its temperature susceptibility. Poor quality control during

production, placement, and compaction has resulted in many premature field application failures in PlusRide II pavements.

The gap-grading of the aggregate produces a coarse textured mix with less rutting and improved skid resistance. The larger rubber aggregates exposed on the surface deflect under tire loading enough to inhibit formation of ice on the pavement. The enhanced binder may increase the ability of the mix to resist reflective cracking. The projected cost of this type of rubber modified hot mix asphalt could be between 20% and 40% higher than conventional hot mix asphalt.

In the design for an open-graded friction coarse, a higher binder content proportional to the CRM content is needed in a similar fashion as with dense-graded mixes. A moderate amount of binder contact with the surface of the rubber is required to prevent delamination. A change in target viscosity is needed in estimating the optimum mixing temperature. An extender oil can be added to the normal grade of asphalt used for a particular project to provide the aromatic oils required for the asphalt/CRM reaction. Another option is to select a softer grade of asphalt. The reaction of the CRM with the lower viscosity asphalt increases the binder viscosity to reflect the original target grade. The CRM should be ground so the volume of the CRM particles can fit into the voids in the mineral aggregate (VMA) and minimize interference with aggregate to aggregate contact.

The blending and reaction of the asphalt cement and CRM reduces the temperature susceptibility of the binder resulting in more uniform fatigue characteristics of the hot mix asphalt over a range of operating temperatures. The reduced temperature susceptibility

also increases rutting resistance in the high temperature range and thermal cracking resistance in the low temperature range. The enhanced elasticity increases reflective cracking resistance, and the thicker binder increases aging and oxidation resistance.

3.8 Krutz, et al, 1992

This paper was published in the 1992 Transportation Research Record No. 1339, and was funded by Asphalt Rubber Producers Group. It summarizes the results of an extensive laboratory research program dealing with:

- The use of conventional mix design methods for determining the optimum asphalt content for rubberized mixes,
- Permanent deformation characteristics of rubberized and unmodified mixes,
- Low-temperature cracking resistance of rubberized and unmodified mixes, and
- Fatigue characteristics for rubberized and unmodified mixes.

Each test was conducted on unmodified samples of AC-5, AC-20, and AC-40 grade asphalts. Tests were conducted using combinations of AC-5 with 17% rubber (i.e., designated as AC5R), AC-5 with 16% rubber and 5% extender oil (i.e., designated as AC5RE), and AC-20 with 16% rubber (i.e., designated as AC20R). The optimum modified asphalt content used in preparing samples was estimated to be 8.5% for AC5R, 8.3% for AC5RE, and 7.9% for AC20R.

Two tests were conducted to determine the permanent deformation of the samples. The first was a static-loading uniaxial unconfined creep test, and the second was a confined repeated-loading triaxial test. Deformations were continuously measured for

both tests using two linear variable differential transducers. Twelve samples for each of the six types of binders were prepared in order to allow three replicates to be tested under each condition. Table 3.2 and Table 3.3 show the results from the static permanent deformation tests at 77°F and 104°F, respectively, while Table 3.4 and Table 3.5 show the results from the repeated load permanent deformation tests at 77°F and 104°F, respectively. The AC-40 data was not included in Table 3.2 because of sample damage before testing.

From Table 3.2, it can be concluded that for this procedure at 77°F, the addition of ground rubber produced mixes that exhibit less deformation under creep load. For the samples tested at 104°F, all rubberized mixes exhibited less strain than the conventional AC-20. All three of the rubberized mixes showed a smaller reduction in stiffness than the conventional AC-20. This indicates that rubberized mixes undergo a larger reduction in stiffness with increasing temperatures than the unmodified mixes.

In analyzing the repeated load permanent deformation testing at 77°F, it can be seen that both the AC 5 and AC5RE failed during testing. This is due to the relatively low viscosity of the unmodified AC 5 and rubberized AC 5 that incorporates an extender oil, which is also of a very low viscosity. The AC5R finished the testing without failure, however, it exhibited large plastic strains. It is interesting to note that the AC20R exhibited a higher plastic strain than the conventional AC 20. In this case, the conventional AC 20 samples exhibited strains similar to those of AC 40. No explanation was offered for this anomaly.

Table 3.2:
Simple statistics for strain at end of loading for static permanent deformation tests conducted at 77°F (After Krutz, 1992)

Binder Type	Strain at 3600 Seconds of Loading (in/in)			Average Strain	Standard Deviation	Coefficient of Variation %	Creep Modulus (psi)
	Rep. A	Rep. B	Rep. C				
AC5	F	F	F	---	---	---	0
AC20	0.0079	0.0072	0.0122	0.0091	0.0027	29.8	5495
AC40	NA	NA	NA	NA	NA	NA	NA
AC5RE	0.0157	0.0165	0.0174	0.0165	0.0009	5.1	3024
AC5R	0.0132	0.0137	NA	0.0135	0.0004	2.6	3717
AC2OR	0.0069	0.0090	0.0059	0.0073	0.0016	21.8	6881

F - indicates sample failure prior to sixty minutes of loading
NA - indicates data not available

Table 3.3:
Simple statistics for strain at end of loading for static permanent deformation tests conducted at 104°F (After Krutz, 1992)

Binder Type	Strain at 3600 Seconds of Loading (in/in)			Average Strain	Standard Deviation	Coefficient of Variation %	Creep Modulus (psi)
	Rep. A	Rep. B	Rep. C				
AC5	F	F	F	---	---	---	0
AC20	0.0087	0.0056	NA	0.0072	0.0022	30.7	2797
AC40	NA	NA	NA	NA	NA	NA	NA
AC5RE	0.0045	0.0064	NA	0.0055	0.0013	24.7	3670
AC5R	0.0045	0.0051	0.0042	0.0046	0.0005	10.0	4348
AC2OR	0.0037	0.0041	0.0059	0.0046	0.0012	25.7	4380

F - indicates sample failure prior to sixty minutes of loading
NA - indicates data not available

Table 3.4:
Simple statistics for strain at end of loading for repeated load permanent deformation tests at 77°F (After Krutz, 1992)

Binder Type	Strain at 3600 Seconds of Loading (in/in)			Average Strain	Standard Deviation	Coefficient of Variation %	Creep Modulus (psi)
	Rep. A	Rep. B	Rep. C				
AC5	F	F	F	---	---	---	0
AC20	0.0056	0.0037	0.0037	0.0043	0.0011	25.3	11538
AC40	NA	0.0031	0.0034	0.0033	0.0002	6.5	15385
AC5RE	F	F	F	---	--	---	0
AC5R	0.0015	NA	0.0104	0.0110	0.0008	7.1	4566
AC2OR	0.0088	0.0053	NA	0.0071	0.0025	35.1	7092

F - indicates sample failure prior to sixty minutes of loading
NA - indicates data not available

Table 3.5:
Simple statistics for strain at end of loading for repeated load permanent deformation tests at 104°F (After Krutz, 1992)

Binder Type	Strain at 3600 Seconds of Loading (in/in)			Average Strain	Standard Deviation	Coefficient of Variation %	Creep Modulus (psi)
	Rep. A	Rep. B	Rep. C				
AC5	F	F	F	---	---	---	0
AC20	F	F	F	---	---	---	0
AC40	0.0091	0.0050	0.0067	0.0069	0.0021	29.7	2885
AC5RE	0.0141	0.0108	0.0114	0.0121	0.0018	14.5	1653
AC5R	0.0076	0.0097	NA	0.0087	0.0015	17.2	2312
AC2OR	0.0033	NA	0.0036	0.0035	0.0002	6.1	5797

F - indicates sample failure prior to sixty minutes of loading
NA - indicates data not available

For the tests at 104°F, it can be seen that the AC5R exhibited similar properties to the AC 40, whereas the AC20R exhibited the lowest amount of strain. This indicates that for this particular aggregate source and gradation, an AC5R could be expected to behave like an AC 40 in warmer temperatures, and an AC20R could be expected to exhibit a smaller permanent deformation than a conventional mix using AC 40. It can be concluded that the addition of rubber to the mix produces a stiffer mix at higher temperatures.

On the basis of the information available, permanent deformation testing should be carried out at elevated temperatures. Not only does rutting occur primarily at the elevated temperatures, but the modified mixes appear to behave differently at lower temperatures. This conclusion is supported by both the static and repeated load test results. Also, permanent deformation testing should be based on repeated loading. •

In conclusion, these tests showed that the addition of ground tire rubber to the asphalt mixes results in mixes that exhibit less permanent deformation at high temperatures compared with unmodified mixes for both static and repeated load testing.

3.9 Maupin, 1992

This paper was published in the 1992 Transportation Research Record No. 1339, and was funded by the Virginia Department of Transportation. It summarizes the results of laboratory and field testing. The paper contains the specific processes and performance observations of the test sections in Virginia constructed with CRM and the results of laboratory testing done on these materials.

In August of 1990, two sections of control mix and two sections of experimental rubberized asphalt mix were placed as an overlay in an urban area carrying slow-moving traffic. The control mix contained 4.5% AC-30 asphalt cement, and the experimental mix contained 6.75% asphalt-rubber consisting of 77% AC-30, 6% extender oil, and 17% finely ground CRM. All test results were from tests conducted on mixes sampled during construction. No performance evaluation was conducted for the field sections.

Marshall, gyratory testing machine (GTM), creep, resilient modulus, indirect tensile, and stripping tests were conducted on mixes sampled during construction. These tests provided the following information:

- For one section of the asphalt-rubber mix, the voids filled with asphalt (VFA) was higher than desirable, and the voids in the total mix (VTM) was lower than desirable. The VTM was at the upper limit for both control sections.
- Both asphalt rubber mixes failed all of the GTM tests, which would indicate that the compaction effected by traffic would result in undesirable characteristics and probably cause premature failure of these sections. The GTM results may be biased toward mixes without rubber since the tests were performed at high temperatures, at which the deformation resistance of the asphalt rubber is reduced. Both control mixes passed all GTM tests.
- The modified mixes had a lower modulus and a higher plastic strain compared to that of the control mixes.
- The indirect tensile strength of the modified mixes was significantly lower than that of the control mixes.

Results of the mixes sampled during construction indicate that mixes containing asphalt rubber were less resistant to permanent deformation but more resistant to stripping than mixes without rubber. However, laboratory tests may not be indicative of field performance.

Laboratory tests were conducted using AC-20 asphalt cement containing 5, 10, and 15% rubber. Marshall designs were performed at each rubber content with different percentages of binder to determine the optimum asphalt content at 4.5% VTM. The gyratory shear, resilient modulus and indirect tensile tests were then performed at the optimum asphalt content. The tests provided the following information:

- The VMA increases in all mixes for increasing percentages of rubber, therefore, it is anticipated that the rubber mixes with higher asphalt content would have a higher resilient modulus than conventional mixes.
- There was no trend observed with respect to the shear strengths for mixes with different rubber contents, but all of the strength values were very low.
- The resilient modulus appeared to increase as the rubber content was increased.

When the average values were tested, there was no significant difference between any of the average values, therefore, this apparent trend could not be confirmed.

An optimum rubber content of 5% to 10% yielded the maximum resilient modulus and indirect tensile strength for mixes containing rubber.

3.10 Page et al, 1992

This paper was published in the 1992 Transportation Research Record No. 1339, and was funded by the Florida Department of Transportation (FDOT). Its objective was to provide a concise overview of all FDOT and University of Florida activities, including field projects and laboratory testing, pertaining to the development and use of CRM in binders for specific asphalt concrete mixes and other highway construction applications.

Field experimentation was limited to dense-graded and open-graded friction courses in order to study the expected improvement in the properties of these mixes over those of conventional mixes. The expected improvements included improved durability and resistance to shoving at intersections for the dense-graded mixes, and increased binder film thickness for improved durability, aggregate retention, and improved resistance to binder drainage for the open-graded mixes. Three projects were constructed in 1989 and 1990 to evaluate the use of CRM in asphalt concrete friction courses.

The first project involved dense-graded modified mixes with three different percentages of CRM added to the binder. Gyrotory test machine (GTM) tests indicated that the mix with 5% CRM had an increased resistance to shear. The second and third projects involved open-graded modified mixes with varying percentages of CRM added to the binder. The constructability and short-term performance of these asphalt-rubber test pavements indicated that it is feasible to use CRM in a modified binder for friction course construction without any major changes in construction operations.

Although the long-term performance of these pavements cannot be evaluated until some time in the future, sufficient test data and corroborating information suggested that

asphalt-rubber friction courses, particularly the open-graded, have improved durability over conventional friction course mixes. This improvement was due to reduced age hardening, increased film thickness, improved aggregate retention, and greater resilience of the binders. Larger binder contents and the retention of thicker binder films on the aggregates were possible because of the increase in viscosity produced by the addition of CRM. No data or analysis on pavement tests or performance evaluation was presented.

It was shown that properly proportioned asphalt-rubber binders can be used in dense or open-graded friction course mixes without requiring significant changes to the conventional mix production operations. It was also shown that conventional paving operations for friction course mixes can be used with asphalt-rubber mixes. Long-term performance data was not available for the asphalt-rubber mixes, but some performance predictions were made on the basis of laboratory testing. Dense-graded friction course mixes with asphalt-rubber tended to reduce pavement distortions because of the improved resilient properties of the asphalt-rubber. Open-graded friction course mixes with asphalt-rubber tended to eliminate binder drainage from the aggregate in trucks even for increased binder contents. These mixes should provide improved aggregate retention and improved durability and life.

3.11 Stroup-Gardiner et al, 1992

This paper was prepared by the University of Minnesota, and presented at the 1993 Transportation Research Board Annual Meeting. The objective was to evaluate the influence of rubber, the rubber type, and asphalt chemistry on asphalt-rubber reactions by

conducting laboratory tests using a Brookfield rotational viscometer. The test procedure used to determine the viscosity of the asphalt-rubber binders was a modified ASTM D2994 for rubberized tars.

It was suggested that the results of the laboratory testing should be viewed only in a relative manner because of possible errors, such as:

- using a different spindle size for each percentage of rubber tested,
- testing speeds were changed during experimentation, and
- no hot oil bath was available which could reach 175°C, so hot plates, heating mantles, and ovens were used in an attempt to maintain test temperatures.

Since all tests were run in the same manner, the trends exhibited were suggested to be valuable for comparison purposes. The coefficient of variation of the viscosity measurements ranged from 9% to 16% (Table 3.6).

With sufficient time and heat, a partial polymer modified asphalt cement developed as the rubber slowly depolymerized. A high degree of interaction between the asphalt and rubber is desired to accelerate the depolymerization process. In the wet process, a relatively high percentage of light fractions is desirable for asphalt. This can be achieved by adding an extender oil or selecting a lower viscosity grade binder. Both have the added advantage of compensating for the increased viscosity when rubber is added, as well as providing sufficient aromatics for the rubber reaction without removing key asphalt components.

Most high molecular polymers (i.e., rubber) exhibit increased volume characteristics when submerged in low molecular liquids. Swelling is not a chemical

Table 3.6:
Estimate of Test Variability (After Stroup-Gardiner, 1992)

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

reaction, but rather a diffusion process. Swelling results from the liquid moving into the internal matrix of the polymer. Just after a polymer is immersed in a liquid, the surface of the rubber has a high liquid concentration. As time progresses, the liquid moves into the rubber interior. This is controlled by the compatibility of the liquid and the rubber, the viscosity of the liquid, and the time the rubber particle is submerged in the liquid.

It is the viscosity of the liquid that controls the rate of swelling, whereas a faster rate of swelling is expected when the rubber is added to a softer binder. As the swelling increases, there is a corresponding degeneration of the polymer properties. By increasing the non-rubber portion of the CRM, swelling can be decreased. Therefore, when the amount of carbon black in the CRM increases, there is a linear decrease in swelling.

An increase in viscosity can be used as an indicator of asphalt-rubber compatibility. However, viscosity increases for the modified binders could be primarily a function of the

introduction of spherical solids into the asphalt cement instead of swelling due to the solubility of the rubber. Measured viscosities of CRM binders were approximately 2.3 and 10.5 times greater than that of the unmodified viscosity for 10% and 20% rubber, respectively. This would indicate that the viscosity did increase due to the addition of rubber, and this increase was mainly the result of swelling due to solubility rather than the inclusion of solid particles. Each combination of asphalt and type of rubber produces a unique modified binder. Therefore, assessing the compatibility of the rubber and asphalt cement should be part of the quality control testing during construction in order to identify changes in the composition of the crumb rubber source.

The following conclusions are drawn from the information given in this paper:

- viscosities increase with increasing amounts of rubber, regardless of the rubber type,
- non-Newtonian behavior of rubber-modified binders increases with increasing amounts of rubber,
- a lower viscosity asphalt increases the rate of the asphalt-rubber reaction when compared to higher viscosity asphalts from the same source, and
- all combinations of rubber and asphalt produces a uniquely modified binder.

Assessing the compatibility of the rubber and asphalt cement should be part of the quality control during construction in order to identify changes in the composition of the CRM.

3.12 Swearingen et al, 1992

This paper was written by the staff of the Washington State Department of Transportation (WSDOT). Its purpose was to examine the types of recycled materials which can be utilized in paving products and to identify other recycled products which can be utilized in other types of transportation applications. This review analyzes the portion dealing with the use of recycled rubber tires in asphalt pavements. No laboratory testing was conducted specifically for this paper.

Washington is one of the states which has enacted legislation to regulate the scrap tire problem. WSDOT has had experience with rubber in stress absorbing membranes (SAMs), stress absorbing membrane interlayers (SAMIs), open-graded rubberized friction course mixes, and PlusRide II mixes. WSDOT has stopped using the rubber-modified SAMs and SAMIs because of the added cost and undesirable performance of these applications.

Five rubberized open-graded friction courses have been constructed since 1982. All of these projects are showing good to very good performance except the I-405 bridge deck overlay. In this case, some distress is showing in the wheel path areas of the pavement. Other performance evaluations are as follows:

- S-Curve/Cedar R. Bridge & RR Bridge built in 1984: Successful after seven years of service under high traffic volumes,
- Evergreen Point Br. to SR-908 built in 1982: Very good performance with only minor rutting noted and some pot holing after nine years of heavy traffic volumes,

- Columbia River to 39th Street built in 1986: Very good performance after five years of service, and
- Armstrong Road to Albion Road built in 1990 and 22nd Street to Little Hoquim Br. & Riverside Br. built in 1991: No performance history to date.

The rubberized open-graded friction courses provided the benefits of lower tire noise and decreased spray from vehicles in wet weather. Ravelling, however, seems to be a problem with all of these sections. The cost-effectiveness of the rubberized open-graded friction courses is undetermined at this time. The initial costs of these modified mixes ranged from 1.1 to 3.7 times that of the conventional mixes, but long-term performance has not been evaluated yet because most of these sections are only seven years old.

Seven PlusRide projects have been constructed since 1982. The performance evaluations of these projects are as follows:

- Main Street to South First Street built in 1982: Flushing and rutting have occurred marring performance,
- Bridge No. 82/205 et al built in 1982: PlusRide II on Br. No. 82/114N lasted eight and a half years while ACP Class D control on Br. No. 82/115N only lasted seven years. The added cost for the PlusRide II mix was 50% over the ACP Class D control,
- 84th Ave. S I/C and Auburn Ramps built in 1983: Performance has been excellent on this low traffic ramp,
- S-Curve/Cedar R. Br. & RR Bridge built in 1984: Large sections of overlay ravelled in wheel paths after only two years of service,

- Fautleroy Ferry Dock built in 1985: Total failure due to instability of mix; replaced with dense-graded ACP,
- Skagit Co. Line to Dalgren Rd. built in 1985: Performance satisfactory after six years of service with some longitudinal cracking present, and
- 35th Ave. NE to SR-5 built in 1986: Exhibited transverse and longitudinal cracking very early.

The PlusRide mixes have had dubious results, with some sections performing well while others failing immediately after construction. WSDOT has had some construction problems with these mixes, which may have contributed to the failure of certain sections. The initial average cost of these mixes were approximately 2.3 times that of the conventional mixes. The Cost-effectiveness of the PlusRide mixes cannot be determined since they have not yet produced a consistent product.

3.13 Takallou, et al, 1992

This paper was published in the 1992 Transportation Research Record No. 1339, and was funded by BAS Engineering Consultants, Inc. It summarizes the results of literature reviewed and laboratory testing of rubber modified binders, and gives a general overview of the progress and new developments in using ground tire rubber in asphalt paving materials.

The paper suggests that there were several barriers to the widespread use of both the wet and dry processes of asphalt rubber, including the use of specialized equipment, unique aggregate gradations, specialized mix designs, lack of standard design criteria, cost

of crumb rubber, and use of patented processes. In the wet process, the increases in cost were attributable to:

- high cost of mobilizing the specialized equipment at the production facility, and
- license fee for using the patented process.

In the dry process, the increases in cost were attributable to:

- unique aggregate gradation,
- handling of crumb rubber through asphalt plants,
- higher asphalt and filler content, and
- fee for using the patented process.

The reaction of the rubber with the asphalt binder, creating an asphalt rubber binder, displayed several improved properties:

- high viscosity,
- ball and ring softening point greater than 60°C,
- high elasticity and high resilience at low temperatures, and
- cohesiveness ten times greater than that of unmodified asphalt at 20°C.

It was discovered that the reaction processes could be improved by incorporating a catalyst into the mix to produce the excess aromatic oils for rubber absorption and binder lubrication. The improvements of the original binder were:

- lower viscosity susceptibility,
- increase in the softening point temperature which indicates that the binder becomes less sensitive to temperature,
- longer preservation of the original elastic properties of the binder, and

- better adhesion.

Viscosity tests conducted in the laboratory showed that the viscosity of asphalt rubber binder at a mixing temperature of 200°C reaches its peak 45 minutes after the introduction of the rubber. Subsequently, the viscosity declined steadily (Figure 3.3) and

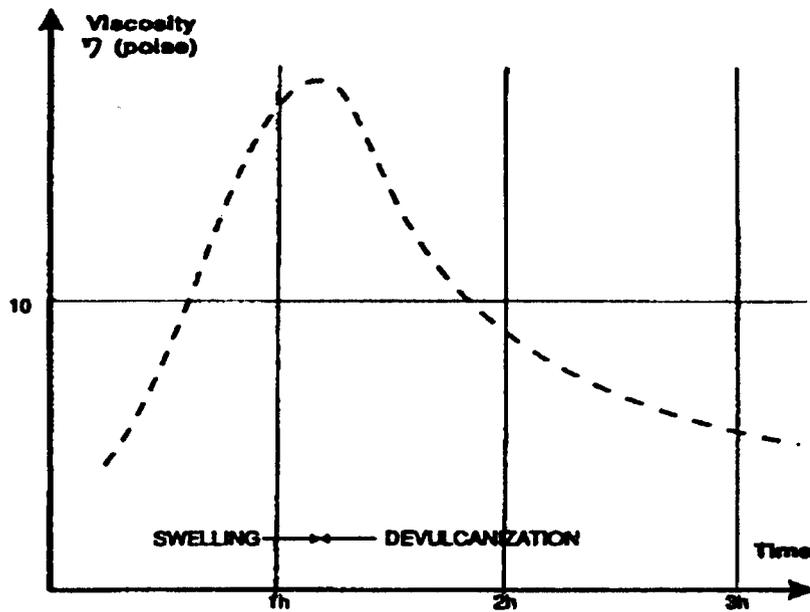


Figure 3.3: Viscosity versus time plot for a rubber digestion period in asphalt (After Takallou, 1992).

the quality of the binder deteriorated. The addition of extender oil reduced the ring and ball softening point while increasing penetration, ductility, and tensile strength. This paper calculated that 6% extender oil provides optimum asphalt rubber binder properties. The results of these tests are shown in Figure 3.4.

Results of several demonstration projects in papers reviewed by Takallou showed that using rubberized asphalt increases fatigue resistance, retardation of reflective

cracking, improves skid resistance, and increases durability. The laboratory results supported these conclusions.

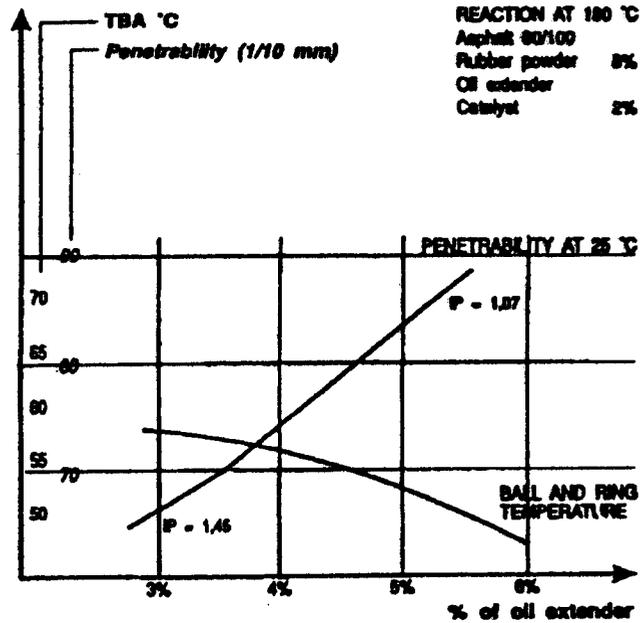


Figure 3.4: Asphalt properties with increasing amounts of extender oil (After Takallou, 1992).

3.14 Van Kirk, 1992

This paper is an overview of experiences the California Transportation Department (Caltrans) experience with rubberized asphalt concrete. It was developed for, and funded by, Caltrans. No laboratory or field testing was conducted specifically for this paper. All pavement characteristics and performance analysis were based on past Caltrans experience with CRM.

Caltrans has been using rubber-modified mixes for over ten years. This experience has included field trials and laboratory testing. Caltrans has constructed over 20 overlay projects using rubber-modified mixes. They have compared equal thicknesses of rubberized asphalt concrete to conventional dense-graded asphalt concrete at numerous locations, and the rubberized asphalt concrete outperformed the conventional mixes.

In 1983, a project was constructed using a section of rubberized asphalt with a reduced thickness and sections of varying thicknesses of conventional dense-graded mixes. This project is still being evaluated, but to date, the thinner sections of rubberized asphalt concrete have outperformed the thicker sections of conventional dense-graded mixes. Almost five years after construction, it became evident that certain types of CRM's may allow thinner overlay sections than conventional dense-graded mixes without compromising service life.

One problem Caltrans has had with the conventional dense-graded mixes is their premature failure where tire chains are used. Los Angeles abrasion tests indicated that rubberized asphalt concrete mixes are more abrasion-resistant compared to conventional mixes. It also showed that rubberized asphalt concrete mixes have extremely low permeability, which decreases oxidation and aging. A lower permeability asphalt can also reduce infiltration of water into the pavement mat, which would prevent much of the freeze-thaw damage that some conventional mixes experience. The rubberized asphalt concrete can also sustain higher deflections than conventional mixes, and can be very effective for mitigation of reflective cracking.

All rubber-modified asphalt concrete projects were reviewed in 1991. The following are project evaluations of some of the test sections:

- Project 1: This project is 13 years old. Both the wet rubber-modified mixes (i.e., Flomix™) and the conventional mixes have performed similarly, both exhibiting the same type and degree of cracking. This CRM material was not cost-effective.
- Project 9 and 10: The material used for these projects was Ramflex™. Both projects exhibited distress in the form of transverse cracks, longitudinal cracks, and raveling within the first two years. This CRM material was not cost-effective either.
- Project 3: This project constructed of Arm-R-Shield™ is 11 years old and has performed extremely well. It now exhibits extensive transverse cracking, longitudinal cracking and surface abrasion and is ready for rehabilitation. Conventional overlays in this area would normally require an overlay or replacement within five years. This modified mix was cost-effective.
- Project 7: This project is made of Plus Ride and is in its 8th year. This was the first rubberized-asphalt reduced thickness project to be compared to different thicknesses of conventional mixes. The modified sections have performed satisfactorily, although they began exhibiting some transverse cracks, longitudinal cracks, surface abrasion, and raveling. All the thin sections of the conventional dense-graded mixes have failed within the first two years.

Overall, the Flomix™ and Ramflex™ mixes were considered not cost-effective, while the Arm-R-Shield™, Overflex™, and PlusRide sections were considered cost-effective for the specific site conditions tested.

3.15 Doty, 1993

The following paper offers a progress report on the rehabilitation projects constructed by Caltrans using asphalt-rubber mixes. Its main objective was to evaluate several flexible pavement rehabilitation alternatives involving the use of asphalt-rubber.

The asphalt-rubber test sections include:

- dense-graded asphalt concrete (DGAC) containing an asphalt-rubber blend, both with and without a stress absorbing membrane interlayer (SAMI),
- PlusRide II DGAC, both with and without a SAMI,
- single- and double-stress absorbing membranes (SAMs) containing an asphalt-rubber binder, and
- a double stress absorbing membrane containing the binder which was marketed by Sahuaro Petroleum in the early 1980s.

This review will only focus on the first and second alternatives, because the rubber-modified SAMs and SAMIs have already proven to be not cost-effective. In addition, some laboratory testing was conducted for this paper. Conventional DGAC was used for short segments involving different overlay thicknesses for comparison regarding the effectiveness of the asphalt-rubber combinations being studied.

Caltrans constructed test sections with conventional and asphalt-rubber DGAC, along with other types such as SAMs and PlusRide, on Route 395 in September of 1983. The asphalt-rubber binder consisted of 78% AR-4000 grade asphalt, 18% CRM, and 4% extender oil (by weight of total binder). The binder for the PlusRide II segments consisted of AR-4000 grade asphalt.

The project was constructed in August through September of 1983. No problems were encountered when placing either the CRM DGAC or the conventional DGAC, but the PlusRide II mix had a consistency "resembling bubble gum when placed and was noticeably springy even after compaction." The weather at the construction site varied throughout the year with the summer having many days with high temperatures above 90°F and winter having temperatures below 0°F. Monitoring of these sections was frequent through 1987 with the last inspection in May, 1987.

The estimated cost for a 0.15 foot thick section of CRM DGAC over CRM SAMI, CRM DGAC, PlusRide II over CRM SAMI, PlusRide II, and Conventional DGAC control is \$6.88, \$5.37, \$7.83, \$6.32, and \$3.04 per square yard, respectively.

It was suggested that the average surface abrasion loss for a conventional DGAC is 35 grams (per the Los Angeles abrasion test, method B). The surface abrasion test results for the CRM DGAC and the PlusRide II mixes indicate an average loss of 17 grams and 13 grams, respectively. This shows that the modified mixes are substantially more resistant to surface abrasion than the conventional DGAC. Towed-trailer skid testing results indicated the PlusRide pavement is adequate and the CRM DGAC and the conventional DGAC are very good.

All sections of this project are now showing some cracking distress. There is a small amount of rutting present in the conventional mixes, and some pot holes have developed in the PlusRide II mixes. The amount of cracking is probably the best indication of the remaining service life for each of the segments. Table 3.7 shows an estimated percentage of cracking that has developed for each pavement segment. It is evident that both the CRM DGAC sections and the PlusRide II DGAC sections were still performing well, while half of the conventional DGAC sections were still performing well while half have already failed.

The tolerable deflection of the asphalt-rubber overlays is greater than conventional DGAC because of the greater amount of recoverable strain. This would suggest that the service life of the asphalt-rubber DGAC overlays should be considerably larger than the equivalent thicknesses of conventional DGAC, at least for certain combinations of climate and traffic. Both conventional sections had failed when the last survey was taken, but the asphalt-rubber sections had not.

It was suggested that some additional similar experiments at locations having both similar and different traffic and climate conditions are needed before final conclusions regarding these asphalt-rubber combinations can be drawn.

Table 3.7:
Estimates of pavement cracking (After Doty, 1993)

Material	Segment Number	Estimated Percent Cracked (May 1987)
ARS DGAC	1	<5%
	2	<5%
	3	5-10%
PlusRide DGAC	4	<5%
	5	5-10%
	6	5-10%
Conv. DGAC	7	70-75%*
	8	75-80%*
	9	10-15%
	10	<5
Double SAM	11	60-65%
	12	65-70%
SAM	13	85-90%

*Failed

3.16 Epps, 1993

The following paper is a NCHRP study was presented at the 1994 Transportation Research Board meeting. It discusses the uses of recycled rubber tires in asphalt paving materials as well as other applications, such as in geotechnical and traffic operations. This paper is an overview of the history, terminology and the performance characteristics of CRM asphalt, which was developed through an extensive literature review. No laboratory or field tests were conducted specifically for the purposes of this study.

The properties of CRM asphalt binders depend on:

- the rubber type, size, and concentration,
- asphalt type and concentration,

- diluent types and concentration, and
- reaction temperature and time.

The field performance of CRM asphalt binders used for hot mixes has varied. This performance variability is due largely to poor design, project selection, and field quality control. Existing quality control and quality assurance methods have not been sufficiently developed to ensure that the desired binder properties are obtained in the field. The study also indicated that the asphalt-rubber binders produced in the laboratory were stiffer than field-produced binders. A portion of this paper is directly dedicated to discussing crumb rubber modified hot-mix experience in various states. The common trend of these results is that the performance of pavements constructed with the dry process have ranged from disastrous to average, where the performance of pavements constructed with the binder produced by the wet process have ranged from good to exceptional.

Some of the laboratory data from the literature, which did correspond with the data obtained in the field, suggest that as the rubber concentration increased, the maximum load required to produce failure increased. The viscosity and force ductility results are also affected by the type of base asphalt cement and extender oil used in the asphalt-rubber blend. The data indicated that asphalt cement and extender oil characteristics significantly influence the physical properties of asphalt-rubber binders. Low-viscosity base asphalts produce lower viscosities, lower failures stresses, and higher failure strain properties in asphalt-rubber binders. Other tests indicate property changes due to the reaction or digestion of synthetic rubber tire buffings and natural rubber tire buffings, and that the properties of the asphalt-rubber binder are a function of the type of rubber and the time

and temperature of reaction or digestion. It was also discovered that reactions at high temperatures for long periods of time may produce undesirable binders.

The following is a summary of the anticipated CRM pavement properties:

- Marshall and Hveem stability is reduced in mixes produced by either the wet or the dry processes compared to conventional mixes.
- Typically, lower resilient modulus values are obtained in mixes containing crumb rubber. Reports of experience in Oregon and California indicate that mixes produced by the dry process have a larger resilient modulus than mixes produced by the wet process for all but very low temperatures.
- Studies conducted in Texas and Nevada suggest that mixes containing CRM and conventional mixes have similar resistance to permanent deformation. The wet and dry process mixes had similar behavior.
- Fatigue life is improved when CRM is added to hot mix asphalt in both the wet and dry processes. It is evident that in case one, the cycles to failure is approximately twice that of the conventional mixes, while in case two, the cycles to failure is approximately the same as the conventional mixes.
- Tensile strength may either increase or decrease when CRM is added to a mix. This variation is most likely due to the extent of compatibility of the asphalt and the CRM being combined. The tensile strengths for the rubberized mixes are less than that of the unmodified asphalts, except for the AC20R at 0°F and -20°F.
- Water sensitivity testing should be performed on mixes containing CRM,

because it was shown to be a problem.

- The degree of asphalt-rubber interaction and the base asphalt low temperature properties contribute to the resistance to thermal cracking. Improved resistance to thermal cracking has been reported in most mixes containing CRM.
- Improved resistance to abrasion is reported based on results from laboratory tests in California, while other data indicates that no improvement in abrasion resistance results with the addition of CRM.
- Typically, the presence of CRM lowers the surface friction values of asphalt concrete pavements.
- Noise reduction of up to a claimed 90% is possible when asphalt-rubber open-graded mixes are used instead of Portland concrete surfaces. Similarly, a noise reduction of 50% is possible from asphalt and Portland cement-bound surfaces.
- Typical cost increases for mixes containing CRM are 1.5 to 2.0 times the cost of conventional mixes. Costs of CRM asphalt mixes are expected to decrease in the future as the result of increased competition, expiration of patents, and increased demand.
- The construction process used for hot-mix asphalt pavements must be modified in order to produce a quality CRM hot mix.

3.17 Ksaibati, et al, 1993

This paper was presented at the 1994 Annual Transportation Research Board Meeting. Its primary objective was to offer an overview of a newly developed CRM processes involving carbonous residue-modified paving asphalts. It must be determined whether carbonous residuals recovered from scrap tires combined with waste oils are viable materials for modifying asphalts. It must also be determined how additions of these materials alter asphalt and asphalt-aggregate properties. A variety of laboratory tests were conducted using these carbonous residual modified asphalts.

A continuous bench-scale reactor system was designed, constructed and operated by the authors and their staff to convert scrap tires and waste oils into useful products other than combustion fuels. 50% of tires and oils are recovered as product oils and 30% as a carbonous residue. The remaining 20% was composed of steel, glass fiber, and water. All carbonous residues used to modify asphalt cements were screened to pass a #325 mesh sieve to prevent sedimentation of the particulates in the modified asphalts. In the specimens constructed for testing, 10% residue was added to AC-10 asphalt.

Table 3.8 shows the viscosity and aging properties for both unmodified and modified asphalts using two different types of carbonous residues. It is evident that the viscosity does increase with the addition of the carbonous residues just as it does with CRM, but to a lesser degree. It is also evident that both additives caused a greater anti-oxidation behavior in the mix. At 10°C, these same additives caused comparable 25°C viscosity increases. This indicates that there is no adverse effects from addition of solid particles on the low temperature flow properties. This data also shows that the net

percentage increase in asphalt stiffness and/or temperature susceptibility at 25°C and 10°C remains almost constant, but the modified viscosity values increased from 165% to 225% for 25°C and 10°C, respectively, for the unmodified asphalt.

Results from other laboratory tests are as follows:

- a long term embrittlement test showed that there is a delayed molecular structuring for the carbonous residue-modified asphalt.
- moisture sensitivity tests showed that specimens containing carbonous residues required a greater number of repeated freeze-thaw cycles to induce failure than did unmodified samples.
- viscosity tests of the two modified asphalt binders at 135°C showed a viscosity increase of 17% to 52% over the conventional AC-10 grade asphalt.

Table 3.8:
Aging properties of unmodified and modified
AC-10 asphalts (After Ksaibati, 1993)

Modifier	Aged	Viscosity, Pa.s		▲ %, Viscosity	
		×10 ⁴ , 25° C	×10 ⁷ , 10° C	25° C	10° C
None	No	20.3	0.20	---	---
None	Yes	53.8	0.65	165	225
WMO-Add ^a	No	30.4	0.45	---	---
WMO-Add ^a	Yes	70.7	1.01	133	124
WMO-Add ^b	No	32.7	0.44	---	---
WMO-Add ^b	Yes	77.6	1.02	137	132
DO ^c	No	25.3	0.35	---	---
DO ^c	Yes	87.7	1.19	246	240
DO-Add ^a	No	24.5	0.38	---	---
DO-Add ^a	Yes	86.0	1.21	251	218

^a 8 wt% indicated carbonous residue + 2 wt % retort additive A

^b 8 wt % WMO carbonous residue + 2 wt % retort additive B

^c 10 wt % DO carbonous residue

- penetration test values exhibited the same trends as the kinematic viscosity values. Table 3.9 shows the viscosity and penetration test results.
- forced ductility tests showed that unaged-modified and age-modified asphalts had larger peak load values than the corresponding control samples. The higher peak load values suggest a lower tendency to produce tenderness problems in bituminous mixes.
- Marshall stability tests showed that both modified mixes satisfied the minimum stability requirements of 544 kg for medium traffic roadways.
- resilient modulus testing showed an average increase in stiffness of 17% at 25°C and 37% at 40°C when compared to conventional mixes. This demonstrates the reinforcing effects of the carbonous residue.

Table 3.9:
Asphalt specification tests (After Ksaibati, 1993)

Sample Description	ASTM D-2170 135°C Viscosity cSt	ASTM D-5 4°C Penetration 200g,60 sec,dmm	ASTM D-5 25°C Penetration 100g,5 sec,dmm	D-70 25°C Specific Gravity
Amoco AC-10	334.4	32.5	83.0	1.030
AC-10 + Additive ^c	399.5	35.9	82.0	1.077
AC-10 + WMO ^a	426.9	31.5	78.5	----
AC-10 + WMO + Additive ^b	509.7	31.5	75.5	1.081
AC-10 + DO + Additive ^b	391.8	37.0	85.0	1.072

^a AC-10 + 10 wt % WMO carbonous residue.

^b AC-10 + 8 wt % indicated carbonous residue + 2 wt % retort additive "B"

^c AC-10 + 10 wt % retort additive "B"

- rut-depth testing using the Georgia load-wheel tester indicated an acceptable deformation value of 7.6 mm after 8,000 cycles. All samples passed this test with the residue and retort-additive "B" residue samples exhibiting the least amount of permanent deformation of 3.0 mm and 4.3 mm, respectively. These results were consistent with the resilient modulus results.

The physical properties of carbonous residue-modified asphalts and carbonous residue-modified asphalt-aggregate mixes were altered to reduce the detrimental effects of oxidation, long-term embrittlement, moisture damage, and permanent deformation of conventional asphalt pavements. The chemistry of the carbonous residue surface is altered to show aliphatic or aromatic characteristics by changing the type of waste oil feed to the reactor. Addition of proprietary additives created anti-oxidizing and anti-stripping properties to carbonous residues when used as a modifier in asphalt cement.

The one thing that must be remembered when utilizing the information in this paper is that waste oils, as well as scrap tires, are added to the asphalt mix, which can greatly alter the properties of the modified asphalt.

3.18 Terrel, 1993

This study was carried out by Oregon State University (OSU) under Clean Washington Center funding. OSU conducted an evaluation of CRM asphalt pavements using Strategic Highway Research Program (SHRP) tests and examined their performance through a number of test sections built in Seattle in 1993. The mixes tested were the conventional WSDOT Class 'A' surface (control mix), PlusRide II base (dry process), PlusRide II surface (dry process), and ARHM-GG surface (wet process). The following SHRP laboratory tests were conducted on various modified asphalt specimens:

- Thermal Stress Restrained Specimen Test (TSRST)
- Environmental Conditioning System (ECS)
- Aging (short and long term)
- Flexural Beam Fatigue Test - Controlled Strain (FBFT-CS)
- Repetitive Shear Strain Test - Constant Height (RSST-CH)

In addition to the SHRP tests, rutting tests were conducted on each mix using the OSU Wheel-tracker machine.

Table 3.10 shows the resilient modulus test results from laboratory specimens and field cores. The laboratory tests showed that conventional mixes have a resilient modulus 1.6 to 4.0 times larger than the modified mixes. The ARHM-GG surface had the next

Table 3.10:
Resilient modulus test results (After Terrel, 1993)

Mix	Asphalt Type	OSU laboratory (ksi)	Field Cores (ksi)	Standard Deviation (ksi)
Class 'A' Surface	AR 4000W	375	234	100
PlusRide II Base	AC 5	95	64	69
PlusRide II Base	AR 4000W	179	117	44
PlusRide II Surface	AC 5	113	N/A	53
PlusRide II Surface	AR 4000W	194	102	46
ARHM-GG Surface	AR 2000	235	126	64

highest resilient modulus, and the PlusRide II base had the lowest. The field tests also showed that the conventional mix had the highest resilient modulus of 1.9 to 3.7 times that of the modified mixes. The CRM mixes were proven to have very little variation in the resilient modulus ratio approximately 95% of the time, regardless of the mix.

Table 3.11 shows a summary of results for the beam rutting test results in which the OSU Wheel Tracker was used. These results showed that the average rutting depth for the conventional mix and the ARHM-GG surface mix are approximately the same, while the PlusRide mixes have rutting depths of 4.8 to 10.3 times that of the conventional Class 'A' surface.

The following conclusions were drawn for the pavement performance of gap-graded asphalt rubberized hot mixes compared to conventional mixes:

Table 3.11:
Summary of statistics for beam rutting test results (After Terrel, 1993)

Mix	Asphalt Type	Mean Air Voids	Average Rutting Accumulated at 1000 Wheel Passes	Average Deformation/ Wheel Pass	Standard Error
		(%)	(in)	(in/log(wp))	(in/log(wp))
Class 'A' Surface	AR 4000W	6.9	0.0446	0.0524	0.00265
PlusRide II Base	AC 5	3.8	0.4596	0.3397	0.02931
PlusRide II Base	AR 4000W	5.2	0.3742	0.2868	0.02575
PlusRide II Surface	AC 5	3.9	0.4012	0.2906	0.03493
PlusRide II Surface	AR 4000W	5.1	0.2139	0.2447	0.03754
ARHM-GG Surface	AR 2000	8.4	0.0482	0.0472	0.00289

- thermal cracking resistance is improved by lower fracture temperature and increased fracture strength,
- Asphalt Residue Hot Mix Gap-Graded Asphalt (ARHM-GG) has a low susceptibility to water damage. An increase in the resilient modulus ratio suggests that the mix may experience stiffening due to moisture, mixing time, and mixing temperature,
- long term aging resistance is improved,
- fatigue resistance is double that of Class A asphalt concrete,
- rutting resistance is superior to all other mixes when tested in simple (block) shear, and

- stiffness, or resilient modulus, is generally lower than Class A mixes, but does give better results compared to all PlusRide II mixes.

These gap-graded surface asphalt concrete mixes could be readily used when Class 'A' mixes are specified.

Results from the Environmental Conditioning System (ECS) showed that each mix had good resistance to water sensitivity. This would suggest that little or no stripping had occurred within the mixes. The gap-graded surface mixes showed a constant increase in strength through all loading cycles. All mixes may have experienced stiffness gains through either oxidation of the mix during water conditioning or increased sample density due to repeated loading. None of the mixes failed the ECS tests.

3.19 U.S.D.O.T., 1993

The following paper is a report to Congress on the study of the use of numerous recycled paving materials, with the main emphasis on CRM technology. This paper was written by the United States Department of Transportation, Federal Highway Administration. It was primarily intended to be an overview of CRM technology, and some of the expected performance characteristics of CRM asphalt pavements. No laboratory or field testing was conducted or evaluated for this paper.

Performance measurements were based on the degree of distress observed in the pavement, which may include more than one performance parameter. The four general categories of variables that affect pavement performance are materials, pavement design/rehabilitation strategy, mix design, and construction. Proper selection of

compatible and quality grade materials is essential. The strategy chosen for any given project must coincide with the desired performance parameters and the expected climate and traffic conditions. The appropriate mix design procedure must be performed correctly to determine the optimum proportions of materials and engineering property limits. Every step of the project must be accomplished with the correct engineering decisions for the pavement to achieve its intended performance.

When new materials are added to a mix, each step of the design process may need to be modified to achieve optimum performance. The failures are generally a result of inexperience with CRM technology in project selection, design engineering, and construction practice.

The degree of binder modification depends on factors such as size and texture of the CRM, compatibility of the CRM and asphalt cement, time and temperature of the reaction, degree of mechanical energy during blending and reaction, and the use of other additives. Either a wet or dry process can be used to get a CRM binder, but the resulting properties can vary significantly between applications.

The performance of CRM in hot mix asphalt pavements is divided between rubberized asphalt binder (wet process) and rubber modified hot mixes (dry process). The performance of rubberized asphalt binder has not been extensively evaluated across the entire country. Based on limited available data, the performance of dense-graded CRM hot mix asphalts has been comparable to conventional dense-graded HMA. Gap-graded CRM hot mix asphalts have shown improved performance over other conventional rehabilitation strategies for certain pavement distress conditions. Open-graded CRM hot

mix asphalts improve the ability to construct this surface mix and improve pavement aging, but it does not improve its principle characteristic of skid resistance and reduced splash/spray.

Rubber modified hot mixes have only been extensively evaluated in Alaska. These mixes were very sensitive to proper design and construction, which has resulted in many premature failures. For mixes that were properly designed and constructed, gap-graded rubber modified hot mixes have performed comparably to conventional hot mixes, and has shown to perform more effectively for low-temperature skid resistance and rutting resistance. There has not been enough research of dense-graded rubber modified mixes to determine its performance.

Cost-effectiveness is project specific. An analysis must account for factors such as:

- Cost of construction,
- User costs,
- Frequency of required pavement improvements,
- Pavement performance, and
- Safety.

Some of the first construction projects of CRM asphalt concretes showed a cost of 150% to over 200% of that of conventional hot mix concretes. Because the practice of using CRM pavements has been constantly increasing, the high initial costs of using this technology has diminished. Now that using CRM pavements has become more accepted and broadly used, the equipment and construction practices required to apply these mixes

are more readily available which results in a reduced increase in cost. More recent projects show initial cost increases of only 20% over conventional mixes. Given the lower added cost of CRM materials and processing and the added performance of a properly designed and constructed CRM modified pavement, it appears that CRM pavements will become increasing cost-effective in the future.

CHAPTER 4

EXPERIMENTATION

4.1 Scope/Objectives

The scope of the lab component of this work is to determine the curing properties of CRM asphalt as a function of time by means of the Brookfield viscometer. The primary objectives of these experiments are to determine:

- the curing properties of CRM asphalt,
- the effect of mixing time, and
- the precision of the Brookfield viscometer.

All tests were conducted at 135°C with a RV series spindle SC4-27 and all rubber particles passing the #80 sieve. The independent variables considered were:

- the asphalt grade, and
- the percent rubber added to the asphalt.

Table 4.1 shows all combinations of asphalt and the rubber percentages tested. Five tests were performed for each combination of the independent variables listed above to determine the extent of variation in the measured viscosity. The AC 20 grade asphalt was not tested with rubber. It was intended to provide a comparison between the conventional AC 20 material commonly used in Washington to the CRM asphalt cements of lower unfilled viscosity. Detailed statistical analysis is performed to test:

- the extent of viscosity modification with respect to the time of curing, and
- the precision of test methods.

Table 4.1:
Independent Variables and Conditions for testing.

Rubber Added (%)	Tests Conducted		
	Asphalt		
	AC 5	AC 10	AC20
0	5	5	5
3	5	5	0
5	5	5	0
7	5	5	0
12	5	5	0
18	5	5	0

4.2 Materials

All asphalt and ground rubber was supplied by U.S. Oil and Refining Co. To ensure material uniformity, all asphalt and rubber samples used in this experimentation were taken from the same sample source.

4.3 Equipment

The following is a list of the equipment used to carry out the experimentation:

- Brookfield Model DV-II+ Viscometer,
- RV Series Spindle SC4-27,
- Thermosel System for Brookfield Viscometer,
- Steel Sample Chamber with extracting tool and insulation cap,
- Industrial Drying Oven,
- Bunsen burner with tripod stand and flint lighter, and
- Digital Scale with .01 gram resolution.

4.4 Procedure

The variables and procedure of the experimentation were discussed in detail with Jim Walters of the Washington State Department of Transportation Materials Lab and Susan McFarland of U.S. Oil and Refining Co. Since there is no current standard procedure for testing CRM asphalts by the Brookfield Viscometer, a testing procedure was developed that would be similar to the standards of other Brookfield tests, while accommodating the addition of ground rubber. The following testing procedure is a variation of ASTM Standards D2196-86 entitled "Standard Test Methods for Rheological Properties of Non-Newtonian Materials by Rotational (Brookfield) Viscometer" and D4402-87 entitled "Standard Test Methods for Viscosity Determinations of Unfilled Asphalts Using the Brookfield Thermosel Apparatus". The procedure is as follows:

- 1) Heat asphalt sample in an oven set to 135°C for a minimum of three hours to ensure the asphalt is sufficiently heated. Preheat thermosel to 135°C.
- 2) Determine the largest size spindle available that will work at 20 rpm.
- 3) Place the sample chamber with the spindle laid on the bottom in the oven and preheat them to 135°C.
- 4) Stir the warm asphalt in the tin can with a steel rod, being careful not to entrap any air bubbles.
- 5) Add required amount of preheated rubber to sample and stir until mixed.
- 6) Remove chamber from oven, place in chamber stand, and place on scale.
Tare scale.

- 7) Pour 9-13 grams of asphalt/rubber mix into the sample chamber. The exact amount varies with the percentage of rubber used. Zero percent rubber will use close to 13 grams while 18 percent rubber will use close to nine grams. Correct amount of asphalt will be 1/8 inch above the bullet on the shaft of the spindle (approximately 1/4 inch below extraction slot).
- 8) Using the extracting tool, place the sample in the thermosel chamber.
- 9) Place the hot spindle on the coupling wire, using care not to contaminate the surface of the spindle.
- 10) Lower the viscometer to the proper position. Place alignment bracket 1/16 inch off the top surface of the thermosel and flush against the positioning ring.
- 11) Replace the insulating cap.
- 12) Quickly check that the viscometer and the thermosel are still level and in alignment.
- 13) Turn viscometer motor on. Check the spindle size and rpm settings on the display.
- 14) Begin readings every 30 seconds for the first ten minutes after the rubber was introduced to the asphalt, then every two minutes until the three hours are up.
- 15) Record viscosity in Pa.s, temperature, spindle number, and speed in rpm's.

4.5 Results

Figure 4.1 shows a typical viscosity versus time curve for an AC 5 asphalt with 7% crumb rubber by weight. Time zero is the moment the crumb rubber was added to the asphalt over a low flame and thoroughly mixed into the asphalt. The reason for doing this was to keep the asphalt-rubber mix at the testing temperature of 135°C so an accurate viscosity reading could be taken when the asphalt was first introduced into the sample chamber and thermosel system.

The viscosity versus time curves for all experiments using 3, 5, 7, and 12% rubber for both asphalt grades have the same characteristics as Figure 4.1. The time delay between time zero and the time the graph starts is the time it took to thoroughly mix the asphalt and rubber, to pour the sample into the sample chamber, to transfer the chamber to the thermosel system, and to center the spindle in the sample to ensure the best results possible. During these first couple of minutes the asphalt-rubber mix, the heated spindle, and the heated sample chamber had time to cool. This is one of the reasons for the initial rapid drop in the viscosity. The other reason is the reaction of the asphalt with the rubber particles. After approximately between 45 and 60 minutes, the viscosity of the mix begins to stabilize.

Figure 4.2 shows a typical viscosity versus time curve for an AC 10 asphalt with 18% rubber added. The graphs with the 18% rubber show a different trend than the others involving lower percentages of rubber. The viscosity reaches a minimum value after approximately 45 to 75 minutes, which is slight longer than some of the experiments with the lower rubber percentages. With the 18% rubber, however, the viscosity starts to

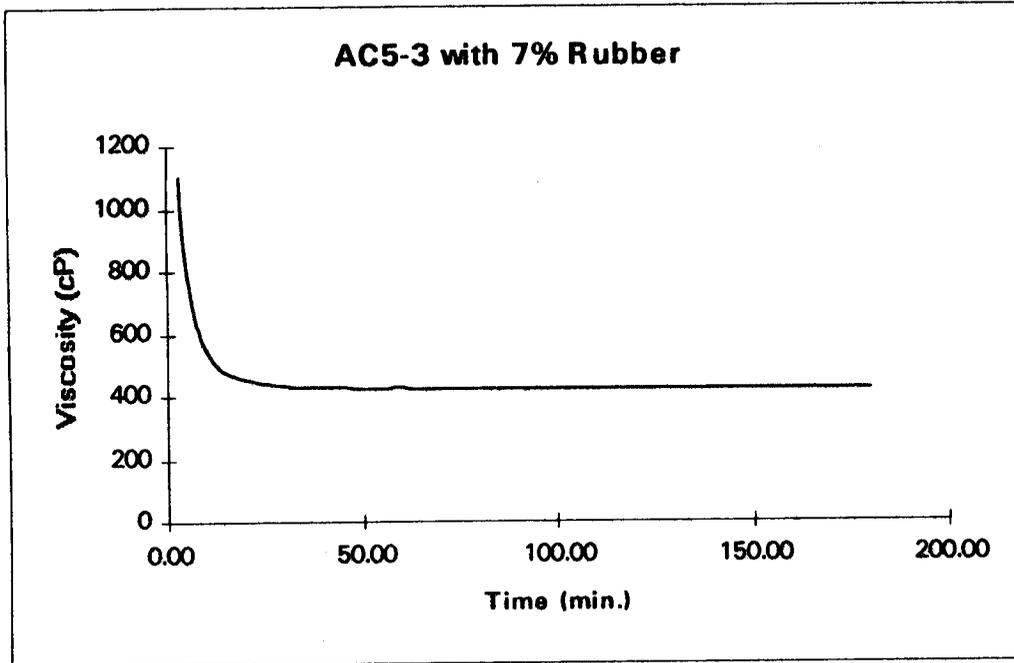


Figure 4.1: Viscosity versus Time curve for AC 5 asphalt with 7% rubber. Test #3.

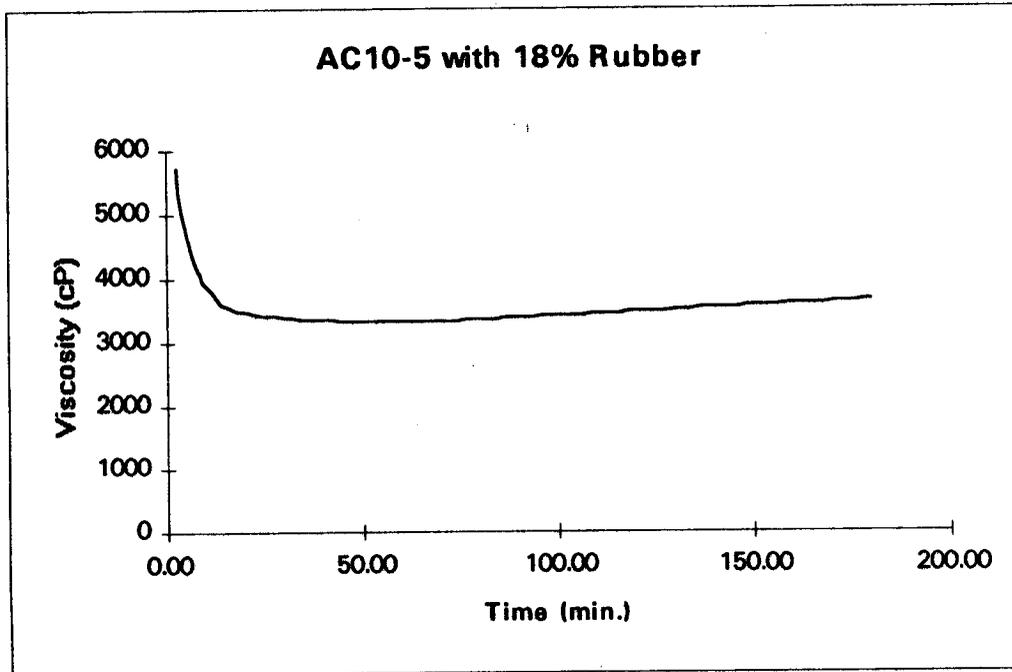


Figure 4.2: Viscosity versus Time curve for AC 10 asphalt with 18% rubber. Test #5.

increase approximately 10 to 30 minutes after the viscosity stabilized. This viscosity increase tends to be gradual and linear. The stabilized viscosity is noted as the minimum viscosity for all tests.

After analyzing all ten graphs in which 18% rubber was used, it appears that the viscosity increase is at a rate of approximately 180 cP per hour. Graphs showing the viscosity versus time plots for all experiments without rubber are shown in Figure 4.3 through Figure 4.5, and the plots using rubber are shown in Figure 4.6 through Figure 4.15. Graphs of representative viscosity versus time curves for each rubber percentage can be found in Figure 4.16 and Figure 4.17.

4.6 Discussion

After the five experiments were completed for each grade of asphalt without rubber, five experiments were conducted for the AC 5 and AC 10 grade asphalts at each rubber percentage. When all 60 experiments were completed using the AC 5 and AC 10 asphalts, five tests were run using AC 20 grade asphalt without rubber.

It is believed that the increase in viscosity of the CRM binder is mainly due to the swelling of the rubber particles and the possible reaction between the rubber and asphalt. This swelling phenomena is apparent in the experiments in which 5% or more rubber was used. A slight change in the volume of the asphalt could be observed in the sample tube after the three hour experiment was completed when 5% rubber was added. The volume increase became much more noticeable for larger amounts of rubber. The volume increase

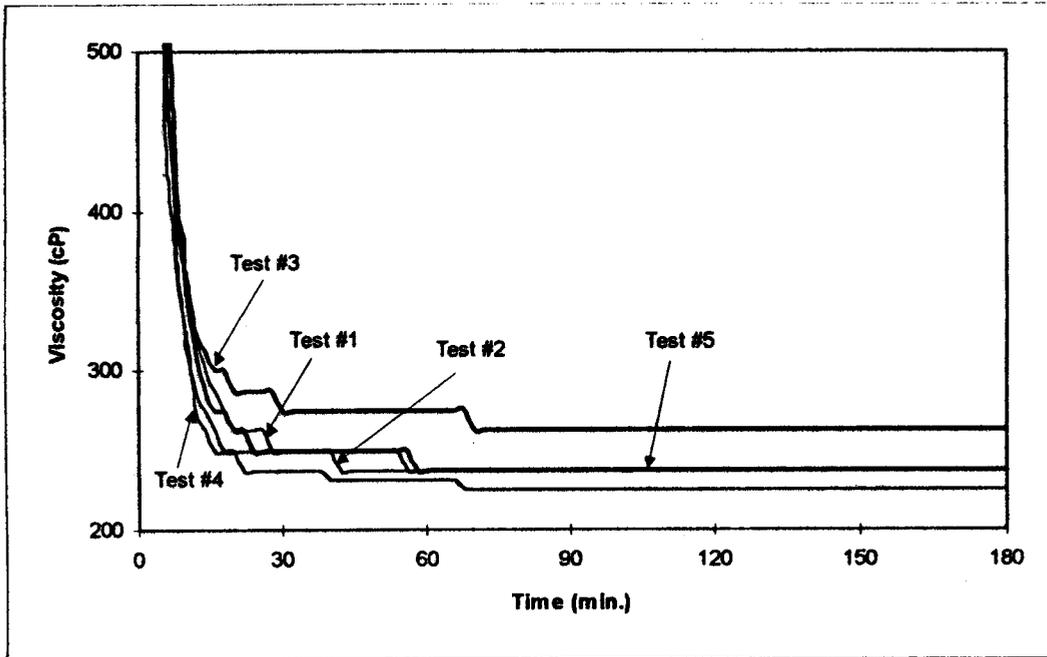


Figure 4.3: Viscosity versus Time curves of tests done with 0% rubber in AC 5 grade asphalt.

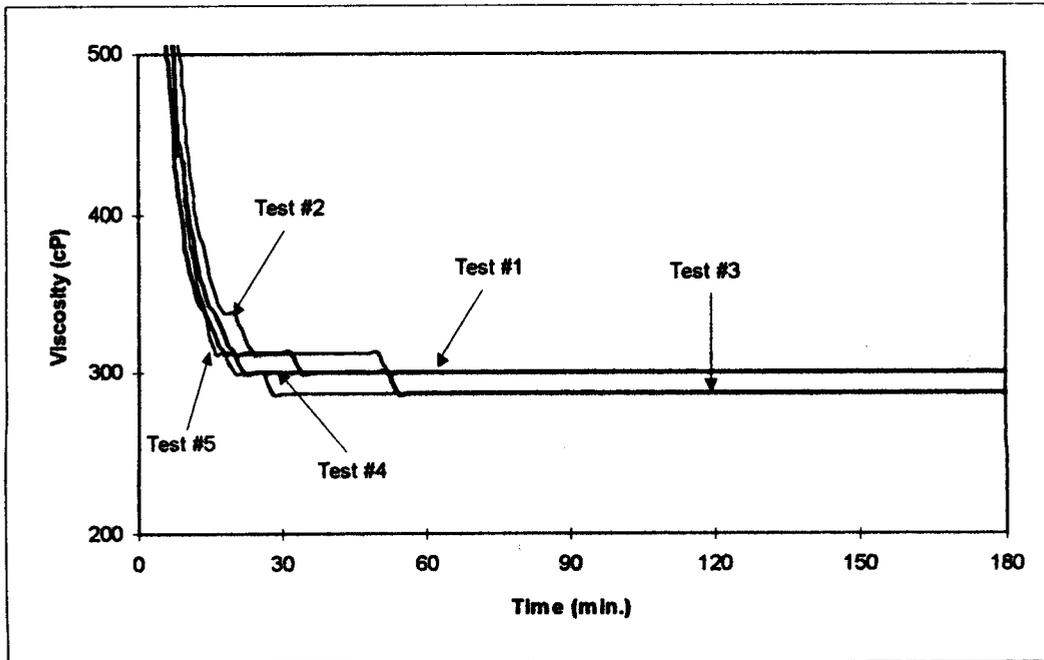


Figure 4.4: Viscosity versus Time curves of tests done with 0% rubber in AC 10 grade asphalt.

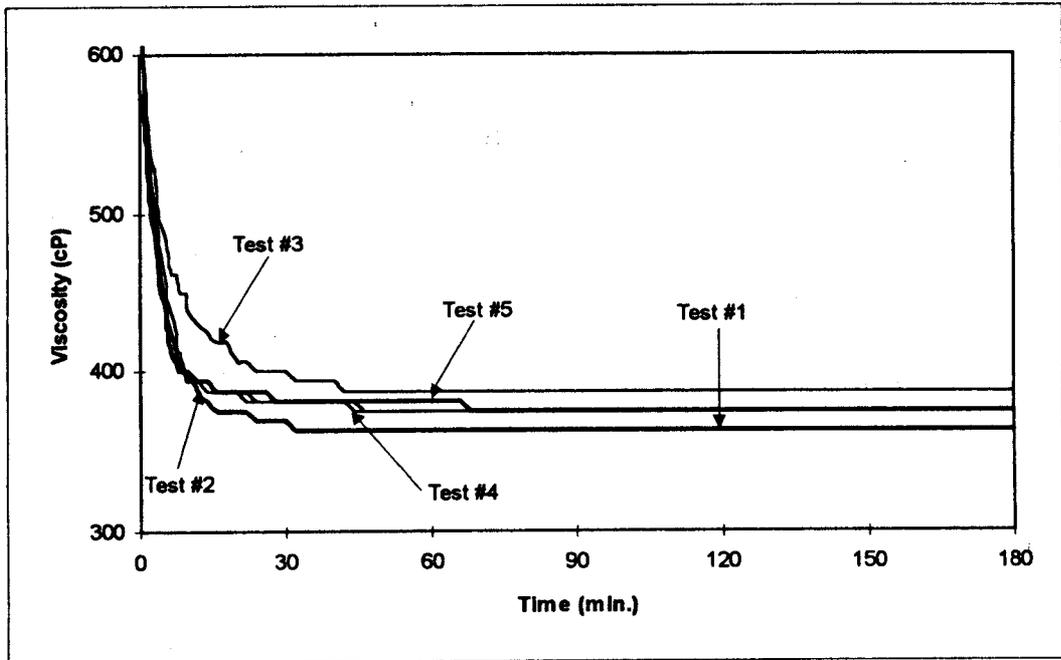


Figure 4.5: Viscosity versus Time curves of tests done with 0% rubber in AC 20 grade asphalt.

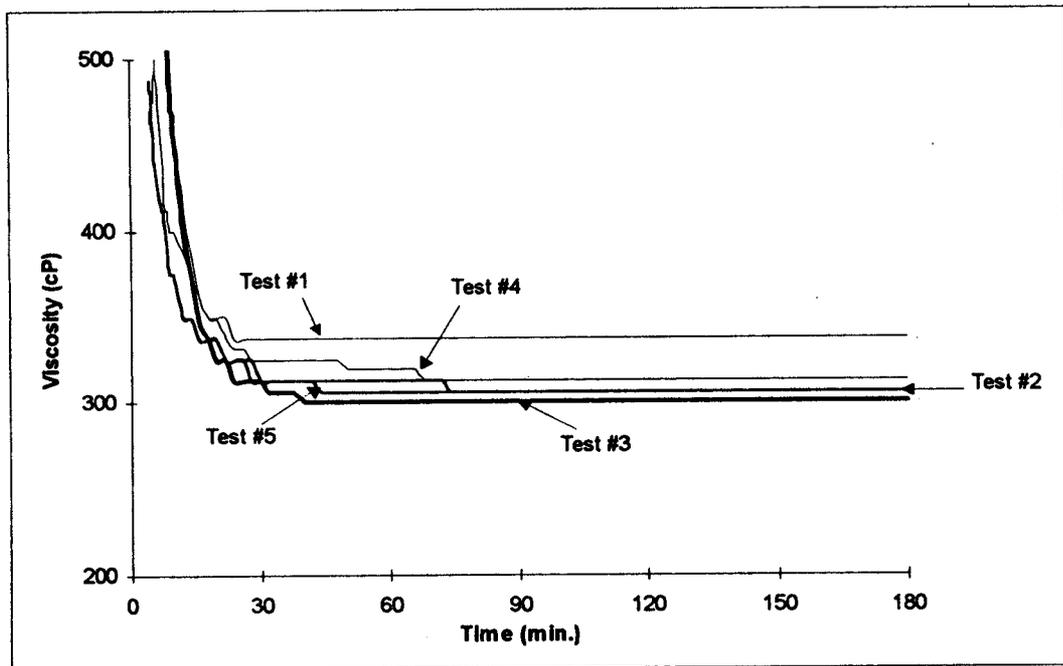


Figure 4.6: Viscosity versus Time curves of tests done with 3% rubber in AC 5 grade asphalt.

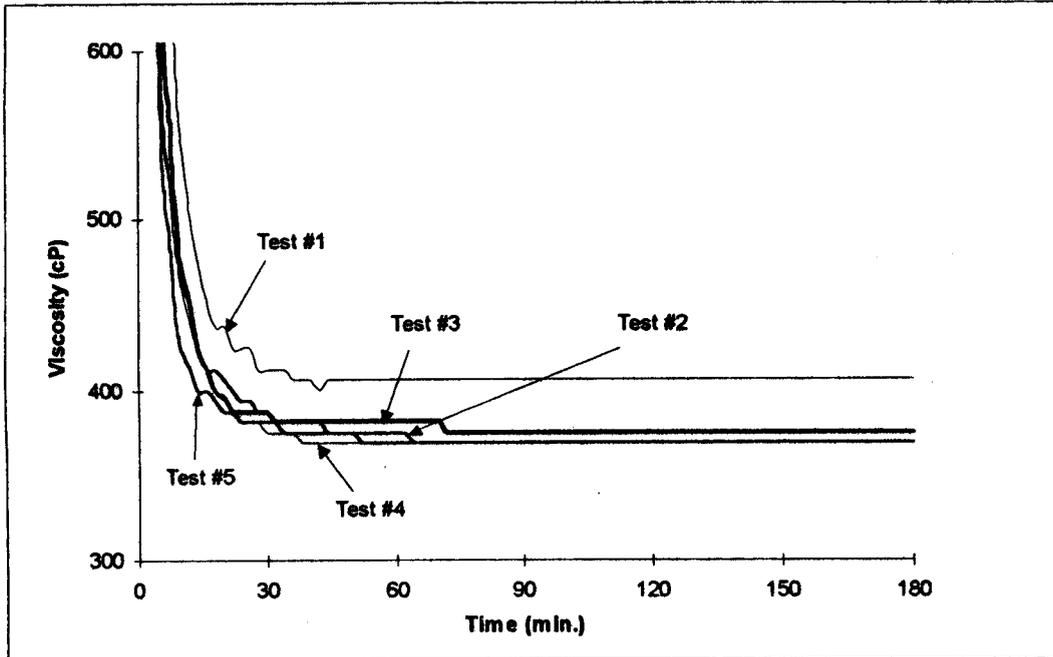


Figure 4.7: Viscosity versus Time curves of tests done with 3% rubber in AC 10 grade asphalt.

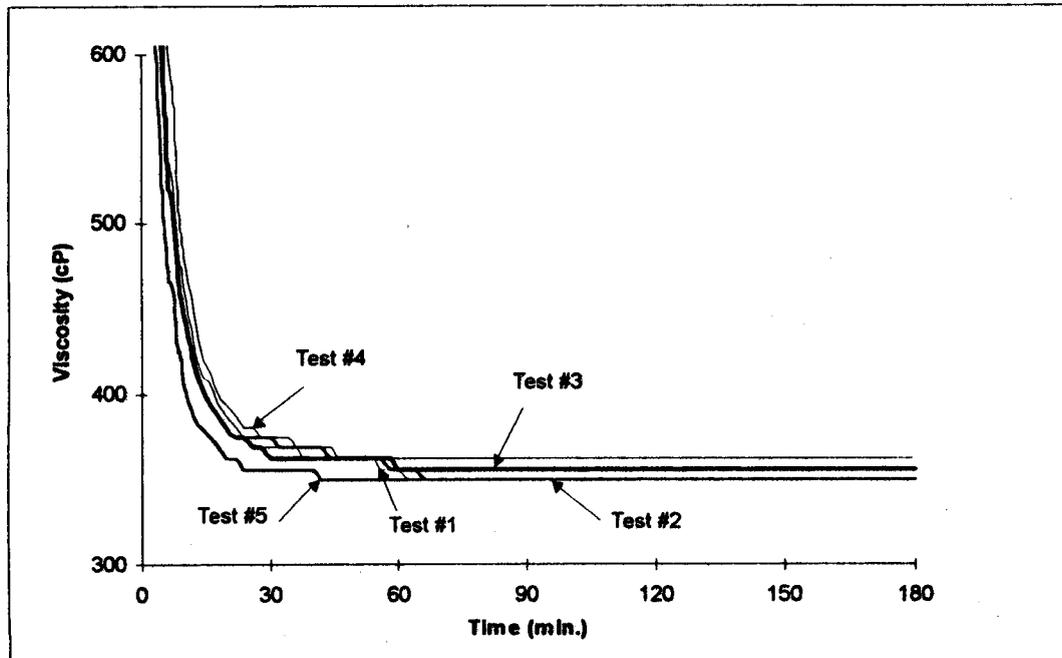


Figure 4.8: Viscosity versus Time curves of tests done with 5% rubber in AC 5 grade asphalt.

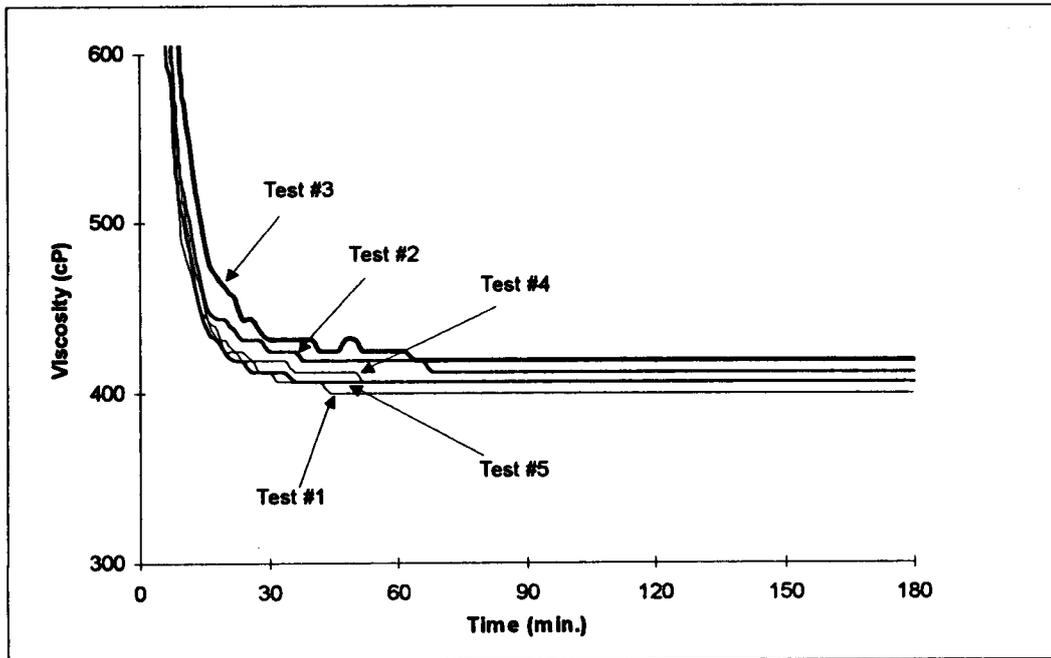


Figure 4.9: Viscosity versus Time curves of tests done with 5% rubber in AC 10 grade asphalt.

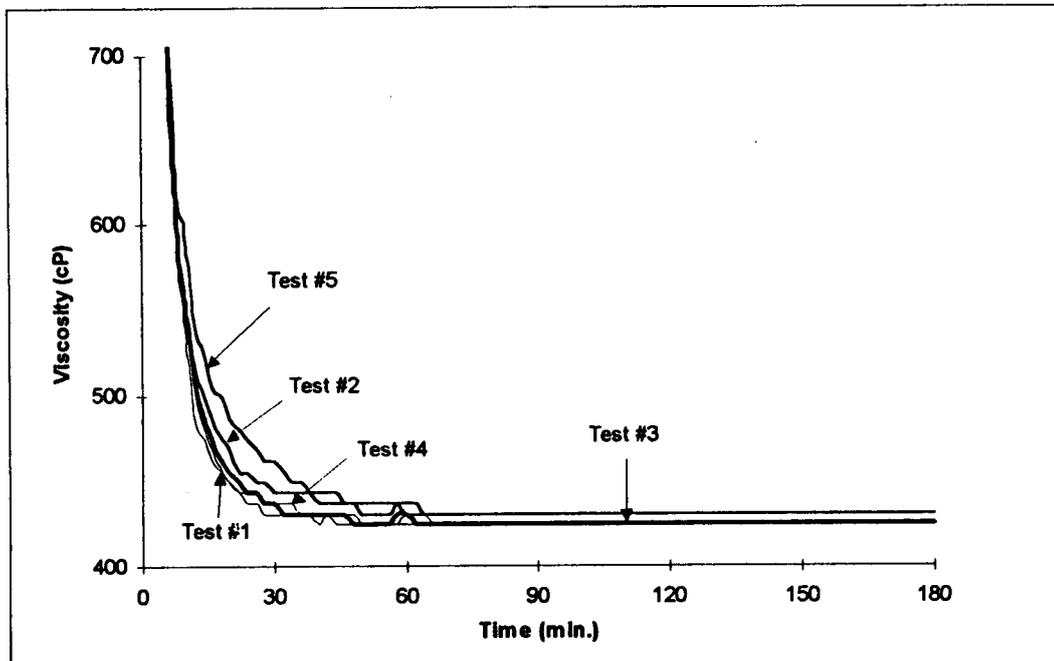


Figure 4.10: Viscosity versus Time curves of tests done with 7% rubber in AC 5 grade asphalt.

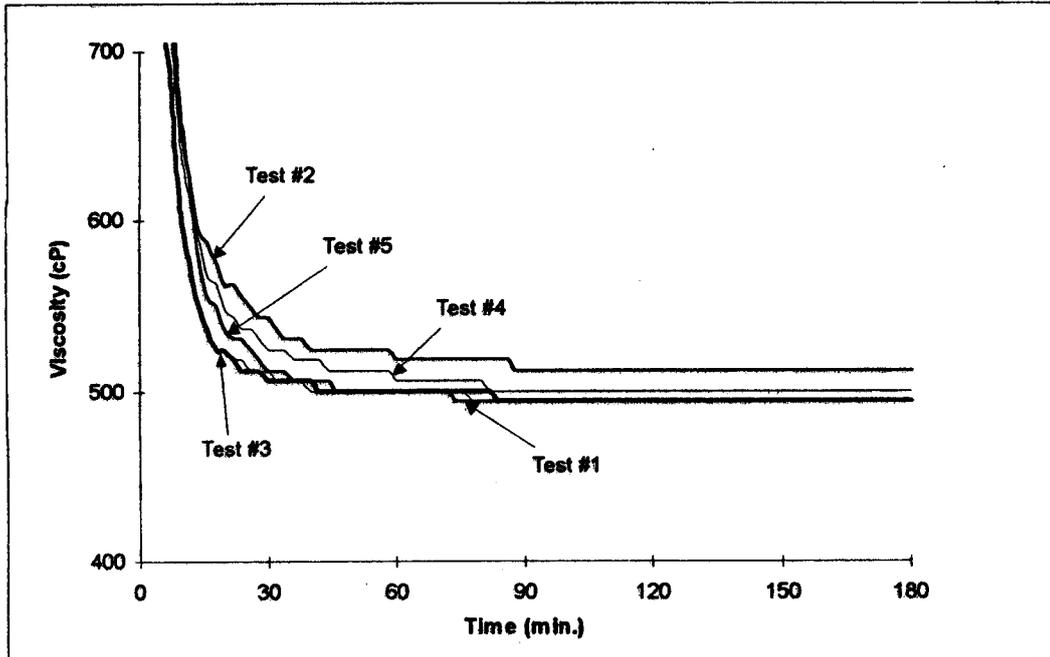


Figure 4.11: Viscosity versus Time curves of tests done with 7% rubber in AC 10 grade asphalt.

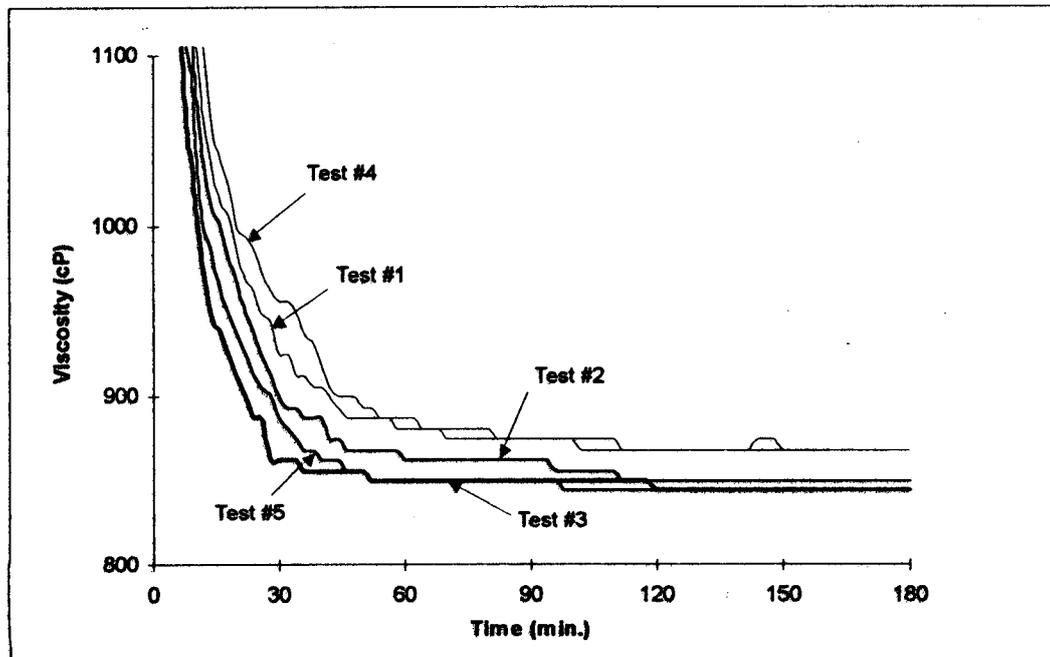


Figure 4.12: Viscosity versus Time curves of tests done with 12% rubber in AC 5 grade asphalt.

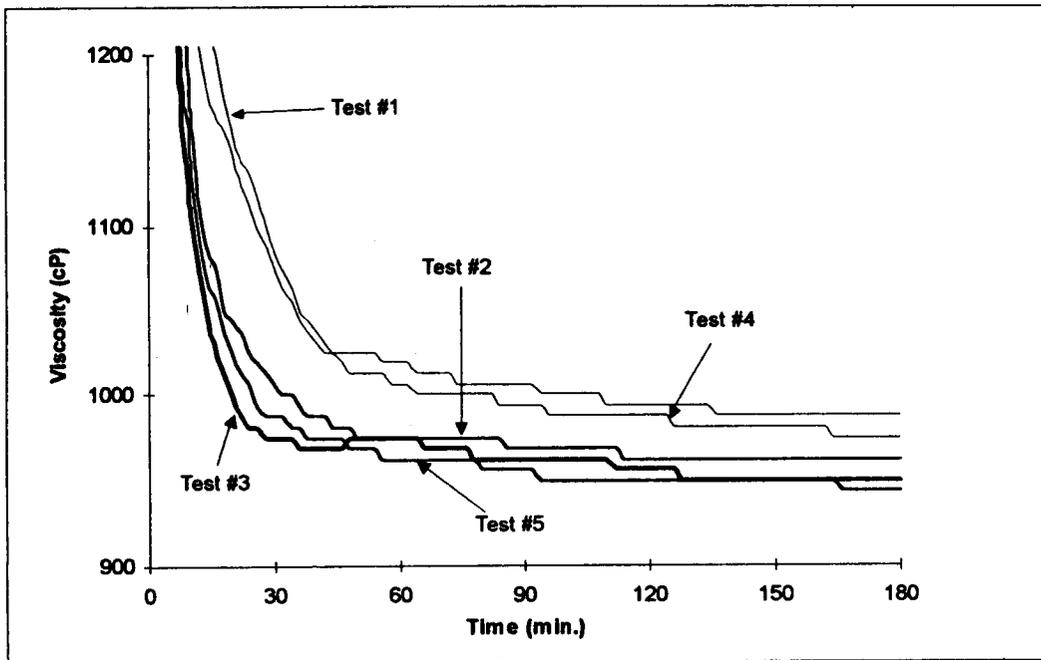


Figure 4.13: Viscosity versus Time curves of tests done with 12% rubber in AC 10 grade asphalt.

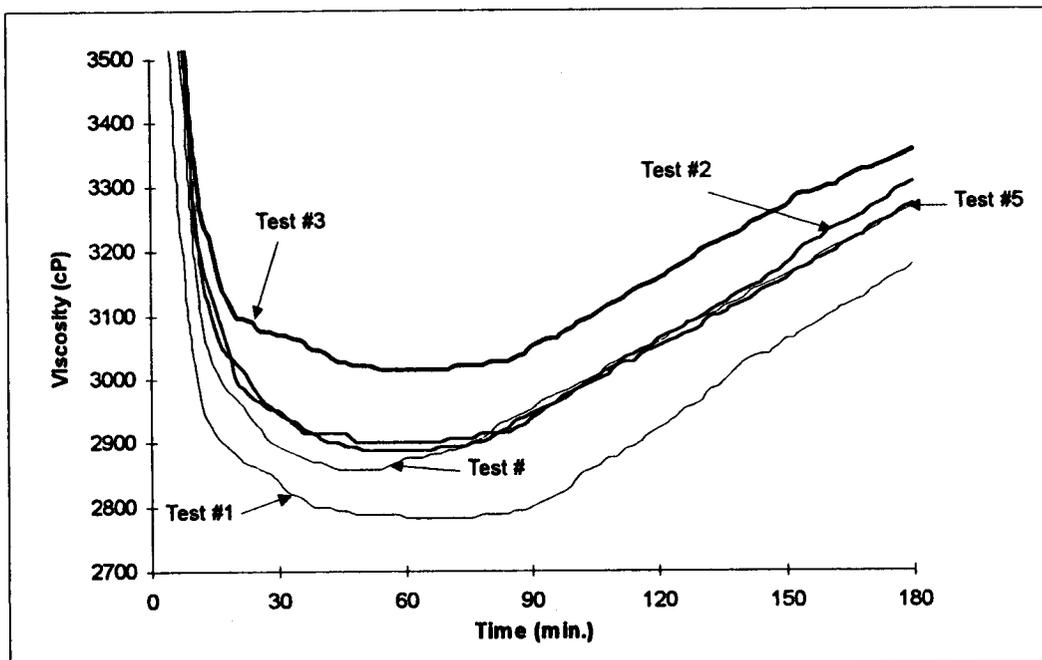


Figure 4.14: Viscosity versus Time curves of tests done with 18% rubber in AC 5 grade asphalt.

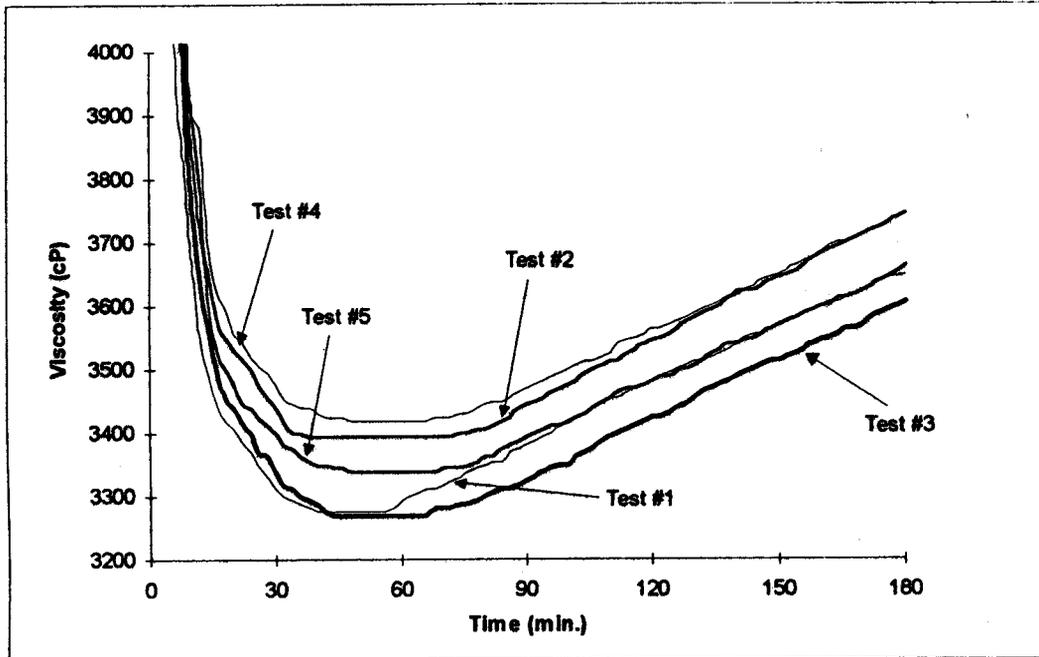


Figure 4.15: Viscosity versus Time curves of tests done with 18% rubber in AC 10 grade asphalt.

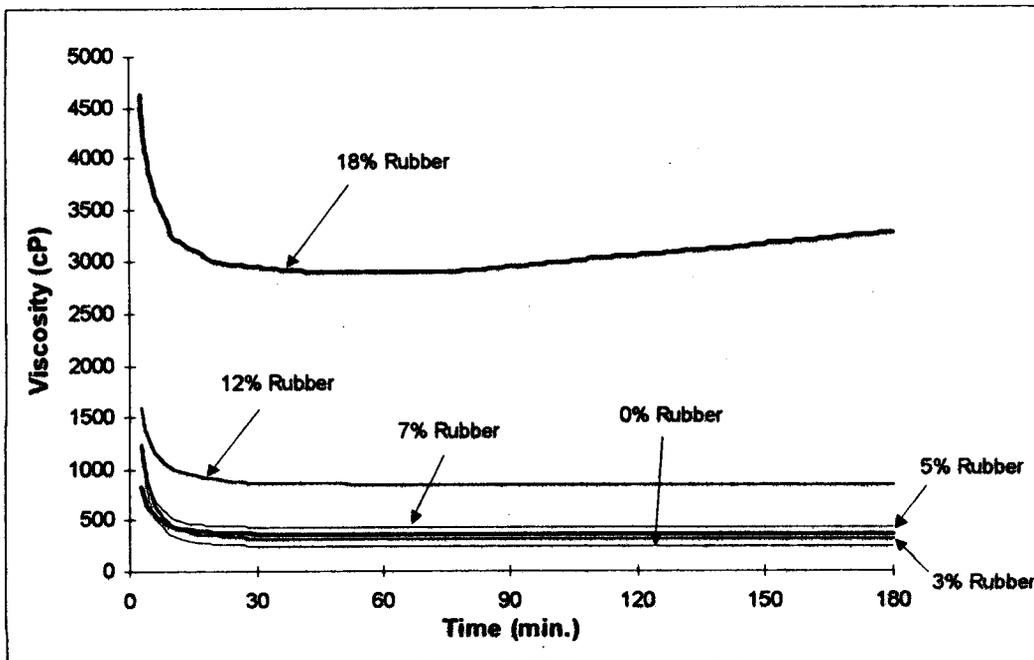


Figure 4.16: Viscosity versus Time curves of tests with AC 5 asphalt with each rubber percentage.

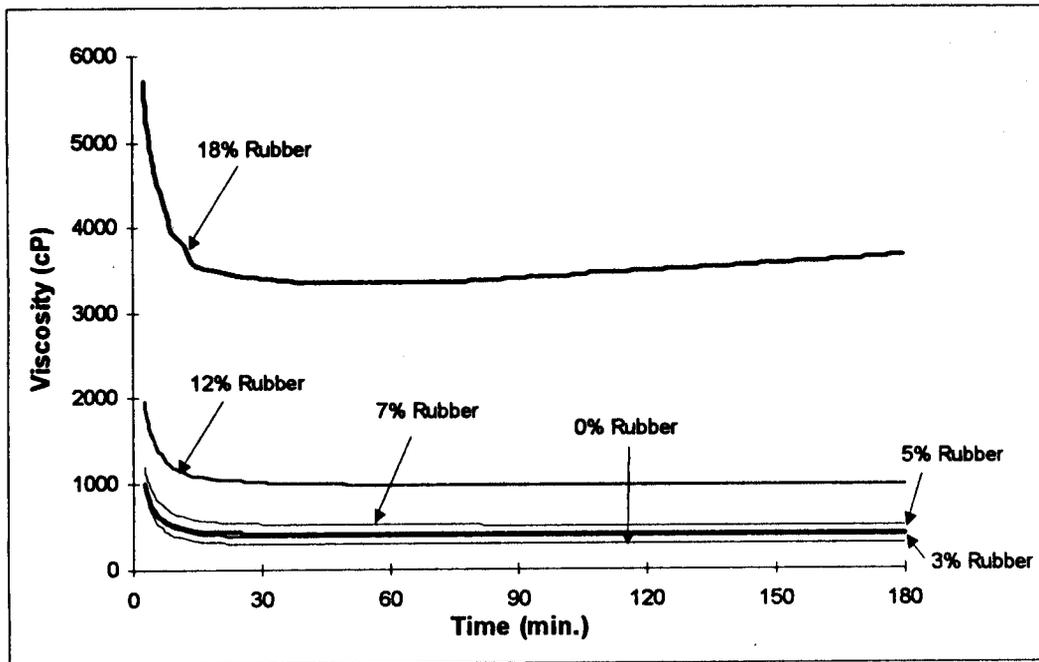


Figure 4.17: Viscosity versus Time curves of tests with AC 10 asphalt with each rubber percentage.

was so high in experiments using 18% rubber that when the insulation cap was removed, the asphalt had risen over the extraction slots of the sample chamber. After this, slightly smaller samples were used to prevent overflow.

This increase in volume resulted in a slight surface area increase of the spindle to be in contact with the asphalt-rubber. This may have resulted in a slight increase of the required torque for rotating the spindle, which would result in a marginal increase in the viscosity reading.

Because swelling of the rubber only caused a small portion of the viscosity increase, it appears that the viscosity of the asphalt binder is being altered by the presence of the CRM. From the literature review, it was concluded that the reaction between the

CRM and asphalt was the absorption of the aromatic oils from the binder into the internal matrix of the rubber. It appears that the majority of the increase in viscosity is due to this removal of these aromatic oils from the binder. When the aromatic oils are removed from the binder, the internal lubrication that allows the binder to flow is being reduced.

When larger amounts of CRM are used, such as in the tests using 18% CRM, the viscosity is much greater when comparing to the asphalts with no CRM or the asphalt-rubber mixes using smaller percentages of CRM. The viscosity increase with time after the initial stabilization in the tests conducted with 18% CRM must also be explained to fully understand the curing properties of CRM binders.

It appears that the depletion of aromatic oils in the binder is the cause of both the viscosity increase phenomenon. The stabilized viscosities of the modified asphalt using 18% CRM are over 11 times the viscosities of the unmodified asphalts. To achieve this type of increase, the excess aromatic oils that previously provided the binder's small viscosity must be nearly depleted. If all of the rubber has not swollen to its potential by the time most of the aromatic oils are gone, the rubber still attempts to remove any remaining oil that exists in the binder. This affect combined with the hardening of the asphalt, which has very little aromatic oils left to allow flow, results in the near-linear viscosity increase with time that can be observed in Figure 4.14 to Figure 4.17.

The coefficient of variation in the control samples ranged between 0.6% to 5.7%. This demonstrates the precision of the Brookfield viscometer used in the experiments. There was a slightly larger variation in the first test involving AC 5 asphalt with 0% and 3% rubber and AC 10 asphalt with 3% rubber when compared to the other four tests

conducted using the same variables. This variation was the result of incorrect centering of the spindle in the asphalt chamber. In later tests of the same variables, the spindle was moved at the completion of the test to imitate incorrect centering of the spindle. When the spindle was off-center as in the first test of the series, the viscosity readings had a slight increase.

Table 4.2 shows the stabilized viscosities for each test completed and the statistical analysis for each set of tests. A slight decrease in viscosity variation was seen in the experiments in which 5, 7, and 12% rubber was used, but the standard deviation is much larger in the tests conducted with 18% rubber. If the initial error in the tests listed in the previous paragraph was eliminated, it would appear that a trend is evident where larger percentages of rubber result in larger variations in the viscosity measurements. The standard deviation at the small percentages of rubber were as large as 16.1 cP. Part of the reason for the larger coefficients of variation in the tests with AC 5 and AC 10 asphalt with 0% and 3% rubber was because of the spindle positioning as stated above. This small variation should be considered negligible in this viscosity range when considering the possible sources of error in these experiments. In conclusion, the reproducibility for asphalt binders with 7% rubber or less was very good.

A larger variation of viscosity can be seen in the experiments in which 12% or 18% rubber was used. The standard deviation in the tests using 12% rubber increased slightly to 18 cP, while the standard deviation increased to 84 cP in the tests using 18% rubber. It is clear that the reproducibility of the asphalt-rubber viscosity decreases as the rubber percentage increases when comparing the viscosities.

Table 4.2:
Stabilized viscosities and summary statistics.

Asphalt Grade	Test #	Stabalized Viscosities (cP)					
		0%	3%	5%	7%	12%	18%
AC5	1	262.5	337.5	350	425	869	2781
	2	237.5	306	350	431	850	2900
	3	225	300	356	425	850	3013
	4	237.5	312.5	362.5	425	869	2856
	5	237.5	306	350	431	844	2888
	Mean	240	312.4	353.7	427.4	856.4	2887.6
AC5	Std. Dev.	13.7	14.7	5.6	3.3	11.8	84.0
	C.V. (%)	5.7	4.7	1.6	0.8	1.4	2.9
AC10	1	300	406	400	494	987.5	3275
	2	287.5	369	412.5	512.5	962.5	3394
	3	287.5	375	419	494	950	3269
	4	300	369	406	500	975	3419
	5	287.5	369	406	494	944	3338
	Mean	292.5	377.6	408.7	498.9	963.8	3339
AC10	Std. Dev.	6.8	16.1	7.3	8.0	17.8	67.9
	C.V. (%)	2.3	4.3	1.8	1.6	1.8	2.0
AC 20	1	362.5	N/A	N/A	N/A	N/A	N/A
	2	375	N/A	N/A	N/A	N/A	N/A
	3	387.5	N/A	N/A	N/A	N/A	N/A
	4	375	N/A	N/A	N/A	N/A	N/A
	5	375	N/A	N/A	N/A	N/A	N/A
	Mean	375.0	N/A	N/A	N/A	N/A	N/A
AC 20	Std. Dev.	5.0	N/A	N/A	N/A	N/A	N/A
	C.V.(%)	0.6	N/A	N/A	N/A	N/A	N/A

There are many factors that could contribute to these variations in viscosity. The primary being that the asphalt binder seems to become more sensitive to the addition of rubber when larger amounts of rubber are used. Part of this could be due to the composition of the crumb rubber additive. The exact ratio of natural rubber to synthetic rubber in the crumb rubber additive is unknown. Its effect on viscosity increases as the amount of rubber introduced to the asphalt increases. This would cause a larger range of viscosities since the swelling potential of the natural rubber and synthetic rubber are

different. All of the rubber used for each test was taken from the same source in an attempt to eliminate most of this source of variation.

Other factors that contribute to the viscosity variation are caused by the laboratory procedure itself and the person running the experiments. For example, when an experiment is done for an asphalt using 18% rubber, it is highly unlikely that the rubber content of the asphalt-rubber mix is going to be exactly 18%; it could be slightly more or slightly less. The first factor is that almost every calculation requires rounding. Next, when the rubber is first introduced to the asphalt, some of the asphalt sticks to the sides and bottom of the transfer dish. When the rubber is mixed with the asphalt, some rubber sticks to the mixing spoon and some sticks to the side of the asphalt sample dish. Even though most of this error is attempted to be eliminated by scraping as much rubber as possible into the asphalt, all of the rubber cannot be mixed uniformly with the asphalt.

Other slight variations in viscosity can be caused by such factors as:

- the testing temperature not being set exactly the same for all tests,
- the viscometer and thermosel units not being leveled the same every time,
- the height of the asphalt in the sample chamber varying from test to test,
- having slight variations in the centering of the viscometer spindle, and
- having ambient temperature changes.

All of these variables can affect the reproducibility of these experiments, and they must be taken into account when analyzing the results.

The purpose of using lower viscosity base asphalt binders when adding crumb rubber is because of the expected effect of viscosity increase. Looking in Table 4.2, it is

clear that there are ways to incorporate rubber modified asphalt in concrete pavements without affecting the workability of the mix to a great extent. It can be seen that the viscosity of the AC 20 asphalt with no rubber added is nearly the same as the viscosity of AC 10 asphalt with 3% rubber and slightly higher than the AC 5 asphalt with 5% rubber. Therefore, there would be no decrease in the degree of workability of these two mixes. If AC 10 asphalt with 5% rubber or AC 5 asphalt with 7% rubber was used instead of the AC 20, there would be only an increase in viscosity of 34 cP and 52 cP, respectively. This would only slightly compromise/reduce the workability of the mixes during construction.

When analyzing the AC 10 asphalt mixes with 7% or more rubber or AC 5 asphalt mixes with more than 7% rubber, the stabilized viscosities become substantially higher. Using these mixes in a hot mix asphalt concrete would greatly reduce workability during construction. One possible solution to this problem would be the addition of extender oils. This would reduce the stabilized viscosity of the asphalt-rubber mixes as well as reduce the linear viscosity increase evident in the 18% rubber experiments. The reason for the reduced viscosity increase effect is that the extender oil supplies the excess aromatic oils required for completion of the reaction between the rubber and the asphalt. The amount of oil required to produce the desired workability would be the amount needed to bring the stabilized viscosity down to the range of the unfilled AC 20 asphalt.

CHAPTER 5

SUMMARY/RECOMMENDATIONS

5.1 Summary of Literature

The following is a summary of the literature reviewed on CRM asphalt concrete. The information included in the summary represents the consensus of the majority of authors Chapter 3.

The blending of crumb rubber with asphalt cement has been practiced for years. The reaction that takes place between the rubber particles and the asphalt binder is not a chemical reaction, but rather a diffusion process that includes the absorption of aromatic oils from the asphalt cement into the polymer chains. Each group of polymer chains affects particular characteristics of the modified binder. As the CRM reacts with the asphalt cement, it softens and swells. During this absorption period, the viscosity of the blend increases as the amount of aromatic oils, which lubricates the binder, decreases. The natural rubber polymers are more compatible with asphalt than synthetic polymers.

The addition of CRM in asphalt produces a thicker binder, which increases aging and oxidation resistance. The presence of carbon black in CRM improves the binder's durability. The property changes of the modified asphalt cement result in a reduced temperature susceptibility of the mix, which results in more uniform fatigue characteristics over the pavement's operating temperatures. This reduced temperature susceptibility improves rutting resistance in the high temperature range and thermal cracking resistance in the low temperature range.

Based on the limited information available, the performance of dense-graded CRM hot mix asphalt concretes has been comparable to that of conventional dense-graded mixes. Dense-graded friction course mixes with asphalt-rubber tend to reduce pavement distortions because of the improved resilient properties of the asphalt-rubber. Gap-graded CRM hot mix asphalts have shown improved performance over conventional methods of rehabilitation for certain pavement distress conditions. Open-graded CRM hot mix asphalts improve the ability to construct open-graded surface mixes and inhibit pavement aging. Open-graded CRM hot mixes, however, do not improve performance in terms of skid resistance and reduced splash/spray during rainfall when compared to conventional open-graded mixes. Open-graded CRM friction course mixes with asphalt-rubber tend to eliminate binder drainage from the aggregate in trucks, even when using increased binder contents. These mixes provide improved aggregate retention, durability and life.

The experiences with all three types of mixes throughout the United States varies greatly, whereas one type of mix has been reported to be very successful at one site, while the same mix has been reported disastrous at another. Much of this mixed performance is due to the inexperience in design, and the lack of quality assurance at many of the construction sites. Other factors may include lack of compatibility of the CRM and the binder, traffic volumes and loads varying from expected values, and environmental conditions.

A relatively high percentage of light fractions is desirable for asphalt used in the wet process. This is achieved by adding extender oil or selecting a lower viscosity grade binder. Both have the added advantage of compensating for the increased viscosity when rubber is added as well as providing sufficient aromatics for the rubber absorption without removing key asphalt

components. An increase in the percentage of extender oil increases penetration, increases the ductility, and reduces resilience.

The following is a summary of the key advantages in using CRM in both the wet and dry asphalt paving applications:

- increased recycling of rubber tires,
- increased viscosity and reduced penetration,
- reduced temperature susceptibility,
- decreased rutting at higher temperatures,
- decreased thermal cracking at lower temperatures,
- increased ductility at lower temperatures,
- enhanced adhesive characteristics,
- reduced freeze-thaw damage,
- increased film thickness,
- reduced age hardening and oxidation,
- increased resilient modulus,
- increased tensile strength,
- increased high temperature modulus,
- increased durability,
- increased resistance to ice formation,
- increased skid resistance,
- increased ductility,
- reduced binder drain-down off the aggregate during transport,

- reduced reflective cracking,
- reduced pavement tire noise,
- reduced abrasion from tire studs and chains,

The following is a summary of the claimed key disadvantages in using CRM in both the wet and dry asphalt paving applications:

- additional cost,
- increased binder content,
- handling and proportioning of aggregate and rubber for dry process,
- license fee for using the patented processes,
- mobilizing specialized equipment at production facility,
- increased tracking,
- increased ravelling,
- increased bleeding and flushing potential,
- reduced stability,
- recyclability of reclaimed CRM asphalt pavements, and
- long-term performance.

There appears to be no certainty as to why certain rubber-modified processes result in sub-standard performances, while others perform well under particular site conditions, because the properties of these mixes can vary significantly from site to site. It appears that quality control is the key in obtaining a mix that performs as designed when using the modified asphalts.

The performance of CRM pavements has been mixed with some pavements out-performing conventional mixes, while others failing prematurely. The failures in the wet process

are generally a result of inexperience with CRM technology in project selection, design engineering, and construction decisions. Existing quality control and quality assurance methods have not been developed enough to ensure that the desired binder properties are obtained in the field. Most failures in the dry process appear to be due to the lack of understanding of the interaction between the asphalt binder and the chunk-rubber, and due to the difficulty to controlling the aggregate-rubber gradations.

5.2 Summary of Brookfield Viscosity Testing

The viscosity increase which occurs when the CRM is added to the asphalt binder, due to the amount of aromatic oil absorption and rubber particle swelling, was confirmed through laboratory testing. It was shown that as the percentage of rubber increased, the effects the rubber had on the viscosity increased significantly. This is demonstrated in Figure 5.1. Binders with 3%, 5%, 7%, 12%, and 18% CRM exhibited an increase in viscosity of approximately 1.3, 1.5, 1.8, 3.4, and 12.0 times that of the unmodified asphalts, respectively. From this data, it appears that the effect of additional crumb rubber on viscosity is more pronounced at higher CRM concentrations.

The viscosity of the blend stabilized approximately between 45 and 60 minutes after the asphalt was charged with CRM for rubber percentages of 12 or less. The viscosity of the blend containing 18% rubber showed a different trend than the others involving lower percentages of rubber. The viscosity reached a minimum value after approximately 45 to 75 minutes, which is slightly longer than some of the experiments with the lower rubber percentages. This minimum viscosity was defined as the "stabilized viscosity" for all tests.

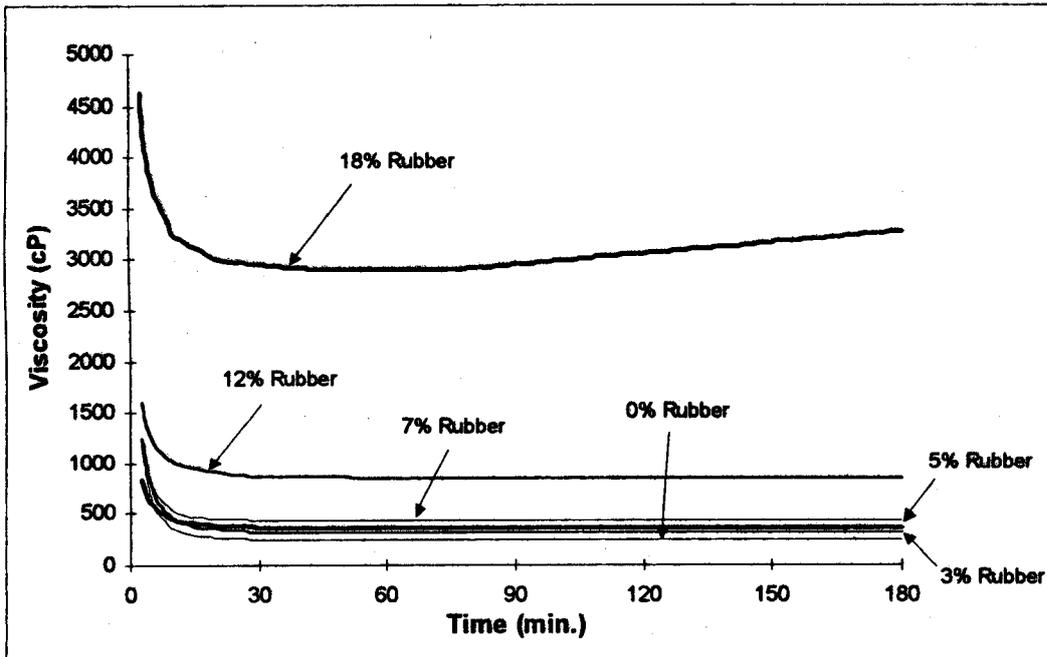


Figure 5.1: Viscosity versus Time curves of tests with AC 5 asphalt with each rubber percentage.

As can be seen from Figure 5.1, the viscosity started to increase approximately 10 to 30 minutes after the viscosity stabilized for the blends containing 18% rubber. This viscosity increase tends to be gradual and near-linear. After analyzing all ten graphs in which 18% rubber was used, it appears that the viscosity increases at a rate of approximately 180 cP per hour. This effect seems to be caused by the depletion of aromatic oils from the binder. The swelling and adhesive characteristics of the crumb rubber also add to the increased viscosity.

5.3 Recommendations

It is evident that the more successful method of incorporating CRM into asphalt paving materials is the wet process. Some modified asphalt paving applications which utilize CRM in the

wet process have already been accepted, and are common practice. An example of this is the rubber-modified crack sealants. This product performs much better than unmodified asphalt binders, and it has been proven to be very cost-effective.

Since using rubberized crack sealants will not count toward meeting the legislative requirements for the amount of CRM utilized by the state agencies, alternative methods must be further explored. Therefore, further research and experimental applications would be best utilized by focusing on CRM modified binders in hot mix asphalt concretes. Developing standard modified mixes that produce products that consistently perform well should be the primary goal in meeting the upcoming legislative mandates. Once the modified mixes become accepted practice in the paving industry their construction costs will decrease, and this may render them a cost-effective alternative which addresses a significant environmental concern.

BIBLIOGRAPHY (Alphabetic)

- Anderson, K.W. and N.C. Jackson, "Rubber-Asphalt Pavements in the State of Washington", Washington Department of Transportation, Report No. WA-RD 268.1, March 1992.
- Cano, J.O. and E. Charania, "The Phoenix Experience Using Asphalt-Rubber", National Seminar on Asphalt-Rubber, Kansas City, Missouri, October 1989.
- Ciesielski, S.K., "A National Overview - The Use of Discarded Materials and By-Products in Hot Mix Asphalt Concrete Pavements", Road Recycling Ahead Seminar, Denver, Colorado, October 1993.
- Harvey, J., C. Rust, N. Coetzee, W. Nokes, and J. van Kirk, "Overview of Caltrans Accelerated Pavement Testing Pilot Project", Strategic Highway Research Program Project A-003A (SHRP A-003A), Minneapolis, Minnesota, February 1994.
- Heerkens, J.P. and A. von Meier, "Open-Graded Rubberized Asphalt for Traffic Noise Reduction in Urban Areas", National Seminar on Asphalt-Rubber, Kansas City, Missouri, October 1989.
- Hoyt, D.M. and R.L. Lytton, "Laboratory Behavior, Performance Prediction, and Cost Effectiveness of Asphalt-Rubber Concrete in Airport Pavements", National Seminar on Asphalt-Rubber, Kansas City, Missouri, October 1989.
- Humphrey, D.N. and R.A. Eaton, "Tire Chips as Subgrade Insulation - Field Trial", Symposium on Recovery and Effective Reuse of Discarded Materials and By-Products for Construction of Highway Facilities, Denver, Colorado, October 1993.
- "Intermodal Surface Transportation Efficiency Act", Section 1033, United States Congress, 1991.
- Jacobson, C.C. and R.H. Schnormeier, "Cost Effectiveness of Asphalt-Rubber", National Seminar on Asphalt-Rubber, Kansas City, Missouri, October 1989.
- Jimenez, R.A., "Viscosity Measurements of Asphalt-Rubber Binders", National Seminar on Asphalt-Rubber, Kansas City, Missouri, October 1989.
- Kirk, T.P., "Asphalt-Rubber Hot Mix Investigation by Test Section for Reflection of Fatigue Cracks", National Seminar on Asphalt-Rubber, Kansas City, Missouri, October 1989.
- Mackay, M. and J. Emery, "Use of Wastes, Surplus Materials, and By-Products in

Transportation Construction", Road Recycling Ahead Seminar, Denver, Colorado, October 1993.

Newcomb, D.E., and A. Drescher, "Engineering Properties of Shredded Tires in Lightweight Fill Applications", Civil and Mineral Engineering Department, University of Minnesota, Minneapolis, TRB Paper No. 940293, January 1994.

Peters, V.J. and D.V. Holmquist, "The Use of Waste Polymers in Asphalt Cement", Road Recycling Ahead Seminar, Denver, Colorado, October 1993.

Renshaw, R.H., "A Review of the Road Performance of Bitumen-Rubber in South and Southern Africa", National Seminar on Asphalt-Rubber, Kansas City, Missouri, October 1989.

Ruth, B.E., "Disposal, Reuse, and Recycling of Highway Materials", Road Recycling Ahead Seminar, Denver, Colorado, October 1993.

Sainton, A., "A Revolution in Asphalt-Rubber Binders: Flexochape Storable Binder", National Seminar on Asphalt-Rubber, Kansas City, Missouri, October 1989.

Stroup-Gradiner, M., N. Krutz, and J. Epps, "Comparison of Mix Design Methods for Rubberized Asphalt Concrete Mixtures, National Seminar on Asphalt-Rubber, Kansas City, Missouri, October 1989.

Turgeon, C.M., "The Use of Asphalt-Rubber Products in Minnesota", National Seminar on Asphalt-Rubber, Kansas City, Missouri, October 1989.

Winters, R.E., "The "Conception and Development of Asphalt Rubber", National Seminar on Asphalt-Rubber, Kansas City, Missouri, October 1989.

REFERENCES (Alphabetic)

- "A Study of the Use of Recycled Paving Material", U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-RD-93-147, Washington D.C., June 1993.
- Ahmed, I. and C.W. Lovell, "Use of Waste Materials in Highway Construction: State-of-the-Practice and Evaluation of the Selected Waste Products", Purdue University, School of Civil Engineering, 1992.
- Chehovits, J.G., "Design Methods for Hot-Mixed Asphalt-Rubber Concrete Paving Materials", National Seminar on Asphalt-Rubber, Kansas City, Missouri, October 1989.
- Doty, "Caltrans Rehabilitation Projects Using Asphalt-Rubber Mixtures", California Transportation Department, 1993.
- Epps, J.A., "Uses of Recycled Rubber Tires in Highways", Transportation Research Board, National Research Council, Synthesis of Highway Practice 198, National Academy Press, Washington, D.C., 1993.
- Estakhri, C.K., J.W. Button, and E.G. Fernando, "Use, Availability, and Cost-Effectiveness of Asphalt Rubber in Texas", Texas Transportation Institute, TRB Record No. 1339, Paper No. 920579, 1992.
- Heitzman, M.A., "An Overview of the Design and Construction of Asphalt Paving Materials with Crumb Rubber Additive", Federal Highway Administration, U.S. Department of Transportation, Washington D.C., TRB Paper No. 920549, January 1992.
- Heitzman, M.A., "State of the Practice - Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier", Federal Highway Administration Report FHWA-SA-92-022, U.S. Department of Transportation, May 1992.
- Justus, H.G., "New Jersey Department of Transportation Experience with recycled Materials", Road Recycling Ahead Seminar, Denver, Colorado, October 1993.
- Krutz, N.C., and M. Stroup-Gardiner, "Permanent Deformation Characteristics of Recycled Tire Rubber-Modified and Unmodified Asphalt Concrete Mixtures", Civil Engineering Department, University of Nevada, Reno, TRB Record No.1339, Paper No. 920537, 1992.
- Ksaibati, K., C.Y. Cha, H. Plancher, and B. Ramanasundaram, "Modification of Asphalt Cements Using Carbonous Residues Recovered from Co-Retorting Tires with Waste Oils", Civil Engineering Department, University of Wyoming, TRB Paper

No. 940148, January 1994.

- Maupin, G.W. Jr., "Virginia's Experimentation with Asphalt Rubber Concrete", Virginia Transportation Research Council, TRB Record No. 1339, 1992.
- Page, G.C., B.E. Ruth, and R.C. West, "Florida's Approach Using Ground Tire Rubber in Asphalt Concrete Mixtures", Florida Department of Transportation, TRB Record No. 1339, 1992.
- Roberts, F.L., P.S. Kandhal, E.R. Brown, and R.L. Dunning, "Investigation and Evaluation of Ground Tire Rubber in Hot Mix Asphalt", National Center for Asphalt Technology, Auburn University, August 1989.
- Shuler, T.S., R.D. Pavlovich, J.A. Epps, and C.K. Adams, "Investigation of Materials and Structural Properties of Asphalt-Rubber Paving Mixtures. Volume I - Technical Report", U.S. Department of Transportation, Federal Highway Administration, September 1985.
- Stroup-Gardiner, M., D.E. Newcomb, and B. Tanquist, "Asphalt-Rubber Interactions", Civil and Mineral Engineering Department, University of Minnesota, Minneapolis, TRB Paper No. 930809, June 1993.
- Swearingen, D.L., N.C. Jackson, and K.W. Anderson, "Use of Recycled Materials in Highway Construction", Washington State Department of Transportation, Olympia, Paper No. WA-RD 252.1, February 1992.
- Takallou, H.B., and A. Sinton, "Advances in Technology of Asphalt Paving Materials Containing Used Tire Rubber", BAS Engineering Consultants, Inc., TRB Record No. 1339, 1992.
- Terrel, R.L., "Evaluation of CRM Asphalt Pavements Using SHRP Tests", Report No. B14, The Clean Washington Center, Seattle, October 1993.
- Van Kirk, J.L., "An Overview of Caltrans Experience with Rubberized Asphalt Concrete", State of California, Department of Transportation, Sacramento, TRB Paper No. 920408, January 1992.