A FEASIBILITY STUDY OF THE USE OF WASTE TIRES IN ASPHALTIC CONCRETE MIXTURES

Serji N. Amirkhanian
Department of Civil Engineering
Clemson University
Clemson, SC 29634-0911

May 1992
FINAL REPORT

Research Project Sponsored by
South Carolina Dept. of Highways & Public Transportation
and
Michelin Tire Corporation

in cooperation with
U.S. Department of Transportation
Federal Highway Administration
A Feasibility Study of the Use of Waste Tires in Asphaltic Concrete Mixtures

In recent years, the increasing need for recycling has forced highway engineers to search for more innovative and economical methods of building and maintaining the nation's highways. There is an urgent need to find ways to recycle waste materials (e.g., tires) to reduce the amount of waste going into landfills each year (a nationwide problem).

This research study was undertaken to investigate the feasibility of the use of tires in asphaltic concrete mixtures. An extensive literature review of work performed in this area was conducted. In addition, an extensive survey (e.g., questionnaire) of all state and federal highway-related agencies was conducted. Several experts knowledgeable in the use of tires in flexible pavements were interviewed.

The findings of the literature review, results of questionnaire, and interviews of experts are summarized and presented in this report. In addition, several recommendations for the next steps to be taken in this area by the South Carolina Department of Highways and Public Transportation are included.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TABLE OF CONTENTS</td>
<td>i</td>
</tr>
<tr>
<td>LIST OF TABLES AND FIGURES</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>CHAPTER 1</td>
<td>1</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Background</td>
<td>2</td>
</tr>
<tr>
<td>Benefits</td>
<td>4</td>
</tr>
<tr>
<td>Objective</td>
<td>5</td>
</tr>
<tr>
<td>Work Plan</td>
<td>5</td>
</tr>
<tr>
<td>CHAPTER 2</td>
<td>6</td>
</tr>
<tr>
<td>Survey Results</td>
<td>6</td>
</tr>
<tr>
<td>CHAPTER 3</td>
<td>11</td>
</tr>
<tr>
<td>Literature Review</td>
<td>11</td>
</tr>
<tr>
<td>Introduction</td>
<td>11</td>
</tr>
<tr>
<td>Literature Review</td>
<td>11</td>
</tr>
<tr>
<td>Experiences by Other States</td>
<td>41</td>
</tr>
<tr>
<td>CHAPTER 4</td>
<td>82</td>
</tr>
<tr>
<td>Summary, Conclusions and Recommendations</td>
<td>82</td>
</tr>
<tr>
<td>Summary</td>
<td>82</td>
</tr>
<tr>
<td>Conclusions</td>
<td>85</td>
</tr>
<tr>
<td>Recommendations</td>
<td>88</td>
</tr>
<tr>
<td>LITERATURE CITED</td>
<td>89</td>
</tr>
<tr>
<td>NON-CITED REFERENCES</td>
<td>95</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1. Existing Pavements and Rehabilitation Treatments (Wisconsin's Experience)</td>
<td>42</td>
</tr>
<tr>
<td>3.2. Recycled Mix Design Properties</td>
<td>44</td>
</tr>
<tr>
<td>3.3. Recycled Mix Design Properties (Cores Tested)</td>
<td>44</td>
</tr>
<tr>
<td>3.4. Summary of Asphalt-Rubber Friction Course Demonstration Project</td>
<td>71</td>
</tr>
<tr>
<td>4.1. Users of Asphalt-Rubber Made From Recycled Tire Rubber Update (As of January 22, 1991)</td>
<td>83</td>
</tr>
</tbody>
</table>

## LIST OF FIGURES

### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1. Pavement Cracking After 2 Winters</td>
<td>45</td>
</tr>
<tr>
<td>3.2. Pavement Cracking After 3 Winters</td>
<td>46</td>
</tr>
<tr>
<td>3.3. Pavement Cost Comparisons</td>
<td>47</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

The author wishes to extend his sincere appreciation to the South Carolina Department of Highways and Public Transportation (SCDHPT) officials for sponsoring and funding this research project. The author also wishes to thank Ms. Catherine Nisbet, Mr. Robert Wentz, and Mr. Stephen Roberts of Clemson University for their assistance and cooperation during the project.

The assistance of those state and federal agencies that participated in the questionnaire is greatly appreciated. The assistance of Mr. Stewart, Mr. Gibson, Mr. Fletcher and Mrs. Gambill of the SCDHPT is also appreciated. In addition, the financial assistance of Michelin Tire Corporation of Greenville, South Carolina, is greatly appreciated.

The contents of this report reflect only the views of the author and do not necessarily reflect those of the SCDHPT, FHWA, or Michelin Tire Corporation officials.
CHAPTER 1
INTRODUCTION

In recent years, the increasing need for recycling has forced highway engineers to search for more innovative and economical methods of building and maintaining the nation's highways. As solid waste landfill space is becoming a problem (e.g., cost and environmental issues) throughout the nation, there is an urgent need to find ways to recycle waste materials (e.g., tires) to reduce the amount of waste going into landfills each year.

Two legislative initiatives currently pending in the U.S. Congress would require states to recycle 120 million tires a year. Scrap tire recycling mandates are written into both the Intermodal Surface Transportation Efficiency Act of 1991 and the Resource Conservation Recovery Act stating that federal-aid highway funding would be withheld from states if they do not comply with these Acts (1). In the last three years, there has been an increase in state legislations' interest in the use of waste materials in pavements. For example, as of January 1989, only five states regulated disposal of used tires. However, by January 1991, thirty five states had laws or regulations addressing this issue (1).

The South Carolina State Legislature, in an effort to reduce the amount of solid waste generated in the state, passed the South Carolina Solid Waste Policy and Management Act of 1991. This Act requires the South Carolina Department of Highways and Public Transportation (SCDHTP) to investigate the use of certain waste products (e.g., tires) in various aspects of highway construction. Because of this Act and environmental concerns, the SCDHTP proposed to initiate a study to investigate the feasibility of use of scrap tire rubber in asphaltic concrete mixtures.
BACKGROUND

There are approximately 240 million waste tires generated annually in the United States. Of these, 200 million are passenger car tires and 40 million are truck tires (2). According to industry figures, there are approximately 2 to 2.5 billion scrap tires currently on the ground in the United States (2).

It is estimated that South Carolina is accumulating scrap tires at a rate of 3.5 million annually. This figure is based on the number of passenger cars and commercial vehicles registered in the state and an average tire life of four years.

A typical scrap tire (passenger car) weighs approximately 20 pounds and will provide approximately 60% rubber, 20% steel and 20% fiber and other waste products (3). Based on these estimates, South Carolina drivers are generating, each year, approximately 21,000 tons of rubber, 7,000 tons of steel, and 7,000 tons of fiber.

For sometime, the Federal Highway Administration (FHWA) has been promoting the experimental use of rubber (i.e., tires) in asphaltic concrete mixtures. Because of growing environmental concerns, the use of tires in flexible pavements has been increasing. In addition, state highway agencies are under public pressure to utilize waste materials to some extent, if possible.

There are few states that have been using tires in their pavements successfully. The South Carolina Department of Highways and Public Transportation (SCDHPT) officials met with the principal investigator to discuss the use of rubber in pavements. Since the acceptance of asphalt-rubber has been regional (e.g., Arizona), the SCDHPT officials and the principal investigator decided there was a need to obtain more information regarding this issue.
There are many factors to consider when a state agency uses rubber in its pavements including cost, specifications, type of equipment to be used, expertise of the contractor, potential recyclability of materials, etc. Due to limited use of rubber in asphaltic concrete pavements in the United States, the information on performance of these materials is fragmented.

There are many advantages for using rubber in asphaltic concrete mixtures. Some of the potential benefits of rubber-asphalt systems include:

1. thinner lift,
2. increased pavement life,
3. retarded reflection cracking,
4. decreased traffic noise,
5. reduced maintenance costs, and
6. decreased pollution and increased environmental quality.

Scrap tires can be used in asphaltic concrete mixtures either as a part of the asphalt binding material or seal coat, or as a part of the aggregate. Asphalt rubber seal coats use about 1,600 tires per mile of a two lane road sealed. Approximately 8,000 to 12,000 tires are used per mile of two lane road (3-inch overlay) if the scrap tires are used as aggregates.

There are many issues and problems associated with the use of tires in asphaltic concrete pavements that must be researched and analyzed. Some of the issues and problems include:

1. High initial costs: Some highway agencies and/or private firms manufacturing the scrap tires claim an increase of approximately 25% to over 200% in the cost of pavement.

2. Lifecycle economics: There are claims of doubling the life of conventional pavements by using these products; however, there has not been a comprehensive study to justify the high initial costs and to determine the lifecycle economics of this type of pavement.

3. Lack of product specifications by ASTM or any other agency.

4. The uniformity of scrap tire rubber could be a problem and must be studied in great detail.
5. The recyclability of the pavement containing scrap tires must be investigated and analyzed.

6. There are some environmental concerns over the use of tires in a pavement.

7. There are some concerns over necessary modifications made to the asphalt plants or equipment used for a typical paving operation.

There are two major processes used in designing and constructing an asphalt-rubber mixture; they are referred to as "wet" and "dry" processes. In the wet process, rubber is added to asphalt cement. In the dry process, crumbled rubber is used as a portion of the aggregate. In the wet process, approximately 5% to 10% of rubber (by weight of the asphalt cement) and in the dry process approximately 3% of rubber (by weight of the total mixture) are added to the asphaltic concrete mixtures. There have been many projects constructed with these two methods; however, the long-term performance and life-cycle cost comparisons of the two methods have not been researched in depth.

**BENEFITS**

The major potential benefits of the use of scrap tires in highway construction include conservation of asphalt binder, aggregates, and energy; along with preservation of the environment. In the last decade, the cost of opening and operating a new landfill, or operating an existing landfill has increased tremendously. There are several reasons for this increase in cost, including federal and state regulations regarding the operation of these landfills. Therefore, the use of scrap tires in highway construction seems to be a valuable option to some of the problems that the nation and the state of South Carolina face regarding landfills.
OBJECTIVE

The major objective of this research proposal was to study the feasibility of the use of waste rubber tires in asphaltic concrete mixtures. In order to achieve this objective the following steps were followed:

1. An extensive literature review of work performed in this area was conducted.

2. An extensive survey (e.g., questionnaire) of all state and federal highway-related agencies was conducted.

3. Several experts knowledgeable in the use of tires in flexible pavements were interviewed.

WORK PLAN

The facilities at Clemson University were used to obtain as much information as possible regarding the subject matter. A questionnaire was prepared and mailed to all state and federal highway agencies in the United States. In addition, several experts throughout the United States were interviewed (either by phone or by arranging a meeting). This report contains a summary of most of the work done by researchers around the country. The report will also discuss the advantages and disadvantages of the use of rubber in flexible pavements. Based on the literature review, surveys of all highway agencies, and interviews of the experts, the report also contains several recommendations for future actions to be taken by the SCDHPT officials.
CHAPTER 2
SURVEY RESULTS

A questionnaire was prepared and mailed to all state highway agencies in the United States. In addition, some federal agencies were asked to complete the questionnaire. The following state highway agencies responded to the questionnaire: Alaska, Arkansas, California, Colorado, Connecticut, District of Columbia, Florida, Georgia, Hawaii, Illinois, Iowa, Kentucky, Maine, Maryland, Michigan, Minnesota, Mississippi, Missouri, Nebraska, Nevada, New Hampshire, New Mexico, New Jersey, New York, Oregon, Pennsylvania, Rhode Island, South Carolina, South Dakota, Tennessee, Texas, Vermont, and Wisconsin. The rate of response was 66%. Nineteen states indicated that they were currently using mixtures containing rubber or had constructed some experimental sections made with asphalt-rubber mixtures. These states included: Alaska, Arkansas, California, Colorado, Connecticut, Florida, Georgia, Illinois, Iowa, Maine, Maryland, Michigan, Missouri, Nebraska, New Hampshire, Oregon, Pennsylvania, Texas, and Wisconsin. Most of these states indicated the use of asphalt-rubber mixtures is in its experimental stages.

The following sections show the questions asked and a summary of the responses from the participating agencies:
QUESTIONNAIRE
FOR ASPHALT-RUBBER MIXES

State : Summary of Questionnaire Responses

Engineer in charge of Flexible Pavement Construction

Name : ____________________________
Address : ____________________________
Telephone: (____) ____ - ______

Please answer the following questions to the best of your knowledge.

1. Approximately how many miles of new flexible pavement were constructed in your state this year?
   a. 10.0% 0-10
   b. 38.0% 11-30
   c. 14.0% 31-50
   d. 7.0% 51-100
   e. 0% 100-150
   f. 31.0% >150

2. Approximately how many miles of asphaltic concrete overlay were placed in your state this year?
   a. 0% 0-10
   b. 10.0% 11-50
   c. 7.0% 51-100
   d. 10.0% 101-150
   e. ___ 151-200
   f. 3.0% 201-250
   g. 3.0% 251-300
   h. 67% >300, if >300, please specify: _____
3. Is there legislation (on books/pending) calling for a waste rubber recycling program in your state? (if yes please mail a copy of requirements to address shown below. Thank you)

38% yes 62% no

4. Please describe the parameters of waste rubber tire disposal in your state. (cost, method of collection, storage/disposal).

- $2.00/ new tire (charged to the user)
- Landfills
- Unknown
- Recycling
- $4-5/whole tire: for disposal

5. What are the primary environmental hazards to the flexible paving in your state (excessive moisture, frost, extreme heat, etc.)?

- Wide variety of answers were received (from extreme heat to extreme cold).

6. Is your organization presently using an asphalt-rubber mix for flexible pavement construction?

14.0% yes 86.0% no

7. Is your organization presently using an asphalt-rubber mix for pavement repairs or overlays?

41.0% yes 59.0% no

If the answers to the above two questions were 'no', please go to question number 15.

8. With regard to asphalt-rubber mixes for flexible pavement, what general disadvantages have you experienced?

- Cold temperature cracking
- Shorter compaction period
- Constructability
- Increased mix temperature
9. Have you experienced any problems in the mixing of asphalt-rubber mixes?

51.0% yes (if yes, please describe) 49.0% no
- Cost
- Dry process had loss of fines
- Difficult to introduce it into machine
- Rubber's tendency to stay in silo and the drum drier
- Increased temperatures and viscosity
- Excessive plant emissions
- Limited supply of rubber

10. Have you experienced any problems in the placing of asphalt-rubber mixes?

38.0% yes (if yes, please describe) 62.0% no
- Hard to rake and compact
- Stickiness
- Failure due to mix and laydown temperatures
- Odor and pollution

11. Have you experienced any problems in the compaction of asphalt-rubber mixes?

58.0% yes (if yes, please describe) 42.0% no
- Problems achieving density
- Roller pattern and equipment need modifications
- Mix has tendency to move in front of mat

12. Have you experienced any increase in pavement life using asphalt-rubber mixes?

18.0% yes (if yes, please describe) 82.0% no

13. Have you experienced any increase in cost using asphalt-rubber mixes?

100% yes (if yes, how much) ___ no
- Averages about twice as much as conventional
14. Did you have to do any modification to your equipment in order to mix, place, and compact the asphalt-rubber mixes?

62.0% yes (if yes, please describe)  38.0% no

- Pneumatic roller not allowed on mat
- Mixing rubber and asphalt required special equipment
- Asphalt plant pump had to be by-passed
- Separate storage of binder required

15. Are you familiar with the advantages associated with asphalt-rubber mixes (if so please list them)?

- Resistance to aging and cracking
- Resistance to permanent deformation
- Increased elasticity

16. Approximately how many waste tires were generated in your state in the last year?

- It is estimated each state generates one tire per person each year (e.g., population of SC: 3,512,000; therefore, SC generates approximately 3.5 million scrap tires per year).

17. Has your organization performed research or received study data concerning the feasibility of asphalt-rubber construction/repair in your state? (if yes, please mail a copy of the findings to the address shown below. Thank you).

- Many states furnished the principal investigator with their research findings. These findings are discussed in the next chapter.

18. If further research is conducted into the feasibility of asphalt-rubber mixes, what specific characteristics would you like to see emphasized? That is, what primary factors/properties would decide whether or not asphalt-rubber mixes would be used in your state?

- Increased rutting resistance
- Cost effectiveness
- Emissions control
- Impact on recycling
- Performance
- Benefit/cost ratio
- Service life
- Maintenance cost
- Differences among dry and wet processes
- Stripping problems
- Plant and equipment modifications
CHAPTER 3
LITERATURE REVIEW
INTRODUCTION

An extensive literature review was conducted in order to obtain information regarding the use of scrap tires in flexible pavements. The Robert Muldrow Cooper Library of Clemson University was used to obtain most of the articles. On-line bibliographic searching service of the library was utilized to access references and abstracts of hundreds of thousands of articles and reports. The inter-loan library service was used if an article was not located in the library. This service enables the library to contact other libraries around the country or other governmental agencies in order to obtain a copy of the requested article or report. The following sections contain a brief summary of reports and articles read for this research project.

LITERATURE REVIEW

Phoenix, Arizona has used asphalt rubber for many purposes, including pavement seal coats, stress absorbing membranes (SAM), stress absorbing membrane interlayers (SAMI), subgrade seals, lake liners, joint and crack sealants, roofing, and airport runway surface covers. There are several types of asphalt rubber used in Arizona. The following is a brief description of each process (4).
Types of Asphalt Rubber Used in Arizona

1. The McDonald Process - Hot asphalt cement is mixed with 25% ground tire rubber and diluted with kerosene to make application easier.

2. Arizona Refinery Process - 18 to 22% ground rubber is mixed with hot asphalt cement and diluted with an extender oil.

3. Asphalt rubber chip seal - It is the application of hot asphalt rubber followed by an application of hot precoated aggregate.

4. SAM - Hot asphalt rubber chip seal is applied to a stressed surface.

5. SAMI - It is the same as a SAM, but it is followed by an asphaltic concrete overlay.

Asphalt rubber has been used primarily on roads in need of reconstruction; however, funds were not available on inexpensive, residential streets, and on low-volume roads (4).

Ten to twelve years of maintenance-free life can be expected from an asphalt rubber seal. Normal chip seals last six to eight years with some maintenance (4). The initial cost of asphalt rubber is twice as much as conventional chip seal, but will equal conventional costs over a 12 year period. Indications show that asphalt rubber life expectancy can go beyond 12 years by resealing it with standard or asphalt rubber seal (4). The benefits of using asphalt rubber include (4):

1. Stops reflective cracking for 8-12 years in pavements with less than 0.25 inch cracks.

2. Stops spalling around potholes and large cracks.

3. Waterproofs the pavement; therefore, obtaining maximum stability.

4. Preserves the original quality of the asphalt cement.

5. Eliminates maintenance because of the above points.

6. Seals the subgrade to minimize volume changes that occur because of moisture changes.

7. Acts as a stress absorbing interlayer to reduce future maintenance.
8. Is an excellent crack and joint sealant.
9. Provides flexibility, which is useful on low-volume roads.

Takallou, et al., examined the effects that rubber gradation and content, air voids, aggregate gradation, mix, temperature, and curing conditions have on the properties of rubber-modified asphalt (5). The tests were performed at 10 °C (50 °F).

Rubber-modified asphalt is typically prepared using 3% by weight of granulated coarse and fine rubber particles to replace some of the aggregate in the mixture. This was originated in the 1960's by the Swedish companies Skega AB and AB Vaegfoerbaettringar (ABV) and was patented as Rubit. In the U.S. it was patented as PlusRide and marketed by All Seasons Surfacing Corporation of Bellevue, Washington.

Test variables used by the researchers included the following (5):

Air voids, %: 2 and 4
Rubber content, %: 2 and 3
Rubber Gradation (coarse, fine) - coarse (80,20) med (60,40) fine (0,100)
Mix/Compaction Treatment, °F: 375/265, 425/265
Mix Curing at 375 °F and 425 °F: 0 and 2 hours
Aggregate Gradation: gap graded, dense graded
Surcharge: 0 and 5 lbs.

Optimizing mix properties and increasing pavement life for the least cost were the main goals of this study. This was accomplished by evaluating the mix ingredients (i.e., rubber, asphalt, and aggregate) (5).

The results indicated that the resilient modulus values for rubber mixes were generally higher for dense-graded aggregates than for gap-graded aggregates. The gap-graded mix had a higher (by 40%) fatigue life at 10 °C than the dense-graded mix. The resilient modulus values for gap-graded and dense-graded aggregates increased at 10 °C as the rubber gradation became finer. The fatigue lives were reduced by about 20% as rubber gradation became finer (5).
As the percent rubber by dry weight of aggregate increased from 2 to 3%, the modulus values generally decreased for gap-graded mixes; but the fatigue life was not significantly affected. Gap-graded aggregate mixtures with a blend of 80% coarse and 20% fine rubber had the lowest modulus and highest fatigue life. A high mixing temperature (425 °F) slightly increased the modulus and fatigue life for gap-graded mixes. Dense-graded mixes showed an increase in modulus, but a decrease in fatigue life with higher mixing temperatures (5).

Stokely and McDonald reported that there are two alternatives when it comes to badly cracking streets - "constant and expensive patching, or complete reconstruction of large sections of pavement and base (6)." Patching is becoming more impractical because of traffic, and reconstruction is too costly in most cases. Reconstruction of a major street in Phoenix at that time was $24,000 per city block. Asphalt-rubber treatment costs approximately $2,400 per city block and causes less disruption of traffic.

**Process**

Asphalt is heated to between 350 and 400 °F. Ground tire tread rubber, #16 to #25 mesh, is the second ingredient (75% asphalt, 25% rubber). Thirty minutes to an hour later, 5.5% to 7.5% kerosene is added to reduce the viscosity sufficiently for spraying. The rubber does not dissolve totally; the particles act as "units of elastic interference to propagation of cracking from below (6)." Lastly, 3/8 inch nominal sized chips, precoated with asphalt, are applied to the surface.

The researchers reported several restraints concerning this type of construction including: a) Hot asphalt-rubber should not be applied when the ambient temperature is below 70 °F or when the pavement temperature is below 85 °F. b) The application rate should be approximately 0.5 gallons per square yard.
for most conditions. At this rate, 3/8" nominal sized chip should be applied at the rate of 35 to 40 pounds per square yard" in order to prevent excessive embedment (6)."

Cleary and Clark report that between 1968 and 1973, over a million pounds of reclaimed rubber (50,000 tires) were recycled and used on the Thomas E. Dewey Thruway in New York (7). They used a rubber sealer to repair joints and cracks in the road. The sealer lasted three times as long as conventional asphalt sealers and also helped to get rid of a growing problem in this country - scrap tires.

Maintenance teams were having to repair the road annually with conventional sealer, so a program was started to find a better material. "The goals were to lower cost, make application easier, lengthen the life of the sealer, and provide a rapid-setting material (7)." Asphalt-rubber was the solution. The process called for 100 lb. bags of powdered rubber to be added to 500 lbs. of asphalt at the roadside site. The mix was cooked, and while some sealer was being used, more was mixed, making it a "continuous operation." The rubber for this process was devulcanized and came to the worksite in crumb form in 50 lb. bags (7).

The results indicated that it costs 3 to 5 cents per pound and beats other sealants "on a dollar-for-dollar basis." It eliminates the lack of flexibility in winter and flow in the summer; increasing the life of the sealer, and making repair necessary every 2 to 3 years instead of annually. Patching is usually done in the fall, but with this sealant, patching can also be accomplished in the winter. These winter patches have performed well in comparison to the conventional winter patches (7).

Way indicated in his report that cracking and rutting often occur in flexible pavement due to the environment, traffic, and the original design (8).
He also indicated that a thin asphaltic overlay is the usual way to solve this problem, but it creates a new problem (i.e., reflective cracking). The Arizona Department of Transportation (ADOT) along with the Federal Highway Administration’s (FHWA) National Experimental and Evaluation Program (NEEP) conducted a study on reducing reflective cracking in bituminous overlays. Eighteen test sections were used on a nine-mile stretch of the Minnetonka-East, near Winslow, Arizona. This highway had a "moderate-to-heavy" traffic load, severe weather conditions, and a history of cracking; therefore, making it an ideal choice for the test (8).

Test sections 1, 3, and 4 used asphalt rubber in their design. Section 1 was asphalt-rubber plus precoated chips. Sections 3 and 4 were asphalt-rubber membrane interlayers. To determine the extent of cracking, a "special photographic technique and an optical grid system" was used. The results showed that five designs significantly reduced reflective cracking. Test sections 1, 3, and 4 were in the top 5; sections 3 and 4 ranked at the top and section 1 ranked fourth. The following table shows the percentages of the reflective cracking in 1975 and 1978 for sections 1, 3 and 4.

<table>
<thead>
<tr>
<th>Test Section #</th>
<th>Treatment</th>
<th>Percentage of Reflective Cracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,4</td>
<td>SAMI</td>
<td>4%</td>
</tr>
<tr>
<td>1</td>
<td>A-R seal coat</td>
<td>19%</td>
</tr>
</tbody>
</table>

For sections 3 and 4 a 0.5 gallons per square yard asphalt-rubber membrane was placed on top of a 1.25 inch AC overlay, and chips were applied and covered with a 0.5 inch ACFC. For section 1, a 1.25 inch AC overlay flushed with 1 gallon per square yard asphalt rubber and coated with chips was used (8).
The results indicated that the SAMI worked the best because of its low modulus of elasticity (approximately 5000 psi). However, a good deal of shoving occurred which caused a rough ride. It was reported that the ADOT is mainly using Asphalt-rubber in high elevation areas (8).

Takallou and Hicks discussed a type of rubber-modified asphalt which is a mixture prepared by using 3 to 4 percent by weight, relatively large rubber particles to replace some of the aggregate (9). The purpose of this study was to evaluate this rubber-modified asphalt in road construction and to develop guidelines for using it.

The key to a successful rubber-modified asphalt is a low percentage of voids in the total mix. Air voids, as seen from laboratory work, should vary depending on the traffic level:

- Low traffic: 2 to 3 percent
- Medium traffic: 3 percent max
- High traffic: 4 percent max

The required level can be reached by increasing the mineral filler and the asphalt cement content, and by carefully following the compaction guidelines (9):

1. Rubber tired rollers should not be used
2. Make sure all water nozzles are working
3. Use liquid detergent in the drum water
4. Use a special wetting agent, Dweko, in the drum water

In Nebraska, the Department of Roads is conducting a test on a section of Highway 4 using rubberized asphalt (10). Approximately 30,000 used tires were grounded up for use in this 12-mile section. Out of the 12 miles, 7.3 were constructed with rubberized asphalt and the other 4.7 were made with conventional asphalt. The main reason for experimenting with the rubber-asphalt mixture was
to demonstrate the ability of these mixtures to retard reflective cracking compared to the conventional asphaltic concrete mixtures. For this project, 18% ground rubber and 82% liquid asphalt were blended together, heated at 400 °F for 45 minutes, and then mixed with the aggregate.

Resurfacing with rubber asphalt costs about three and a half times as much as conventional asphaltic concrete. At this time, the effects of the asphalt-rubber mixture on the performance of the pavement are not yet known (10).

Gina Busscher reported that the Florida Department of Transportation (FDOT) is resurfacing a section of US 17 in Nassau County with a rubber-modified asphalt (11). The FDOT hopes that this will not only help to get rid of scrap tires, but will also create a more "flexible and durable" pavement. They will also try to demonstrate, through this project, that the hot mix additive is the most efficient method of paving with ground rubber. The FDOT will monitor the pavement for the next 2 years and evaluate its performance. They hope to see the pavement last beyond its average 20 year life (11).

McQuillen, et al., reported that the Alaska Department of Transportation and Public Facilities (ADOTPF) is evaluating rubber-modified hot-mix pavement as an alternative to conventional asphalt (12). There are many benefits in favor of rubber-modified asphalt. The main disadvantage, though, is its high initial cost (12). They reported that in order to be cost effective, it must have a pavement life of 20 to 23 years, compared to 15 years for conventional mixes (12).

They also indicated that to make rubber-modified mixes more economically feasible, the life-cycle and/or the capital costs must be reduced (12). The life-cycle costs could be reduced by including the intangible benefits, such as reduced traffic noise; improved skid resistance; reduction of sand, salting, and
winter maintenance costs; and elimination of a solid waste material (i.e., rubber tires). In addition, capital costs could be reduced in several ways depending upon the way they are decided upon. For instance, up to an 8% savings in the total cost could result if the rubber tires were obtained locally. On the other hand, if the mixing time for rubber-asphalt was made the same as for conventional mix, the reduction in cost would only be 0.4% (12).

Another alternative is to reduce the thickness of a layer of rubber-modified mix. Researchers indicate that a rubber-modified mixture could have a thickness in the range of 2 to 2.5 inches and have the same fatigue life as a 3 inch layer of conventional surfacing (12).

The Federal Highway Administration published a report indicating the technical guidance to asphalt pavers on how to use "Crumb Rubber Additive" (CRA) technology (13). This report indicates that each year, 330 million tires are thrown away. From that, 40 million are retreaded, 20 million are resold, and 30 million are used for various other things. That leaves 240 million tires to go to stockpiles, landfills, and illegal dumps. Crumb Rubber Additive has the potential to solve the scrap tire problem and in many cases, benefit the pavement (13).

Crumb Rubber Additive (CRA) technology is a broad term which includes any method for using scrap tire rubber in asphalt paving materials. CRA technology can be divided into two categories- the wet process and the dry process.

The wet process, also called the "Arizona Process" produces what is called asphalt-rubber. Asphalt rubber has been used in crack and joint sealants, surface treatments such as SAM's and SAMI's, and Hot Mix Asphalt.
The dry process produces rubber-modified asphalt. This process is only used in Hot Mix Asphalt applications. The main application of the dry process is called the "PlusRide Process." Newer applications are the "Generic Dry Process," "Chunk Rubber Asphalt Concrete" and "Continuous Blended Asphalt Rubber."

A 20 lb. tire will normally produce 10 to 12 pounds of crumb rubber. The remainder of the material is fiber and steel. The average cost of CRA is 10 to 12 cents per pound and it is usually shipped in 50 to 60 pound bags (13).

Wet Process

When the wet process is used, the CRA acts as a modified binder. There are many variables which affect the interaction between CRA and asphalt cement. These variables are the blending temperature, the type and amount of mixing, the size and texture of the CRA, and the aromatic component of the asphalt cement (13). The reaction which occurs during the wet process is not a melting of the CRA. The reaction is similar to a compressed, hard, dry sponge being placed in a water bath (13). The CRA swells and softens and becomes sticky. This increases the mixture's viscosity.

The wet process means adding the CRA to the asphalt cement "prior to incorporating the binder in the asphalt paving project." The equipment used in the wet process is very portable and the process is usually performed at or near the project site.

The advantages of using the CRA, using the wet process, are reduced thermal cracking, reduced rutting, reduced reflective cracking, slower aging, and better chip retention. These enhancements were measured in the lab and may not be the same when tested in the field (13).
The disadvantages are high initial cost, bleeding and flushing, and tracking. The CRA and the asphalt must be compatible to enhance the properties of the binder. They are generally compatible "if the reaction time and temperature are reasonable (350 °F for 1 hour) and there is a significant flattening in the temperature viscosity curve (13)."

Descriptions of the applications for the wet process are on pages 29-34 of this report. These applications are crack/joint sealant, surface treatments, and Hot Mix Asphalt (HMA).

**Dry Process**

When the dry process is used, the CRA acts as an aggregate substitute. This is done by limiting the reaction time and by using a coarse granulated CRA. By limiting the reaction time, the reaction does not penetrate the entire rubber particle; "This creates an asphalt/rubber interface which bonds the two materials together (13)."

The dry process means "adding the CRA directly into the hot mix asphalt mix process, typically pre-blending the CRA with the heated aggregate prior to charging the mix with asphalt." The aggregate and the CRA are dry blended for about 15 seconds before the asphalt cement is added. The dry process will have some reaction between the asphalt and the CRA, but not much (13).

The advantages of CRA as an aggregate substitute are reduced reflective cracking and ice disbonding. When the stress of a crack in the original pavement reaches a rubber particle in the new overlay, the particle absorbs the stress and delays the advance of the reflective crack. Ice disbonding only occurs when the road is continuously loaded and when the ice is thin. When the rubber particles exposed to the surface are compressed by wheel loads, an area of flexibility is created "that will not retain ice when it begins to crystallize (13)."
The disadvantages are high cost and raveling. Compatibility between CRA and the asphalt cement is not very critical when CRA is used as an aggregate substitute because the reaction between the two is so insignificant.

**Hot Mix Asphalt**

This report indicates that the hot mix asphalt has applications using the wet process and the dry process. However, the report indicates that there is one thing common with both applications (i.e., both are relatively new with respect to appropriate field evaluation) (13). Many factors are still unresolved, such as performance and cost-effectiveness (13).

The wet process HMA costs 50 to 100 percent more than conventional mix. Work conducted to this time shows that it can perform better than conventional mixes in certain situations, but its cost effectiveness has not yet been established (13). Hot mix asphalt from the wet process will give more benefits in severe climates than in moderate climates (13).

Hot mix asphalt from the dry process is tested by measuring the air void content, for which the target is 2 to 4%. The cost of PlusRide, a rubber-modified bituminous surface mixture, ranges from 50 to 100% higher than conventional mixtures. The projected cost of this rubber-modified asphalt could reduce to 30 to 50% above conventional mixes if it becomes more widely used (13).

This report indicates that the major problem with using scrap tire rubber in asphalt is that it is unclear whether or not it can be recycled. If it cannot, the benefits are reduced and "a new waste problem is created (13)."

Turgeon and Allen evaluated the PlusRide process (14). "PlusRide" claims to have unique de-icing properties and an ability to reduce reflective and thermal cracking. The Minnesota DOT conducted a study to determine if it would help in reducing the amount of chemicals used for ice and snow control without
reducing the level of service. Two project sites were used to evaluate "Plus Ride", each approximately 0.7 miles in length (14). The materials used were:

1. Granulated rubber from old tires as a part of the aggregate.
2. Gap graded mineral aggregate with mineral filler added when needed.
3. Asphalt cement (120/150 penetration).

Placement of the rubber-modified mixture was similar to the placement of conventional mixes except the placement temperatures were considerably higher for the rubber-modified asphalt (14).

Compaction was a problem, because the roller was picking up particles. Soap mixed with the water helped but did not eliminate roller pick-up. Low density was another problem with compaction. Two rollers were used to compact the mixture, but if either roller stopped to add water or fuel, serious low density problems could result. The study indicated that the use of three rollers may be better (14).

The results indicated that there was no decrease in tire noise. In addition, after one winter, over 80% of the cracks reflected through. Observations by maintenance personnel also indicated no significant de-icing benefits (14).

In this study, the rubber-modified mixture was over twice the cost per ton of conventional mix, exhibited construction difficulties, and did not show any significant benefits (14). The researchers indicated that rubber-modified mixture can perform equally as well as conventional material, but further construction and investigation is not recommended unless it is only a means to get rid of scrap tires (14).
If further investigation is performed, three 8 to 10 ton steel rollers should be required. Also, 5/8" maximum size aggregate should have a minimum compacted thickness of 1.5 inches (14).

Shuler, et al., evaluated six types of paving systems containing ground tire rubber (15). These six systems were:

1. Asphalt-rubber seal coat
2. Asphalt-rubber interlayer
3. Asphalt-rubber concrete
4. Asphalt-rubber friction course
5. Asphalt concrete rubber filled
6. Friction course rubber filled

Systems 1 through 4 used 18-26% ground tire rubber, and systems 5 and 6 used rubber as an aggregate substitute (15).

Sixteen state highway departments pooled their funds for the research, which was administered by the FHWA. There were 219 test sections evaluated across the U.S. that were constructed between 1977 and 1984 (15).

Crack reduction was judged by noting differences between control and test sections. Because variables such as traffic, climate, and construction techniques were different on all projects, a rating system was developed which judged on the basis of relative performance at each section. The scale was from -3 to +3, with positive numbers indicating an improvement over the control section, and negative numbers meaning the opposite. This system provided an equal basis for evaluation (15).

Conclusions for Interlayers

There was a slight negative performance compared to control sections. This negative performance is believed to be due to inappropriate construction practice or intended use. High strains which come from a joint or thermal crack cannot be "attenuated by interlayer systems (15)." Many of the interlayer test sections
with negative results were constructed before 1979. This factor is important, because new technology developed after that date, and preblending became routine in the summer of 1979. Preblending improves the application process (15).

Conclusions for Asphalt-Rubber Seal Coats

There was a slight negative performance, but it is believed to be due to construction practices. Flushing was the main cause of negative performance and it is caused by "inappropriate application quantities of binder and aggregate (15)." When test sections with flushing are removed from the analysis, there is an overall positive performance. Flushing is something that can be corrected (15).

Conclusions for Asphalt Concrete Rubber Filled

There was improved performance compared to control sections, especially when 1% finely ground rubber was used (15).

Conclusions for other systems are not available, because there were not enough observations made.

Recommendations for Asphalt-Rubber Seal Coats (16)

1. The practice of selecting binder quantity before aggregate quantity should be abandoned.

2. Seal coats should be designed to provide for embedment of one layer of aggregate per application.

3. Seal coats are more effective in the following situations:
   * Maintenance of pavements with alligator cracks or random transverse and longitudinal cracking at less than 8 ft intervals.
   * Maintenance of low-volume roads where conventional seal coat would oxidize and crack due to lack of use (16).

Recommendations for Interlayers (16)

1. "Interlayer design should be modified from seal coat design to allow slightly higher initial embedment."
2. There should be adequate curing time after construction because diluents may cause softening of overlay asphalt concrete if the overlay is applied too soon.

3. "Interlayer systems with dense-graded asphalt concrete overlays are not recommended for reflection crack control on pavements with transverse cracks or joints appearing at regular intervals of more than 15 feet."

The Civil Engineering Department at the University of Connecticut and the Connecticut Department of Transportation tested sections placed at nine locations (17). Sections selected had three levels of average daily traffic (ADT) and three levels of pavement condition. The levels of average daily traffic ranged from 1300 ADT to 10,400 ADT, and the pavement conditions were rated as low, medium, or high. At each location, 0, 1, and 2 percent rubber test sections were placed. The rubber-modified asphalt was placed as an overlay so that its flexibility would stand up to the high stress caused by cracks in the existing pavement (17).

For local aggregates, 1 and 2 percent rubber were used and 0.25 percent more binder for each 1 percent rubber. Marshall tests were performed, and most mixes were within ConnDot specifications (17).

It was found that the demands on an overlay are different, depending on the direction of the crack. The 1% rubber mixture is better at resisting load-induced flexure tensile stresses than resisting direct tension. Rubber-modified asphalt can resist temperature-induced flexing, but not shrinkage. This causes the transverse cracks to reflect through before the longitudinal cracks. Looking at cracking as a whole, there is a 96% chance that 1% mixes have less cracking than control mixes, and a 30% chance that sections with 2% rubber have less cracking than the controls (17).

Pavements classified as medium distress benefitted most from the addition of 1% rubber. Roads with medium traffic levels also benefitted more from the
addition of rubber than low-volume sections (17). In conclusion, the author indicated that rubber-modified mixes are performing better than nonrubberized mixes. There has been less cracking and no reduction in skid resistance. A longer life is also expected (17).

Valeraga, et al., evaluated several systems and their ability to reduce reflective cracking (18). These systems included the SAM, the SAMI, the Plant-Mixed SAM, the SAM with open-grade, and plant-mixed surface. In this article they also described surface preparation and design considerations. The type of asphalt-rubber discussed uses 20 to 25% vulcanized and reclaimed crumb rubber from ground tires (18).

Conclusions made from field evaluations indicated that (18):

1. The SAM is very effective at reducing reflective cracking, as long as the existing cracks are no wider than 3/8 inches. The cracks which do reflect through usually remain narrow and do not spall.

2. The SAMI is very effective and practically eliminates all reflective cracking when used with the proper overlay and when wide cracks are filled in the existing pavement structure.

3. The plant-mixed SAM has potential for reducing reflective cracking when it is used on a prepared surface. The advantage of this system is better proportioning, mixing, and placing. The main disadvantage of this system is the "limited amount of asphalt-rubber which can be incorporated into the mixture."

Witczak performed a research project for Maryland DOT to give them recommendations on the use of asphalt-rubber in pavement (19). He indicated that if only 15 to 35% of the annual total hot mix used ground rubber, all waste tires in the U.S. could be utilized. However, the steel and fiber waste removed from the tires would still have to be disposed of somehow (19).
Economic Considerations of Rubber in Asphalt (19)

Many factors affect the cost of using a pavement containing scrap rubber tires. These factors include time, location, contractor risk, project size, and project type. The initial cost of the rubberized processes is approximately 50-130% more than the conventional methods.

Over a long period of time, the FHWA predicts that the cost of asphalt rubber hot mixes will stabilize at only a 20 to 30% increase over conventional mixes. However, because of the growing market for scrap tires in other industries, 50 to 60% may be a more reasonable estimate.

In general, the use of asphalt-rubber in hot mixes (wet or dry), will have higher costs because of the following reasons:

1. Increased volume of asphalt binder (1-2% more)
2. Addition of granulated rubber
3. Need for more costly stone/filler gradation (only for rubber-filled)
4. Increased energy to heat to higher temperatures and extended mixing time
5. Increased plant labor/ equipment to handle
6. Increased labor/ equipment at work site
7. Contingency for greater mix susceptibility to adverse weather
8. Increased royalties (patented systems only)

Life Cycle Cost Considerations (19)

For asphalt-rubber to be cost-efficient, one of two things must be true:

1. The design life must exceed that of an equivalent alternative. Typical performance ratios necessary for cost effective rubber applications are:
The use of asphalt-rubber blends or rubber-modified mixtures require a service life approximately twice as long (1.5-2.5) as the equivalent conventional mixture.

2. The layer equivalency of asphalt-rubber mixes to a conventional application must be significantly greater than a value of unity. For rubberized hot mixes to be more cost-effective than conventional mixes, layer equivalency values of 1.7 to 2.0 are necessary. In other words, 1" of rubberized hot mix must perform the same as 1.7 to 2.0" of conventional hot mix.

Field Performance / Evaluation (19)

Chapter 5 of the report by Witczak gives a comprehensive review of field performance and evaluation studies by several agencies. There are many variables that enter into each evaluation. These variables are the construction dates, the number of years each section was evaluated, and the different objectives of each experiment.

For SAM systems, the performance ranged from "poor to improved". Some studies have indicated that the SAM will delay reflective cracking, especially for low to medium traffic levels. But other distresses, such as bleeding, roughness, and friction, lower the performance life of the SAM system. Overall, a SAM will perform equivalent to or marginally better than conventional materials.
For the SAMI system, the performance varied greatly. Where the SAMI systems were placed over PCC pavements, they were not effective at reducing reflective cracks. The report indicated that the SAMI system used on existing asphaltic pavements should be limited to places where transverse cracks are less than 15' apart. The SAMI systems are not recommended for cold climates. Also, the thickness of the overlay should be greater in moderate areas than in warm areas. Overall, it is not recommended for rigid pavements, and performance on asphalt pavements is generally equivalent to slightly poorer than conventional pavements.

For asphalt-rubber hot mixes, overall, the performance is equal to poor compared to conventional materials. The results from California is the one exception. In addition, for the rubber-filled hot mixes, there is great variation in performance. Overall, it performs no better or slightly poorer than conventional materials.

In conclusion, the author indicates that because of the general performance and high initial cost, the use of rubber in asphalt appears to be cost-ineffective.

Other Problems/ Considerations (19)

Research to develop new testing procedures is necessary, as well as an accurate method for extracting and evaluating field samples. Currently, the processes using rubber in asphalt rely heavily on manual labor. This can result in several problems during the production process. Automation would keep these problems to a minimum.

Compaction of rubber mixes is a problem because of the stickiness. Compaction should not be allowed until mat temperatures are 275-300 °F. Rubber
tired rollers are not recommended, and steel wheel rollers should have plenty of water available to the wet drum, as well as a mild detergent and/or a wetting agent.

It is not known if rubberized asphalt can be recycled in the future. Further research is needed in this area. Lastly, environmental and health studies need to be performed to determine if the emission production falls within state/federal environmental and health limits. There have been several reports of increased air pollution and visible emissions at the plant site.

The Minnesota Pollution Control Agency (MPCA), the Minnesota Dept. of Natural Resources (DNR), and the Minnesota Department of Transportation (MDOT) joined together to investigate the use of recycled tire rubber and shingle scrap in asphalt paving mixtures (20). The only test sections of importance were the 3% rubber, and 6% rubber sections.

To yield a higher stability in the rubber mixtures, a coarser aggregate than normal was used. The larger stones were used to create a better aggregate interlock and the small rubber particles were supposed to fill in the gaps. It helped some, but the rubber mixtures still yielded very low stability values, and the surface texture was open and porous.

The cost of materials were approximately $3.60 / sq yd for the control mixture, and $4.85 and $5.41 / sq yd for the mixtures containing 3% and 6% rubber, respectively. These costs included the purchase and delivery of the rubber, mixing, and placing. The cost for the rubber mixtures was 35% to 50% higher than the control mix. The increased cost in the rubber mixtures was partly because the use of rubber requires a higher percentage of asphalt cement, which is the most expensive ingredient in the mixture (20).
The rubber mixtures did not perform well. They did not meet MDOT bituminous specifications. They exhibited low densities, low tensile strengths, and high air voids (20).

McCullagh and Poppe investigated a project that was constructed in 1979 to study the performance of Arizona’s Three Layer System (TLS) on a badly cracked portion of portland cement concrete pavement (PCCP) (21). This section is located near Phoenix and is heavily travelled (100,000 ADT) with a large number of trucks travelling the road. The TLS is a 5/8 inch ACFC with 4.5% AR 4000 binder, an asphalt-rubber SAMI with precoated chips, and 5/8 inch ACFC with 6% AR 4000 binder (21).

After five years, significant reflective cracks are just coming through. It is limited, though, to the transverse joints and the longitudinal joint between the shoulder and the right lane. Most of the cracks are narrow. Only a few are double cracks and there are three that have spalled in small areas. For the first four years, the section performed exceptionally well, with less than 10% cracking (21).

This project has shown that the TLS can perform well for up to four years, even under the conditions of heavy traffic, heavy loads, and extremely high temperatures (up to 115 °F). The TLS was also cost-effective. In 1979, the TLS was estimated to be about 1/3 the cost of the grinding and grooving method, which is usually performed to restore cracked PCCP. It also does not disrupt traffic as much during construction (21). The TLS is recommended for the overlay of rigid pavements, such as the PCCP (21).

Schnormeier in a study indicated the advantages of an asphalt-rubber mixture include the following (22):

1. It prevents reflective cracking and spalling at pothole edges.
2. It improves with time by molding itself to the pavement subgrade conditions, and stops cracking in spite of the movement.

3. It provides a flexible surface.

4. It has no need for maintenance for at least eight years, and therefore delays reconstruction.

5. It retains the characteristics of the existing asphaltic concrete, which would normally be lost.

However, he indicated that the trouble with asphalt-rubber comes during its application. At least half of the aggregate should be embedded in asphalt-rubber. To do this, there should be as little time as possible between the spreader truck, the chip spreader, and rollers. Asphalt-rubber also has a poor appearance for the first year, but it improves with time (22).

From 1971 to 1982, asphalt-rubber's price increased an average of 6% annually, while the cost of conventional chip seal rose an average of 41% annually. The reduction in the initial cost difference has created a stronger argument for the use of asphalt-rubber (22).

Schnormeier also indicated that the life expectancy of asphalt-rubber is 10-12 years, whereas for conventional chip seal it is 6-8 years. In addition, asphalt-rubber requires almost no maintenance for 10 to 12 years, whereas conventional chip seal requires crack filling and pothole repairs by the third year (22).

He concluded that asphalt-rubber on low-cost, low-volume roads eliminates maintenance and doubles the life of the pavement. He also concluded that this type of mixture gives a reasonably good surface at a reduced overall cost (22).

The Alaska Department of Transportation and Public Facilities tested seven sections of roadway which were constructed between 1979 and 1981 and which included 3 to 4 percent coarse rubber particles (23). It was hypothesized that this rubber-modified asphalt would increase skid resistance and durability as
well as provide ice control (23). Ice control was a primary concern for this project. The use of sand for ice control is only temporary and clogs gutters and inlets in urban areas. Salt causes premature corrosion of the vehicle and can also contaminate ground and surface water.

Samples were loaded to failure at selected tensile strain levels and results showed the fatigue life to be more than 10 times greater than that of normal mixes. In addition, observations by the public indicated a reduction in skidding incidents, and improved traction. Tests to measure stopping distances showed an average 25% reduction in stopping distances. However, there was a 50% increase in cost over conventional pavements (23).

The report indicated that the benefit of rubber added to the mixture is most notable in higher-speed and higher-traffic areas, where traffic blows away the snow and ice particles from the road. Such applications are bridge decks and insulated roadway sections (23).

Wisconsin tested asphalt-rubber as a binder in recycled roads in order to reduce reflective cracking (24). It was the first time that asphalt-rubber was used in a recycling project. Two test sections were placed by the WDOT (24).

Wisconsin's problem is roads that were originally constructed using portland cement concrete. When the roads were widened, bituminous mix was placed directly on the soil or gravel shoulders. The roads developed reflective cracks and, consequently, a poor riding surface (24).

In resurfacing the roads, 2.5 to 3 inches of asphalt concrete were milled and a 3 inch overlay of asphalt-rubber recycled bituminous surface was placed. An asphalt-rubber SAMI was also placed on a different section of the road, and the remainder of the road was resurfaced with a 3 inch layer of conventional recycled bituminous surface (24).
There were some problems encountered including the mix was very soft after the rolling and opening to traffic. A harder grade of asphalt cement could help this problem. Another problem was attaining the required density of 93% for the binder and 95% for the surface course. The addition of a pneumatic-tired roller behind the cold roller helped this slightly—by 1 to 3% (24). There is no additional data at this time, and the pavement will be monitored for reflective cracking (24).

Piggot, et al., in their work investigated the following: 1) the rubber-asphalt interaction; 2) hot mix design; 3) strength, toughness, and ductility; and 4) application problems (25).

They indicated that there was no significant interaction between asphalt and rubber when they were kept at 200 °C for periods of about an hour. Marshall tests showed small differences between specimens containing rubber added as aggregate and specimens where the rubber was added to the asphalt initially. Since these differences were not great, it was recommended to avoid trouble and to just add the rubber to the aggregate first (25).

Regarding the hot mix design, they indicated that the viscosity tests showed that there is little chance of gel formation when the rubber is mixed with the hot asphalt. Actually, it settles out very easily and can block pipes if not constantly mixed (25).

Flexural tests proved the rubber-asphalt to be about 30% more ductile than normal concrete. This increase is more evident at higher temperatures, but even at -20 °C, there is a 10% increase in ductility and toughness. This suggests an increased performance at lower temperatures, compared to normal asphalt concrete (25).
It was found that it was necessary to wait 10 minutes before rolling. There was very little pick-up on the roller, but raking was slightly difficult. Some hair checking was observed, but overall, the appearance of the surface was good. The low Marshall stability could be a problem, but so far there has been no signs of wear (25).

Huff and Vallerga indicated that the scrap rubber from tires could improve asphalt in ways besides the addition of rubber-like properties (26). The components that contribute are:

1. Carbon black- which adds reinforcing properties to the asphalt (27, 28)
2. Antioxidants- which add durability to the asphalt rubber
3. Amines- which aid in resistance to stripping
4. Aromatic oils- which prolong the life of the asphalt-rubber

Through laboratory and field tests, and observations, a mixture (formulation of asphalt, extender oil, and scrap rubber) was developed which can be used as a surface treatment (chip seal), or a SAMI, or a waterproofing membrane, or a crack and joint sealant. In this mixture, the flexibility and solubility of the devulcanized rubber; the elasticity, toughness, adhesion of the natural rubber; and the resilience of the insoluble synthetic rubber are incorporated together (26).

There is no method for determining the chemical state of the blend at present; however, the physical properties can be measured on the basis of consistency, durability, and adhesion (26). The authors indicate the following:

**Consistency**- Consistency versus temperature data shows a decreased susceptibility to temperature.

**Durability**- Durability is improved by the addition of the extender oil.

**Adhesion**- Asphalt-rubber maintains its ductility at lower temperatures and has the ability to recover elastically whereas regular asphalt has practically no ductility at lower temperatures and no elastic recovery.
After mixing, the asphalt-rubber is ready for application by either hot spraying or hot pouring within a temperature range of 375-425 °F. During a delay, the heat can be turned off until ready to start again (26). The asphalt-rubber described here is easily prepared using conventional equipment and is smooth in texture and uniform in consistency (26).

When hot-sprayed, it forms a tough, durable, and adhesive membrane that is useful in the construction of surface treatments, SAMI’s, and waterproofing membranes for bridge decks and hydraulic linings. When hot-poured, the material is an effective crack and joint sealant (26).

Morris and McDonald investigated the performance of stress-absorbing membranes placed since 1967 (29). In addition, they investigated the membrane’s potential for preventing reflective cracking, providing bridge deck protection, controlling differential movement of existing pavement, providing economical construction of low-volume roads, and providing improved elastomeric sealing of cracks and joints (29).

They indicated that conventional pavement has a problem; either the elastic properties or the tensile strength of the pavement is "insufficient in responding without fracture to the forces acting on the pavement (29)." These forces include flexural stress, direct tensile stress, and differential vertical movement between adjacent sections (29).

Three projects by the Arizona Department of Transportation have had a great impact on the development of asphalt-rubber systems. The Aguila project was done as a temporary treatment for a road that needed reconstruction; an asphalt-rubber seal coat was placed. At the time this article was written, seal coat was still doing well. The cracking in the existing pavement was so bad that the pattern could be seen through the coat, but no cracks had propagated through (29).
The Flagstaff project was the first asphalt-rubber treatment in the Northern, cold region of the state. The existing pavement was badly cracked (alligator cracking) and was nearly impassable in the spring of 1973 because of thawing after the winter. Since the asphalt-rubber treatment, the road has done extremely well. At the time this paper was written there was still no reflective cracking, and the road had required no maintenance (29).

The Minnetonka project showed the SAMI to be very effective in reducing reflective cracks of all types and the asphalt-rubber seal coat to be effective in reducing fatigue cracks (29). Other test projects by the ADOT showed that asphalt-rubber also provides an impervious membrane. It has been tested and used as a waterproof membrane on several bridges. Also, on tests performed by the ADOT, asphalt-rubber was found to substantially resist moisture through the surface, even after only one application (29).

Jimenez in his report discussed an asphalt rubber that contained 25% rubber by weight, and the goal of this study was to develop methods for making and testing this type of asphalt-rubber (30). Both vulcanized and devulcanized rubber were used, as well as an aggregate with low surface area (9.5 mm max.) to overcome coating problems. This study was mostly concerned with the testing of a strain-attenuating layer (SAL) (30).

The compaction of the specimen was a slight problem, because the rubber particles allowed the layer to recover on the release of stress. That is a necessary function of a SAL, but it works against compaction. To get around the problem, a vibratory kneading compactor (along with static compaction) was used to compact the specimen (30). Tests were performed to determine the density and air-void content, the tensile strength and elasticity, and the resistance to debonding. The results showed that (30),
1. Good coating of the dense-graded and open-graded aggregate occurred when the aggregate was at a temperature of 300 °F.

2. The 9.5 mm dense-graded specimens had a much higher air void content with vulcanized rubber than they did with devulcanized rubber.

3. The asphalt-rubber values for dynamic modulus of elasticity were approximately 70% of those for conventional asphalt. This was true for both types of aggregate and both types of rubber. The lowest modulus was at 4 °C and was 896 MPa (130,000 psi).

4. It was necessary for the aggregate to be very clean in order to resist debonding, due to the high void content of the 9.5mm dense-graded specimen made with vulcanized rubber.

In this study, as a SAL interlayer, the specimens were not expected to have strength values equivalent to those of normal asphalt concrete (30).

Oliver in his article indicated the results of evaluation of different types of rubber, natural and synthetic, and how the different methods used to generate the crumb rubber affect the outcome of the rubber-modified asphalt (31). Elastic recovery and creep of the samples were measured with a Shell sliding-plate rheometer. Each particular asphalt-rubber combination was digested in the reaction vessel at a controlled temperature for times of 0.5, 1, and 2 hours before being removed (31). The tests were performed on each of the samples, and the results reflect the mean of the outcome for the three time periods.

Results and Conclusions (31)

1. Rubber particle morphology is a critical factor that affects the elastic properties of rubber-asphalt. Examination with a scanning electron microscope showed two main types of morphology where in one the surface is covered with nodules, and the other one the surface is smooth. The smoother the surface of the particle, the worse its elastic recovery.

2. For car-tire buffings, elastic recovery tends to increase as the size of the rubber particle decreases.
3. Natural rubber tends to act superior to synthetic rubber when digested in asphalt, but conditions such as time and temperature are less critical for the digestion of synthetic rubber.

4. Elastic recovery is linearly related to the rubber concentration.

5. There was no significant change in elastic recovery of certain specimens after being stored at 55 °C. This temperature imitates the curing process over an extended period of time.
A brief summary of several reports or articles are presented in this section. These reports or articles were furnished by several highway agencies to the principal investigator.

WISCONSIN'S EXPERIENCE (32)

Introduction

There has been an increasing interest in trying to minimize reflective cracking and in utilizing waste materials in recent years. To try to solve both of these problems, Wisconsin built two experimental pavements in 1987.

The main problem being addressed with these experimental sections is reflective cracking. Conventional overlays have proved incapable of deterring reflective cracking in the past, and although they provide adequate strength, the roadway offers motorists a generally rough ride.

Experimental Design

All pavement reconstruction was performed under conventional construction techniques and done while maintaining traffic flow. The existing sections and the reconstructed sections are shown in Table 3.1.

Wisconsin DOT standard procedures governed the mix designs for the control section, while the mix design for the asphalt-rubber was done by Crafo, Inc. The sub-contractor for the asphalt-rubber work was International Surfacing, Inc.

This study was not undertaken to provide large volumes of technical data; rather, it was designed and carried out to be a large scale effort to use scrap rubber tires in an asphalt paving mixture.
Table 3.1. Existing Pavements and Rehabilitation Treatments  
(WISCONSIN'S EXPERIENCE)

<table>
<thead>
<tr>
<th>Route</th>
<th>Location</th>
<th>Year</th>
<th>Surface</th>
<th>ADT</th>
<th>T</th>
<th>Estimated 20 year Design Loadings</th>
<th>Existing Pavement</th>
<th>Rehab. Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>USH 12, Eau Claire County</td>
<td>(8 miles)</td>
<td>1973</td>
<td>Surface</td>
<td>1680</td>
<td>12%</td>
<td>400,000 ESAL's</td>
<td>Variable Thickness (5&quot;-15&quot;) Bituminous Overlay Over PCC Pavement</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.6 mi. - Mill 2 1/2&quot;, 3&quot; Recycled Surface (35% Salvaged)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.3 mi. - Mill 2 1/2&quot;, 3&quot; Recycled Surface (35% Salvaged) with A-R Interlayer - % Salvaged</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.6 mi. - Mill 2 1/2&quot;, 3&quot; Recycled Asphalt-Rubber Surface (35% Salvaged Pavement) - % Salvaged</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.4 mi. - Remove and Replace Pavement at Bridge Replace.</td>
<td></td>
</tr>
<tr>
<td>STH 35, Vernon County</td>
<td>(10 miles)</td>
<td>1966</td>
<td>Surface</td>
<td>6100</td>
<td>10.8%</td>
<td>1,500,000 ESAL's</td>
<td>6&quot; Bituminous pavement, 8&quot; granular base 12&quot;-18&quot; Granular Subbase</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.8 mi. - Mill 3&quot;, 3&quot; Recycled Surface (50% Salvaged)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.0 mi. - Mill 2&quot;, 3&quot; Recycled Surface with A-R Interlayer (50% Salvaged Pavement)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.0 mi. - Mill 3&quot;, 3&quot; Recycled Asphalt-Rubber Surface (35% Salvaged Pavement)</td>
<td></td>
</tr>
<tr>
<td>USH 18, Iowa County</td>
<td>(14 miles)</td>
<td>1971</td>
<td>Surface</td>
<td>4000</td>
<td>15.8%</td>
<td>1,300,000 ESAL's</td>
<td>6&quot; Bituminous Pavement, 12&quot; Granular Base, 9&quot; Subbase</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mill 2&quot;, Reprocess remainder in Place, 4&quot; Recycled Surface (40% Salvaged Pavement)</td>
<td></td>
</tr>
</tbody>
</table>
Mix Techniques

The scrap rubber and asphalt cement were blended by the subcontractor in a special blending unit. The interlayer was placed between two layers of recycled pavement. The blend was agitated for a minimum of 30 minutes and contained 18% scrap rubber by weight. The asphalt-rubber was placed at a rate of 0.5 gallon per square yard. Precoated cover chips were then placed at 35 lb. per square yard.

The recycled mixes were prepared in drum mix plants. A 200-300 penetration A.C. was used on all projects. The mixing temperature for the control mixes was under 300 °F, while the asphalt-rubber mixes required temperatures generally higher than 300 °F. The control section and the two experimental sections all used conventional rollers for compaction. The mix design data is shown in Table 3.2.

Results

The results of this study were disappointing to the engineers at Wisconsin DOT. Tables 3.2, 3.3 and Figures 3.2, 3.3 and 3.4 show some of the results obtained from this research project. The following observations were made by those engineers:

1. Asphalt-Rubber paving mixtures can be prepared and placed on the roadway. In addition, these projects demonstrated that scrap rubber tires can be used in a blend with asphalt cement; this blend may then be incorporated into a recycled asphalt paving mixture. No major problems were encountered during the paving operation. In addition, a good mix can be placed with the same degree of quality as a normal asphalt paving mixture.

2. Visible emission problems were noted at both plants while producing the asphalt-rubber mix. This could be a problem if asphalt-rubber is used on a large
Table 3.2. Recycled Mix Design Properties

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Control Mix</th>
<th>AsphAlt-Rubber Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>USH 12 STH 35</td>
<td>USH 18</td>
</tr>
<tr>
<td>Recycled Asphalt Pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% RAP in Mix</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>AC Content of RAP (%)</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Pen. of AC in RAP</td>
<td>23</td>
<td>21</td>
</tr>
<tr>
<td>Designed AC Content</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recommended Added AC (%)</td>
<td>4.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Total AC Content (%)</td>
<td>6.2</td>
<td>6.2</td>
</tr>
<tr>
<td>Designed Mix Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density (lb./c.f.)</td>
<td>147.6</td>
<td>152.5</td>
</tr>
<tr>
<td>Air Voids(%) Dry Back Method</td>
<td>2.7</td>
<td>2.1</td>
</tr>
<tr>
<td>Stability (lb.)</td>
<td>1,580</td>
<td>2,670</td>
</tr>
</tbody>
</table>

Table 3.3. Recycled Mix Design Properties (Cores Tested)*

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Control Mix</th>
<th>AsphAlt-Rubber Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>USH 12 STH 35</td>
<td>USH 18</td>
</tr>
<tr>
<td></td>
<td>USH 12 STH 35</td>
<td>USH 18</td>
</tr>
<tr>
<td>Density (lb./c.f.)</td>
<td>148.0</td>
<td>152.1</td>
</tr>
<tr>
<td>Air Voids(%) Dry Back Method</td>
<td>2.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Resilient Modulus (ksi) 40 °F</td>
<td>1000</td>
<td>1900</td>
</tr>
<tr>
<td>72 °F</td>
<td>215</td>
<td>350</td>
</tr>
<tr>
<td>104 °F</td>
<td>30</td>
<td>55</td>
</tr>
<tr>
<td>Tensile Strength (psi)</td>
<td>84</td>
<td>169</td>
</tr>
</tbody>
</table>

* Tests on the core samples were performed by the National Center for Asphalt Technology.
Figure 3.1. Pavement Cracking After 2 Winters
Figure 3.2. Pavement Cracking After 3 Winters
Figure 3.3. Pavement Cost Comparisons
scale. Some new method would have to be found to reduce the "blue smoke" or some allowance would have to be obtained from the regulatory agencies.

3. Mix design technology needs to be improved to assure that the design pavement mixture for each project will be adequate. For instance, in this research project, it appears that Highway 12 project did not have enough asphalt-rubber binder in the mix. However, the Highway 35 project mix design for the asphalt-rubber mix had a 1% greater binder content than the control mix. The appearance of this pavement reinforces that this mix is more satisfactory than the Highway 12 mix.

4. On these projects, the engineers did not obtain asphalt-rubber paving mixes showing improved properties compared to the normal recycled asphaltic concrete mixtures. The results from pavement core samples are tabulated in Table 3.3. The reduced amount of asphalt-rubber binder compared to a mixture not containing recycled asphalt pavement (RAP) may be part of the problem. It may mean that a higher percentage of scrap tires would need to be blended with the added A.C. for recycled mixes. In addition, it indicates that these mix designs for the asphalt-rubber mixes did not contain enough binder to provide greater elastic and cohesive properties.

5. Early performance indicators from these projects are not encouraging for increased service life. Compared to a standard recycled asphalt concrete overlay constructed on a partially milled pavement, the recycled asphalt-rubber overlay developed up to five times as much transverse cracking during the first two years (Figure 3.1).

6. At the present time and with the available level of technology, incorporating an asphalt-rubber blend as binder in a recycled asphalt concrete pavement would probably double the cost of the pavement rehabilitation. This
requires a substantial increase in service life in order to be of equal life-cycle cost. The data is not yet available for these economic comparisons for these projects.

7. An asphalt-rubber interlayer can be added to a partial mill and recycle rehabilitation for about $2 per square yard -- about a 50% increase in cost. This cost increase would have to be offset by an increase in service life, but not as much as for an asphalt-rubber recycled pavement.

8. The early performance results indicate that the performance of the pavement with an asphalt-rubber interlayer may be about equal to the standard recycled asphalt concrete overlay constructed on a partially milled pavement.

9. Early performance indicators for the third Wisconsin project indicate that the best method to minimize the development of reflective cracks is to reprocess the old pavement in place, thus eliminating the cracked pavement under the recycled pavement. The cold reprocessing can be accomplished for about 25% of the cost of adding the scrap rubber to the recycled pavement. The total cost for this alternative rehabilitation process can be very close to the total cost to mill and recycle the top portion of the old pavement.
CONNECTICUT'S EXPERIENCE

Introduction

This project was conducted by the Office of Research of the Connecticut Department of Transportation, The Civil Engineering Department of the University of Connecticut, the Solid Waste Section of the Department of Environmental Protection, and the Reclaiming Division of Uniroyal, Inc (33-40).

Four distinct tasks were chosen to be explored: 1) overlays; 2) stress-relieving interlayers; 3) seal coats; and 4) joint seals.

Construction

Before construction could take place, sites had to be selected. Selections were based on condition, volume of traffic, and construction problems. The selection of locations were to have three levels of traffic and three levels of pavement conditions.

Many of the proposed sites were very deteriorated in certain areas but not throughout. Test sections were chosen based on areas where conditions were similar from lane to lane and for several hundred feet.

Typical mixes for the test sections were as follows: contractor's ConnDOT-approved mix, the same mix with 1% rubber and 1/4% binder added, and with 2% rubber and 1/2% binder added.

Mixing

According to field personnel, reactions to the mix during paving were generally positive. Only one of the seven plants used generated complaints concerning the hot rubber odors. The mix was said to be more workable than the conventional mix. It should be noted, however, that the mixes were generally small in size and produced in short-runs. Long term effects of odor, workability, and other factors could not be determined.
All Rubber-Modified Sections vs Controls

Evaluation was done statistically on a three year set of data. The evaluation found that there is a 90% chance that 1% rubber sections have fewer longitudinal cracks and a 35% probability that fewer transverse cracks are experienced.

Cost

The laydown cost for 1% rubber mixes was approximately $33.50/ton. This cost includes increased shipping and handling and reduced plant capacity due to longer batch times. The laydown cost for 2% rubber mixes, including the same increases, was approximately $41.75/ton. These costs, as compared to Class 1 material, would amount to a 30% increase for 1% rubber mixes, and a 60% increase for 2% rubber mixes.

Conclusions

For overlays:

1. For thick overlays cracks developed slowest in the test sections containing one percent reclaimed rubber.

2. The improvement in performance was observed to be the greatest in the medium condition pavement under medium to heavy traffic.

3. In order for rubber to be effective in the thin overlays, the layer thickness must exceed 0.5".

4. The optimum rubber content in the thin overlays of adequate thickness was significantly higher than for thick overlays. Although the optimum level was not established, it appears it is at least 3 percent.

For stress relieving interlayers:

1. Reflective cracking was less where an interlayer was present.

2. There were no major improvement in performance by including a stress relieving layer. That is, the performance of a rubber modified overlay combined with a stress relieving layer was about the same as either alone.
For Seal coats:

1. The rubber-asphalt binder provides a flexible binder which resists the formation of cracks better than the emulsion-sand seal.

2. The placement of a light emulsion-sand seal over the stone chip increased the retention of the stone chips. The sand filled the void space between the stones locking the stones in place.

3. The cost of the stone chip seal is double that of a sand-emulsion seal; however, the life is several times greater.

For Joint sealing:

1. The rubber-asphalt mixed in the field adhered to the concrete joint faces better than the control material.

2. The field mixed material remained adhesive longer.

3. Narrow cracks need to be routed wider for either the field mixed material or the control material to penetrate adequately.
MISSOURI'S EXPERIENCE

Introduction

The Missouri Highway and Transportation Department (MHTD) placed a test section of asphaltic concrete overlay modified with reclaimed ground rubber on 08/27/90. The MHTD test section is one mile long, located in the westbound driving lane of I-70 in Boone County, Missouri. It has been used to determine the performance of reclaimed rubber modified asphaltic concrete mixture. A control section was also placed in this location, one mile in length and immediately following the test section (41).

Experimental Design

Baker Rubber, Inc., of South Bend Indiana, supplied the ground rubber and reported that the ground rubber used in the test section was largely composed of tire buffings from retreading operations. The asphalt-rubber mix was designed by International Surface, Inc., of Chandler Arizona. The asphalt-rubber concrete (ARC) overlay mix contained 6.75\% binder by total weight of mix. The control mix contained 4.1\% binder by total weight of mix.

Observations

Performance indicators and measurements showed that both the control and the test section experienced slight rutting, probably occurring during the first week of traffic. The test section also showed some flushing in the wheelpaths, which gave the surface a slick appearance. Friction numbers for the test section were significantly lower than were those obtained from the control section, and some reflective cracking was observed in the test section.

Costs

The construction costs of the asphalt-rubber test section were approximately 3.5 times as much as conventional asphaltic concrete mixtures. The
test section cost was $80.45/ton whereas the control section was $22.73/ton. Much of the increase in cost was attributed to mobilization. Five special vehicles and trailers were brought in from International Surface, Inc., from Arizona. These special machines were necessary and on site during the blending and mixing process. However, aside from the special blending units, no additional or specialized equipment was required by the contractor.

**Recommendations**

1. The addition of the ground rubber to the blending unit should be monitored more closely. More quality control is necessary for the asphalt-rubber mixes to perform well.

2. Interlock the asphalt-rubber pump with the asphalt plant’s computer system rather than relying on a manual switching device. This would ensure better results in mix consistency.

3. The compacted mat should be allowed to sufficiently cool before being opened to traffic. Opening the mat too soon can result in premature rutting.

4. Density testing for acceptance should be completed before the roadway is opened to traffic.

5. Standard testing procedures for evaluating the ground rubber product should be established.

**Conclusions**

The MHTD found that the overall performance of the asphalt-rubber concrete was satisfactory with the exception of the low friction values. The MHTD intends to evaluate the test section on an annual basis and determine the performance of the pavement including rutting, reflective cracking, ridability, and friction values.
NEW YORK'S EXPERIENCE

Background

A 1986 report was drafted in retrospect to the New York State’s Department of Transportation (NYSDOT) response to a Governor’s appeal for research into the impact of requiring the use of ground tire rubber in the state’s paving operations. This report provided an in depth look at potential effects of such requirements as well as pointing out the importance of preliminary reviews of technical, economic, and environmental impacts of mandatory requirements.

Both Department and industry personnel expressed concern for the increased costs of using the new material for not only the material itself but also for changes in complication of construction. Concerns were also focused on the dangers of requiring a material whose economic and environmental impacts were still questionable.

However, the 1987 New York State Laws’ chapter 599 was amended to address the use of scrap tire rubber in paving materials used in state public works. Requirements for investigation into technical and monetary impacts of initializing the use of the new material as well as reports of the effect such action would have on supplies of waste tires were given to the Commissioner of Transportation.

Information Synthesis

Two pilot test sections were constructed in order to help in the evaluation of the use of the new material. These test sections along with similar rubber-modified asphalt projects in other states were used in order to produce a basis on which to build cost evaluations. In review of these projects, it was established that lack of experience with the material and its behavior contributed to much of the inflation of cost. For this reason, realistic survey
of increased costs based on the addition of ground tire rubber to asphalt concrete mixtures is not possible until construction of the material becomes a more familiar practice. The pilot projects reflected bid prices for the asphalt-rubber mixes to be 50 to 100 percent higher than conventional asphalt mixes; however, in-place costs for the rubber mixes were established as 25 to 50 percent higher than conventional hot mixes.

Application Methods

Placing asphalt-rubber mixtures is analogous to placing conventional mixtures as long as the proper equipment and good weather is available. If favorable weather is not available, the rubber-modified asphalt is more negatively affected in areas of preparation and compaction. The NYSDOT reported a few difficulties that were encountered during their pilot projects: 1) difficulty acquiring correct rubber granulation, 2) higher material costs, 3) higher labor costs, 4) higher heating costs, and 5) need for contractor personnel training for the administration of mix design and quality control of the new material.

Performance Comparisons

According to laboratory experiments and the pilot projects, asphalt-rubber concrete mixtures should perform better and have twice the life span of conventional mixtures when used as overlays on portland cement concrete pavements with thicknesses of 1.5 inches. The rubber-modified mixes, however, did not provide any performance advantages over conventional mixes in experimental projects performed in California, Connecticut, Alaska, and Washington.

Optimum Percentages and Availability of Scrap Rubber

One to three percent rubber by weight of asphalt cement was added to produce rubber-modified asphalt mixes for the projects that were used in cost and
performance evaluations. These percentages were used because they caused little need for change in the process and equipment of conventional paving.

Costs of rubber-modified mixes based on life-cycles were predicted to be lower than conventional mixes according to laboratory tests. Field tests established that the life-cycle of rubber modified mixes should be 2 - 3 times that of conventional asphalt to prove cost effective; however, these tests indicated that the rubber modified mixes showed no performance benefits.

The New York State's market for resurfacing or overlays would call for 130 to 260 percent of scrap tires currently available. The New York Department of Environmental Conservation predicts, with conservative estimations of 2 percent rubber by weight of asphalt cement for rubber-modified mixes and taking into consideration that rubber-modified mixes would not be used in 100 percent of the projects, a demand for the entire available supply of scrap tire rubber.

At the present, this supply of scrap tires is approximately 15 million with the addition of 12 million tires annually as established by the New York State Solid Management Plan (42). Because one automobile tire will provide 11 -14 pounds of reusable rubber (43, 44), this translates New York State's scrap tire supply to 66,000 tons of recyclable rubber a year. With these figures and consideration for the current accumulated supply, 1990's availability of reusable scrap tire rubber could exceed 100,000 tons.

Independent studies of the paving market for ground tire rubber were performed by the Asphalt Institute (45) and the National Asphalt Pavement Association (46). Results indicated that the annual use of asphalt concrete is approximately 12.8 million tons for New York State, about 61 million tons for Northeastern States, and approximately 369 million tons for the United States. The study performed by the Asphalt Pavement Association (46) also highlighted a
variety of markets for the scrap tire rubber including interstate highways, state highways, municipal and county roads, airports, private and commercial, and others.

In using the average of 2 percent rubber by weight of asphalt cement, the available supply of scrap tires in New York would be depleted in 3.2 years. If 3 percent rubber were used, the available supply and incoming tires would be eliminated in 14 months.

**Impediment to Using Rubber-Modified Asphalt Concrete**

Increases in cost and changes in construction processes have both been two main issues in the negative attitude toward rubber-modified asphalt. In addition to these impediments, several other issues serve as negative factors.

Not only does the material itself require extra costs, but processing alterations and labor for these changes also cause inflated expenses. Much of the labor used for such operations is in need of training. Trained and experienced contractors, for example, are in short supply causing inflated bid prices for rubber-modified contracts. This increased bid pricing is also a result of the addition of contingency costs to offset construction risks.

Engineers and public agencies show hesitations in the material's use because of its undefined track record and lack of establishment. Much of this questionable background is as a result of mixed reports of performances, many of which have been lower than anticipated.

Available rubber supplies are often not made up of the required grade for rubber granulation. In addition, although current supplies of scrap tires exceed demand, success of rubber-modified asphalt could change this situation of surplus to a shortage. Competing industries that use scrap tires add to this threat.
Using rubber-modified pavement may need to be encouraged through the use of incentive programs. Only experience and a continued growth in familiarity can bring an end to these impediments.

Actions that could be taken for promotion of scrap tire rubber include recycling taxes on tire purchases or disposal taxes to consumers, funding or incentives or rebates to municipalities, alternate bids, mandatory use requirements, and tax incentives to promote its use.

Potential Use of Rubber Modified Asphalt Mixes by Public Agencies

The use of scrap tire rubber in asphalt paving mixes is favored in the utilization of scrap tires over simply stockpiling the waste, due to health and safety aspects. In order to prove economical, however, substantial advantages and methods of improvements due to the inflated costs of rubber-modified mixes need to be confirmed. Municipal Agencies in New York show some interest in initiating a rubber recycling program due to this problem. Because of the inflated cost of the addition of scrap tire rubber to asphalt mixes, disposing of tires through paving is not expected to be a well accepted approach to the problem.

Facilities must be available for the collection and recycling of waste tires. Not only must the market for ground tire rubber become better established, but funding for this establishment and initiating the recycling must be provided.

Additional Expense to State and Local Agencies

Much of the additional costs for the utilization of rubber in asphalt mixes depends upon a variety of factors: 1) availability of tires, 2) grinding facilities, and 3) contractor's familiarity with the process. If a market was
well established for the rubber-modified asphalt, the actual material would cause a 25 - 50 percent increase in cost over conventional mixes. Experimental projects, however, have reflected 50 to 100 percent increases in cost. Much of this estimation difference is due to other factors of cost such as those listed previously. Extra costs for New York State based on the 2 percent rubber by weight of asphalt cement and estimates of demand could translate to total increases in using rubber-modified asphalt concrete of $22 - $87 million per year.
In September 1989 Texas Senate Bill 1516 emerged in order to address the State Department of Highway and Public Transportation (SDHPT) on issues involving rubberized asphalt paving. The Department was mandated to use scrap tires modified to rubberized asphalt by a facility in the state, if this type of paving was to be used. The Department was also allowed to give preference to bids that included the use of rubberized asphalt produced in accordance to this mandate.

The Department organized a study in order to address current use of asphalt rubber in Texas, availability of asphalt rubber in Texas, and comparative cost effectiveness of asphalt rubber versus conventional materials when considering current information and Department personnel. This study consisted of phone interviews of knowledgeable Department personnel, evaluation of laboratory data through mathematical modeling, and review of important literature. The study dealt with SAMS, SAMI, crack fillers, and dense and open-graded hot-mixed asphalt.

Availability and Use

Today the existing total of scrap tires in the United States of 2 billion increases at a rate of 240 million annually (47). Of these figures, Texas' discard rate is 18 million annually, adding to an existing 150 million. This supply of waste tires is also a potential annual producer of 108,000 tons of rubber. Currently Texas only replaces less than two percent of its asphalt paving cement with asphalt rubber; and of the 13,000 tons of asphalt rubber used per year by Texas SDHPT, most of the material is provided by other states.

The potential for use of tires in asphalt rubber is great enough that if taken to its limits could cause a dramatic impact on the number of waste tires.
The number of scrap tires produced annually in Texas could be reduced by one-fifth if the State SDHPT made it practice to replace 10 percent of the paving asphalt cement with asphalt rubber.

Present tire-rubber and asphalt-rubber suppliers indicate that the primary requirements that would be needed to maintain a profitable facility for ground tire rubber for use in asphalt would be a supply of 1 to 3 million tires annually, a substantial amount of real estate, and about 1 million dollars in capital. Studies indicate that seven to ten million tires may be recycled in plants in Texas next year.

Asphalt Rubber Chip Seals (SAMS)

Many of the problems that arose with the use of asphalt rubber during the beginning phases of research were caused by construction practices rather than by the actual new material. Asphalt-rubber chip seals displayed more distress than traditional asphalt chip seals in early research because of this lack of experience. Flushing, a condition attributed to insufficient amounts of binder and aggregate, is the main type of distress in asphalt-rubber. This condition, however, is not as grave in asphalt containing rubber chips as in asphalt produced by conventional methods.

Currently only five of the twenty four Texan districts use asphalt rubber chip seals in frequent practice. Over 50 percent of the districts do not plan to use asphalt-rubber chip seals. Much of this lack of interest in implementation is due to monetary concerns attributed to the fact that rubber enhanced chip seals cost two to three times more than conventional chip seals.

Personnel in two of the districts that favor asphalt-rubber chip seals describe the material as cost effective if used and constructed properly; they report that the material is capable of lasting twice as long as traditional chip
seals (50, 51). Although the results of experimental use of the new material as seen here highlight cost-effectiveness and quality improvements, these positive results have been limited to a localized scale.

Results compiled nationally fall short of underscoring vital advancements in asphalt-rubber chip seal performance over that exhibited by conventional chip seals; moreover, the life of the rubberized chips would have to exceed conventional chip seal life by 200 percent to equalize their annual costs (47, 50). Such results cannot be weighed on a strict black and white scale because of the many ingredients that are mixed to produce the final output. Construction and design were also experimental in carrying out the production of the new SAMs.

Asphalt-rubber chips seals produced in Texas are not typically used in situations where conventional asphalt would be a valid consideration. It is used as a rehabilitative material in preference to preventative purposes, and it is used on surfaces serving high volumes of traffic. Cost-effective comparisons between the two types of chip seals might therefore be more credible with a thin overlay or multiple chip seals.

**Asphalt-Rubber Interlayers (SAMIs)**

Because of the subordinate role that asphalt rubber interlayers or SAMIs play in pavement construction, it is difficult to separate its performance from the effectiveness of the entire structure for evaluation purposes; therefore, much of the testing completed thus far has provided unclear results. Some of the testing shows only slight improvements in pavement performance, while other results show more substantial improvements in performance by way of decreasing the rate of reflective cracks and protecting sub-layers in the pavement structure from water damage because of the materials waterproofing ability.

The Texas SDHPT overall favors asphalt rubber interlayers to chip seals.
Six of the 24 highway districts use the interlayers on a fairly regular basis, and the groups that have used the SAMIs believe that the material is working in delaying reflective cracks. Although establishing exact cost-effectiveness of SAMIs is not possible with current information, comparisons of a 2-inch overly with a 2-inch overlay and SAMI based on an annualized cost analysis confirmed that the overlay and SAMI would need to last approximately 50 percent longer than the independent overlay to prove to be cost-effective.

**Asphalt-Rubber Crack Sealants**

Asphalt-rubber crack sealant is made up of 80 percent asphalt and 20 percent ground tire rubber. Crafo Inc. located in Chandler, Arizona currently supplies 95 percent of all asphalt-rubber crack sealant that is used in Texas. This large percentage is partially due to the fact that it is the product of choice of the Texas district personnel, and it is also attributed to a lack of competitive bidding from other suppliers. Crafo provided approximately 3.5 million pounds of the crack sealant material to Texas in 1989 at a price of 0.19 cents/lb. This price was inflated, due to Crafo's market domination, compared to the costs over the past few years of 0.12 cents to 0.15 cents per pound.

Unlike the SAMs and SAMIs, asphalt-rubber crack sealant is used regularly by all 24 of the highway districts. It is preferred over all other products for sealing cracks in asphalt concrete and portland cement concrete pavements. Because of its extensive use throughout the state, cost-effective comparisons to other materials used only rarely is not possible.

**Rubber-Modified Asphalt Concrete Mixtures (52-61)**

The Asphalt-Rubber Producers Group (ARPG) survey revealed that 12 different states had used asphalt rubber as a binder in asphalt concrete mixtures, to collectively produce a total of over 35 projects between 1975 and 1987 (52).
Eight of these twelve states' experiences are presented in the following text, followed by an overall evaluation of performance and cost.

**ALASKA**

The Alaska Department of Transportation and Public Facilities has more than ten years of experience in working with rubber-modified asphalt pavements. Part of this experience includes the building of test sections of the rubber enhanced pavement verses similarly constructed test sections. Twelve of these test sections were created between 1979 and 1987 totaling 34.1 miles (52). Based on weight of the total mixture, three percent of coarse particles were added into the hot-mix asphalt pavement sections. Both batch and drum mix plants were found to be effective for producing the mixtures.

Based on the evaluations taken in 1987, eight of the twelve sections highlighted positive results. The other four sections encountered various problems including distress, rutting, and slight to moderate flushing. These results provide little evidence on which one can build conclusions, due to the fact that the service time for the roads at the time of the survey were minimum.

**ARIZONA**

The Arizona Department of Transportation's experience with asphalt rubber dates back to the mid-1960's. Until 1987, over 90 percent of its implementation of asphalt rubber had been with stress-absorbing membranes and stress-absorbing membrane interlayers for the purpose of modifying reflection cracking (53). Since that time, open-graded and dense-graded paving mixtures have become the focus. The primary use for these mixtures is for overlays.
CALIFORNIA

The California Department of Transportation uses its rubber-modified asphalt mixtures for overlays. From experimental evaluations, the Department has noted improvements in abrasion resistance and in lower permeability over conventional asphalt (54). These results have also meant less maintenance work, and longer predicted pavement life due to decreases in water infiltration and oxidative aging.

Experiments with thickness of asphalt-rubber overlays has also been a focus for the Department. Conclusions from experiments indicate that asphalt-rubber mixtures require less thickness than conventional asphalt mixtures; however, reduction percentages have not yet been established.

CONNECTICUT

The Connecticut Department of Transportation (ConnDOT) conducted an experiment with asphalt-rubber overlays on State Route 79 in Madison, Connecticut in 1980, in which and a 900-foot test section of the rubberized overlay was compared to a standard ConnDOT Class 2 mix overlay (55). Based on an evaluation taken after 8 years of performance, the asphalt-rubber pavement showed less transverse, longitudinal, and alligator cracking. Both sections showed similar performances for skid resistance and roughness.

FLORIDA

Florida legislature passed a bill directed to the Florida DOT prompting investigation into the use of ground tire rubber in asphalt concrete mixtures. The bill was formed primarily to aid in disposing of the 15 million waste tires that are collected each year. Prior to actual demonstration, Florida DOT contracted the National Center for Asphalt Technology (NCAT) to research ground tire rubber use in asphalt concrete mixtures. The main establishment made from
this review was the importance of the use of virgin materials for the development of surface friction course mixtures that are to be used with ground tire rubber (56). Several factors contributed to this finding including an increase in air pollution, unknown effects caused from combining the rubber with recycled material, the usefulness of a rejuvenating agent when combined with rubber, and possible chemical problems as a result of combining the materials.

Following this review in 1989, the Florida DOT organized two demonstration projects (57). Variations of amounts and sizes of ground tire rubber were used to fabricate both fine-graded and open-graded surface friction courses. Evaluations were made on both constructability of the material and short-term field performance of the finished product. Conclusions from the first project were that the best additive for fine-grade surface friction courses of those tested was the minus 80 mesh ground tire rubber pre-blended at five percent (by weight of the asphalt cement), and that higher percentages influenced problems with construction.

The second project indicated that the minus 80 mesh blend at ten percent may have been the best candidate of those tested for open-graded friction courses. Construction also highlighted that large amounts of binder with increased amounts of ground tire rubber could cause an excess of asphalt, which in turn could cause flushing in the wheelpaths.

**MINNESOTA**

In 1984, The Minnesota Department of Transportation tested asphalt-rubber as a binder in a dense-graded mix (58). Both overlaid and reconstructed sections were used. No significant differences were noted for the overlays, however, less cracking was observed for the reconstructed pavements containing rubber in comparison to conventional pavement.
Two other demonstration sections were constructed in which the finer components of dense graded aggregate were replaced by ground tire rubber before asphalt was added (PlusRide system). No substantial improvements were observed by field personnel.

Due to the increased prices in utilizing asphalt-rubber and the limited amounts of improvements observed in every case, the Department has terminated any plans to construct more asphalt-rubber dense-graded sections.

WISCONSIN

Wisconsin's Department of Transportation carried out tests with ground tire rubber in the asphalt cement for a recycled mix (59). The asphalt-rubber mix, when compared to a conventional mix, created a significant increase in the amount of transverse cracking. Future testing of ground tire rubber was planned for 1990.

TEXAS

(FIELD EXPERIENCE)

Texas' annual use of hot-mix asphalt is averaged from the past five years at 9.4 million tons. Despite this large demand, only two of the districts have experimented with the use of asphalt rubber for this application. District 21 carried out an unsuccessful experiment ten years ago with a one mile test section; the section was resurfaced with a chip seal only after three months. District 10 experimented with the asphalt rubber in order to solve a serious rutting problem. The material proved to be an answer to the problem; however, because it was a small job, the cost of the asphalt-rubber was roughly $80/ton. This figure was quite expensive compared to conventional hot-mix prices of $30-$35/ton. District 4 is undertaking the only other project yet scheduled, which is an asphalt-rubber hot-mix job of ten lane miles at $52/ton.
The overall evaluation of asphalt-rubber concrete mixtures indicates that the use of the material in situations where fatigue cracking is expected may be an alternative worth considering, regardless of the extra expense of the asphalt-rubber. This conclusion is based on the material's ability to reduce problems with distress in comparison to performance of conventional asphalt mixtures. Comparisons to additive-modified mixtures, however, do not lead to deductions with such disregard to price; the asphalt-rubber performance would need to improve in order to dismiss prove competitive. An FAA study revealed that the asphalt rubber binder contributes to 41 to 45 percent of the overall in place cost (60).

Cost-effectiveness evaluations did not include considerations of maintenance, user cost, and abstract benefits. Such benefits encompass environmental issues such as the reduction of tires as a solid waste product, potential reduction of traffic noise, and potential abatement of driving hazards such as skidding (61). The elimination of all of these considerations discolors the true representation of the overall economic analysis.
In 1988 Senate Bill 1192, through the creation of Section 336.044 of the Florida Statutes, prompted the Florida Department of Transportation (FDOT) to focus on the use of recovered waste materials for highway construction. The bill uniquely called for one year of investigation and testing of the use of ground tire rubber (GTR) from recycled waste tires in asphalt concrete mixtures, from which a report was to be provided for state government. Modifications of highway standards and specifications to encourage the use of the recycled material were also required.

Testing had already begun 10 years prior to the 1192 Bill in the evaluation of asphalt rubber (a blend of GTR with paving grade asphalt) as an interlayer and binder. In accordance with 1988 provisions, investigation and testing was carried out through a series of three demonstration projects. Foregoing the actual demonstration, the National Center for Asphalt Technology at Auburn University was hired for the preliminary research and documentation of necessary information for the utilization of GTR and asphalt-rubber binders.

In addition, the FDOT Materials Office carried out laboratory investigations to test asphalt-rubber blends and mix designs for the first two phases of the project. Other studies involving asphalt-rubber mixture requirements and extraction testing effectiveness were also carried out. Not only was a preliminary materials evaluation required, but prior project planning was also needed to assure proper conditions for testing and qualified personnel for administration. The University of Florida aided in carrying out the first two demonstration projects. Demonstration took place from 1989 through 1990; Table 3.4 provides a summary.
Table 3.4. Summary of Asphalt-Rubber Friction Course Demonstration Projects

<table>
<thead>
<tr>
<th>Date Constructed</th>
<th>1st Demonstration Project</th>
<th>2nd Demonstration Project</th>
<th>3rd Demonstration Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>N.E. 23rd Ave. Gainesville, FL</td>
<td>State Rd 16 Starke, FL</td>
<td>Interstate 95 St Johns County</td>
</tr>
<tr>
<td>Type of Mix</td>
<td>Dense-Graded Friction Course (FC-4)</td>
<td>Open-Graded Friction Course (FC-2)</td>
<td>Open-Graded Friction Course (FC-2)</td>
</tr>
<tr>
<td>GTR Test Sections</td>
<td>1) 80 mesh/3%</td>
<td>1) 80 mesh/5%</td>
<td>1) 80 mesh/10%</td>
</tr>
<tr>
<td>Size/%GTR*</td>
<td>2) 80 mesh/5%</td>
<td>2) 80 mesh/10%</td>
<td>2) 80 mesh/10%</td>
</tr>
<tr>
<td></td>
<td>3) 40 mesh/10%#</td>
<td>3) 80 mesh/15%</td>
<td>3) 80 mesh/10%</td>
</tr>
<tr>
<td></td>
<td>4) control/0%</td>
<td>4) 24 mesh/17%</td>
<td>4) 80 mesh/10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5) control/0%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6) 80 mesh/10%@</td>
<td></td>
</tr>
<tr>
<td>Total Binder Content</td>
<td>1) 7.1%</td>
<td>1) 8.0%</td>
<td>1) 7.17%</td>
</tr>
<tr>
<td></td>
<td>2) 7.3%</td>
<td>2) 8.4%</td>
<td>2) 7.17%</td>
</tr>
<tr>
<td></td>
<td>3) 8.2%#</td>
<td>3) 11.4%</td>
<td>3) 7.17%</td>
</tr>
<tr>
<td></td>
<td>4) 7.0%</td>
<td>4) 10.3%</td>
<td>4) 7.17%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5) 6.3%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6) 6.9%</td>
<td></td>
</tr>
<tr>
<td>Length of Test Section (ft)</td>
<td>1) 3520</td>
<td>1) 2100</td>
<td>1) 5260</td>
</tr>
<tr>
<td></td>
<td>2) 3656</td>
<td>2) 2532</td>
<td>2) 5655</td>
</tr>
<tr>
<td></td>
<td>3) 2460</td>
<td>3) 1818</td>
<td>3) 5513</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4) 2880</td>
<td>4) 5937</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5) 1761</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6) 263</td>
<td></td>
</tr>
<tr>
<td>Comments:</td>
<td>5% GTR of 80 mesh GTR produced the best results during construction.</td>
<td>10 to 15% GTR appears satisfactory. Either 80 or 24 mesh GTR could probably be used.</td>
<td>Blending temp too low (275F) Increased blending time to 45 min. Both asphalt rubber and conventional mix were placed with equal ease.</td>
</tr>
</tbody>
</table>

* By weight of total binder  
# Also included 5.0% extender oil  
@ Not preblended - mixed in pugmill
The first project took place in March of 1989 in Gainesville, Florida. Testing was executed for the evaluation of dense-graded friction course (FC-4) by testing hot-mix samples with GTR percentages (by weight of total binder) of 3, 5, and 10. The best mix appeared to be that containing 5.0 percent GTR. Each GTR mixture displayed a tendency to stick to the paver screed; however, an extreme degree of this sticking behavior was evident in the 10 percent GTR mixture.

Construction of the second demonstration project was in June 1989 on SR 16 near Starke. Open-graded friction course (FG-2) mixtures containing 5 to 17 percent GTR (by weight of total binder) were tested. The high total binder contents of 15 and 17 percent GTR could exhibit long term performance and hydroplaning problems. GTR percentages of 10 to 15 proved to be effective for open-graded course mixtures; however, it was advised that less total binder contents should be used in comparison to those used in these percentages of this project.

The final demonstration project was constructed in September 1990 on Interstate 95. Practical usability of asphalt-rubber blends was the focus of this project. Ten percent GTR (by weight of asphalt cement) was blended into an open-graded friction course mixture on construction site with the use of a prototype production blending unit to test for problems that could cause construction delays or imperfections. The main problem that arose was the lower temperature of the asphalt cement (275 °F vs 310 °F), which led to an increase of 45 minutes in the required blending time to cause acceptable reaction between the GTR and the asphalt cement. This project, hence, highlighted the need to provide more heating for the blending unit or to increase the unit's capacity to maintain desired production rates of 100 tons/hr.

72
Through these demonstrations a successful short term performance was observed. In addition, feasible use of the mixtures without significant changes in construction operations was observed. Increases in film thickness, resiliency, viscosity, and shear susceptibility due to the addition of GTR further lead to improvements in durability, retention of aggregates, binder content, and age hardening.

The type and amount of rubber required weighs heavily upon the application for which it is needed. Dense-graded friction course mixtures are generally more open to changes in particle size of GTR and binder content than open-graded mixtures. At the present, ambiently ground tires are viewed as satisfactory at an acceptable fineness.

Five percent (by weight of asphalt cement) of GTR passing the No. 50 sieve can be used in dense-graded friction course mixtures. Open-graded mixtures are more accepting of higher GTR percentages and larger fragments of rubber; 15 percent (by weight of asphalt cement) of GTR passing the No. 30 sieve can be combined with the asphalt cement. For the use of binding as a membrane interlayer, 25 percent (by weight of asphalt cement) of GTR passing the No. 10 sieve is used in unification with asphalt cement. This blend which is applied by a spraying method at 0.6 gal/sq.yd acts as a membrane underneath rolled aggregate to prevent moisture problems and to prolong reflective cracks. Exact requirements are provided in specifications.

BLENDING REQUIREMENTS

A required blending time must be met in combining GTR with asphalt cement to produce a homogeneous mixture with a stable consistency. Blending time is reduced by using higher temperatures, softer asphalt cement, and/or smaller
particulates of GTR. Excessive temperatures, however, as well as sustained high temperatures will promote volatile hardening and accelerated hardening which, in turn, reduce the quality of the asphalt-rubber binder. Finer ground GTR also helps to make the blend more uniform and more suitable for quality control and viscosity tests.

GTR is usually mixed with the asphalt cement in the feeding unit; packaged plastic bags of GTR are opened and dumped into the hopper. Blending requirements differ according to construction needs. Specifications provide information on temperature and reaction time requirements.

EFFECTS ON CONSTRUCTION AND PAVEMENT PERFORMANCE

Asphalt-rubber binders when used properly and mixed by specification pose no major problems in normal construction operations. If spray bar orifices do not restrict flow, asphalt plants with weigh buckets will operate without significant difficulty; however, plants with asphalt metering pumps may not prove functional because of the material's increased viscosity.

In addition to improvements in retention, durability, and in binder content for open-graded friction course mixtures mentioned previously; asphalt-rubber decreases distortions in the pavement at intersections due to improved resilience for dense-graded friction course mixtures. Recycling of GTR enhanced mixtures is not predicted to be a problem for normal mill depths.

ESTIMATED GTR USAGE AND COST

The estimated use of GTR, based on annual total tonnage of open and dense graded normally used plus estimations of GTR's use as an interlayer, totals to 12,164 tons/year for FDOT alone. Knowing that the total annual use of asphalt
concrete by cities, counties, and developers is in excess in comparison to this estimation; it would be a conservative, yet reasonable assumption that the anticipated highway usage of GTR from waste tires in Florida is 50% of the total generated (estimated at 48,750 tons/year). This assumption disregards usage by roofing and tire manufacturing industry and amounts bought by GTR national suppliers.

FDOT State Materials Office cost estimations show increases in cost of 10 percent with GTR in binder mix. This additional cost results in a 46 percent increase in total binder cost.

DEVELOPMENTAL SPECS FOR ASPHALT-RUBBER HIGHWAY CONSTRUCTION

Developmental specifications were prepared by the FDOT State Materials Office through the use of information obtained through investigation and demonstration (Appendix A, B, & C). Appendix D pertains to the use of asphalt-rubber binders in friction course construction as specified by Section 337 of the Florida Department of Transportation Standard Specifications for Road and Bridge Construction. Revisions may be required when more information becomes available.

OTHER METHODS USED FOR TIRE RECYCLING

Whole tires provide numerous products. Whole tires are used as the structural front for retaining walls on secondary roads by the U.S. Forest Service, as stabilizers on highway slopes, and as controllers for erosion along drainage channels. Currently, Malaysia is looking for 35 million tires to use as a barrier reef. Other uses include tires for crash barriers, playground equipment, breakwaters, and soil and beach erosion control.
Because tires contain approximately 14,500 BTU's/lb more than high grade coal, they are a good source of fuel. The Oxford Energy Company has formulated a way to use whole tires for fuel in industrial and power plants. Such a power plant exists in Modesto, California where 4.5 to 5 million tires are burned per year (700 tires/hour). Shredded tires have also been used as fuel in a variety of industrial plants. To reach a satisfactory temperature for combustion of the rubber, a "fluidized bed" burning system is required. Waste products from such a process must be removed by advanced scrubber systems.

The University of Wisconsin is researching the use of shredded tires instead of sand and gravel for fills. This role would help to conserve mineral aggregates, reduce Wisconsin's 20 million waste tires, and reduce the weight of fill without affecting ground water.

Mud guards, floor mats, carpet padding, adhesives, new tires, and a variety of other products can be produced from a mixture containing a percentage of crumb rubber. Marketability, however, has proved questionable.

The following sections (Sections 1 - 3) contain three appendices in the reports containing some information regarding the specifications used by the Florida DOT. For more detailed information, the reader is encouraged to read the references mentioned in this part of the report.
SECTION 1

DEVELOPMENT SPECIFICATION

FOR

GROUND TIRE RUBBER FOR USE IN ASPHALT-RUBBER BINDER

AAA-1 SCOPE

1.1 This document provides guidelines for GTR use in an assortment of roadway applications.

1.2 Safety and environmental aspects are not regarded in this specification.

AAA-2 GENERAL REQUIREMENTS

2.1 Ambient grinding shall be used to manufacture GTR. The rubber used shall be dry and free from contaminants with the exception of talc which may be added in an amount up to 4% (by wt. of rubber) to prevent sticking and caking.

AAA-3 PHYSICAL REQUIREMENTS

3.1 Gradation shall abide by limits provided in Table A1, when testing a 50g sample in adherence to FM 1-T 027.

3.2 Specific Gravity shall be 1.15 ± 0.05 (ASTM D-297).

3.3 Moisture Content - Maximum 0.75% by weight as measured by heating to 230 °F to a constant weight.

3.4 Mineral Contaminants - Maximum 0.25% by weight (FM to be developed).

3.5 Metal Contaminants - None (FM to be developed).

AAA-4 CHEMICAL REQUIREMENTS

4.1 Acetone Extract - Maximum 25%

4.2 Rubber Hydrocarbon Content - 40 to 55%

4.3 Ash Content - Maximum 10%

4.4 Carbon Black Content - 20 to 40%
5.1 GTR shall be packaged in moisture resistant bags/containers which are to be labeled with the rubber type, maximum nominal size, and weight, along with the manufacturer's batch or lot number.

6.1 The manufacturer shall provide the Engineer with test results, for each shipment of material to each project, which prove adherence to these specifications and indicate the project number and manufacturer's batch or lot number with which the material is associated.

6.2 Certification that tires used in the production of GTR were waste tires from the State of Florida must be provided.
SECTION 2  

DEVELOPMENT SPECIFICATION  

FOR  

ASPHALT-RUBBER BINDER

BBB-1  SCOPE

1.1 This specification regulates the production of asphalt-rubber binder for its application in asphalt concrete friction courses and asphalt-rubber membrane interlayers.

1.2 Safety and environmental aspects are not regarded in this specification.

BBB-2  MATERIALS

2.1 Asphalt Cement - See Table B1 and Section 916 for requirements.

2.2 Ground Tire Rubber - See Appendix A for requirements.

2.3 Asphalt-Rubber Binder - See Table B1 for mixing requirements. Batch or continuous type blending units may be used.

BBB-3  METHOD OF MEASUREMENT

4.1 Ground tire rubber content in asphalt-rubber binder shall be regulated according to its weight used vs. gallons of the binder in accordance to Table B1.
SECTION 3

DEVELOPMENT SPECIFICATION

FOR

ASPHALT-RUBBER MEMBRANE INTERLAYER

CCC-1 GENERAL

This document specifies the development of an asphalt-rubber membrane interlayer consisting of a layer of aggregate on a layer of asphalt-rubber binder material.

CCC-2 MATERIALS

2.1 Asphalt-Rubber Binder - See Table B1 (Type III) for requirements.

2.2 Cover Material - Cover shall be size No. 6 stone, slag, or gravel aggregate (100% passing 3/4" sieve) meeting Section 901 requirements.

CCC-3 EQUIPMENT

The power broom for treatment of existing pavement shall be capable of removing debris from the surface. A rotary sweeper shall be used for similar treatment of finished surfaces.

A self-propelled aggregate spreader shall be used in the application of the cover material.

Rollers used shall be self-propelled and of pneumatic-tired traffic type with at least seven smooth-tread, low-pressure tires capable of carrying an eight ton gross load. All tires shall be pressurized within a 5 psi range.

Mixing equipment shall be designed for blending asphalt-rubber and shall be capable of manufacturing and sustaining a homogeneous mixture at specified temperatures.

A pressure type distributor capable of sustaining specified temperatures, consistency, and uniformity of asphalt and rubber shall be used for the application of the asphalt-rubber.

CCC-4 PREPARATION OF ASPHALT-RUBBER BINDER

4.1 Time and temperature for blending shall be specified in Table B1. After proper consistency is reached, the mixture shall not be held at temperatures exceeding 325 F for more than one hour for any reason.
4.2 After full reaction of materials used, a kerosene type diluent with a boiling point exceeding 350 F shall be added in an amount of 5.5 to 7.5% (by volume of the hot asphalt-rubber binder). Temperature of the mixture shall be less than 350 F during this kerosene addition.

CCC-5 CONSTRUCTION PROCEDURE

5.1 Preparation of Surface - See specifications in Section 300-4.

5.2 Application of Asphalt-Rubber Binder - The following conditions shall be met:
   a) Air temperature above 40 F and rising.
   b) Pavement is absolutely dry.
   c) Wind conditions not able to cool asphalt-rubber binder at a rate that will prevent good binding with aggregate.

5.3 Application of Cover Material - Cover material shall be uniformly spread at a rate of between 0.26 to 0.33 cubic feet per square yard immediately (no more than 150') after asphalt-rubber is applied.

5.4 Rolling - The entire width of the mat shall be covered immediately by traffic rollers meeting requirements of section CCC-3. A minimum of three traffic rollers shall be provided for the first coverage, after which a minimum of four coverages shall be provided.

5.5 Traffic Control - All efforts shall be made to minimize membrane exposure to traffic. If this is not possible due to extenuating circumstances, traffic shall not be permitted on the membrane for a period exceeding two hours.

CCC-6 UNACCEPTABLE ASPHALT RUBBER MEMBRANE INTERLAYER

Unacceptable asphalt-rubber membranes shall be removed and replaced. Excessive amounts of the binder may not be allowed under any circumstances.

CCC-7 METHOD OF MEASUREMENT

See Section 9-1.3 for determination of the area of asphalt-rubber membrane interlayer.

CCC-8 BASIS OF PAYMENT

Payment shall be made in accordance with a contract unit price for work specified in Appendix B including furnishing cover material, asphalt cement, ground tire rubber, diluent, and all processing, mixing, handling, spreading, rolling, and other incidental work necessary to complete this item.
CHAPTER 4

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

This research study was conducted to investigate the feasibility of the use of tires in asphaltic concrete mixtures in the state of South Carolina. An extensive literature review of work performed in this area was conducted. In addition, an extensive survey (e.g., questionnaire) of all state and federal highway-related agencies was conducted. Several experts knowledgeable in the use of tires in flexible pavements were interviewed. The following conclusions and recommendations are based on the literature survey, questionnaire and interviews with the experts. Table 4.1 is a summary of cost and performance data of asphalt-rubber systems used by some of the states.
Table 4.1. Users of Asphalt Rubber Made From Recycled Tire Rubber
Update (As of January 22, 1991)

<table>
<thead>
<tr>
<th>STATE</th>
<th>RELATIVE COST</th>
<th>PERFORMANCE/COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>40% higher costs.</td>
<td>Approx. 20 asphalt-rubber hot mix projects have been performed with improved performance as the main objective. Good performance.</td>
</tr>
<tr>
<td>Idaho</td>
<td>1990 project used AC-20R. Generally, 50% higher cost to use asphalt rubber.</td>
<td>Inconclusive</td>
</tr>
<tr>
<td>Illinois</td>
<td></td>
<td>No hot mix applications attempted and none planned.</td>
</tr>
<tr>
<td>Indiana</td>
<td></td>
<td>Tried three seal coats resulting in one failure and two successes.</td>
</tr>
<tr>
<td>Kansas</td>
<td>(AC-10) AC Mix (BM-1B) $17.91/ton (AC-5) AR Mix (BMO1B) $48.70/ton 172% higher cost</td>
<td>Will try an asphalt-rubber hot mix project as a portion of a research project evaluating the performance of seven different modifiers.</td>
</tr>
<tr>
<td>Michigan</td>
<td>Initial 1990 project showed AC Mix at $20/ton and AR Mix nearly four times the cost.</td>
<td>Tried two unsuccessful SAMI projects in 1978 and 1979. US 75 asphalt concrete south of Topeka completed in fall of 1990. Performance is inconclusive. Will have another trial hot mix project this spring, motivated primarily by environmental objectives. Improved performance is a secondary objective. One hot mix project in 1984 which is not providing performance superior to conventional asphalt.</td>
</tr>
<tr>
<td>STATE</td>
<td>RELATIVE COST</td>
<td>PERFORMANCE/COMMENTS</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Kansas City,</td>
<td>AC rubber mix $45.90/ton</td>
<td>Inconclusive</td>
</tr>
<tr>
<td>Missouri</td>
<td>AC mix $26.00/ton</td>
<td>(Documented by International Surfacing, Inc.)</td>
</tr>
<tr>
<td></td>
<td>75% higher cost</td>
<td></td>
</tr>
<tr>
<td>Nebraska</td>
<td>1990 project</td>
<td>Inconclusive. A large project (@6.2 miles).</td>
</tr>
<tr>
<td></td>
<td>-AC rubber $48.95/ton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Conventional AC Mix $23.45/ton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(109% higher cost)</td>
<td></td>
</tr>
<tr>
<td>New Jersey</td>
<td>Costs run typically 25% to 87% higher for crumb rubber project than conventional mix.</td>
<td>Tried PlusRide in 1984 at cost of $46/ton and got good performance. No other asphalt-rubber applications attempted.</td>
</tr>
<tr>
<td></td>
<td>(1978 project)</td>
<td></td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>Open graded mix</td>
<td>Two hot mix projects constructed in 1989 due to legislative requests. Performance is inconclusive.</td>
</tr>
<tr>
<td></td>
<td>A.R. Mix $52.24/ton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reg. AC Mix $35.99/ton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(45% higher)</td>
<td></td>
</tr>
<tr>
<td>Texas</td>
<td>1990 Amarillo project</td>
<td>Good stability on Amarillo project. Performance is inconclusive. Use asphalt rubber in seal coats and SAMI's. Have two or three hot mix projects coming up. A bill was passed allowing recycled asphalt rubber as an alternative even if the cost is 15% higher than the low bid.</td>
</tr>
<tr>
<td></td>
<td>(approximate in-place costs)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-AC Mix $30/ton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-AR Mix $60/ton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(100% higher)</td>
<td></td>
</tr>
<tr>
<td>Virginia</td>
<td>1990 project</td>
<td>Performance is inconclusive. No other asphalt rubber projects planned.</td>
</tr>
<tr>
<td></td>
<td>(approximate in-place costs)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-AC Mix $26.30/ton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-AR Mix $48/ton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(83% higher)</td>
<td></td>
</tr>
<tr>
<td>Wisconsin</td>
<td>1990 project</td>
<td>Tried several projects last year attempting to reduce reflective cracking. Neither was particularly successful. There will be another project this summer.</td>
</tr>
<tr>
<td></td>
<td>(approximate in-place costs)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-AC Mix $16/ton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-AR Mix $35.12/ton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(120% higher)</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

1. The following is a summary of the responses given to a questionnaire mailed to all state and federal agencies involved with highway construction:
   a) Fourteen (14%) percent of respondees indicated that they are using asphalt-rubber mixtures for flexible pavements.
   b) The disadvantages of using an asphalt rubber mixture, mentioned by the respondees included cold temperature cracking, shorter compaction period, constructibility and increased mix temperature.
   c) The problems encountered by the agencies using the asphalt-rubber systems included cost, increased temperature and viscosities, excessive plant emissions and limited supply of rubber.
   d) The problems during placing the mixtures encountered by the agencies utilizing the asphalt-rubber mixtures included the compaction difficulties, stickiness, odor and pollution.
   e) All of the respondees indicated that the increase in cost is a major concern of their agencies.
   f) The future research topics indicted by the respondees included studies of rutting resistance of the mixtures, cost effectiveness, emissions control, recyclability of the asphalt-rubber mixtures, service life, stripping problems, and performance.

2. Drivers in the South Carolina generate approximately 3.5 million scrap tires each year. This amount of waste tires could generate approximately 21,000 tons of rubber, 7,000 tons of steel and 7,000 tons of fiber annually. These figures are based on the assumption that each passenger tire (weighing 20 pounds) produces approximately 60% rubber, 20% steel and 20% fiber and other waste materials.

3. Based on the limited trials conducted around the nation, in general, the performance of flexible pavements containing scrap tires has been satisfactory. However, there were some cases in which engineers concluded that the performance was not acceptable.
4. There are two processes involved with the use of tires in asphaltic concrete mixtures referred to as dry and wet process. In the dry process, the rubber is added to the aggregate and in the wet process, the rubber is added to the asphalt cement. There are some experimental pavements containing these two processes around the nation. In general, both of the processes proved to be effective. However, the dry process uses many more tires than the wet process, because the dry process uses approximately 3% to 5% rubber by weight of the total mixture and the wet process uses approximately 5% to 10% rubber by weight of asphalt cement.

For instance, for a typical paving job requiring 5,000 tons of hot mix, if the dry process is being used approximately 25,000 tires could be utilized (based on 3% rubber in the mixture). However, for the same mixture, if the wet process is chosen, then approximately 4,000 tires could be used (based on 6% asphalt cement content and 8% rubber in the mixture).

5. The cost of either process is much higher than the conventional paving process. In some cases, the cost of using the rubber in asphaltic concrete mixtures doubled the cost of the construction. However, it is anticipated that the cost would be higher by 20-40% in the future due to wider use of these materials in pavements.

6. Some of the potential benefits of using the asphalt-rubber mixtures include conservation of asphalt cement and aggregates; preservation of the environment; thinner lift; increased pavement life; retarded reflection cracking; decreased traffic noise; reduced maintenance costs; and decreased pollution.

7. Some of the disadvantages of using such a system include the initial high cost; expertise of contractors; necessary modifications to equipment or
plants; lack of specifications by agencies such as ASTM; and potential problems with recyclability of these materials.
Recommendations

There is a need for a comprehensive study to establish the laboratory and field procedures for using rubber-asphalt systems in South Carolina. The materials used in a typical surface asphaltic concrete mixture in the state must be used in the laboratory testing. Two processes used in asphalt-rubber systems (i.e., dry and wet processes) must be evaluated in the laboratory. In addition, there must be several field trial sections to test both processes and also to investigate the difficulties, if any, with the construction process. It is recommended that rubber used in any pavement in the state should come from waste tires generated in South Carolina.

However, at this time in the state, there are not many locations that could process a large number of tires to be used in flexible pavements. Therefore, it might be necessary to obtain the tires within the state and shred them out of state for a project. This, of course, will increase the cost of the mixture and should be avoided, if possible.

Based on the findings of this research project, the use of scrap tire in asphaltic concrete mixtures is recommended. However, due to high initial costs associated with the use of waste tires in pavements, initially, it is recommended to construct a section of a pavement (i.e., Pelham Road) with a mixture containing asphalt-rubber mix. The dry process (i.e., PlusRide) is recommended to be used. After analyzing the results of limited laboratory work and the initial trial section, several more trial sections containing various processes (e.g., wet process) must be evaluated. It is recommended that the state of South Carolina to establish its own generic asphalt-rubber mix design in order to avoid paying the service fees and some other costs associated with some of the current asphalt-rubber mixes.
LITERATURE CITED


9. H.B. Takallou and R.G. Hicks, "Development of Improved Mix and Construction Guidelines for Rubber-Modified Asphalt Pavements", Transportation Research Record 1171, 1988, p.113


17. Jack E. Stephens, "Field Evaluation of Rubber-Modified Bituminous Concrete", Transportation Research Record 843, p. 11


30. R.A. Jimenez, "Laboratory Measurements of Asphalt-Rubber Concrete Mixtures", Transportation Research Record 843, 1982, p.4


32. Clinton E. Solberg and David L. Lyford, "Recycling with Asphalt-Rubber, Wisconsin Experience," Wisconsin Department of Transportation's Internal Report


35. Standard Specifications for Roads, Bridges and Incidental Construction, Form 811, State of Connecticut, Department of Transportation, 1974


43. Takallou, H., "Evaluation of Mix Ingredients on the Performance of Rubber Modified Asphalt Mixtures," Transportation Research Institute, Oregon State University, June 1987


45. "Asphalt Usage", The Asphalt Institute, College Park, Maryland


51. Letter from Joe M. Battle, Texas SDHPT District Engineer in El Paso, to Cindy Estakhri, Texas Transportation Institute, June 12, 1990


93
69. G. Keller, "Retaining Forest Roads," Civil Engineering, American Society of Civil Engineers, December 1990, pp. 50-53

70. G. Berthelsen, "Erosion Control," AASHTO Quarterly, April 1989, pp. 6-7

NON-CITED REFERENCES


