



USE OF SCRAP TIRE RUBBER

STATE OF THE TECHNOLOGY
AND BEST PRACTICES



State of California Department of Transportation
Materials Engineering and Testing Services
Office of Flexible Pavement Materials
5900 Folsom Blvd
Sacramento, California 95819

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EXECUTIVE SUMMARY

The California Department of Transportation (Caltrans) has been using scrap tire rubber (called crumb rubber modifier (CRM)) in asphalt pavements since the 1970s in chip seals and the 1980s in rubberized asphalt concrete (RAC). The performance of the projects has varied from poor to excellent, with relatively good overall performance. In recent years, however, improved specifications and practices have yielded more consistent performance.

To evaluate the state of the technology of using scrap tire rubber in paving materials, a comprehensive review of the literature search was undertaken. Nearly 400 documents representing a cross-section of information and focused primarily on experience throughout the United States were reviewed. Findings were organized in the following topics areas, with some overlap: historical perspective; applications/field operations; materials selection and design; structural design; performance; recycling; cost; environmental issues; other uses; and specifications.

Much of the research on CRM-modified paving materials was prompted by the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, which mandated that each state use scrap tire rubber in asphalt pavements with minimum utilization levels increasing from 5% in 1994 to 20% of total asphalt concrete (AC) 1997. Studies conducted by a number of states and the Province of Ontario, Canada, varied significantly in terms of experimental design, materials, mix design methodology, testing and analyses conducted. For example, some studies tried to incorporate CRM into existing DOT mixes, while others incorporated extensive laboratory testing into their trial mix design and reworked their mix design procedures to accommodate the inclusion of CRM. The challenge was further complicated by differences in the two generic technologies: the “wet” and “dry” processes. These represent considerably different systems and mechanisms. Review of the reports of various field and laboratory studies conducted clearly shows a very fragmented approach as each agency tried to use CRM-modified materials in its own way, often without understanding how these materials could or should be optimized to provide the desired performance and serve specific needs. These differences in the research approaches make it difficult to compare the results and draw firm conclusions.

The studies reviewed showed widely differing performance for a variety of CRM-modified asphalt paving materials, which may be influenced by a number of issues relating to specifications, design (including materials selection), and project selection. Field performance was also affected by contractors’ inexperience in working with CRM-modified paving materials. This inexperience included that associated with materials handling, production, placement and compaction.

In addition to variable performance, many agencies recorded a noticeable cost increase associated with the use of CRM materials. High costs were due primarily to two factors: long-distance mobilization of equipment and personnel for small tonnage experimental or demonstration projects; and, until the patents expired in the early 1990s, use of proprietary materials. Most agencies did not observe the consistent, high-level pavement performance needed to justify the added expense of CRM. Therefore, the mandate to use CRM was waived and subsequently repealed.

However, DOTs in Arizona, California, Florida and Texas had better success with CRM-modified asphalt materials. These agencies found that CRM-modified paving materials, including RAC, provide a number of benefits: increased resistance to rutting, fatigue and reflective cracking; and improved durability as a result of the higher binder contents of RAC mixes compared to conventional asphalt concrete. Therefore, these four states continue to utilize CRM-modified materials to a large extent on their pavement networks. Their extensive experience with CRM as well as current practices and specifications for using CRM-modified materials is summarized.

To assess Caltrans use of CRM relative to its counterparts nationwide two surveys were conducted. Survey results confirm that Caltrans is one only four state DOTs that consistently use significant quantities of CRM in paving applications. Other DOTs making extensive use of CRM in paving applications are, as previously noted, those in Arizona, Florida and Texas. From a more global perspective, the surveys revealed that only California, Florida and Texas produce an annual report documenting the end-use of scrap tires. Although the nomenclature varies slightly, all three states have general end-use categories pertaining to crumb rubber, energy, civil engineering and disposal. Noteworthy statistics with respect to scrap tire end-use from the 2002 “tire reports” are as follows:

- Disposal accounts for nearly 24% in California, 15% in Florida and 4% in Texas.
- Tire Derived Fuel (TDF) accounts for 46% in Florida, 45% in Texas and 17% in California.
- Civil Engineering applications account for 15% in Texas, 13% in Florida and 9% in California.
- The broad category of transportation-related applications account for 25% in Florida, 16.6% in California and 4.5% in Texas.

Comparisons of CRM in HMA based on absolute (tonnage) or relative (percent CRM-HMA placed as a percent of total HMA placed) terms can be misleading. To account for differences in strategies the data may be “normalized” in terms of scrap tires used per tonne of HMA. Using this approach DOT scrap tire use per tonne of hot mix is as follows:

- Arizona: 4.4
- California: 3.3
- Florida: 1.9
- Texas: 4.9

Based on the DOT projected use, Caltrans will very likely lead the nation in not only tonnes of CRM HMA placed but also in terms of tires consumed. By 2005, Caltrans could consume more than double the number of scrap tires of its nearest state DOT counterpart: approximately 3.9 million for Caltrans vs. 1.9 million for ADOT.

Based on the findings of the literature review and the state of the art as practiced by the four primary CRM-user states, recommendations are presented to refine, broaden and increase Caltrans use of scrap tires in paving applications.

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USE OF SCRAP TIRE RUBBER – STATE OF THE TECHNOLOGY AND BEST PRACTICES

1.0 BACKGROUND AND OBJECTIVES

The California Department of Transportation (Caltrans) has been using scrap tire rubber (called crumb rubber modifier (CRM)) in asphalt pavements since the 1970s in chip seals and the 1980s in rubberized asphalt concrete (RAC) [Shatnawi and Holleran, 2003; Shatnawi and Long, 2000]. Early trials included the use of both the wet and dry processes of incorporating CRM; however, most of the work completed in the 1990s and in this decade has employed the wet process. The performance of the projects has varied from poor to excellent, but in recent years improved specifications and practices have provided more consistent performance. Other agencies, primarily the Arizona, Florida and Texas Departments of Transportation, have also used scrap tire rubber in asphalt pavements over this same period, generally with good success.

Caltrans has established a goal of using at least 15% rubberized asphalt concrete (RAC) in paving which would consume about one million tires annually. Beyond the obvious environmental benefit of reducing landfill waste by recycling scrap tires for use in pavements, there are also pavement performance enhancements such as improved durability, potentially longer service life, and reduced noise. In January 2004, Caltrans and the California Integrated Waste Management Board (CIWMB) entered into an interagency agreement to supplement Caltrans efforts in arriving at technically sound, cost effective, and environmentally friendly solutions to scrap tire management through the increased use of scrap tire rubber in roadway projects.

The overall objective of the Caltrans-CIWMB interagency agreement is to increase and broaden the use of scrap tires in roadway construction and maintenance. Figure 1.1 illustrates the topics addressed, specific tasks and key work elements within each task. Task 1, Product Evaluation, includes a synthesis of the state of the technology and best practices which is the subject of this report. This report summarizes past and current research conducted throughout the U.S., current use of scrap tires in paving materials, best practices based on successful use, and presents recommendations for using CRM to enhance the performance of asphalt concrete pavements. Other civil engineering applications for scrap tire rubber are outlined for information purposes only.

1.1 ORGANIZATION OF REPORT

This report focuses on the state of the technology and best practices resulting from a detailed literature review and survey of agency practices. It is organized as follows:

- Chapter 2 presents the results of a comprehensive review and synthesis of the literature. It addresses key findings with respect to applications; materials and structural design, specifications, performance, cost and environmental considerations.
- Chapter 3 presents the results of the survey of user-agencies.
- Chapter 4 presents a summary of key conclusions and recommendations.

Appendices are included to support the findings presented.

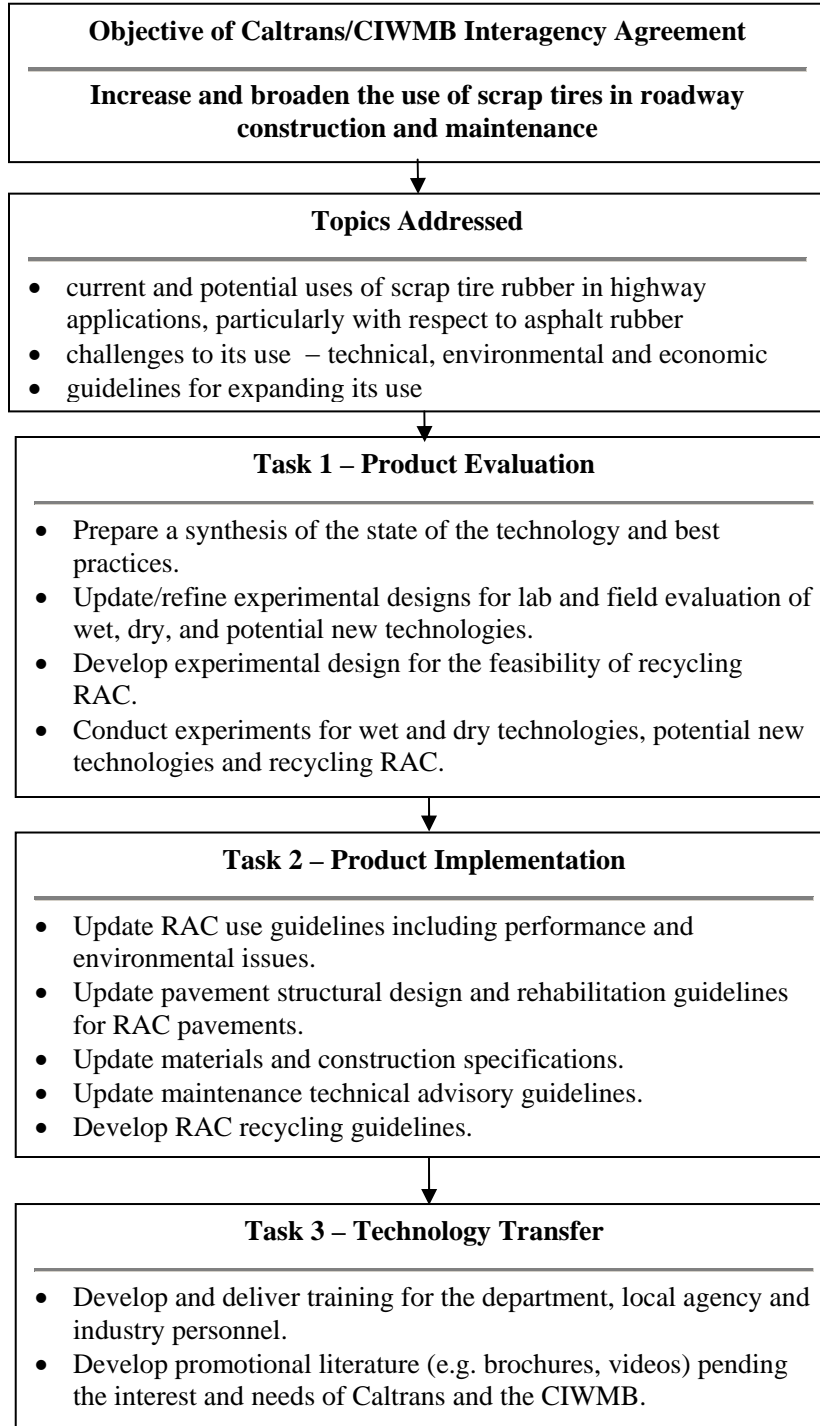


Figure 1.1: Study Objective, Tasks and Key Work Elements

2.0 LITERATURE REVIEW

A comprehensive literature search and review was performed for this study that focused on experience with use of scrap tire rubber in paving materials throughout the United States. Caltrans extensive experience in this area is summarized, and more detailed information is presented in the “*Asphalt Rubber Usage Guide*” (Caltrans 2002) that is currently posted on the Caltrans website.

This chapter describes the approach and findings of the literature review, and presents some basic terminology. A detailed glossary of terminology pertaining to rubber modified materials is included in Appendix A.

2.1 APPROACH

The search focused on a full investigation of literature relating to use of CRM in paving materials and identified nearly 400 documents. Literature searches were conducted using search engines such as the Transportation Research Information System (TRIS, a bibliographic database funded by sponsors of the Transportation Research Board [TRB]) and the National Technical Information System (NTIS). Internet searches of the TRB state highway agency, and research center websites were also conducted. A review of the Rubber Pavements Association (RPA) website and library yielded additional documents of interest. The documents identified were screened based on abstracts and selected documents were reviewed for this report. This report incorporates a representative cross-section of the available information.

2.2 TERMINOLOGY

A variety of terminology has been used to describe rubber-modified asphalt materials and products, which has caused some confusion over time. As noted above a glossary is provided in Appendix A. Descriptions of individual documents may include an initial reference to the specific terminology used therein, but current terminology is typically included to maintain uniformity. To promote clear understanding of this report, definitions for the various processes of rubber modification are included. The wet process CRM products have been divided into two families to make a clearer distinction and eliminate some of the confusion between the two very different types of CRM modification currently in use. The terminology presented is intended to provide a better description and understanding of the subject products and is related to definitions being considered by ASTM Subcommittees D04.45 (Modified Asphalt) and D04.95 (Quality Control, Inspection and Testing Agencies).

“**Wet Process**” is a term which describes the method of modifying asphalt cement with CRM produced from scrap tire rubber and, if required, other components. The wet process requires thorough mixing of the CRM in hot asphalt cement (176°C to 226°C) and holding the resulting blend at elevated temperatures (150°C to 218°C) for a designated period of time (typically 45 to 60 minutes, shorter for some variations) to permit an interaction between the rubber and asphalt. Other components may be included, depending on applicable specifications. The interaction (also referred to as reaction) includes swelling of the rubber particles and development of specified physical properties of the asphalt and CRM blend to meet requirements. Typical specification requirements include an operating range for rotational viscosity, and minimum values of softening point, resilience, and penetration (needle or cone, at cold and/or room temperature). Requirements for components, minimum temperatures for the asphalt cement at CRM addition and for interaction of the asphalt and CRM blend, interaction periods, and resulting physical properties of the blend vary among agencies that use this process (e.g. DOTs in Arizona, California, Florida, and Texas) and are presented in this report.

Some agencies, such as Caltrans, require the use of extender oils, and the addition of CRM, which has a higher natural rubber content than typical CRM made from passenger vehicle tires. This CRM is manufactured from scrap tennis balls, mat rubber, or heavy truck tires (California Standard Specifications 1999). Other agencies such as TxDOT have allowed the use of various modifiers (extender oil for use in asphalt concrete, diluent for spray applications) but do not require these modifiers. For spray applications Florida DOT allows but does not require extender oil and diluent; neither is used in AC mixes. Arizona DOT does not allow the use of extender oils or diluent in asphalt rubber binders (MACTEC Materials Survey Questionnaire July 2004).

The wet process can be used to produce a wide variety of CRM modified binders with a range of physical properties. The most important distinctions among the various blends seem to be related to rotational viscosity of the resulting CRM-asphalt cement blend at high temperature (threshold is 1,500 centipoise (cPs) or 1.5 Pascal•seconds (Pa•sec) at 177°C (ASTM, ADOT, TxDOT) or 190°C (Caltrans) depending on governing specification) and whether or not the blend requires constant agitation to maintain a relatively uniform distribution of rubber particles. Viscosity is strongly related to the size of the scrap tire CRM particles and relative tire rubber content of the CRM-modified blend. CRM-modified binders with viscosities \geq 1,500 cPs at 177°C or 190°C should be assumed to require agitation.

Wet Process-No Agitation - The term “terminal blend” is often used to describe rubber-modified binders that do not require constant agitation to keep discrete rubber particles uniformly distributed in the hot asphalt cement. However such binders may be produced in the field or at an asphalt concrete plant as well, such that calling them terminal blends may be misleading and is unnecessarily restrictive. The preferred description for this type of binder is, therefore, “**wet process-no agitation**”. These binders are typically modified with CRM particles passing the 300 μ m (No. 50 sieve) that can be digested (broken down and melted in) relatively quickly and/or can be kept dispersed by normal circulation within the storage tank rather than with agitation by special augers or paddles. Polymers and other additives may also be included. In the past, rubber contents for such blends have generally been \leq 10% by weight of asphalt or total binder, but some California products now include 15% or more CRM. Although such binders may develop a considerable level of rubber modification, rotational viscosity values rarely approach the minimum threshold of 1,500 cPs or 1.5 Pa•s at 177°C or 190°C, that is necessary to significantly increase binder contents above those of conventional AC mixes without excessive drain-down. This type of product is used in Arizona, California, Texas and Florida with various concentrations of CRM.

Wet Process-High Viscosity - CRM-modified binders that maintain or exceed the minimum rotational viscosity threshold of 1,500 cPs at 177°C or 190°C over the interaction period should be described as “**wet process-high viscosity**” binders to distinguish their physical properties from those of wet process-no agitation materials. These materials require agitation to keep the CRM particles uniformly distributed. They may be manufactured in large stationary tanks or in mobile blending units that pump into agitated stationary or mobile storage tanks. Wet process-high viscosity binders include asphalt rubber materials that meet the requirements of ASTM D6114. Wet process-high viscosity binders typically require at least 15% scrap tire rubber to achieve the threshold viscosity. However CRM-modified binders that meet Caltrans asphalt rubber recipe requirements for minimum total CRM content and relative proportions of scrap tire and high natural CRM with less than 15% tire rubber generally achieve sufficient viscosity to be included in this category and should be assumed to require agitation.

Dry Process -The dry process includes CRM as a substitute for 1 to 3 % of the aggregate in the AC mix, not as a modifier of the asphalt cement. Care must be taken during the mix design to make appropriate adjustments for the low specific gravity of the CRM compared to the aggregate material to assure proper volumetric analysis. Several methods of feeding the CRM into hot plant mixing units have been established, including use of filler augers, vane feeders and air blowing. A variety of CRM gradations have been used, ranging from coarse rubber (passing the 6 mm (1/4-inch) and retained on 2.36 mm (No. 8)

sieve sizes) to “Ultrafine” (passing the 300 μm (No. 50) sieve size). Caltrans has a special provision for RUMAC which includes an intermediate CRM gradation specification. Although there may be some limited interaction of the CRM with the asphalt cement during mixing in the AC plant, silo storage, hauling, placement and compaction, the asphalt cement is not considered to be modified in the dry process.

2.3 SUMMARY OF LITERATURE REVIEW

2.3.1 Historical Perspective

The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 caused many states to initiate experiments and/or field trials to investigate the use of CRM in asphalt pavement materials. The impetus was Subsection 1038(d) of the ISTEA legislation which specified that by 1994 all states were required to use scrap tire rubber in a minimum of 5% of their asphalt pavements with minimum utilization levels increasing to 20% of asphalt pavements by 1997 (Epps 1993). It is important to understand that much of the sponsored research regarding use of CRM in paving materials that was conducted in the early 1990s would not have been performed without the ISTEA mandate. Most of the reports reviewed directly reference ISTEA as the reason for the respective individual studies. Notable exceptions were in California and Arizona, where the use of CRM had been pioneered and successes of early experiments had created considerable interest and related study, and in Washington and Florida, where state legislation regulating scrap tire rubber had been enacted in 1981 and 1988, respectively. Research conducted in Ontario, Canada was also independent of ISTEA.

In 1991, CRM-modification of paving materials was a relatively new technology that was not readily available to most state highway agencies and was widely considered to be unproven. Costs for CRM-modified materials were significantly greater than conventional hot mix asphalt (HMA) and field performance data were limited and mixed. The fact that much of the performance history available at that time had been accumulated in California and Arizona led to the misconception that CRM-modified materials were only effective in warm climate areas. Many agencies had little interest in experimenting with CRM materials, and limited resources for monitoring performance over time. The ISTEA mandate was thus a major concern. The mandate created a considerable backlash among AASHTO members, which led to a moratorium on CRM usage requirements until the mandate was repealed by subsequent legislation.

One of the authors of this report served as a materials engineer for the largest supplier of CRM-modified binder during this period and has direct personal knowledge of a number of CRM-related research projects undertaken as a result of the ISTEA mandate, not all of which were reported in the literature. This experience provides additional historical perspective on the nature of the various independent studies performed during this time, and an understanding of related issues with design, production and construction that may have contributed to the mixed results reported.

The ISTEA mandate to incorporate scrap tire rubber in asphalt paving materials spurred a great deal of research and experimentation. It also created a tremendous backlash that nearly killed the developing asphalt rubber industry, although this fact is not reported in the technical literature described herein. Review of the reports of the various field experiments conducted throughout the U.S. clearly shows a very fragmented approach as each agency tried to use CRM-modified materials in its own way, often without any understanding of how these materials could or should be optimized to provide the desired performance and serve specific needs. Test sections were often relatively small such that the HMA plants barely had a chance to stabilize mix production within each section, which resulted in highly variable materials. Long-distance mobilization of the limited number of asphalt rubber suppliers was very expensive, and combined with small tonnages, increased unit costs for the modified materials to

unacceptably high levels. Some state DOTs tried very hard to make CRM-modification succeed, and a few were willing to allow modifications to their existing specifications to do so. Many states did not vary their practices to accommodate the modified materials. Contractors were unfamiliar with the materials and did not change their materials handling and construction practices or use “best practices.” Consequently, most agencies did not get the consistent high level of performance needed to justify the added expense.

The trial studies conducted by a number of states and the Province of Ontario, Canada, showed differing results in terms of performance of the asphalt paving materials containing CRM (Epps 1993; Baker and Connolly 1995 New Jersey; Emery 1995 Ontario; Van Bramer 1997 New York; Volle 2000 Illinois; Fager 2001 Kansas; Hunt 2002 Oregon; Sebaaly, Bazi, and Vivekanathan 2003 Nevada). The mixed performance seems to be due to issues relating to specifications, design (including materials selection), project selection, and field quality control (Epps 1993). There were also many problems related to contractors’ inexperience in working with CRM-modified paving materials that included issues with materials handling and construction procedures and practices.

In addition to variable performance, many studies determined that there was a noticeable increase in the cost associated with the use of CRM in the asphalt materials (Emery 1995; Trepanier 1995; Albritton, Barstis, and Gatlin 1999). The range of cost increases varied widely from as little as 10% to 360% (Huang 2002). The high costs were due primarily to two factors: long-distance mobilization of equipment and personnel and, until the patents expired in the early 1990s, use of proprietary materials. The suppliers were located in California, Arizona, Rhode Island, Canada, and later in Florida, Texas, and Mississippi. Many of the field trials and studies included very little tonnage over which to amortize high mobilization costs from these locations resulting in high costs for the CRM-modified paving materials.

Other DOTs including Arizona, California, Florida, and Texas saw more success with CRM-modified asphalt materials. They have used and evaluated the CRM materials more extensively (Page, Ruth, and West 1992; Flintsch, Scofield, and Zaniewski 1994; Hicks et al. 1995; Rebala and Estakhri 1995; Choubane et al. 1999; Way 2000; Herritt 2001; Tahmoressi 2001). Due to successful results, these agencies continue to utilize CRM-modified materials to a large extent on their pavement networks. For example, as of 2000 the Arizona Department of Transportation (ADOT) had constructed asphalt rubber mixes on over 2,000 miles of roadway pavement (Way 2000) using wet process high-viscosity binders.

Success in these locations is no coincidence. Major suppliers of asphalt rubber and other rubber-modified asphalt binder materials are located in Arizona, California and Texas, so mobilization costs are more reasonable. Furthermore, the suppliers of wet process high-viscosity binders have acted as local “champions” to promote the use of these materials and have provided corresponding technical support to the agencies and contractors. This has led to relatively routine use in some areas. Unit costs have been further reduced by limiting the use of CRM materials to relatively high tonnage projects.

However, Florida represents a different situation. A 1988 state legislative mandate to incorporate scrap tire rubber in Florida prior to ISTEA was accomplished using a different approach. Rather than engineering highly rubber-modified asphalt binders to maximize possible benefits, Florida opted to incorporate relatively low contents of finely ground scrap tire rubber into asphalt cement for use in dense- and open-graded asphalt concrete mixes. The purpose was to minimize requirements for special handling and storage (no agitation), and to limit impacts on conventional mixture production and placement operations. The results have generally been considered successful (Page, Ruth, and West 1992).

Wet process CRM binders have been used for joint and crack sealers, in spray applications for chip seals and stress-absorbing membrane interlayers (SAMIs), and in asphalt concrete hot mixes. Research has shown that the properties of wet-process CRM-modified binders depend upon a variety of parameters (Epps 1993) including but not limited to the following primary factors which are often the subject of specifications:

- Rubber source and processing method (ambient or cryogenic)
- CRM particle size
- CRM concentration
- Asphalt cement source and grade
- Asphalt additive type(s) and concentration(s)
- Interaction temperature
- Interaction time

The wet process involves blending and interacting the CRM with hot asphalt cement to yield a modified binder; the two primary wet process products, high viscosity and no agitation were described previously in section 2.2 of this report. The temperature range specified for interaction of the asphalt and CRM varies with agency, but the minimum interaction temperature is typically 150°C (300°F). As noted previously, CRM has also been incorporated as a substitute for a small portion of the mineral aggregate in asphalt concrete mixes in what is typically called the dry process.

As mentioned, a variety of small trial studies were independently conducted over a period of years by a number of DOTs. Studies varied significantly in terms of experimental designs, ranges of materials that were tested, types of mix designs, testing methods, CRM and analyses conducted. For example, some studies tried to incorporate CRM into their existing mix designs while others incorporated extensive laboratory testing into their trial mix design and reworked their mix design procedures to accommodate the inclusion of CRM. Furthermore, the respective wet and dry processes represent considerably different systems that perform in different ways, using different mechanisms. These types of differences in the research approaches make it difficult to compare the results of the literature and draw conclusive results.

The findings of some of the studies reported herein contradict each other and/or current experience and knowledge about the behavior of CRM-modified paving materials. Some studies show that laboratory test results may not necessarily be reliable indicators of field performance of these materials. However, such studies must be presented to provide a full perspective on the development and use of CRM-modified paving materials.

This synthesis involves an examination of the results presented in the literature relating to the use of CRM. To organize the vast amount of literature that addresses the use of scrap tire rubber in asphalt paving materials, the synthesis has been divided up into specific areas of interest to draw some basic conclusions regarding use of CRM. Literature related to recycling is addressed in a separate report, “Feasibility of Recycling Rubber-Modified Paving Materials”.

There is a considerable amount of overlap as many of the studies reviewed deal with more than one of the following categories.

- Applications/Field Operations
- Materials Selection and Design
- Structural Design
- Performance
- Recycling
- Cost
- Environmental Issues
- Other Uses
- Specifications

Each topic area includes findings for both wet and dry processes of using CRM in asphalt paving materials. The topic areas are discussed in more detail in the remainder of this report.

2.3.2 Applications/Field Operations

The literature shows that agencies tried a variety of applications of CRM in asphalt paving materials. CRM has been used in various mix types and membrane layers. The use of these applications and the constructability of these materials are discussed in more detail in this section.

AC Mix Types

CRM materials have been used by agencies throughout the world in a variety of asphalt concrete mix types. Specifically, CRM has been used in dense-graded, gap-graded, and open-graded asphalt concrete mixes using both the wet and dry processes. A variety of testing and performance results have been noted for each of these mix types. The following definitions apply to the respective types of aggregate gradations discussed in this section.

- **Dense-graded** – Continuously graded aggregate blend typically used to make hot-mix asphalt concrete pavements (DGAC) with conventional or modified binders.
- **Gap-graded** – Aggregate that is not continuously graded for all size fractions, but is typically missing or low on some of the finer size fractions (passing the 2.36 mm (No. 8 sieve)). Such gradations typically plot below the maximum density line on a 0.45 power gradation chart. Gap grading is used to promote stone-to-stone contact in hot-mix asphalt concrete and is similar to the gradations used in stone matrix asphalt, but with relatively low percentages passing the 75 μ m (No. 200) sieve. This type of gradation is most frequently used to make rubberized asphalt concrete-gap graded (RAC-G) paving mixes.
- **Open-graded** – Aggregate gradation that is intended to be free draining and consists mostly of 2 or 3 nominal sizes of clean aggregate particles with few fines and 0 to 4 % by mass passing the 75 μ m (No. 200) sieve. Open grading is used in hot-mix applications to provide relatively thin asphalt concrete surface or wearing courses with good frictional characteristics that quickly drain surface water to reduce hydroplaning, splash and spray. Studies conducted since 1990 also suggest that open-graded mixes may reduce noise generated at the tire-pavement interface. A number of abbreviations are used to identify open-graded AC mixes, including but not limited to OGAC, RAC-O, OGFC, and ACFC.

New Jersey

A study conducted by the New Jersey Department of Transportation (NJDOT) evaluated the use of wet and dry processes of incorporating crumb rubber in seven experimental field projects constructed in 1991 through 1994. Emissions tests were conducted on six of these projects. One project used a continuous blend wet process (no agitation) binder to incorporate 10% CRM (passing the 180 μ m (No. 80) sieve) in a standard NJDOT DGAC surface mix. Another project included wet process high viscosity binder with 16% CRM (passing the 425 μ m (No. 40) sieve) and extender oil (similar to Caltrans asphalt rubber) in standard NJDOT surface and base mixes. Overall, the wet process DGAC mixes provided pavements with performance similar to DGAC control sections. These results indicated that the standard NJDOT specifications successfully accommodated both types of CRM asphalt binder into the mix design without major modification (Baker and Connolly 1995). However, this result is not always the standard.

New Jersey's study also included open-graded friction courses (OGFC) produced with two different wet-process asphalt binders: 15% CRM passing the 180 μ m (No. 80) sieve and 15% CRM passing the 425 μ m (No. 40) sieve, respectively. Results showed these CRM formulations to be effective in eliminating drain-down during transportation of the OGFC. Thicker consistency, i.e. higher viscosity, of the wet process binders ensured better coating of the aggregate (Baker and Connolly 1995). However, performance data were not included in the referenced report.

Generic and proprietary (PlusRide) dry processes were used to produce gap-graded mixes for surface and base courses of respective projects. Performance was variable. The PlusRide surface mix raveled, but the corresponding base course did not. A previously failed PlusRide mix was recycled into a conventional DGAC pavement at 20% of aggregate weight with no apparent problem and reportedly performed relatively well through 2002 according to a telephone conversation with Joe Smith, formerly of NJDOT and currently at Rutgers University (2004).

Oregon

The Oregon Department of Transportation (ODOT) constructed a total of seventeen test sections throughout the state from 1985 to 1994. The performance of the dense-graded mixes modified with CRM using both the wet process and the dry process respectively had visual condition ratings (based on ODOT's modified SHRP method) that were worse than the control sections. Also, the ride values for the same sections as measured by a South Dakota-type profilometer were noticeably worse than the control sections (Hunt 2002).

ODOT also evaluated the use of CRM in open-graded mixes. The test sections constructed with PBA-6GR binder (an ODOT designation for asphalt cement modified with 10 to 12% CRM passing the 180 μm (No. 80) sieve, to meet a modified Performance Based Asphalt (PBA-6) specification) performed as well or better than the control sections. However the open-graded asphalt concrete mixes made with wet process high-viscosity binder and a wet-process no agitation type binder called "powdered rubber asphalt rubber cement" (PRARC), a PBA-2 with 15% CRM passing the 180 μm (No. 80) sieve and 6% extender oil were in worse condition than the control sections (Hunt 2002). These two studies illustrate differing performance outcomes for open-graded mix types.

The ODOT study also examined the use of a gap-graded dry-process PlusRide mix. The gap-graded nature of the mix provides space for the crumb rubber. No major problems were encountered during the handling or construction of this mix, but raveling occurred shortly after construction. Of all the mixes evaluated, the dry process mixes exhibited the worst performance. However several counties in Oregon, including Jackson, Linn, and Benton reported generally good experience with both wet and dry process gap-graded mixes (Hunt 2002). For the other dense-graded and open-graded mixes evaluated by ODOT, there were no major construction issues. The main difference in field operations in the study was that higher mix discharge and laydown temperatures were needed and utilized for the majority of mixes with wet-process binders. Higher temperatures (compared to unmodified control mixes) are necessary when using high-viscosity CRM-modified binders.

Washington

Other states including Washington tested a variety of mix types using wet process and dry-process CRM modification that have also resulted in variable performance. Open-graded mixes with wet process CRM-modified binders had inconsistent performance with some mixes performing exceptionally well (15 year service life under severe traffic conditions) and others exhibiting rutting problems after only four years of service (Hunt 2002). Some of the wet process CRM-modified binders used were high-viscosity materials and some were no-agitation type; this factor alone does not account for the variations in performance. Some dry-process PlusRide mixes using both dense- and gap-gradations respectively have shown very good performance in the state of Washington, and some CRM-modified sections have performed better than the conventional asphalt concrete control sections. However four of seven PlusRide projects constructed in Washington from 1982 through 1986 reportedly exhibited distresses ranging from flushing and rutting to cracking and raveling, with two early failures (Swearington et al, 1992). Some of this variable performance was attributed to problems with construction.

Alaska

In Alaska, PlusRide mixes (proprietary dry CRM modification process now replaced by generic method) exhibited good performance in resisting low-temperature and fatigue cracking and in improving ice control and surface frictional characteristics (Raad and Saboundjian 1998; Esch 1984). However in some cases there was relatively little difference in field performance between the dry process and control mixes.

Florida

The Florida Department of Transportation (FDOT) has conducted extensive research and field tests regarding the use of CRM. Two demonstration projects placed by FDOT in 1989 evaluated the constructability and short term field performance of various percentages of finely ground CRM pre-blended with asphalt cement (wet process-no agitation) in plant-produced, fine, dense-graded and open-graded surface course mixes using all virgin materials. A third demonstration project was constructed in 1990 to evaluate compatibility of these materials to a typical production project.

The first FDOT demonstration project, which included three test sections and a control section, focused on producing a fine dense-graded surface mix. Mix designs that incorporated wet-process (no agitation) binders with 3, 5, and 10% CRM by total weight of binder (3.1%, 5.3% and 11.1% by asphalt cement weight) were developed using the Florida DOT Marshall Mix Design procedure. Some problems were encountered during production and placement including the occurrence of mix pickup with the rollers. In the section with 10% CRM, the mix was tender and marked under traffic. Laboratory test results on plant-produced samples revealed that all sections except that containing the 10% CRM had Marshall stabilities comparable to the design values. The section with 10% rubber had a stability value that was half that of the design. It was theorized that the reduced stability might be due to high binder content and low “fines,” i.e., material passing the No. 200 sieve.

The second FDOT demonstration project included five test sections and one control section, and focused on producing an open-graded surface mix. Mix designs that incorporated 5, 10, 15, and 17 % CRM by weight of total binder (5.3 to 20% by weight of asphalt cement) into the mix were developed using a Florida DOT modification of the recommended FHWA procedure. The optimum asphalt content was determined and used for the 5% CRM mix. An additional 0.5% of asphalt was added for each 5% of additional rubber. The mixes with higher rubber and asphalt contents seemed to be “over-asphalted.”

The construction process indicated that total binder content corresponding to the 10% CRM had the best potential for mix design and construction. Although laboratory testing indicated that performance could be further enhanced by increasing the CRM content, FDOT chose to place more emphasis on staying within existing specifications for conventional mixes and on constructability than on optimizing the CRM-modified binder and mix properties (Page et al, 1992).

The final demonstration project used four test sections to determine if a new piece of equipment could be used to continuously blend and “react” the CRM with the asphalt cement. Mix tests showed that those designed with 10% CRM were close to design specifications. Also, it was concluded that existing equipment was suitable for production (Page, 1992). Dense-graded mixes were found to be more sensitive to changes in CRM particle size and binder content than open-graded mixes, which is a function of the amount of void space available in these respective mix types. Based upon the trial projects, FDOT drafted specifications for CRM use in its surface course (friction course) mixes. These have been validated and are still in use. For dense-graded friction (surface) courses, a requirement of 5% CRM passing the 300 μm (No. 50) sieve by weight of asphalt cement was selected. For open-graded surface mixes, 12% CRM passing the 600 μm (No. 30) sieve by weight of asphalt cement was recommended.

Ontario, Canada

The Ontario, Canada Ministries of Environment and Energy, and Transportation, funded and constructed 11 CRM asphalt demonstration projects between 1990 and 1992 and added 12 more projects in 1993. The first 11 projects were studied in more detail than the 1993 projects, and included 8 generic dry process (RUMAC) projects with variations in CRM gradation, content, and processing (cryogenic and ambient ground); two projects in which CRM was added during cold-in-place recycling of conventional pavements; and one project with a wet process, continuous-blending, no agitation CRM-modified binder. One of the RUMAC projects placed in 1990 failed and was plant recycled in 1991; as of 1994, performance of the recycled RUMAC pavement was variable, indicated by a range of ratings from “somewhat poor to very good” (Emery 1994). The cold-in-place recycled mixes with CRM added failed by widespread rutting and raveling shortly after being opened to traffic. Both were reprocessed with additional asphalt emulsion and overlaid with a conventional DGAC surface (Emery 1994). Control sections were not included in many of the projects, which made analysis more difficult.

The final report on the Ontario projects (Emery 1997) states that the dry process mixes with high concentrations (2% or more by aggregate weight) of coarse ground CRM (retained on the 4.75 mm (No. 4) sieve) did not perform as well as conventional DGAC, and exhibited early raveling and pop outs, and cracking along construction joints. Dry process mixes made with lower concentrations (1 to 1.5% by weight of aggregate) of finer CRM (passing the 2 mm (No. 10) sieve) performed comparably to conventional DGAC pavements. Few wet process mixes were evaluated; these were listed as performing as well or slightly better than conventional DGAC through 1997. Overall, conclusions were that the generic dry process was feasible but required further development of mix design and construction procedures to achieve the desired performance. Also, it was concluded that mixes made with wet process no agitation binders could be engineered to perform as well or better than conventional DGAC pavements.

Arizona

Arizona DOT (ADOT) has had excellent success with wet process high viscosity CRM-modified paving materials in locations throughout the state, in spite of the wide range of climate zones from hot, low desert (Yuma, Bullhead City) to high altitude, alpine where there is a real winter season (Flagstaff, Grand Canyon). ADOT routinely applies thin lifts (nominal ½- or ¾-inch thick) of open-graded asphalt rubber asphalt concrete friction courses (AR-ACFC, or ARFC) over existing and new pavements to provide good surface frictional characteristics and protect the underlying pavement from environmental aging factors. The AR-ACFC mixes include high contents of wet process high viscosity binders, typically about 9 to 9.5% by weight of mix. According to ADOT engineers, this is about 2% more than the amount of asphalt cement that can be included without excessive drain-down. Such high binder content mixes have proven to be highly resistant to reflective cracking and fatigue (Way 2000). On the Superstition Freeway (US 60), the AR-ACFC thickness was increased to one inch due to extremely high traffic volumes (over 100,000 ADT) and the overlay has performed very well to date. ADOT has identified an additional benefit in the noise reduction that was achieved on this urban freeway, which triggered a public demand to surface the entire freeway system in the Phoenix metropolitan area with AR-ACFC. ADOT uses gap-graded asphalt rubber asphalt concrete (GG ARAC) mixes for structural overlays. These mixes typically include 7.5 to 8% wet process high viscosity binder, which is about 2% more than the amount of performance graded (PG) asphalt cement that can be accommodated without excessive drain-down. The ARAC pavements are typically surfaced with ½-inch of AR-ACFC. ADOT does not use dry process mixes.

ADOT now allows wet process no agitation binders designated as PG 76-22 TR+ (tire rubber) in some gap-graded mixes. These binders include a minimum of 9% CRM, and have requirements for maximum phase angle and elastic recovery that make it necessary to add 1 to 2% elastic polymers. Such binders

have been used primarily at the request of contractors for projects with relatively low tonnage, and for spot repairs to ARAC or AR-ACFC pavements, i.e. in cases where it is not economical to use wet process high viscosity binders. Primarily for reasons of economy when only small batches of CRM-modified mix are needed, ADOT may choose to allow use PG 76-22 TR+ materials as an alternative to wet process high viscosity binders, but does not consider them as an equivalent. The significantly lower viscosity of the PG 76-22 TR+ limits binder content without excessive drain-down to only about 0.5 to 1% more than that of PG asphalt cement, which is at least 1% lower than would be achieved with high viscosity CRM-modified binders. ADOT does not use PG 76-22 TR+ in open-graded mixes.

California

In 1978, the first Caltrans dry process CRM HMA pavement was constructed on SR 50 at Meyers Flat. It included 1% CRM by mass of the dry aggregate added prior to mixing with the asphalt cement. Performance was rated good. The first Caltrans rubberized asphalt concrete (RAC) pavements made with early versions of wet-process high viscosity CRM binder and dense-graded aggregate were constructed in 1980 at Strawberry (SR 50) and at Donner Summit (I-80). The Strawberry project was an emergency repair to a dramatically failed pavement. The repair included pavement reinforcing fabric (PRF), and a 60 mm (0.2 ft, 2.4 inches) layer of DGAC to restore structural capacity, over which a thin (30 mm, 0.1 ft, 1.2 inches) RAC wearing course was placed. The first three projects are all located in “snow country” at high elevations where tire chains are used in winter. The RAC pavements reportedly performed well in resisting both chain abrasion and reflective cracking (Hildebrand and Van Kirk, 1996).

The Ravendale project (02-Las-395) constructed in 1983 significantly changed Caltrans approach to the use of wet process high viscosity CRM-modified binders. This project presented a typical dilemma. The cost of rehabilitation by overlaying with DGAC was prohibitive, so less costly alternatives were considered, including thinner sections of RAC. The project was designed as a series of 13 test sections that included two different thicknesses each of wet process (dense-graded) and dry process (gap-graded) RAC with 4 sections of wet process high viscosity stress absorbing membrane interlayer (SAMI), wet and dry RAC at 46 mm (0.15 ft, 1.8 inches) thick without SAMI (2 sections), four control sections with different thicknesses of DGAC from 46 to 152 mm (1.8 to 6 inches), two sections surfaced only by double asphalt rubber chip seals, and one section surfaced with a single asphalt rubber chip seal (Doty 1988). The test sections were monitored over time and the overall performance of the CRM materials (CRM-modified mixes, SAMIs and chip seals) was rated excellent by Caltrans (DeLaubenfels 1985). The dry process section at this site lasted over 19 years before it was overlaid in 2002, but performance of such pavements elsewhere has varied (Van Kirk, 1992).

Through 1987, Caltrans constructed one or two RAC projects a year. Dense- or open-graded RAC mixes were placed as surface courses at compacted thicknesses ranging from 24 mm for open-graded to 76 mm for RAC-D (0.08 to 0.25 ft). Some projects included PRF (pavement reinforcing fabric) and/or a leveling course, and others included SAMI under the RAC mixes. By 1987, it was clear that the thin RAC pavements were generally performing better than thicker conventional DGAC. Caltrans built more RAC projects and continued to study the performance of RAC constructed at reduced thickness relative to DGAC structural requirements.

In March 1992 Caltrans published a “Design Guide for Asphalt Rubber Hot Mix-Gap Graded (ARHM-GG)” based on these studies and project reviews. The Guide presents structural and reflection crack retardation equivalencies for gap-graded RAC mixes (RAC-G) with respect to DGAC, and with and without SAMI. These equivalencies have since been validated and incorporated in Chapter 6, Tables 3 and 4 of the Caltrans Flexible Pavement Rehabilitation Manual (June 2001). RAC-G can generally be substituted for DGAC at about one-half the DGAC thickness.

By 1995, over 100 Caltrans RAC projects had been constructed. Cities and counties in California had by then constructed more than 400 asphalt rubber projects, including asphalt rubber chip seals. However

some problems occurred, including some cases of premature distress. Caltrans engineers reviewed RAC performance on the Caltrans projects, selected California city and county projects, and 41 Arizona DOT projects. Some of the problems observed were clearly construction related; many of the contractors involved in those projects had little if any experience working with the RAC mixes (Hildebrand and Van Kirk, 1996).

The Caltrans review indicated that CRM materials can perform very well when properly designed and constructed, and that Caltrans should continue using and studying high viscosity wet process binders. A very important finding was that the distresses observed in RAC pavements generally appeared to progress at a much slower rate than would be expected in a structurally equivalent conventional DGAC pavement. In many of the cases where premature RAC distress (particularly cracking) had occurred, relatively little maintenance was required to achieve adequate pavement service life because the subsequent distress developed slowly. One-third of the Strawberry RAC pavement was reportedly still exposed and performing after 15 years, with less maintenance resources and time expended than for all pavements in that district with the exception of another RAC section (Hildebrand and Van Kirk, 1996).

By mid-2001 Caltrans had constructed more than 210 RAC projects throughout the state. Municipalities and counties also continued to use asphalt rubber for hot mixes and surface treatments with generally good performance. However some of the old problems with product selection, design, and construction continue to arise. Districts 7 and 8 reportedly experienced several major RAC failures.

Los Angeles County, California

The Los Angeles County Department of Public Works (Public Works) has specified the use of RAC in its road resurfacing and maintenance program for almost 15 years. RAC was first used in 1985 and by 1992 it was used extensively. LA County considers itself a leader in the use of RAC among cities and counties, and since 2001 nearly half the tonnage of AC placed in LA County has been RAC.

The County has used wet process high viscosity and no agitation binders, respectively, in RAC mixes, and has also used the dry process. They report that although some problems with material being produced out of specification and workmanship have occasionally occurred, no systematic or inherent problems have been experienced with wet or dry process RAC mixes. Public Works has used the Greenbook Standard Specifications for Public Works Construction exclusively without modifications.

Public Works has placed RAC in both designed thicknesses (based on deflection testing or gravel equivalent methods) and in non-designed thicknesses. Public Works specifies a minimum thickness of 1.5 inches for RAC mixes, and applies the Caltrans reduced thickness design criteria only to asphalt rubber hot mix (ARHM) which is made with high viscosity wet process binder. Many County projects include both resurfacing and reconstruction segments, and RAC has been specified as the surface course for each. While no reduction in thickness is permitted in the reconstruction surface course application, the additional tonnage of RAC provides further economies of scale and a uniform surface course over the entire project limits.

Many of the RAC project are approaching 10 years of service and still performing well. A detailed quantitative and quality study of LA County streets and roads which have been surfaced with RAC has been proposed. Based on the overall positive experience, LA County plans to continue its extensive use of RAC.

Summary

Review of the referenced studies indicates that the performance of CRM paving mixes has been highly variable not only from state to state, but also within a state. The range of performance experienced by ODOT is but one example.

However, overall field and laboratory results for a wide variety of mix types (dense graded, gap graded, and open graded) and crumb rubber modification processes (wet high viscosity, wet no agitation, and dry with various CRM gradations) evaluated by various organizations and researchers, indicate that wet process mixes yield more consistent and better performance than dry-process mixes (Madapati et al. 1996; Choubane et al. 1999; Hunt 2000; Volle 2000). Although most agencies that have used the dry process have found improved performance versus DGAC control mixes when an open- or gap-graded mix is utilized to accommodate the CRM, some dense-graded dry process mixes with fine CRM (passing the 300 μm (No. 50) sieve have provided satisfactory performance (Huang et al. 2002).

A number of studies (Amirkhanian 1993; Eaton et al 1991; Hansen and Anderton 1993; Khandal 1993; Lundy et al 1993) indicate that one of the reasons that the wet process generally seems to provide a more consistent product is because even when CRM is used as an aggregate substitute rather than a binder component, there is potential for some low-level interaction between the asphalt cement and CRM. In the wet process, most of the interaction has been completed before the CRM binder is mixed with the aggregate and any subsequent interaction is usually minor unless the binder is heated long enough to depolymerize the CRM. CRM has an affinity for absorbing light fractions of the asphalt cement and when added dry without any pretreatment, it may do so over time even within an in-place paving mix. One of the primary modes of distress reported for dry process mixes is raveling, an indicator of insufficient asphalt content which may be a function of the mix design and/or mix production. The mix design must provide sufficient asphalt cement to compensate for absorption by the CRM, and resulting mixes may have to be produced somewhat binder-rich to avoid raveling and provide long term durability (Emery 1995). The Hveem mix design method requires long-term oven aging of the loose mix (15 to 18 hours) which should substantially account for the asphalt cement absorbed by the CRM. The Marshall method does not require such aging, although knowledgeable designers often cure mixes with potential for high absorption (by aggregate or CRM) for up to 4 hours.

Overall, gap-graded CRM mixes made with wet and dry processes seem to perform better and more consistently than dense-graded CRM mixes. The gap-gradation provides sufficient void space to accommodate CRM particles finer than the 2.0 mm (No. 10) sieve, particularly when using wet process high viscosity materials. Higher binder contents typically improve durability and resistance to reflective and fatigue cracking of HMA in general, whether CRM or conventional.

Dense-graded mixes can accommodate only limited CRM modification due to limited void space in the aggregate matrix/structure, and are sensitive to minor changes in binder content and CRM gradation. CRM modification (wet or dry process) of dense-graded mixes is best accomplished using fine CRM gradations (passing 300 μm (No. 50) sieve size or finer). Field performance of properly designed dense-graded CRM-modified mixes typically differs little from that of conventional DGAC.

Open-graded CRM mixes appear to perform well when designed with sufficient binder (without excessive drain-down) to avoid raveling. Although open-graded mixes include sufficient void space to use coarse CRM gradations (retained on the 4.75 mm (No. 4) sieve), findings for dry process mixes indicate that use of coarse CRM increased the frequency and severity of raveling, pop-outs, and cracking (particularly along construction joints) compared to mixes made with finer CRM (passing the 2.0 mm (No. 10) sieve) material. Wet process binders for hot mix use CRM passing the 2.0 mm (No. 10) sieve or finer CRM. High viscosity binders minimize drain-down and permit binder contents to be increased to 9.5 or 10% by weight of mix, which has provided very good pavement performance and durability.

Membranes- Surface and Interlayers

In addition to its use in HMA mix types, CRM has also been used in membranes: in chip seals which are placed on the surface; or stress absorbing membrane interlayers (SAMIs) which are chip seals placed between pavement layers. A chip seal is a maintenance tool used primarily to restore surface friction and seal distressed pavement surfaces from further infiltration by surface water.

Although it seems that chip seal construction should be a relatively simple and straightforward process, it is actually very sensitive to a number of factors, particularly site conditions including ambient temperature and condition of the cover aggregate. This sensitivity accounts for some of the variability in reported performance of CRM chip seals. Appropriate CRM binder (typically wet process high viscosity) and uniform spray application rate are critical. Also, high-natural rubber content CRM has been shown to enhance chip retention (Hildebrand and Van Kirk, 1996). The aggregate chips must be large enough to handle the expected vehicle traffic and to protrude above the binder membrane. A single size fraction of aggregate is preferred, but not all specifications include this feature. Use of graded chips may interfere with adhesion and embedment of the larger sizes. The chips must be clean, as any dust coating will interfere with adhesion to the membrane. Ideally, chips should be heated and precoated with paving grade asphalt to kill the dust and promote embedment and adhesion. Temperature (ambient, membrane and chips) is critical to obtaining embedment and adhesion of chips. Chip application rate is also important and may require adjustment during construction. Applying too few chips leaves areas of binder exposed, resulting in bleeding and pick-up by tires. Excess chips tend to displace embedded chips, causing the same types of distress. Chip retention is not an issue with interlayers, as the hot mix asphalt concrete overlay (modified or conventional) will hold the chips in place.

Rhode Island

The use of preventive maintenance treatments such as surface treatments can extend pavement life by 5 to 6 years and stretch highway funding. The Rhode Island Department of Transportation (RIDOT) has been able to add life to existing pavement and expects to save money on repairs and labor through the use of asphalt-rubber repair techniques and other "thin" resurfacing treatments. Upon examining roads for deterioration, RIDOT applies treatments such as asphalt-rubber chip seals or SAMIs on large resurfacing projects that are at the appropriate condition level. The treatments have proved to be cost effective for RIDOT because the treatments are quick to apply (reducing labor costs) and have material savings due to the reduced amounts of material used for such applications (Courret 2000).

City of Phoenix, Arizona

The City of Phoenix began placing asphalt rubber chip seals in 1969 using wet process high viscosity binder. After initial issues with chip loss were resolved, overall performance was considered to be very good and the City made extensive use of this maintenance tool. Asphalt rubber chip seals were first placed over severely distressed and fatigued asphalt concrete pavements that were designated for reconstruction, in an attempt to maintain serviceability until funding became available for reconstruction (Schnormeier, 1986). Some of these pavements were major arterial streets with high traffic volumes. An asphalt rubber chip seal remained on a freeway frontage road for 17 years before reconstruction, and a chip seal on a major arterial street lasted nearly 15 years. Reports indicate that reflective cracking generally took 8 to 10 years to manifest through such seals and that maintenance requirements were significantly reduced over the life of the chip seal. Reports also indicate that such surface seals significantly reduced the amount of surface water that infiltrated into the underlying pavement structure. The City obtained significant extension of pavement life by applying asphalt rubber chip seals, typically 8 to 10 years, and in some cases nearly twice that – 16 to 20 years. Asphalt rubber chip seals were also used for new construction of residential streets in some areas. However chip sealing of major arterial streets became impractical as traffic volumes increased and pilot cars were no longer able to control traffic (Charania, Cano and Schnormeier, 1991). This forced the City to develop a substitute treatment, which evolved into thin lifts of gap-graded asphalt rubber concrete hot mix.

Arizona

Arizona Department of Transportation (ADOT) has made extensive use of asphalt-rubber materials in the construction and rehabilitation of pavements for more than 25 years. Besides incorporating wet process

high viscosity CRM-modified binders into gap- and open-graded asphalt paving mixes, ADOT has also used high viscosity binders in chip seals as stress absorbing membranes (SAMs) and stress absorbing membrane interlayers (SAMIs) on a substantial portion of the pavement network. ADOT has also placed three-layer systems which include a layer of asphalt concrete (typically conventional DGAC), an asphalt rubber SAMI, and a surface course of conventional or CRM HMA. However, ADOT's use of SAMIs has declined as design policies have varied.

Previous studies by ADOT in 1989 indicated that SAMs had an average service life of 5.3, 10.0, and 8.2 years on Interstate highways, state routes, and U.S. routes, respectively. The investigation also revealed that typical service life for SAMIs was 9.0, 9.5, and 7.8 years for Interstate highways, state routes, and U.S. routes, respectively. From a 1994 study, data were extracted from the pavement management system (PMS) to evaluate the service life, roughness, and cracking characteristics of the various asphalt rubber materials. The service life data obtained during the study showed either increased or the same service life compared to the values obtained in 1989. For example, the SAMs were found to have an average service life of 6.4, 10.3, and 8.9 years while the SAMIs had an average service life of 10.7, 9.5, and 10.7 for Interstate highways, state routes, and U.S. routes. The analysis also resulted in the development of rates of roughness and cracking occurrence with time on SAMs and SAMIs for each of the route classes. Data regarding three-layer systems are more limited and only general conclusions could be drawn from the data available in 1994 (Flintsch, Scofield, and Zaniewski 1994).

California

In 1975, Caltrans began experimenting with asphalt rubber chip seals in the laboratory and small test patches located in Yolo and Sacramento counties with generally favorable results. In 1983, SAMIs were included in the Ravendale project, an experiment that included 13 test sections and yielded results that significantly changed Caltrans approach to the use of asphalt rubber (Doty 1988). The test sections included two different thicknesses each of wet process dense-graded and dry process gap-graded AC, with and without SAMI, four control sections of DGAC each at a different thickness, and sections surfaced only with single and double asphalt rubber chip seal. Based on the findings of this project and subsequent research, Caltrans developed structural and reflection crack retardation equivalencies for gap-graded rubberized asphalt concrete (RAC-G) with respect to DGAC, and with and without SAMI-R. Table 3 of the Caltrans 2001 Flexible Pavement Rehabilitation Manual indicates that when required RAC-G overlay thickness for structural purposes is at least 0.15 feet (1.8 inches, 46 mm) a SAMI-R may be substituted for an equivalent 0.05 foot (0.6 inch, 15 mm) of RAC-G. Table 4 of the Rehabilitation Manual shows the same 0.05 foot equivalency for use of SAMI-R to retard reflective cracking in an overlay.

Caltrans requires use of extender oil and high natural CRM in CRM-modified chip seal binders. The high natural CRM has been demonstrated to enhance chip retention. However, the benefits of extender oil in chip seal binders are not as apparent. Occasional problems with tenderness, bleeding, and flushing of CRM-modified chip seals have been reported, particularly in southern California, which may in some cases be related to the use of extender oil in hot climate areas. To provide stiffer CRM-modified chip seal binders, Caltrans District 8 is considering substituting AR-8000 for AR-4000 as the base asphalt cement.

Los Angeles County, California

The Los Angeles County Department of Public Works (Public Works) reports that it has utilized Asphalt Rubber Aggregate Membranes (ARAM) in its pavement rehabilitation and preservation strategies for the past four years. ARAM is increasingly being used as an interlayer to retard reflective cracking on resurfacing projects as part of a two or three layer system. Resurfacing of some rural roads and urban arterial streets has been designed using a two layer system. Resurfacing over existing PCC pavement is designed almost entirely using a three layer system. ARAM has also recently been used in a cape seal

(slurry seal over CRM-modified chip seal) placed on local streets. To date Public Works reports that it has been very pleased with the performance of ARAM.

Florida

FDOT began investigating the use of CRM for interlayers and binders for seal coats about the same time as ADOT. Based on the findings of a demonstration project reported in 1980, (Murphy and Potts, 1980) FDOT allowed the use of CRM in surface treatments and interlayers in selected projects. A considerable length of I-10 in Florida includes CRM interlayers under surface overlays. FDOT SAMI binders include 20% CRM (passing the 1.18 mm (No. 16) sieve) by weight of asphalt to yield a high viscosity material.

Texas

As part of the Texas Department of Transportation's (TxDOT) Supplemental Maintenance Effectiveness Research Program, TxDOT studied several of its commonly used maintenance treatments. Examination of asphalt rubber chip seals was included in the evaluation. Statistical analysis of the condition information for the respective test sites showed that wet process high viscosity (asphalt rubber) chip seals were effective at reducing reflective cracking, especially for pavement sections that exhibited relatively high concentrations and/or severity of cracking prior to treatment. However, asphalt rubber chip seals did not increase the life of sections that exhibited bleeding, and in some cases had a negative effect due to the additional asphalt. The study noted that in most cases the use of the asphalt rubber seal coat improved the performance condition index (PCI) and helped to retard the rate of pavement deterioration. Overall, the study showed that under appropriate conditions (no bleeding or instability of the existing underlying pavement) the use of asphalt rubber chip seals was a good treatment option (Freeman et al. 2002).

Asphalt rubber chip seals are a routine rehabilitation strategy in some TxDOT districts (Tahmoressi, 2001). TxDOT representatives report that wet process no agitation binders are now used for the majority of chip seals. The reason is that high viscosity CRM binders are customarily applied at relatively high rates of 0.5 to 0.6 gallons per square yard, and thus require use of properly-sized aggregate chips (5/8-inch maximum size) that protrude above the membrane to avoid flushing and bleeding. However, such coarse chips are considered too noisy for surface use in many areas. The high viscosity binders are thus used primarily for SAMIs or in rural areas (MACTEC Materials Survey 2004). Whether used on the surface or in between pavement layers, the high viscosity binders have been observed to provide good to excellent resistance to reflective cracking and good chip retention. The literature does not indicate how many of the chip seals reviewed in 2001 included high natural CRM (Tahmoressi, 2001).

Summary

CRM chip seals use wet process binders. High viscosity binders allow for higher application rates than no agitation binders, but the aggregate chips need to be sized accordingly (nominal 1/2-inch to 5/8-inch maximum size) to avoid flushing and bleeding. Heavier binder application rates appear to promote durability and increase the service life of chip seals, but such seals should not be applied to pavements that are flushing or bleeding. Chip seal construction is sensitive to a number of factors and good practices are required when working with highly modified materials to achieve a good finished product.

Although both Arizona and Florida have shown overall good performance of membrane layers, the experience of other states (including California) as reported by Flintsch, Scofield, and Zaniewski (1994) has been mixed. Experience since 1994 has also yielded mixed results. How much of the reported variability is due to materials or to construction issues is still not clear.

CRM-modified SAMIs have proved effective as crack interruption layers in reducing the onset and severity of reflective cracking. Based on field performance data, Caltrans has assigned a minor structural

and reflective cracking equivalency of 0.05 ft (15 mm) of RAC-G to SAMIs. SAMIs have been widely used in Florida and have performed well.

2.3.3 Materials Selection and Design

Due to the variety of materials utilized in CRM paving materials, there are numerous issues relating to selection and design. Physical and engineering properties of modified binders are highly dependent on the unique interactions between the component materials: asphalt cement and CRM. These interactions depend primarily on respective chemical and physical properties of the asphalt cement and CRM, as well as CRM particle size and gradation, and interaction temperature and time. Some combinations of high quality asphalt and CRM materials which individually meet specification requirements are not compatible and cannot produce a satisfactory blend. Aromatic extender oils and high natural rubber content CRM can be used to eliminate issues of compatibility. However, extender oils are expensive and typically increase emissions of aromatic and volatile compounds at high temperatures.

Crumb Rubber Modifier (CRM)

Throughout the numerous studies various types and sizes of scrap tire and other CRM materials, including but not limited to scrap tennis balls and mat rubber, have been tried and tested. Much of the work specifically related to CRM was included in reports on binders and is discussed in the next section; the overlap of these two highly inter-related topics makes separation difficult.

CRM materials are typically defined as either ambient or cryogenically processed. Ambient processing consists of grinding the scrap tire rubber at room temperature. Cryogenic processing cools the rubber below its embrittlement (glass transition) temperature with liquid nitrogen and shatters it in a hammer mill (Witzak 1991). This method yields CRM particles with a smooth glassy surface with low ratios of surface area to volume and limited contact area for the interaction with the asphalt cement. Most studies have focused on the use of ambient CRM for wet process binders because it has been established that ambient grinding provides irregularly shaped particles with relatively large surface areas with respect to particle size. This promotes contact and interaction with the asphalt cement (Hicks et al, 1995; Baker 1993). To minimize processing costs, CRM specifications typically allow cryogenic processing for initial size reduction, but require finish grinding at ambient temperatures.

The overall literature review indicates that Ontario may be the leader in the use of cryogenically processed CRM. Ontario's experience indicates no apparent differences between the cryogenic process CRM and the ambient process CRM (Emery 1995). However most of the Ontario sections were dry process mixes. Of the wet process materials used, most were no agitation binders with relatively low contents of fine CRM for which cryogenic processing would have the least impact. These demonstration projects don't provide sufficient data to allow one to draw definitive conclusions as to the effect of the grinding process on physical properties of the binders and pavement performance.

In addition to the method of processing the CRM, the source of the rubber also has a significant effect on the properties of the material. Specific studies have shown that rubber materials from different sources have different chemical compositions which result in varying properties when incorporated with asphalt binder using the wet-process (Green and Tolonen, 1977; Pavlovich, Shuler & Rosner, 1979; Rosner & Chehovits, 1982; Abdelrahman and Carpenter 1999).

For purposes of this report, the primary sources of CRM are scrap tire rubber from passenger vehicles and heavy trucks, which contain varying amounts of synthetic and natural rubber compounds respectively. Furthermore, tread rubber has a different composition than sidewall rubber for both passenger and truck tires and tire rubber formulations change over time with advances in tire technology. Most CRM includes a variety of rubber and other compounds (Baker, 1993). The chemical specifications for scrap tire CRM

listed in the Caltrans Standard Special Provisions for Asphalt-Rubber Binder represent typical ranges of chemical composition of whole tire rubber, incorporating both the tread and sidewall materials, at the time these specifications were developed (Baker, 1993). The intent was to require the use of scrap tires.

The literature does not indicate whether the chemical requirements for high natural CRM are based on the scrap tennis ball rubber that served as an early source of this material. Truck tires have replaced scrap tennis balls and mat rubber as the primary source of the “high natural” rubber material required by Caltrans. Natural rubber depolymerizes relatively quickly and thickens the asphalt cement phase of CRM binders, which helps to promote interaction with other rubber compounds in the scrap tire CRM. Natural rubber has also been found to enhance adhesion of aggregates in chip seals (Hildebrand and Van Kirk, 1996).

Because of the chemical complexity of CRM and asphalt cement, it has not been possible to develop a purely chemical approach to designing CRM paving materials. CRM binder designs must be performed with the proposed CRM and asphalt cement to assess compatibility and physical properties. That said however, ADOT, FDOT and TxDOT do not require the addition of high natural rubber content CRM to wet process high viscosity binders (MACTEC Materials Survey 2004).

Gradation and concentration of the CRM also have significant effects on resulting binder properties (Green and Tolonen, 1977; Pavlovich, Shuler & Rosner, 1979; Rosner & Chehovits, 1982; Abdelrahman and Carpenter 1999). Coarser rubber particles increase viscosity. Increasing rubber concentrations also increases viscosity. Finer rubber particles, particularly those passing the 300 μm (No. 50) sieve, are more quickly digested. Although high concentrations of fine CRM particles may initially provide significant increases in binder viscosity, continued interaction at elevated temperatures promotes digestion of the CRM which reduces binder viscosity.

Examples of the effects of CRM on binder properties are presented in the next section on CRM-modified binder. An example of the effects of rubber composition that supports findings of previous studies (including those referenced in the preceding paragraph) using a different approach is a study conducted by Abdelrahman and Carpenter (1999). This study used the Superpave Performance Graded (PG) binder tests to characterize the binders instead of the conventional methods; e.g., resilience, softening point and penetration. The variables were CRM composition and particle size. Four different CRM materials were evaluated at 10% CRM (by weight of asphalt cement) with an AC-10 asphalt cement (wet process- no agitation). The four CRMs examined included three ambient processed products: BLEND, SBR, and NR. The BLEND rubber is a combination of both natural and synthetic rubber. The SBR rubber is made mostly of synthetic rubber (styrene-butadiene) and the NR rubber is mainly natural rubber. The fourth product evaluated was a cryogenically processed CRM, CRYOG. Each CRM was tested at two particle sizes: the fine gradation consisted of CRM passing the 250 μm (No. 60) sieve and retained on the 80 μm (No. 80) sieve; the coarse gradation consisted of CRM passing the 600 μm (No. 30) sieve and retained on the 425 μm (No. 40) sieve. The CRM gradation selected was influenced by the size of the gap of the dynamic shear rheometer test equipment and does not necessarily represent typical CRM gradations used in paving applications. However, the findings correlated with observed field and laboratory behavior of asphalt modified with coarser CRM materials.

The study results showed that the interaction process affects the binder properties of shear modulus (G^* , a measure of stiffness) and the phase angle, δ . Also noted during the study was that the swelling of rubber particles decreases the distance between particles (increasing the filler concentration) and absorbs the lighter fractions which makes the binder matrix stiffer. For the CRMs in the study, higher test temperatures cause depolymerization to occur, which releases rubber components back into the liquid phase. The result of depolymerization is a decrease in the shear modulus (stiffness) and ultimately the phase angle of the binder returns to its original unmodified value as the added elasticity is degraded.

In terms of particle size, the research showed that the fine rubber swells and depolymerizes faster than coarser rubber particles especially at the higher temperatures, which causes a stiffer binder with increased elastic component (reduced δ) until depolymerization is complete. At intermediate and high temperatures, the effect of the rubber source and gradation on the binder behavior is evident. Even when subjected to the same interaction conditions, the different rubber sources and gradations yield different interaction profiles. For example the BLEND and SBR were observed to be more reactive than the NR and the CRYOG, based on rate and extent of change in properties. The results of this study underscore the importance of CRM composition, particle size, and overall interaction time and temperature on the resultant binder properties (Abdelrahman and Carpenter 1999).

Representatives of TxDOT and FDOT reported that there are significant problems with the control and consistency of the gradation of CRM materials currently supplied. In Florida, CRM gradation issues are affecting the uniformity and quality of CRM binders. Non-compliance with CRM gradation requirements has become so widespread that FDOT is currently substituting polymer-modified asphalt cements for CRM binders on the interstate routes (Jim Musselman, October 15, 2004 RACTG meeting). Caltrans has also encountered issues with CRM gradation compliance, which were the subject of several meetings of the joint Caltrans/Industry CRM Gradation Subcommittee from 2001 through 2003. Sampling and testing were evaluated as possible sources of variability in gradation testing and improvements to sampling methods were suggested.

Crumb Rubber Modified Binder

Several methods of wet process modification described in this chapter were used in various laboratory research programs and/or in field trials encountered in the literature review. However, the literature review revealed a glaring lack of data on the basic physical properties of the various wet process binders used in many of the laboratory and field evaluations. Very few of the reports reviewed indicated that any type of specification compliance type testing was performed on the subject CRM binders, and only rarely were any of those test results included. Considerably more results of the Superpave PG type testing are presented (which may or may not be applicable to high viscosity binders) than results of rotational viscosity (Haake-type, field go-no go test), resilience, and softening point tests upon which the high viscosity binder specifications used by ADOT, Caltrans, FDOT and TxDOT are based. This lack of fundamental information makes it difficult to assess the value of many of the studies reviewed, as it is rarely clear whether the CRM binders used in specific studies would have been considered suitable for the use to which they were put. Inferences can and have been made regarding which CRM binders would have been high viscosity or no agitation, based on CRM content and gradation. However the omission of such basic property information indicates that many of the researchers did not understand the important effects of CRM binder properties on the performance of the resulting CRM mixes, chip seals or interlayers.

The chemical and physical attributes of the CRM have significant effects on the resulting properties of wet-process CRM-modified binders. So do the chemical and physical properties of the asphalt cement. Because these properties are so complex, the only way to determine if particular CRM and asphalt materials can interact to provide a suitable modified binder is to blend and interact them in the laboratory and to obtain and test samples for specification properties over a 24-hour period. The full interaction process between asphalt cement and CRM consists of two main types of mechanisms that affect the produced binder properties: particle swelling and degradation (devulcanization and depolymerization). As the CRM particles swell, a gel phase develops along the particle boundaries. These mechanisms occur as the binder is subjected to different combinations of interaction time and temperature. During the creation of the CRM-modified asphalt, an increase in temperature results in an increase in the rate of swelling along with a decrease in the extent of swelling. Also, the particle size of the CRM modifier has been shown to control the swelling mechanism and affect the binder matrix. In fact, the time required for swelling increases with the particle radius squared. The occurrence of depolymerization and

devulcanization involves the reduction in the molecular weight of the rubber while the chemical reactions break the chemical bonds (Abdelrahman and Carpenter 1999).

During the early development of wet process high viscosity modification, two methods were patented. A patent search (MACTEC, March 2002 for Caltrans METS) showed that in 1975, a private individual (Charles MacDonald) obtained Patent No. 3,891,585 “Elastomeric pavement repair composition for pavement failure and a method of making the same,” the ingredients of which consisted of paving grade asphalt and processed reclaimed or unprocessed rubber buffings. Another similar patent, No. 4,069,182 “Elastomeric pavement repair composition”, was granted to the same individual in 1978, based on the same two constituents. This method of modification later came to be designated as “Type 1”. Also in 1978, an oil company in California was granted Patent No. 4,068,023 “Rubberized asphalt paving composition and use thereof” which included high natural rubber and high aromatic mineral oil solvent (extender oil) in addition to paving grade asphalt and reclaimed tire rubber. This method of modification later came to be designated as “Type 2”. These patents expired in 1992.

In the early 1990s, Caltrans treated Type 1 and Type 2 CRM binders as bid alternatives and allowed use of each as equivalent wet process high viscosity binders. The Caltrans Design Guide for ARHM-GG (RAC-G) Memorandum dated February 28, 1992 includes specifications for both Type 1 and Type 2 binders. Based on the 1996 project review by Hildebrand and Van Kirk, Caltrans chose to eliminate use of Type 1 binders. FDOT and TxDOT allow use of Type 2 binders, but do not require it. They report that only Type 1 binders are used. ADOT specifies only Type 1 binders.

A different method of wet process modification was developed by a CRM producer that reduced interaction time and temperature by continuous blending of “powdered” rubber (fine CRM, i.e., passing the 180 μm (No. 50) sieve) with the paving grade asphalt. Interaction temperature was reduced to a range of 135 to 149°C (275 to 300°F). The resulting product was a wet process no agitation binder.

It is important to remember that wet process binders are a two-phase system with CRM particles dispersed in the asphalt phase, which is in turn modified by absorption of its light fractions into the CRM phase. High natural rubber content CRM depolymerizes more quickly than most scrap tire CRM at high temperatures and further modifies and thickens the asphalt phase (Green & Tolonen, 1977; Pavlovich, R.D, T.S. Shuler & J.C. Rosner, 1979; Rosner & Chehovits, 1982). These studies also provided evidence that when the CRM is heated above approximately 121°C (250°F) it begins to release compounding oils similar to extender oils that make up about 25% of its composition, indicating an exchange of light fractions. The aromatic extender oils that Caltrans requires include additional light fractions to promote the CRM-asphalt interaction and minimize problems with compatibility.

There are two schools of thought regarding crumb rubber modification. Some researchers believe that modification should provide a homogeneous system that does not require agitated storage. This approach requires that the CRM be depolymerized and completely digested into the liquid phase of the binder. Depolymerization typically requires application of elevated temperatures over time, which consumes considerable energy. Depolymerization significantly reduces viscosity and elasticity from initial levels, the very properties that the designer considers to be of greatest benefit. These properties govern the use of CRM in HMA and chip seals. Depolymerization results in a decrease in shear modulus (G^*) and the phase angle, δ , returns to its previous unmodified value (Abdelrahman and Carpenter 1999). In other words, the beneficial effects of modification are lost as a result of depolymerization.

Wet process no agitation binders typically use low concentrations ($\leq 10\%$ by weight of asphalt, although higher concentrations may be used) of fine CRM (passing the 300 μm (No. 50) sieve) particles small enough to remain in suspension by normal circulation in the storage tank. The rubber particles are not necessarily depolymerized, and may or may not be completely dissolved; there is no requirement that they must be. Caltrans, FDOT, TxDOT and ADOT do use varying amounts of wet process no agitation CRM-modified binders. FDOT uses these in dense- and open-graded AC mixes, but not in SAMIs. TxDOT

uses them in surface seals and dense-graded mixes, but not in SAMIs. ADOT allows no agitation binders as an alternate but not an equal to high viscosity binders in some gap-graded mixes. Summary tables of CRM gradation requirements, and of specifications for respective wet process no agitation materials are included in the specification section of this report; further related information is included in Appendix B. Based on verbal reports regarding this type of binder from representatives of ADOT and FDOT to the Caltrans Rubberized Asphalt Concrete Task Group (RACTG) at a meeting on October 15, 2004, not all of the fine CRM particles dissolve; some remain distinguishable. However, the TxDOT representative reported that the CRM used in TxDOT AC-20-5TR for surface seals is completely digested.

Caltrans developed the Modified Binder (MB) specification in the early 1990s as part of a continuing movement towards performance-based specifications from method type or “recipe” specifications. MBs are typically wet process no agitation materials and there is no minimum viscosity requirement. This specification requires that the CRM pass a 600 μm (No. 30) sieve size, but sets no minimum CRM content requirement and does not require use of high natural CRM. Based on analysis of rheological measurements of samples of asphalt rubber binders and limited evaluations of their field performance, Caltrans researchers developed two new parameters for specifying rubberized binders, using residues aged in the Pressure Aging Vessel (PAV).

- Shear susceptibility of the phase angle delta, SSD, which is related to elastic properties, and
- Shear susceptibility of viscosity, SSV, which is related to stiffness.

Ten pilot projects were constructed between December 1997 and November 1999 to evaluate the performance of materials meeting the MB specification. The MB pilots are located mostly in the coastal regions of California and include both dense-graded and gap-graded mixes placed over a range of structural sections. These projects were reviewed by a joint Caltrans-Industry group: eight were rated as “good,” one as “fair”, and one that exhibited base failure and pumping as “poor”. Caltrans has prepared a report on these MB pilot projects (Hicks and Holleran 2002). However, findings to date are limited and additional research is in progress. Heavy vehicle simulator (HVS) trials are currently being conducted at the University of California Berkeley to provide further data. In 2004, new test sections of Type D (dense) and Type G (gap) MB were constructed at Firebaugh as part of a large field experiment, and Type G MB was used for the fifth pilot RAC Warranty project in District 2. Samples have been obtained for laboratory testing by Caltrans and/or UC Berkeley, and the condition and performance of these MB pavements will be monitored over time.

The second school of thought is that discrete rubber particles are actors in the CRM binder that promote high viscosity ($\geq 1,500$ cPs at 190°C (375°F) per Caltrans) and elasticity (resilience, reduced phase angle), and also serve as actors in the resulting mix by affecting the void structure. Current Caltrans, ADOT, FDOT, and TxDOT specifications for wet process high viscosity binders are written based on the second school of thought, thus limiting depolymerization of the CRM in the binder by limiting the interaction period and requiring minimum viscosity values.

The research by Abdelrahman and Carpenter (1999) indicates that the noted increase in shear modulus of rubberized binders appears to occur during the swelling of particles. This interaction mechanism seems to differ from the mechanism that controls the change in the rubberized binders’ elastic properties. Instead, the devulcanization and depolymerization seem to decrease the phase angle of the asphalt binder until depolymerization is complete and the phase angle converges on that of the original base asphalt cement.

Additional studies using the PG binder tests and proposed alternate Superpave methods for modified binders were also conducted by the Wisconsin DOT to evaluate the effect of CRMs in asphalt binders. Extensive laboratory tests revealed that CRM does affect properties of the binder and that the effects vary with the gradation and concentration of CRM added. Specifically, there was an increase in viscosity of the binder as the size of the CRM decreased and the concentration increased. Other property changes noted in the CRM binder included higher strain dependency, increased strain at failure and increased

stress at failure (Loh, Kim and Bahia 2000). Overall the studies showed the need for laboratory testing of each modified binder to assure that physical properties are appropriate and meet specification requirements.

It has generally been accepted that wet process high viscosity binders should be designed in the laboratory to assure that they meet requirements over a 24-hour period to evaluate stability of the interaction. Each combination of CRM and asphalt cement provides a distinctive design profile of the change in the specified physical properties over time that can be used as a guide for quality control and assurance during modified binder production. Significant departures from the profile may indicate issues with proportioning or changes in materials that must be addressed to provide the desired finished pavement product.

Rubberized Asphalt Concrete (RAC) Mixes

The selection of CRM materials and the resulting binder properties are essential components for RAC design of a suitable rubberized asphalt concrete (RAC) mix. The study conducted by the Wisconsin DOT not only characterized the CRM binders but extended it by testing the mix. The results showed that the incorporation of CRM affects the air void content and frictional resistance of the mix and is dependent upon the material characteristics and stage of densification. Effects of CRM gradation on air void structure and content are supported by considerable laboratory and field experience of several agencies, including Arizona (Way 2000), Kansas (Fager, 2001), Florida (Ruth, 1989), and Rhode Island (Madapati et al, 1996) among others. Coarser, larger particle size CRM gradations (minus 2.36 mm (No. 8) to retained 600 μ m (No. 30) sieve sizes) tend to increase air voids content and the size of the resulting voids may be larger as occurs when coarse, relatively large aggregate particles are used in AC. Finer CRM (minus 600 μ m (No. 30) sieve size) is more likely to fill air voids, and thus to reduce air voids content with relatively little effect on the size of the air voids.

Rhode Island

Rhode Island DOT (RIDOT) examined the use of CRM in dense-graded, dense-graded friction course (surface mix that provide desired surface frictional characteristics) and gap-graded mixes. The objective of the research was twofold: to compare Marshall and Superpave-determined optimum binder contents and mix properties with and without CRM; and to predict performance mixes with and without CRM. For the RIDOT laboratory study, aggregates were obtained from four contractors and used to develop four dense-graded and four dense-graded friction course mixes using the wet process to prepare the CRM binders. Two were used to create the gap-graded mixes using the dry process. Marshall properties revealed that all CM mixes had higher optimum binder contents than the corresponding control mixes. The stability of the dense-graded mixes was consistent with that of the control whereas the stability of the dense-graded friction course was lower than that of the control for three of the four mixes evaluated. The same trends were true for an evaluation of the tensile strength of the dense-graded and dense-graded friction course. The resilient modulus values for the dense-graded and dense-graded friction course were very similar to the corresponding control sections. The mixes were also developed for the dense-graded, dense-graded friction course and the gap-graded mix using Superpave mix design methods. Results showed that the design binder content for the mixes were slightly lower for the all Superpave mixes as compared to the corresponding Marshall designs (Madapati et al. 1996). The study also suggests the need for test sections to validate the proposed mix designs (Madapati et al. 1996).

Texas

Until mid 1992, the Texas Department of Transportation (TxDOT) used specifications for conventional Type D (1/2-inch maximum size) and Type C (5/8-inch maximum size, used for a single project) DGAC for design and construction of CRM-modified AC using wet process high viscosity binders. At that time, mix compaction was achieved using the Texas gyratory. Compacted specimens were tested with the

Hveem stabilometer. The Type C CRM-modified mix placed on US 84 in the Lubbock district raveled and was covered with a seal coat. Each of the Type D CRM mixes placed reportedly failed prematurely (Tahmoressi 2001), including an overlay of IH-10 in San Antonio (Crockford et al, 1995). Based on these failures and the successful performance of modifications to the IH-10 CRM mix during construction, TxDOT developed a gap-graded CRM asphalt concrete design method based upon the stone matrix concept to accommodate the wet process high viscosity binders. This new approach was called “coarse matrix high binder” (CMHB). CMHB pavements constructed with wet process high viscosity binders have generally performed well. Two exceptions were attributed to base structural failures that were not related to the CRM-modified CMHB pavements (Tahmoressi 2001). The CMHB gradation (terminology changed to SMA in the TxDOT 2004 Standard Specifications) is also used with wet process no agitation and conventional PG asphalt binders, but TxDOT representatives report that the resulting optimum binder contents are about 2% lower by weight of mix than typical contents of high-viscosity binders (RACTG meeting October 15, 2004).

In 1994, the Texas Transportation Institute (TTI) conducted an extensive laboratory evaluation of TxDOT’s newly developed rubber modified CMHB mix design procedure (Tex-232-F) that included a comparison with CRM DGAC mixes and an unmodified DGAC control mix designed according to TxDOT’s standard volumetric method. However, a California kneading compactor rather than a Texas gyratory compactor was used to prepare the test specimens for this study. Hveem stability test results, normally a part of the TxDOT procedure, were not referenced in the report (Rebala and Estakhri 1995). Wet and dry process mixes were evaluated with fine CRM (passing the 180µm (No. 80) sieve) and coarse CRM (passing the 2.0 mm (No. 10) sieve), respectively. The various mixes evaluated are listed in Table 2.1. Physical properties of the wet process binders were not included in the report. However, the 18% CRM binders included sufficient CRM to be considered high viscosity binders. The 10% CRM binders likely did not reach the minimum viscosity threshold of 1,500 cPs, but the coarse CRM binders (passing the 2.0 mm (No. 10) sieve) require agitation to remain uniformly distributed in the asphalt cement.

Table 2.1 shows the matrix of CRM-modified binders and mixtures used in the TTI study. The tests performed on compacted mixture specimens included: resilient modulus and indirect tensile strength at 5°C (41°F), 25°C (77°F), and 40°C (104°F); indirect tensile creep; compressive strength; compressive static creep; and compressive dynamic (repeated load) uniaxial creep at 40°C (104°F). These tests are indicators of mix strength and stiffness, and of recoverable and permanent strain (deformation) response to load. Evaluations were performed according to the methods of NCHRP Report 338: Asphalt-Aggregate Mix Analysis System (AAMAS).

Table 2.1: TTI TxDOT CRM-Modified Mixture Testing Matrix

Mix Type	CRM Modification Process	CRM Content	CRM Gradation (Passing Sieve Size)
Dense-graded Control	None	0	NA
Dense-graded	Dry	0.5% by aggregate weight	Fine (-180µm, No. 80)
Dense-graded	Dry	0.5% by aggregate weight	Coarse (-2.0 mm, No. 10)
Gap-graded	Dry	18% by wt of asphalt cement	Fine (-180µm, No. 80)
Gap-graded	Dry	18% by wt of asphalt cement	Coarse (-2.0 mm, No. 10)
Gap-graded	Wet	10% by wt of asphalt cement	Fine (-180µm, No. 80)
Gap-graded	Wet	10% by wt of asphalt cement	Coarse (-2.0 mm, No. 10)
Gap-graded	Wet	18% by wt of asphalt cement	Fine (-180µm, No. 80)
Gap-graded	Wet	18% by wt of asphalt cement	Coarse (-2.0 mm, No. 10)

Resilient modulus test results show that CRM-modification may decrease the temperature susceptibility of a mix, reducing stiffness at low and intermediate temperatures and increasing stiffness at higher

temperatures, as exhibited by the wet process gap-graded mix with 18% fine CRM. All CRM dense-graded mixes (wet and dry process) had similar or increased indirect tensile strengths compared to the conventional TxDOT Type D dense-graded control mix. Except for the 18% fine CRM wet process mix, the gap-graded mixes exhibited a decrease in tensile strength with respect to the dense-graded control mix. This mix had significantly higher failure strength and strain compared to the other mixes, indicating that significant modification had been accomplished.

The creep tests revealed no statistically significant difference in performance from the others or the control. However the uniaxial creep tests were run without confining pressure. The authors state in the report (Rebala and Estakhri 1995) that this testing condition may have affected [reduced] the results for the gap-graded mixes, and that it may not be appropriate to compare unconfined creep of dense-graded mixes with that of gap-graded mixes. They also state that field performance for the gap-graded mixes may be better than the laboratory results indicate, as the pavement is only unconfined along the outside edges.

The issue of unconfined creep may also affect this study's evaluation of rutting resistance, because AAMAS estimates rutting potential from plots of creep modulus versus loading time. This approach indicated that all the mixes including the Type D dense-graded control had low or moderate rutting potential. The fine CRM dry process mixes were the most rut resistant and the gap-graded wet process 18% coarse CRM were the least rut resistant (Rebala and Estakhri 1995).

The AAMAS approach estimates fatigue potential based on logarithmic plots of tensile strain at failure versus total resilient modulus, and relationship to a standard FHWA fatigue curve. According to this method, the wet process mixes indicated better fatigue resistance, with the 18% fine CRM ranked highest.

The CRM mixes had lower resilient modulus values compared to the control. According to the AASHTO structural pavement design method this would require a thicker section compared to DGAC when designing a CRM new pavement or overlay. This may be another case where laboratory testing does not accurately reflect field performance. Caltrans experience has shown that RAC-G performs well at resisting reflective cracking at half the thickness of conventional DGAC (Van Kirk 1992). Furthermore, both TxDOT and ADOT have been assigning the same structural coefficients to their wet process high viscosity gap-graded mixes as they do to DGAC (October 15, 2004 RACTG meeting) without apparent problems.

Caltrans and ADOT acknowledge the fact that CRM gap-graded (wet process, high viscosity) typically have lower modulus than conventional DGAC. Caltrans specifies a reduced minimum Hveem stability of 23 for RAC-G (SSP 39-400) compared to 1999 Standard Specifications of minimum stability of 37 and 35 for Types A and B DGAC, respectively, and 30 for conventional 9.5 and 4.75 mm mixes. ADOT does not include any minimum Marshall stability requirement for gap-graded asphalt rubber asphalt concrete (ADOT Standard Specifications 2000). The characteristically high CRM binder contents of these mixes reduce stiffness but also make them more resistant to fatigue and reflective cracking (Shatnawi 1997, RACTG Meeting October 15, 2004).

TxDOT is conducting an in-depth evaluation of their CMHB mix design procedure to propose a method for accurately determining critical mix design properties. The research will focus on specifications that address how mixes should be handled in the laboratory to replicate field created mixes. The study will assess the ability of proposed testing methods to characterize and predict the performance of CMHB (now called SMAR) mixes (Texas Department of Transportation 2003).

As of 2001, TxDOT had constructed five open-graded porous friction course (PFC) projects with wet process high viscosity binders that were reportedly in excellent condition and performing well. One of these projects (Lufkin District, SH 146) included a control section without CRM which illustrated a major contrast in performance between the CRM-modified PFC, in which reflective cracking was not

distinguishable, and the control which exhibited extensive reflective cracking (Tahmoressi 2001). TxDOT designates CRM-modified PFC pavements as “specialized” materials and targets their use where reflective cracking is expected to be a problem, including overlays of PCC pavements. TxDOT reported very good performance with these asphalt rubber PFCs, and is further increasing their use. The mixes are designed using 50 gyrations of a Superpave Gyrotory Compactor (SGC) to provide a minimum of 18% air voids. The aggregates are primarily nominal 1/2-inch chips. AR PFC mixes are placed at nominal thicknesses of 1 to 1.5 inches (RACTG meeting October 15, 2004). High viscosity binder contents range from 8.5 to 9.5% by weight of mix without excessive drain off, which have proved effective in resisting raveling as well as reflective cracking.

California

As described earlier in this report, Caltrans has been using CRM materials for paving since the 1970s. Caltrans currently uses RAC-G mixes made with wet process high viscosity binders more frequently than other CRM paving materials. RAC-O mixes with wet process high viscosity binders have also been used with some success with asphalt rubber binder contents increased by a factor of 1.2 times the binder content of mixes made with AR-4000. RAC-O (HB) high-binder content mixes use 1.6 times the binder content of mixes made with AR-4000 (similar range as ADOT AR ACFC). These have been used on a very limited basis. Caltrans also has SSPs for Type G MB and Type D MB made with wet process no agitation binders. These materials are currently used only for experimental and pilot projects pending results of HVS (Heavy Vehicle Simulator) testing by the University of California and continuing field performance evaluations of in-place pavements. Caltrans has not been using dry process CRM modification but is re-evaluating this method on the Firebaugh project along with wet process mixes made with respective high viscosity and no agitation CRM-modified binders.

The Firebaugh project was constructed in June 2004 on Highway 33 near the town of Firebaugh. The purpose is to provide adjacent test sections for performance evaluation of RAC-G, Type G MB, Type D MB, and RUMAC (gap-graded, dry process CRM mix), and a control DGAC. No open-graded mixes are included in this project. Each mix type was placed at two thicknesses, 45 and 90 mm. Caltrans obtained samples of the component materials and mixes for evaluation. Mix tests may include beam fatigue and shear testing. The 2004 Firebaugh project is near the location of a Pilot RAC Warranty project using RAC-G that was constructed as an overlay on Highway 33 (06-343531 Fre-33-100.0/111.7) in August 2003. Another RAC Warranty project was constructed in 2004 in District 2, Lassen County which used a Type G MB mix. It is anticipated that these additional field studies will aid in refining specifications for design and construction of CRM pavements, and in improving guidelines for materials selection and use.

Summary

Review of the various studies of RAC mixes shows that a wide range of combinations of CRM gradations and concentrations, types of modification (wet or dry), grades of asphalt cement, and aggregate gradation (dense-, gap-, and open-graded) have been evaluated. The materials utilized and tested have been dependent upon the desires of the agency sponsoring the research. A number of approaches have been tried with varying success, of which more than one has been successful.

The current primary users of CRM modification are Arizona, California, Florida and Texas. There are some common factors among the respective DOTs that have resulted in successful use of CRM, and also some fundamental differences in approaches and practices, as follows.

Common Factors

- All four of the primary user DOTs use wet process crumb rubber modification routinely, but rarely if ever use dry process modification.
- Each agency has specifications for wet process high viscosity binders and for wet process no agitation binders. Arizona, Florida and Texas consider the no agitation binders to be very different materials than the high viscosity binders (or polymer-modified binders) and use the two types of wet process binders differently. Caltrans is currently re-evaluating appropriate applications of each type of wet process binder.
- Coarser CRM gradations (passing the 2.0 mm (No. 10) sieve) may be used more effectively in high viscosity binders than in no agitation binders, which typically require nearly 100% of CRM particles finer than the 600 μ m (No. 30) sieve.
- High viscosity wet process binders are suitable for use and seem to provide the best performance in gap- and open-graded mixes where their high viscosity and corresponding resistance to drain-down allow increased binder contents of up to 2% greater by weight of mix than can be accommodated in dense-graded mixes. The high binder contents promote durability and resistance to fatigue and reflective cracking. Caltrans, ADOT, and TxDOT use such binders in gap- and open-graded mixes, primarily in the top 2 to 3 inches of the pavement structure, but not in dense-graded mixes. Florida uses high viscosity wet process binders only for SAMIs, and not in hot mixes. High viscosity binders are generally not suitable for use in dense-graded mixes.
- No agitation CRM binders are suitable for use in dense-graded mixes. TxDOT allows such binders as substitutes for SHRP Performance graded asphalt cement, and FDOT uses them routinely. Caltrans has an SSP for Type D MB which is currently under evaluation.
- No agitation CRM binders may be used in gap- or open-graded mixes, but caution must be used to minimize drain-down. Such binders do not have sufficient viscosity to permit significant increases in binder content from the optimum content for un-modified asphalt cement. FDOT routinely uses such binders in open-graded mixes. TxDOT requires that fibers and lime be added to reduce drain-down when no-agitation binders are used in PFCs (open-graded). ADOT has allowed substitution of no agitation binders for high viscosity binders in gap-graded mixes for low tonnage projects and patching of CRM-modified pavements, but treats the mixes differently and requires evaluation of drain-down. ADOT does not allow the use of no agitation binders in open-graded mixes.

Differences

- Only Caltrans requires use of extender oil and high natural rubber content CRM in high viscosity wet process binders for paving mixes.
- MB specifications are based on completely different physical properties than no agitation CRM binders used in Arizona, Florida and Texas. The differences in properties provide no basis for direct comparison (See Section 2.4 more detailed information on specifications).

2.3.4 Structural Design

In addition to materials, i.e. CRM versus conventional paving materials, adequate structural design is a critical factor in long-term pavement performance. The limited studies on the topic of structural design reflect the use of traditional empirical or mechanistic-empirical approaches. They are described in the following narrative.

Arizona DOT

To minimize reflective cracking, ADOT developed a mechanistic-empirical approach for overlay design. Based upon finite element modeling, laboratory testing, and field performance monitoring of pavement sections, the research produced a spreadsheet tool that allows the designer to input a user-defined level of acceptable cracking, pavement layer thickness and corresponding elastic modulus. The output is overlay thickness for either a conventional dense-graded asphalt pavement or a gap-graded asphalt rubber pavement (Chen, DiVito and Morris, 1982).

This design tool has been calibrated only for the two surface types mentioned and is based upon the use of wet-process high viscosity binders containing a minimum 20 percent CRM by weight of the asphalt cement (17% by total weight of binder). Although calibrated specifically for ADOT, Chen, DiVito and Morris believe that the approach is applicable for Southern California and western Texas where there are similar environments and materials. Good correlation between the reflective cracking selected in the design stage and that observed in the as-built pavements was observed (Sousa 2002).

California

In terms of structural design issues related to Caltrans, there are two primary strategies for the overlay of flexible pavements: overlay with dense-graded asphalt concrete (DGAC) and overlay with asphalt rubber hot mix gap graded (ARHM-GG). (Note: Caltrans now refers to ARHM-GG as RAC-G and this report uses the new terminology, RAC-G.) In cases where additional structure is required, a lift of DGAC might be placed and then overlaid with RAC-G. To design the overlay thickness for a DGAC, Caltrans uses an empirical relationship between surface deflection and thickness of the existing pavement where the overlay thickness is that needed to retard fatigue cracking. Also, the design procedure makes use of empirical relationships to determine the overlay thickness needed to retard reflective cracking. Caltrans then uses equivalence ratios (1.5 to 2.0 if fatigue cracking is the expected distress mode or 1.5 to 2.33 if reflection cracking is the expected distress mode) to determine the appropriate RAC-G thickness. However, use of these equivalencies is based on a 10-year design life for overlays, assuming that the existing pavement is structurally adequate. Caltrans also specifies a minimum thickness of 30 mm and a maximum thickness of 60 mm (Caltrans Flexible Pavement Rehabilitation Manual, June 2001).

The current deflection-based method has not yet been extensively validated for overlay design of RAC-G materials. However, some work has been conducted. Caltrans evaluated the performance of both DGAC and RAC-G using 8-meter test sections and the Heavy Vehicle Simulator (HVS). Results from the trafficked test sections revealed that the DGAC accumulated more rutting than the sections with the RAC-G overlay. Also back-calculated moduli (using data from the multi-depth deflectometer) indicated that the DGAC overlays had higher moduli than the RAC-G overlay. A review of the digital crack maps showed that the half-thickness RAC overlays performed approximately as well as the DGAC overlays. Using the Caltrans specified cracking failure criterion of 2.5 meters per square meter, neither overlay type showed a clear trend indicating that one type is a superior performer. Therefore, the use of the half thickness RAC overlay appears to be a reasonable method for designing the pavement to handle reflection cracking (Harvey and Bejarano 2001).

In another study of fatigue performance Caltrans DGAC and RAC-G mixes were evaluated. Laboratory testing of beam specimens extracted from the field projects indicated that the “remaining life” of the RAC-G pavements exceeded that of the DGAC pavements. The difference in remaining fatigue life is directly proportional to thickness and underlying support and inversely proportional to initial degree of fatigue cracking.

From the fatigue analysis, equivalent thicknesses of each mix were determined based upon assumed base and subgrade moduli. The analysis yielded a RAC-G thickness that was less than half the thickness of the DGAC mix. The analysis also revealed that the reduction in RAC-G thickness was very sensitive to

underlying support. The researchers concluded that the RAC-G material is a very effective overlay approach for an existing section with substantial underlying support (Raad, Saboundjian, and Corcoran 1993). This is reflected in the equivalencies presented in the 2001 Caltrans Flexible Pavement Rehabilitation manual.

The University of California Berkeley Pavement Research Center (UCB/PRC) has a study underway to evaluate the performance of various CRM binders in overlay strategies using the HVS and companion laboratory testing. The overlay test sections include the following: a full-thickness (90 mm) DGAC; a half thickness (45 mm) RAC-G; a half-thickness MB-4 Type-G; a full-thickness MB-4 Type-G; a half-thickness MB 15% CRM Type-G; and a half-thickness MAC-15% CRM Type-G. It is anticipated that the results of this study will provide additional data to improve Caltrans overlay design methodology for RAC.

Caltrans uses two types of SAMIs: SAMI-R which is a rubberized stress absorbing membrane interlayer and SAMI-F which is fabric stress absorbing membrane interlayer. Depending upon the design purpose and underlying pavement structure, the SAMI-R may be given credit for some structural strength, equivalent to 0.05 ft (15 mm) of RAC-G. The same 15 mm equivalency may be applied for reflective crack retardation (Caltrans Flexible Pavement Rehabilitation Manual, June 2001).

Kansas DOT

An important component of the AASHTO design procedure is the use of structural layer coefficients. To generate realistic layer coefficients for CRM materials, a study was conducted by the Kansas Department of Transportation using both the AASHTO Design Method and the Equal Mechanistic Approach. The Equal Mechanistic Approach makes use of a comparison between the compressive strain on the top of the subgrade of a control section (i.e., conventional materials with known layer properties) to that of the experimental section. For the Kansas study, identical pavement structures (i.e., one with a conventional asphalt layer and one with a CRM asphalt layer) were compared using an elastic layer program. The thicknesses of the pavement layers needed to obtain equal vertical compressive strain on the subgrade are determined. A ratio of the thickness of the CRM layer to the conventional asphalt layer provides the layer thickness equivalency. From this value, the structural layer coefficient of the material with the unknown layer properties can be determined by multiplying the structural layer coefficient of the known material by the inverse of the layer thickness equivalency (Hossain and Habib 1997).

Five CRM pavement sections were analyzed. Back-calculated moduli and structural layer coefficients were computed for the test sections. The analysis yielded large variability in the computed structural layer coefficients. Values using the AASHTO method were consistently lower than those determined from the Equal Mechanistic Approach. The researchers attributed the variability to the rubberized asphalt base material and the use of very thin overlays on jointed reinforced concrete pavements. Overall, the computed structural layer coefficients were lower than those used in the initial design of the pavement structures.

Due to the high variability in the coefficients developed with the AASHTO approach, the researchers suggest using the Equal Mechanistic Approach to generate layer coefficients for new materials. The Equal Mechanistic Approach resulted in coefficients of 0.11 to 0.46 with the majority of values falling around 0.30 for CRM overlays. Values ranged from 0.25 to 0.48 for the layer coefficient for newly constructed CRM asphalt mix overlays with an average value around 0.35. From the analysis an equation was derived to estimate the structural layer coefficient value for the CRM mixes based upon a modulus value. However, due to the variability in the data, the researchers suggest further study to consider factors such as layer thickness, material type, layer location, traffic level and failure criterion in the development of this equation prior to its use (Hossain and Habib 1997).

Louisiana DOT

Tests conducted at the Louisiana Accelerated Loading Facility (ALF) site were also used to develop structural layer coefficients for use in structural design of CRM pavements. Three full scale test sections were constructed to compare the performance of a CRM surface course and a CRM base course with conventional materials (Roberts et al. 2003).

The resilient modulus and indirect tensile strength test data showed no difference between the conventional mixes and the CRM mixes. Indirect tensile creep test results suggest that the CRM base was more rut resistant than the conventional base. However, there was no statistical difference in rutting resistance between the CRM and conventional surface mixes. Furthermore, there was no statistically significant difference between the CRM and the conventional mixes as measured by dynamic shear modulus, shear phase angle or the repetitive shear at a constant height. The observed rutting in the test sections was consistent with the laboratory test results. The surface course mixes performed similarly, whereas the CRM base course mix performed better than the conventional base course mix.

The researchers reported that the addition of CRM passing the 300 μm (No. 50) sieve to the surface course mix reduced performance leading to a structural coefficient of 0.25 compared to a structural coefficient for the conventional mix of 0.35. However, the addition of CRM passing 300 μm (No. 50) sieve (at a rate of 10 percent by weight of asphalt) to the base course mix improved performance leading to a structural coefficient ranging from 0.40 to 0.45, which is within the range suggested by AASHTO and used by a number of state DOTs for AC surface course mixes. Addition of the CRM was estimated to increase the total cost by 10 percent making it cost effective (Roberts et al. 2003). As was the case in other studies, the variable results preclude definitive statements about structural coefficients. Recall that another Louisiana study described previously in section 2.3.5 (Huang et al 2002) indicated that the lower moduli and Marshall stability values of CRM mixes were not reflected in field performance (i.e., field performance was better than that anticipated by these test parameters).

Other Agencies

Other agencies have different methods for handling the structural design of CRM mixes. For example, FDOT assigns a structural coefficient of 0.44 to its dense-graded 9.5 and 12.5 mm CRM mixes. The extent of modification is low and these mixes are considered structurally commensurate with conventional DGAC. TxDOT treats CRM-modified gap-graded asphalt concrete mixes as conventional DGAC for new construction rehabilitation and maintenance. ADOT's structural design methodology for gap-graded CRM mixes is the same as that its conventional dense-graded mixes regardless of application. None of the agencies (AZ, FL or TX) assigns any structural credit for open-graded mixes or SAMIs. Caltrans does not consider any structural value for OGAC.

Summary

The literature review indicates that several methods have been used in an attempt to establish structural design parameters for RAC mixtures, including:

- ADOT's mechanistic-empirical- method based on the finite element modeling, laboratory testing and field performance data
- Caltrans thickness reduction method on surface deflection, traffic index, and existing pavement structure
- AASHTO structural layer coefficient approach attempted by several agencies based on layer properties.

The results of the literature review indicate that there is no consensus on design methodology for CRM materials. The experience of the four primary user-agencies indicates that assigning a structural

coefficient for CRM hot mix asphalt concrete equivalent to that of dense-graded asphalt concrete is reasonable.

Arizona, Florida and Texas DOTs do not assign any structural value to OGAC.

Caltrans considers the structural contribution of SAMIs during pavement rehabilitation design.

2.3.5 Performance

A major concern with the use of any new material is its expected performance. Many states have documented the performance of their trial test sections of rubber modified asphalt materials, but some did not have resources for long-term performance monitoring. The materials tested and their performance varied widely among and within respective agencies. There are a number of reasons for the observed variability in the performance of the CRM-modified materials studied, including but not limited to the following:

- Differences among specifications
- Differences among the processes of rubber-modification used
- Differences among binder and mix design procedures
- Appropriateness of the application for the intended use
- Changes in materials from those used in the original design
- Experience of contractors and paving crew with highly modified paving materials
- Willingness to modify production, handling, and/or construction procedures to accommodate modified materials
- Level of quality control exercised during material production (modified binders and mixes)
- Temperature control of paving mixes for placement and compaction
- Quality of construction, including placement and compaction equipment and procedures

A summary of the performance documented by the various states is described in this section. Several of the projects that documented performance of the CRM mixes involved laboratory testing of the materials.

Maryland

A study conducted in Maryland involved the laboratory assessment of field cores from 13 different CRM mixes and one control mix (conventional DGAC with AC-20 asphalt cement) (Ayres and Witczak, 1995). The mixes were placed in test sections on two different highways. Six of the 13 mixes used wet process binders that were field-blended at the HMA plant. Although the properties of the CRM-modified binders were not listed in the report, the CRM contents indicate that both high viscosity and no agitation-type binders were used. Five of the mixes were dry process, and two were no agitation wet process mixes using Neste SAR 10/10 and Bitumar (Ecoflex) binders respectively. Within the wet field-blended mixes three levels each of CRM content and of extender oil content were used with two asphalt cements (AC-10 and AC-20). Extender oil content varied with CRM content by weight of asphalt cement: 1% extender with 10% CRM; 3% extender with 15% CRM; 7% extender with 20% CRM. The five dry process mixes were PlusRide (No. 12 and No. 16 mixes with 3% CRM by weight of aggregate and three generic dry mixes with respective CRM contents of 0.75, 1.5, and 2.25% by weight of aggregate. The mixes, except for the SAR 10/10, Ecoflex, and one control section, were placed at two different thicknesses, 1.5 and 3 inches.

Using five different approaches, the resilient modulus (M_r) was determined for all fourteen mixes. The testing results show that with only a few exceptions the control mix had the highest M_r of all test sections, i.e., was the stiffest mix. The other mixes had M_r ratios to the control of approximately 0.8 to 0.9. For

the wet process mixes, the amount of CRM used in the mix did not result in any specific trends in the M_r results. However, the mixes with AC-20 tended to have slightly higher M_r values than the AC-10 blends due to the stiffer binder. For the dry process asphalts, the M_r decreased with increasing CRM content in the mix. The M_r results indicated that the CRM mixes were less temperature susceptible. This is evidenced by the fact that the overall M_r values of the CRM mixes were lower with respect to the control section (lower ratio) at the lowest test temperature of 4.4°C (40°F) and ratios of CRM mixes were higher with respect to the control at the higher test temperatures of 21.2°C (70°F) and 37.8°C (100°F). This means that the CRM mixes had lower moduli at low temperatures and higher moduli at high temperatures than the DGAC control mix (Ayres and Witczak 1995).

Field performance evaluations of these test sections conducted in 1995 consisted of visual condition surveys according to the PAVER method used by the American Public Works Association (APWA) and the US Army Corps of Engineers (Witczak and Qi, 1995). The data were analyzed and converted to Pavement Condition Index values within a range of 0 (failed) to 100 (excellent). Two years after construction, PCI values for each section were 95 or better indicating excellent initial performance. Distress types observed included spot occurrences of low severity bleeding, raveling, transverse cracking and polished aggregate. Rutting of less than 5 mm occurred on each section, and was slightly greater in the conventional DGAC control sections. Preliminary evaluation indicated that increasing the CRM content decreased rutting, but longer term evaluation would be required to confirm this with time.

Minnesota

Other studies incorporated both laboratory and field testing of materials. For example, a study was conducted in Babbitt, Minnesota to compare the properties of the CRM and control section mixes and to evaluate the construction processes (Stroup-Gardiner, Chadbourn, and Newcomb 1996). A total of seven test sections were constructed with five CRM sections and two control sections. CRM was added using a dry process at 1% for the various pavement layers. In some cases, the CRM was pretreated with a light oil petroleum product added at 10% of the weight of the rubber. In other cases, the CRM was untreated.

Marshall Mix design was used to determine the optimum binder content. Compaction effort of 20 blows-per-face was used to prepare the samples for testing. A lower value (compared to a 50 blow per face specimen) was chosen to increase the air void content to the anticipated field level of 6 to 8%. The control mix consisted of a blend of 20% coarse and 80% fine aggregate with optimum binder content of 5.0%. Aggregate gradations with 35% coarse/65% fine and 50% coarse/50% fine were used for the CRM mixes. Optimum asphalt contents were 6.5% by dry weight of aggregate for the pretreated rubber and 6% for the untreated rubber.

Resilient modulus testing of laboratory and behind-the-paver mixes show little difference between untreated and treated CRM mixes. Low temperature indirect tensile testing showed that the CRM mixes increased strain from 35 to 42% indicating greater resistance to thermal cracking. Creep test results revealed that the control mix had the highest modulus. Moisture sensitivity indicated that the CRM mixes may be susceptible to stripping. FWD testing of the as-built sections yielded moduli comparable to the laboratory obtained values (Stroup-Gardiner, Chadbourn, and Newcomb 1996).

Louisiana

A study conducted by the Louisiana Department of Transportation and Development evaluated the mix characteristics and field performance of eight asphalt pavement sections constructed with wet and dry process CRM versus conventional DGAC control mixes (Huang et al 2002). The study included two asphalt cements (AC-30 and a polymer modified), three aggregates (limestone, sandstone, and crushed gravel), and five CRM materials. The CRM materials consisted of the following: passing the 2.36 mm (No. 8) sieve; passing the 2.00 mm (No. 10) sieve; passing the 300 μ m (No. 50) sieve; passing the 850 μ m (No. 20) sieve; and a PlusRide passing the 6.3 mm (1/4-inch) sieve. Dense-, gap- and open-graded CRM

mixes were evaluated, including a 3-layer CRM system with SAMI. The mixes were evaluated in terms of indirect tensile strength and resilient modulus, as well as Marshall stability and flow.

Optimum asphalt content was determined for the eight experimental CRM pavements using the Marshall design procedure. The respective mix designs yielded generally higher binder contents for the CRM-modified mixes than the DGAC controls. Results of the Marshall stability and flow tests revealed that the conventional mixes had higher or equal values of Marshall stability and lower flow numbers than the CRM mixes. The dense-graded CRM mixes had higher Marshall stabilities than did the gap-graded mixes.

The majority of CRM sections had higher strain values (as measured in the indirect tensile mode) than the conventional wearing course mixes indicating that the CRM mixes are more ductile and resistant to fatigue cracking. Resilient modulus testing showed the majority of the control sections to have significantly higher values than the CRM mixes. However the lower laboratory Marshall stability and M_r results for the wet process mixes were not reflected in field performance.

Based upon FWD tests conducted shortly after paving, structural numbers were determined for the various pavement sections. Compared to the control sections, the wet-processed CRM pavements exhibited higher structural numbers while the dry-processed CRM pavement exhibited lower structural numbers than the control sections, likely a function of the substitution of CRM for aggregate. Except for the wet process OGFC and the gap-graded dry process PlusRide, pavement sections constructed with CRM had higher in-place modulus values than the control sections according to Dynaflect results, although laboratory M_r tests yielded lower modulus values. This is another case where laboratory testing did not accurately predict field performance. Field testing also revealed that after 5 to 7 years of service, the majority of CRM sections exhibited similar or lower IRI numbers and rut depths than the control sections. One gap-graded mix did show higher rut depths than the corresponding control section. In terms of cracking, the CRM pavement sections had less cracking than the control sections (Huang et al 2002).

Illinois

The Illinois Department of Transportation (IDOT) constructed six demonstration test sections using the generic dry process method (RUMAC). The projects evaluated the use of the following amounts of CRM added to each ton of hot mix: ½, 1, 1-½, 2 or 20 pounds, equivalent to 0.025 to 1.0% CRM per ton. IDOT used two terms to define the various quantities of CRM added to HMA: variable rate and fixed rate. Variable rate defines a small quantity of no more than 5 lb (0.25%) of CRM added per ton of HMA. Fixed rate defines a larger quantity of CRM added which is no less than 20 lb (1.0%) of CRM per ton of HMA. The segments containing 2 lb or less of CRM per ton of hot mix did not show a significant difference in performance as compared to the control sections. Tests of the use of the nuclear density gauge and the nuclear AC content gauge showed that the low addition of CRM did not affect accuracy. In fact, it was determined that at such a low addition rate no special mix design, laydown procedures, or equipment is needed for CRM mixes. Also the addition of the CRM at the low rate does not affect the mix properties (Marshall voids, stability, flow density, split tensile strengths).

Sections containing 20 lb of CRM per ton of hot mix presented more problems. The 20 lb mixes were difficult to compact. The researcher noted that these mixes could not be compacted with a pneumatic roller. Once placed, it was determined that evaluation with the nuclear density gauge was effective. However, measuring binder content of dry process mixes was problematic because hydrogen in the CRM was counted as part of the asphalt cement rather than part of the aggregate (Trepanier 1995). This is not an issue when wet process binders are used.

The problems with the 1.0% CRM content mixes illustrate some of the major issues with the various experiments, which included lack of understanding in how best to incorporate dry and/or wet process

CRM into asphalt concrete paving mixes. Dense-graded mixes do not have sufficient void space to accommodate such a relatively large volume of rubber particles, and modification to the aggregate gradation is necessary to provide appropriate mix volumetrics. Mixes that cannot be compacted in the lab cannot be compacted in the field and thus will not perform well. The authors noted that mixes having volumetric deficiencies should be remedied in the laboratory design phase prior to attempting full-scale production and placement.

IDOT built a total of 11 CRM-modified projects from 1991 through 1995, one of which assessed the use of wet process CRM mixes. Based on visual survey data from the 11 projects through 1999, the wet process fixed rate mixes performed the best and the dry process fixed rate mixes the worst (Volle 2000). Overall performance of the dry process variable and fixed rate mixes was not as good as that of the control sections. All rubberized asphalt projects were within the acceptable range of friction numbers and rut depth, with little difference from the DGAC control. The ride values for the rubberized asphalt sections were in a range of 63 to 184 inches per mile and showed no substantial difference compared to the control sections. The wet process fixed rate mix performed better than the control section in resisting reflective cracking through 1999, but cost more than twice that of conventional DGAC.

Because the dry process mixes did not perform as well as standard DGAC and cost an average of 17% more, IDOT did not consider dry process modification to be a viable option. To consider any type of crumb rubber modification economically viable, IDOT concluded that the material would have to be mass-produced at the local level and perform better than standard DGAC. An investment in the necessary equipment by local industry would be needed but would not be accomplished without increased demand for CRM materials (Volle 2000).

Colorado

The Colorado Department of Transportation (CDOT) conducted a study to assess the use of minimal amounts of crumb rubber in a dry process asphalt mix. The PlusRide and generic dry processes were evaluated. Three of the PlusRide projects exhibited early raveling and one performed well. The study conducted was similar to that conducted by IDOT. After selecting a low volume road, CDOT incorporated crumb rubber at three addition rates of respectively 1, 3, and 20 pounds of crumb rubber per ton. The mix created with 1 pound of CRM per ton of mix did not require any change to the aggregate gradation. However, adjustments to the aggregate gradation were necessary when adding 5 pounds (or more) of CRM per ton of mix. This result is the same as the findings of the IDOT study. No problems were noted with the construction of the test sections other than some reduced production for the 20 pound CRM mixes. After five years, performance data showed the control and test sections were performing equally. However, the cost increase of 21% made the incorporation of even small amounts of CRM uneconomical for CDOT (Harmelink 1999).

Florida

The field performance of three CRM asphalt test pavements constructed by FDOT was evaluated ten years after construction. The three projects included test sections of both wet and dry processed CRM. Each section's performance was determined in terms of rideability, rutting, cracking and patching, and skid resistance. The performance results indicated that the wet process mixes performed significantly better than the control and dry process CRM sections. Observations of cracking accumulation plots indicate that the wet process test sections with 10 to 15% CRM have basically no occurrence of cracking, which indicates this as a potential optimum rubber content range. Higher ride qualities were determined on the wet process section for rubber contents up to 15%. The dry process mixes had the lowest ride quality along with the highest rut depths. There were no observable differences in skid resistance for the various sections (Choubane 1999).

Oregon

An early study conducted by ODOT investigated the use of various additives to increase the life of an asphalt overlay. Of the nine mixes evaluated, two involved the use of CRM. In 1985, sections of PlusRide (dry process) and Arm-R-Shield (wet process) along with dense- and open-graded mixes and a control section were constructed. Performance was subsequently monitored for ten years. Results showed the Arm-R-Shield performed best in terms of resistance to fatigue cracking, block cracking, and raveling. The PlusRide mix had very low resistance to fatigue cracking, block cracking, and raveling and performed worse than the control section (Edgar 1995).

A total of seventeen CRM-modified test sections (13 projects) were constructed throughout the state of Oregon from 1985 to 1994. The test sections included wet process and dry process open-graded and dense-graded mixes. Control sections were built to correspond to the test sections. The test sections and corresponding control sections were evaluated in terms of visual distress, rut depth, and frictional characteristics (Hunt 2002).

Field cores were evaluated for in-place void content and stripping. Dense-graded CRM pavements with in-place void contents closer to the design exhibited less distress than sections with higher voids. Void contents of the open-graded CRM mixes met the post-construction void content criterion. Stripping did not appear to be a problem in any of the mixes evaluated (Hunt 2002). Visual condition surveys showed that the dense-graded control sections were in better condition than the dense-graded CRM-modified mixes. Performance of the open-graded test sections was more variable. Some CRM-modified open-graded mixes performed as well or better than the control sections while others did not.

A review of friction test results indicated that friction measurements of the CRM-modified test sections were consistent with those of the control sections. Ride values showed that the dense-graded CRM mixes consistently had higher roughness values than the control sections. However, data for the open-graded mixes did not show a distinct roughness trend.

Hunt's 2002 ODOT report also compared and contrasted ODOT's experience with that of the Washington State Department of Transportation (WSDOT). WSDOT reported rutting within six years of construction on two of its five asphalt rubber concrete projects that utilized wet process high viscosity CRM binder. ODOT did not have this problem on similar wet process high viscosity binder sections, and suggested the difference in rutting performance might be attributed to the lower traffic levels on the ODOT sections. In addition, both ODOT and WSDOT had projects that were constructed with different asphalt rubber mixes that were performing as well as control sections. Dry process projects, including the PlusRide process, generally performed well for WSDOT but not for ODOT. It was thought that the good performance of the dry process projects in Washington might also be the result of lower traffic levels. Again, comparison of test sections does not provide consistent results. This may be due to a number of factors, including lack of consistent bases for comparisons between these small independent studies (Hunt 2002).

Kansas

From 1990 to 1995, the Kansas Department of Transportation (KDOT) constructed 13 projects with CRM products, five with modified dry process with fine CRM (passing the 300 μm (No. 50) sieve) and eight wet process, with a number of variations among the respective projects. A total of approximately 2,637 tons of CRM was used. Dense-, gap- and open-gradations were tried, along with an experiment in recycling conventional reclaimed asphalt pavement (RAP) in a dry process CRM mix, thick RAC-G type sections of 180 and 225 mm on rubblized PCC, and 360 mm full-depth RAC on lime stabilized subgrade. Some noise testing was also conducted. Performance was mixed, although the gap-graded mixes generally seemed to perform best. Rankings assigned by KDOT indicate that three of the projects performed well, three were average, four performed poorly, and three failed catastrophically. KDOT

found that for large projects, CRM HMA may be cost-competitive with PCC. To compete with conventional HMA, CRM-modified materials would have to provide significantly longer performance life and/or reduced thickness. Based on its experience, KDOT determined that the use of CRM in bituminous mixes was not economically feasible. (Fager 2001)

Arizona

The performance of CRM in flexible paving materials has been very good, but more recently has been evaluated as a rehabilitation technique for concrete pavements (Way 2000). Within the state a non-reinforced concrete pavement was chosen as a candidate for placement of an asphalt rubber overlay along with sections in the Strategic Highway Research Program (SHRP) SPS-6 (special pavement studies) test sections. The asphalt overlay was designed for a 10-year life. However, those involved in the project believed that due to the very poor condition of the underlying concrete pavement the best life expectancy of the overlay would be 6 years.

The final design of the pavement rehabilitation was to install edge drains, crack and seat the concrete pavement, overlay with 3 inches of conventional dense-graded HMA and 2 inches of gap-graded asphalt rubber mix (AR-AC). Lastly, a one-half inch thick asphalt rubber open graded friction course (AR-ACFC) was placed as the final wearing course.

The construction cost of the asphalt rubber mix was \$45 per ton versus \$23 per ton for the HMA. Immediately following construction minor roughness was noted and attributed to the problems in the seating process. After nine years of service, the section was evaluated and considered to performing satisfactorily. No reflective cracking had occurred and the ride values indicated a very smooth ride. Rutting was basically non-existent and the skid resistance was reported to be adequate.

The ADOT study concluded that although the CRM mixes cost nearly twice as much as conventional HMA, they can normally be placed half as thick. Furthermore, the CRM mixes crack at a rate of approximately one-fourth that of a conventional mix, making them a better rehabilitation choice for the roadway characteristics experienced in Arizona (Way 2000).

California

Besides extensive field performance studies, other studies have made use of large-scale test sections to evaluate the performance of CRM mixes. Although gap-graded mixes did not meet the Caltrans requirements for Hveem stabilometer values; however, field performance data have shown the mixes to provide adequate rut resistance. Experimental large-scale test sections of both dense- and gap-graded mixes were constructed and tested using the HVS to evaluate rutting behavior. Test results show that, overall, the 62 mm gap-graded asphalt rubber and the 50 to 75 mm dense-graded overlays had similar performance (Harvey and Popescu 2000).

The research did note that the gap-graded asphalt rubber cools very quickly after placement requiring attention to detail during construction. The researcher also noted that inadequate compaction of the gap-graded mixes may result in considerable shear flow (Harvey and Popescu 2000).

Summary of Field Performance Studies

The field performance studies reviewed showed the variable experience that states have had with CRM in asphalt paving materials. Studies conducted by the Illinois, Colorado, and Kansas Departments of Transportation showed crumb rubber modification to be feasible in certain circumstances but not a significant enough improvement over unmodified mixes to make it a wise economic investment. Many other agencies share that experience and therefore are not using CRM as an asphalt modifier. However, the positive performance of CRM used in Arizona, California, Florida, and Texas has reinforced its use as

a routine strategy in a variety of applications. Thus, only these four states routinely use these materials. Improved resistance to common modes of pavement distress improves the overall durability of the resulting pavements, and Arizona and Texas have reported some corresponding reductions in maintenance and repairs of CRM-modified AC pavements.

Most studies have documented the behavior of test sections through laboratory or field testing. The majority of these studies have proven effective at helping agencies determine their specific approach to the use of CRM in various paving applications. Nevertheless, the wide variety of materials, methods of testing, and varied test results make it difficult to compare and contrast the majority of the studies to draw some standard conclusions. Conclusions that can be drawn are as follows.

- Although some dry process mixes have performed very well under traffic in a variety of environments, their overall performance is generally more variable and thus less reliable than that of wet process mixes.
- Use of relatively fine CRM (passing the 2.0 mm, No. 10 sieve) or very fine (passing the 300 μm , No. 50 sieve) seems to improve the overall performance of dry process mixes. Coarser CRM seems to make dry process mixes more susceptible to raveling, cracking, and pop-outs.
- Gap-graded and open-graded CRM mixes can perform well in both wet and dry processes.
- Although laboratory tests indicate that wet process mixes are not as stiff as conventional DGAC (i.e. typically have lower modulus and stability values), a number of field performance tests show that such mixes (when properly designed) exhibit increased resistance to rutting and cracking. This may be a function of higher recoverable strain due to CRM modification.
- Mixes with high viscosity CRM binders seem to be more effective in resisting rutting, raveling, fatigue and reflective cracking than mixes with no agitation binders or conventional DGAC, in part because of the higher binder contents that are used. Performance is further enhanced when relatively high contents of high viscosity binder can be accommodated in the mix.
- High viscosity binders are not well-suited for use in dense-graded mixes.

A number of studies are underway by various agencies to further evaluate and improve the performance of CRM pavements. Caltrans is one of these agencies. Caltrans is currently building test sections and pursuing HVS studies to provide up-to-date information on the use and effectiveness of high viscosity and no agitation binders, as well as the dry process, in improving the performance of asphalt pavements. ADOT is sponsoring a study to refine and improve their Marshall mix design method for gap-graded asphalt rubber asphalt concrete. The Nebraska Department of Roads (NDOR) has constructed CRM asphalt overlays in the past and is now undertaking a study to evaluate the costs and performance of the sections relative to nearby conventional pavement sections (Nebraska Department of Roads 2003). NDOR is also building new CRM test sections. Such studies will continue to contribute to the literature and provide a more solid basis for CRM product evaluation in the years to come.

In summary, the performance of CRM mixes, particularly dry process mixes, has been variable. Those states and local agencies with good experiences have continued to develop and use these products. Those that have experienced mixed or poor performance or high costs have chosen to use other modifiers to improve the properties of their binders and HMA.

2.3.6 Cost

Costs are often the factor given the greatest consideration in the selection of rehabilitation strategies as well as for new construction. Decisions regarding when and where to use asphalt rubber should be based on cost and expected performance for the proposed application. There are typically two types of costs that should be taken into consideration: initial costs and life cycle costs.

Initial Costs

Initial costs are the total costs to construct a rehabilitation alternative or new pavement. Initial costs should include design or engineering costs, as well as all construction costs. If the design costs of multiple alternatives are approximately the same, then those costs can be ignored and only construction costs or material costs should be considered.

A discussion of findings of various state studies related to initial costs of using CRM HMA versus conventional HMA follows. The studies indicate that initial unit costs for CRM-modified paving materials were consistently higher than for conventional materials. The increased cost is due to two primary factors:

- Field trials and/or respective studies conducted by the various agencies were generally small, i.e. low tonnage projects.
- Equipment and materials needed were new (and sometimes proprietary) technology not locally available to most agencies and contractors, and costly long distance mobilization was often required.

Washington

In the early 1990s, the Washington State Department of Transportation had already had up to 15 years of experience with the use of CRM in asphalt paving materials. The review of the performance and cost of the variety of projects showed the use of SAMs and SAMIs not to be cost effective. In fact, the cost of unmodified asphalt binders was approximately one-third of the cost of CRM binders.

Ontario, Canada

A study conducted in Ontario also assessed the economic benefits/drawbacks of the CRM projects. In doing so, Ontario assessed equipment requirements, serviceability factors, performance factors, societal concerns, and material costs. The economic analysis is detailed and resulted in the finding that regardless of the incentive selected for disposal savings of the tires (societal concerns), RUMAC (generic dry process) mixes are 15 to 20% more costly than conventional HMA mixes when incentives are utilized and 32 to 39% higher when incentives are not included in the analysis of initial costs (Emery 1995).

Illinois

Studies in Illinois showed that addition of 2 pounds or less of CRM per ton of hot mix ($\leq 0.1\%$ by mix weight) using the dry process increased the cost of the mix by approximately 20%. The addition of 20 pounds of CRM per ton of hot mix (1.0% by mix weight) increased the cost of the mix by approximately 28% (Trepanier 1995). Subsequent studies by IDOT resulted in various conclusions relating to CRM asphalt performance and cost compared to conventional asphalt pavements. For example, considering all CRM asphalt projects, the cost averaged 30% higher than the conventional asphalt pavement. Specifically, one wet process CRM asphalt pavement cost 101% more than the conventional mix, which in turn means that the pavement would have to last twice as long to make it cost effective (Volle 2002).

Louisiana

The Louisiana Department of Transportation and Development determined the cost of a 10% CRM wet process mix (passing the 300 μ m (No. 50) sieve) to be similar to the control section cost. However, the remainder of the sections that they evaluated (wet process high viscosity binder, CRM passing the 1.18

mm (No. 16) sieve; no agitation terminal blend, CRM passing the 850 μm (No. 20) sieve; and a PlusRide shredded rubber) cost 118 to 360% of the conventional mixes (Huang et al 2002).

Nevada

Nevada Department of Transportation (NDOT) evaluated a total of six CRM experimental projects. If CRM mixtures had not been used on the sections, each of the test sections would have received a 2-inch dense-graded conventional HMA layer with a 3/4-inch open-graded friction course. However, due to the increased cost of the CRM mixes the thicknesses of the CRM overlays were reduced. Two of the six projects utilized very thin CRM overlays (3/4-inch) with and without the use of a stress absorbing membrane interlayer (SAMI). The SAMI proved ineffective in helping control reflective cracking. Instead the sections ended up with very unsatisfactory performance, with cracking showing up one year after construction.

Based upon the poor performance of the 3/4-inch CRM overlays, 1-1/2 inch overlays combined with the use of SAMI were analyzed. Both test sections had useful lives of approximately 5 years. However, conventional HMA placed under the same environmental and traffic loading conditions yielded more than eight years of service.

Lastly, two CRM sections (one with and the other without open-graded friction course) with cross sections equivalent to the standard NDOT HMA overlay were constructed. The section with the open-graded friction course performed appropriately but the section without the OGFC again did not perform as well as the control section. Based upon the results of the study, the cost of the CRM section with a cross section equivalent to the conventional HMA pavement was determined too costly for further construction consideration (Sebaaly, Bazi, and Vivekanathan 2003).

Mississippi

Mississippi DOT conducted “proof of concept-type” field evaluation using both CRM binder course and surface course materials. Also, the agency evaluated the recyclability of the CRM paving materials. An evaluation of the difference in costs of all the contractor bid prices for the various bituminous surfaces used in the project was conducted during the study. The costs show that the CRM surface and binder courses were approximately 25 to 50% more expensive than the conventional HMA pavement (Albritton, Barstis, and Gatlin 1999).

California

Caltrans publishes the *Contract Item Cost Data* book annually (Contract Cost Data, 2003). Based on the 2003 cost data, Caltrans has used roughly 1.8 million tons of conventional HMA (including Type A and B of various grading and OGAC) and nearly a 250,000 tons of RAC (including RAC-G and RAC-O) for highway construction projects. The weighted average cost for the conventional AC mixes is \$52.43 per ton and the weighted average cost for the RAC mixes is \$60.80 per ton. The data indicate that the weighted average cost of RAC mixes is about 16% higher than that of the conventional mixes.

Initial costs also depend on the size of the project, i.e. the amount of tonnage of CRM material to be produced. For large projects, mobilization costs can be spread over enough tonnage so that they can generally be offset by increased service life, lower maintenance costs, and/or reduced thickness. However, the mobilization of wet process high viscosity production equipment costs just as much for a small project as for a large one, which increases unit cost. For small projects, the increase in unit costs may not be fully offset.

In 1998, Caltrans conducted an analysis of RAC and DGAC unit prices versus mix quantity using data from 1996 and 1997 Caltrans projects. The results were reported in a July 7, 1998 memorandum that

indicated that units costs of CRM modification increased considerably for jobs using less than 2,250 tonnes (2,500 tons) of RAC. The memo suggests that smaller RAC projects may not be cost effective due to initial high unit costs. The “break-even” quantity may have changed since 1998. However projects with three days of paving or less are likely to have significantly higher unit costs than larger projects, and initial costs should be evaluated with respect to the expected benefits of using CRM-modified materials (Caltrans Asphalt Rubber Usage Guide, 2002).

Life Cycle Costs

Initial costs are often used to compare and select rehabilitation treatment strategies or pavement type for new construction. However, using only the initial costs for comparison of different strategies may not be appropriate. For example, one design strategy may cost more but it may last longer; another design strategy may cost less but it may not perform as well as the other one. Without using the same basis (time) for comparing the alternates, it would be difficult to tell which strategy is more economical and cost effective.

Life cycle costs account not only for the initial construction cost, but for all of the costs that are associated with the selected strategy over its life. In the life cycle costing, costs that occur at different times (such as regular maintenance and repairs during service life, subsequent rehabilitation or reconstruction) in a specified analysis period are converted to a common basis for comparison purposes; therefore, costs incurred at different points in time can be compared with one another on an equivalent basis.

The FHWA and several state highway agencies advocate the use of life cycle cost analysis (LCCA) to aid in determining the most appropriate rehabilitation and maintenance strategies for a given situation. FHWA has developed a training course titled “Life Cycle Cost Analysis in Pavement Design” to train agencies in the importance and use of sound procedures to aid in the selection of alternate designs or rehabilitation strategies (FHWA 1998). The FHWA position on LCCA is defined in its Final Policy Statement published in the September 18, 1996, *Federal Register* (Walls J. and Smith M.R., 1998). FHWA policy indicates that LCCA is a decision support tool. The 1986 AASHTO Guide for the Design of Pavement Structures and subsequent editions encouraged the use of LCCA and laid out a process to evaluate the cost effectiveness of alternative designs (AASHTO, 1993). Information on LCCA techniques is included in the Appendix C.

Current research is also being undertaken to provide a life-cycle analysis model and supporting tool that would allow agencies to assess the use of recycled materials in highway construction. The tool would provide a fast systematic way to determine which recycled methods are cost-effective. While the tool will have many applications, one use would be to determine if CRM is cost-effective for a particular application (Recycled Materials Resource Center 2001).

Descriptions of life cycle cost analysis along with an example were presented in a paper by Hicks and Epps in 2000. The example used data collected from Arizona, California, and Texas. Various design strategies and typical lives and costs for these strategies experienced by these state agencies were used in the LCCA. These strategies/scenarios included the use of conventional asphalt concrete (dense-graded and friction course) mixes, asphalt rubber (wet process high viscosity) asphalt concrete (gap-graded, open-graded, and friction course mixes), and asphalt rubber chip seal in applications such as mill/fill, overlay, or surface treatment. This example is based on wet process high viscosity CRM modification, and does not apply to mixes with wet process no agitation binders.

In the scenarios considered both the deterministic and probabilistic approaches were used to evaluate variation in design inputs (e.g., variation in initial costs and expected lives) on the life cycle costs. General observations from the example indicated that for Arizona DOT, the results showed the asphalt rubber to be cost effective in all applications; for Caltrans most of the applications were cost effective over 70% of the time, except the use of multiple asphalt rubber chip seals did not prove to be cost

effective; for Texas DOT variable results were obtained. The authors emphasize the importance of collecting accurate data on cost and expected life of the respective pavement applications for the LCCA to provide realistic outcomes.

Based on the information provided by the agencies and the results of the LCCA analyses, the following conclusions were drawn:

- For the scenarios evaluated, asphalt rubber is a cost effective alternate for many highway pavement applications.
- When variability is considered in the inputs (cost, expected life, etc.), the asphalt rubber alternates would be the best choice in most of the applications considered.
- Asphalt rubber was not cost effective in all applications. LCCA allows one to determine when and where AR will be cost effective.

The results of LCCA are highly dependent on the input variables. Many times these inputs are only best estimates. Every effort is needed to obtain accurate estimates of the average value and expected variability for each input variable. Further, the cost effectiveness of asphalt rubber is dependent in many of the cases on the ability to reduce thickness when using asphalt rubber. Without a reduction in thickness, or longer service life for equal thicknesses, the CRM-modified alternates would not be cost effective.

Summary

Studies or data from Washington, Ontario, Illinois, Louisiana, Nevada, Mississippi, and California that incorporated cost evaluation indicate the initial cost of CRM mixtures to be higher than for conventional asphalt paving materials. One of the primary cost factors was long-distance mobilization costs associated with importing the technology, equipment and expertise.

The LCCA can be a useful tool in the determination of a most economical and cost-effective pavement design alternative over the long-run. The critical information for the LCCA is the collection of accurate data on various costs and expected life of the respective pavement applications. In order to improve LCCA, more information is needed to develop better estimates of the frequency and type of maintenance and repair activities required for the various types of CRM-modified paving materials, and the life of the repairs. Additional information regarding actual serviceable life of CRM-modified pavement is also needed.

2.3.7 Recycling

Literature related to recycling is reviewed in a separate report, “Feasibility of Recycling Rubber-Modified Paving Materials.” The reclaiming and recycling of CRM-modified paving materials has been an area of interest since CRM was first used in asphalt paving materials. Some agencies have used CRM materials in limited recycling experiments or demonstration projects including the Arizona, Texas (Crockford et al 1995), and Florida DOT (MACTEC Materials Survey 2004), and the Province of Ontario (Emery 1995, 1997). New Jersey (Baker and Connolly, 1995), Michigan (Gunkel, 1994), Mississippi (Albritton, Barstis and Gatlin 1999), and Kansas (Fager 2001) have recycled CRM-modified asphalt pavements that were constructed as demonstration or test projects. The respective studies include different types of wet process binders and/or various gradations of crumb rubber modifier (CRM) as an aggregate substitute (dry process). One of the few common features of these experiments was general success based on the following criteria:

- The recycled AC could be plant-produced using reclaimed RAC
- The recycled HMA made with reclaimed RAC could be placed and compacted using conventional equipment and practices.
- The resulting recycled pavements typically appeared to perform at least as well as conventional mixes that included conventional RAP.
- Results of emissions test were typically similar to those for conventional virgin and RAP mixes and rarely exceeded EPA limits.

The results indicate that a wide range of CRM-modified paving materials can apparently be successfully reclaimed and recycled. Due to the concerns regarding possible emissions from recycling CRM-modified paving materials, many of the studies of recycling CRM materials include an assessment of the emissions. The overall results of emissions assessments indicate little difference and no apparent increase in risk from conventional AC mix production.

2.3.8 Environmental Issues

A variety of studies have been conducted to assess possible environmental impacts of the use of CRM in a number of locations throughout the United States. There are clearly environmental benefits to using scrap tire rubber in paving materials, but there have also been concerns regarding emissions associated with CRM HMA production and placement. There is also concern about groundwater contamination as a result of leachate from CRM pavements.

Benefits

There are a number of benefits of using recycled scrap tires to engineer and build pavements, including but not limited to the following:

Reduction in Scrap Tire Stockpiles

A primary benefit is putting newly generated waste tires into a secondary value-added use instead of contributing to tire stockpiles. Caltrans 2003 annual report to the Legislature and the California Integrated Waste Management Board (CIWMB) states that over 30 million waste tires are generated in California, and over 3 million more waste tires are imported into the State each year, of which only about 19 million are recycled yearly. This does not account for tires that have been stockpiled legally or otherwise in the past, although CIWMB reports that stockpiles have been substantially reduced.

Improved Pavement Durability

Improved resistance to rutting, cracking and fatigue, as described previously in sections 2.3.2 and 2.3.5, enhance the overall performance and durability of asphalt pavements. Improved durability can reduce the frequency and extent of maintenance and repair operations over the life of the pavement. This leads to reduced life-cycle cost and traffic-delay for the driving public.

Pavement Noise Reduction

Another benefit of CRM pavements is in noise reduction. Reduced traffic noise (primarily tire noise) is another important benefit of using asphalt rubber materials that has been documented in Europe (Belgium, France, Germany, Austria, the Netherlands), Canada, Arizona, and California (Orange, Sacramento and Los Angeles counties). Significant reductions in traffic noise, ranging from 40 to 88 %, have been measured not only for open-graded but also for gap-graded RAC. Questions as to how long the noise abatement would continue were the impetus for a study by the Sacramento County Department of Environmental Review and Assessment. A consultant specializing in acoustics and noise control

conducted a six-year study on gap-graded RAC pavements (Sacramento DERPA and Bollard & Brennan, Inc. 1999). Completed in 1999, the results supported the findings of similar studies on noise reduction. The Sacramento study showed that the gap-graded RAC continued to mitigate traffic noise for six years, while noise measured on the conventional DGAC returned to pre-paving levels within four years.

Arizona DOT conducted a study of potential noise reduction of open-graded asphalt rubber asphalt concrete friction courses (AR-ACFC) used as overlays for portland cement concrete pavements (PCCP) on freeways. Noise measurements were performed on both types of pavement using two different techniques to compare the frequency content of the noise generated (Henderson and Kalevela 1996). The data indicated that the AR-ACFC surface produced lower noise levels than the PCCP, and that the frequency was lower which may have significant effects on how people perceive the noise. Some frequencies create considerable discomfort, and AR-ACFC mixes appear to dampen some of the most annoying frequencies.

ADOT and Caltrans are currently participating in a collaborative 10-year study with FHWA to evaluate the noise-reduction potential of rubber-modified paving mixes. It is anticipated that pavement surface may be incorporated in the FHWA calculations for height of noise barrier walls. On-going research by Caltrans and ADOT shows a sustained noise reduction with open-graded conventional and RAC mixes when compared to dense graded mixes and standard PCCP surfaces (Larry Scofield, ADOT, 2004).

Currently pavement surface type is specifically excluded from FHWA noise models, but the current joint Caltrans-ADOT study and research by Purdue University may lead to future changes. Caltrans and ADOT representatives participated in a workshop with FHWA at Purdue University from September 14-16, 2004. The workshop focused on how to establish and implement a new federal policy on highway noise mitigation to allow surface textures and/or materials to be used by the states as part of a noise mitigation plan.

Based on results of current research by ADOT, FHWA has granted a 4-dB noise reduction credit to ADOT for specific projects in the ADOT Quiet Pavement Pilot Program, which will be monitored for 10 years. The research will monitor the noise benefits of AR-ACFC in-place and determine the longevity of the 4-dBA benefit. (Note: 4-dB is equivalent to approximately 8 feet of additional noise wall height.) On-going ADOT research includes measurements of 12-year old open- and gap-graded asphalt rubber pavements to evaluate long-term noise reduction. Findings to date indicate that noise reduction persists over time, although in some cases the amount of reduction may decrease somewhat. Typical noise levels ranged from 94 to 98 dBA (Scofield and Donovan, 2003). ADOT is continuing to study noise generated not only by CRM surfaces, but also by a variety of rigid and flexible pavements with different types of gradations (dense-, gap- and open-graded), surface textures and thicknesses.

Air Quality

Concerns have been expressed regarding the effects of CRM-modified paving materials on air quality, particularly related to HMA plant emissions and worker health and safety. CRM consists mostly of various types of rubber and other hydrocarbons, carbon black, extender oils, and inert fillers. Most of the chemical compounds in CRM are also present to some extent in paving grade asphalt, although the proportions are likely to differ. CRM does not include exotic chemicals that present any new health risks. Although a number of stack emissions and worker exposure studies have been performed throughout the U.S. that have not indicated any increased risk due to CRM-related emissions, concerns seem to persist. Findings of selected Federal, state, and private studies are presented herein.

FHWA/USEPA

In June, 1993, FHWA and the US Environmental Protection Administration (EPA) issued a report on the “Study Of The Use Of Recycled Paving Material - Report To Congress” which described an analysis of

the results of seven studies to compare the relative threats/risks to human health and the environment of conventional asphalt paving to CRM asphalt paving. The report discussed some of the variables that influenced the health and environmental comparison. Conclusions indicated that the data evaluated contained no obvious trends to indicate a significant increase or decrease in emissions attributed to the use of CRM. The FHWA/USEPA report recommended further study of this issue. Subsequent studies have been conducted but have not provided sufficient evidence to change the original conclusions.

AC Plant Emissions Tests

To evaluate emissions issues, AC plant “stack tests” were performed during asphalt rubber hot mix production in New Jersey (1994), Michigan (1994), Texas (1995), and California (1994 and 2001). The results generally indicate that emissions measured during asphalt rubber production at HMA plants remain statistically about the same as for conventional AC and that amounts of any hazardous components and particulates remain below mandated limits (Stout & Carlson, 2003). That does not mean that there are no differences in raw emissions data between production of CRM paving materials and conventional DGAC; in many cases there are. However the actual amounts of the various compounds of interest that are measured are typically very small for both conventional and CRM mixes, and the differences measured are not large enough to indicate any adverse impacts.

New Jersey

The New Jersey Department of Transportation (NJDOT) initiated a study of CRM- modified AC mixes using both the wet and dry processes for major projects within the state. The study, which was developed to help reduce the number of scrap tires landfilled and stockpiled in the state, assessed the emissions for a total of six CRM mixes. Included in the study was a project section that included rubber RAP in the surface course mix. The emissions tests conducted at the asphalt plant indicated that total hydrocarbons and particulates were within emissions limits for the rubber RAP surface course mix. However, one carbon monoxide reading for the mix was at the limit. Four of the five remaining mixes that were evaluated had some form of unacceptable emissions levels (carbon monoxide, total hydrocarbons, particulates emissions, odors, or visual emissions). Overall, the CRM mixes had emissions levels that were higher than those of the corresponding non-CRM mixes (Baker and Connolly 1995).

Ontario

Emissions tests were also conducted on the test sections in Ontario. The tests revealed that there were no discernable differences in the emissions from the RUMAC production and that of the conventional HMA. Also the occupational health exposures that were monitored showed the levels to be similar for the conventional HMA and RUMAC (Emery 1995).

California AC Plant Emissions Studies

In 2001, Caltrans investigated emissions at two AC plants in the San Francisco Bay area. The Bay Area study was the result of severe blue smoke problems that occurred at a plant in November 2000, which were attributed to use of CRM. Data from other tests in other states were not acceptable to the Bay Area, and a partnership developed among Bay Area Air Quality Management District (BA AQMD), Caltrans, and paving industry organizations. This partnership developed a plan to test AC plants producing RAC during summer 2001. The scope of the testing program included the following:

- Cal ARB Method 429 - Polyaromatic Hydrocarbons (PAH)
- Cal ARB Modified Method 5 – Determination of Particulate (BTEX)

- Test during production of Conventional AC and RAC in triplicate at two hot plants
- Testing during normal production runs

For this study, the County of Sacramento Public Works Agency conducted stack emission tests at two production facilities, a batch plant in Richmond and a drum mix plant in Sunol, to compare emissions during production of RAC and DGAC mixes. The asphalt rubber conformed to Caltrans RAC requirements for wet process high viscosity binder. Although results at the batch plant were influenced by benzene exhaust from haul truck tailpipes in the truck load-out shed (other possible sources were evaluated and ruled out), measured emissions of particulate and specified toxic air contaminants were consistently lower than EPA AP-42 emission factors for production of both types of mixes and both types of plants. The conclusions of the Public Works Agency letter report on Results of Stack Emission Testing Asphalt Rubber and Conventional Asphalt Concrete, dated Feb 5, 2002, were as follows:

- Emissions from the production of RAC are not significantly different than those from the production of conventional DGAC
- Asphalt rubber is one of many types of “asphalt”; and emissions from its production are not dissimilar to the emissions from the production of conventional asphalt
- Therefore, existing production plants in the Bay Area that are permitted to produce AC should be permitted to produce RAC.

In some cases of RAC production there has been a significant rise in particulates within the vapors that has been tied to use of soft asphalt cements that often include extender oils. Caltrans specifications require the addition of 2.5 to 6.0% of extender oils that include at least 55% aromatic hydrocarbon compounds, which based on these findings would be expected to increase the amount of emissions (fumes and smoke). However review of the Bay Area study findings seems to indicate that this is not necessarily true.

Worker Health and Safety

A number of studies of worker exposure to potentially hazardous compounds in fumes from CRM-modified asphalt paving materials have been performed. Although the compounds evaluated, terminology and methods may vary among these studies, the same trends are generally repeated. Fumes generated by CRM materials at elevated temperatures compared to conventional AC mixes often have increased concentrations of a number of compounds of interest, but these compounds rarely exceed established permissible exposure limits.

National Institute for Occupational Safety and Health (NIOSH)

NIOSH in cooperation with FHWA has performed evaluations of possible differences in the occupational exposures and potential health effects of CRM and conventional HMA. NIOSH Health Hazard Evaluations were performed at seven paving projects located in Michigan, Indiana, Florida, Arizona, Massachusetts, and California (2) from 1994 through 1997. The purposes of the multiple studies were to assess site-specific information relative to each project to compile results and compare the effects of exposure due to CRM and conventional materials. The assessments included an evaluation of collected area air samples in order to characterize the asphalt fume emission, personal breathing zone (PBZ) air samples to evaluate worker exposures, and a medical component including questionnaires and lung function tests.

The study conducted by NIOSH in Evansville, Indiana, found that asphalt fume exposures varied across the days of survey but were consistently higher during CRM asphalt paving. The Evansville study indicated that higher worker symptom rates were consistent with higher air concentrations during the CRM paving compared to the conventional paving (Miller and Burr 1996). The NIOSH assessment of

paving operations in San Diego, California yielded the same overall findings, as did the studies performed at sites in Lansing, Michigan; Sacramento California; and Yeehaw Junction, Florida. However, the study in Casa Grande, Arizona showed little difference between worker symptom rates for the CRM and conventional asphalt paving periods (Burr and Miller 1996).

The NIOSH studies showed that the various exposure measurements evaluated for both conventional AC and CRM asphalt paving were below the NIOSH recommended exposure limits. Based upon the results of the individual studies, NIOSH did not draw any definitive conclusions regarding the potential health effects of CRM asphalt compared to conventional asphalt. These reports indicate that increases in plant emissions were related to the elevation temperatures, not the presence of the CRM.

NIOSH has released some preliminary information on individual projects and a report on the Michigan study was presented at an annual meeting of the Transportation Research Board. However the December 2000 NIOSH report on “Health Effects of Occupational Exposure to Asphalt” (No. 2001-110) that references seven CRM assessments performed from 1994 through 1997, specifically states that it does not present any of the findings for asphalt mixes containing CRM. This report is the latest version and no updates had been posted by NIOSH as of October 2004. The December 2000 NIOSH report does not recommend any changes to the 1977 NIOSH criteria for recommended exposure standards, which can be readily accessed through the NIOSH and OSHA web sites.

Industry Studies in California

A 2.5-year study was performed in Southern California to assess the effects of “Exposure of Paving Workers to Asphalt Emissions (When Using Asphalt Rubber Mixes)”. The study began in 1989 and results were published in 1991 (Rinck, Napier and Null), before fume exhaust ventilation and capture devices were implemented on paving equipment. The study monitored a number of individual paving workers in direct contact with fumes during hot mix paving operations as well as spray applications. The researchers found that emission exposures in asphalt rubber operations did not differ statistically from those of conventional asphalt operations. Based on results of this study, “there is no evidence to indicate that persons who are involved in the application of asphalt rubber products are at risk from asphalt rubber emissions.”

A worker exposure study of CRM HMA was conducted during highway construction near Holtville (Caltrans Contract No. 11-172504) from November 30 through December 1, 1994. Personal exposures were reportedly well under the existing Cal-OSHA limits. However measured concentrations of fumes did not vary consistently with respect to mix temperature as has typically been noted in such studies.

One of the few studies where emissions did exceed specified limits was the Asphalt/Rubber Fume Pilot Study in Sacramento, CA conducted at two paving sites in Valencia CA in August 1992. This study measured exposure of paving workers to total particulate and benzene soluble fraction thereof, polyaromatic hydrocarbons (PAHs), sulfur heterocyclic compounds (SH), volatile aromatic compounds (VArCs), styrene, 1,3-butadiene and nitrosamines. Personal air samples showed lower concentrations of contaminants with established PELs (all below) than did the area air samples; this has not been the case for most similar studies. The area air samples indicated average asphalt fume concentrations of 5.54 mg/m³, about 11% above the Cal-OSHA PEL of 5 mm/m³, a value which was not exceeded in the other studies reviewed. This was reportedly the only measured exposure value that exceeded PEL. This study also evaluated fumes in the headspace of heated asphalt and asphalt rubber storage tanks, where no worker should be, and found that PAH and SH concentrations were higher in the asphalt cement than in the asphalt rubber. However higher concentrations of VArCs, 1, 3-butadiene and nitrosamines were found in the asphalt rubber headspace. Observations indicated that paving operations using asphalt rubber generates a denser asphalt fume than traditional asphalt materials.

Summary

The literature review indicated that numerous studies of worker exposure to potentially hazardous compounds in asphalt rubber fumes have been performed. Fumes generated by CRM-modified materials at elevated temperatures often have increased concentrations of a number of compounds of interest compared to conventional asphalt materials, but these rarely exceed established permissible exposure limits. Thus there is no pattern of evidence that asphalt rubber materials present greater health hazards than conventional asphalt materials.

Water Quality

Water quality is another area of concern regarding the use of CRM. One study conducted for the Rhode Island Department of Transportation focused on potential groundwater contamination as a result of leachates from CRM pavements. The report provides extensive background on the literature concerning the investigation of contaminants from the use of CRM in asphalt pavements.

The study was conducted in three main phases. The first phase involved the identification of contaminants from CRM samples. Through extensive testing, the results showed that zinc concentrations were at least an order of magnitude higher than any other metal for the CRM samples. Various testing methods provided contradictory results in terms of what metals were present.

The second phase of the study involved assessing the water quality from the CRM samples for varying environmental conditions. The metal concentrations were shown to be the highest at the most acidic and basic conditions and at the highest temperatures. The majority of test specimens showed no difference in metal concentrations between control, dry and wet CRM specimens. In terms of organic materials benzothiazoles were the only major compounds leached.

The final phase of the research involved evaluated the water quality of the CRM samples under simulated rainfall conditions. The results showed that chromium, nickel and lead never exceeded the aquatic or drinking water criteria. However copper and cadmium exceeded maximum concentration levels for 6.5 and 13 % of the samples, respectively. However, testing conditions were the worst-case scenario because issues such as waster dilution were not taken into consideration. The study recommends further research before final conclusions are reached, but concluded that the research does not show evidence that the use of CRM will pose a problem to the environment or human health (Wright et al. 1999).

Southwestern Laboratories tested leachate from stockpiles of reclaimed CRM pavement milled from IH-10 in San Antonio, Texas, to evaluate the potential for contamination of surface runoff and groundwater. Simulated precipitation leachates were prepared to represent the cumulative effects of acid rainwater leaching and were analyzed for the presence of trace metals, volatile organic compounds (VOCs) and semivolatile organic compounds. The only compound of interest that was present at a level above the analytical detection limit was mercury, but levels detected were below EPA limits (Crockford et al, 1995). The report concluded that levels of detectable leachates were too low to be environmentally significant or dangerous.

2.3.9 Other Uses of Scrap Tire Rubber

The use of and demand for rubber products is pervasive in today's consumer and industrial economies. While 60 % of rubber production is used in tire manufacture, the balance is employed in making rubber components supplied to the aerospace, appliance, medical, transportation, construction, electrical and electronic industries -- to name a few.

Transportation and Civil Engineering Applications

The use of scrap tires for transportation-related activities is not limited to CRM asphalt pavement materials. In fact, the use of scrap tire rubber for various other value-added applications has been assessed through differing field trials and laboratory experiments. A number of civil engineering applications are being explored, including embankments, lightweight fills, walls, and rubber soils.

In addition to the reduction in noise that CRM pavements can provide, the use of CRM is also being examined as a potential addition to the creation of noise-reduction sound barriers. In the past, these barriers have been primarily made of concrete. While concrete meets the standard requirements of sound barriers in terms of cost-effectiveness, technology maturity, durability, and convenience in installation and maintenance/repair and aesthetics, it does not provide good sound absorption because it has a high acoustical reflectivity. Therefore, a study is underway to evaluate the use of CRM as component of an asphalt coating that can be sprayed as layer on existing or new concrete sound barriers. The goal of the study is to develop technology that will spray application of the coating (Arizona Department of Transportation 1999).

Caltrans has established a variety of uses for recycled content tire products for civil engineering applications in transportation projects. Caltrans is committed to reduce the number of waste tires entering California's landfills by aggressively pursuing innovative uses for these tires. Although RAC is viewed by many as the main avenue to aid in this effort, there are limits to how much rubber can be incorporated into pavements. Since the year 2000, Caltrans usage of waste tires in RAC projects has decreased due to significant reductions in highway funding and consequently construction. Although concrete pavement and asphalt pavement show dramatic decreases in use, RAC is holding relatively steady according to the 2003 Annual Report to the Legislature. Therefore Caltrans is pursuing other uses that consume larger quantities of waste tires.

Shredded waste tires show promise for using large quantities of waste tires in engineering applications. Caltrans has worked in partnership with the California Integrated Waste Management Board (CIWMB) on projects that promote the innovative use of shredded waste tires in highway construction. In 2001, Caltrans constructed an embankment made of lightweight fill from shredded waste tires on a project in Santa Clara County. This year, Caltrans installed tire shreds as lightweight backfill material behind a retaining wall on Route 91 in Riverside County. This pilot project allows Caltrans to perform a full-scale test of a tire shred installation to measure the anticipated reduced lateral pressure on the retaining wall. Reductions in pressure on the retaining wall related to the use of tire shreds may allow for a significant reduction in the retaining wall mass in future designs, potentially reducing retaining wall costs. The retaining wall test section is 260 feet in length and will utilize approximately 75,000 shredded tires. A similar installation of lightweight backfill using tire shreds is being designed for another retaining wall in Riverside County. Installation of the tire shreds for this project is anticipated in 2005 and preliminary estimates indicate that roughly 150,000 tires will be used. Caltrans is currently developing Standard Special Provisions (SSP) for lightweight fills and backfills for retaining walls.

In many test sections, tire shreds have performed well as embankment fill. Specifically, a tire-chip fill constructed in Maine was determined to have an in-place density that was less than 50% of that for a typical gravel fill. These properties make tire chips an ideal lightweight fill to lower the risk of landslide. Material properties such as low unit weight and high permeability make the tire chips an attractive retaining-wall backfill. The University of Maine constructed a test wall that showed that the lateral earth pressure at the base of tire-chip fill 4.3 m (14 ft) thick with a 36 kPa (750 16/ft²) surcharge was less than 50% of that for a typical gravel fill. The lower pressures allow thinner walls to be constructed, resulting in significant cost savings for retaining walls and bridge abutments (Humphrey 1996).

Although the potential benefits of the use of tire shreds are apparent, the behavior of the material is sometimes unexpected and unpredictable. For example, one shredded tire embankment construction

project in Washington State resulted in severe degradation due to exothermic reactions occurring in the tire mass. The embankment was constructed with few problems. Within 2 months of completion, however, problems developed: steam was emitted from the embankment and finally oil was observed seeping into the groundwater. Although five alternatives for remediation were considered, a decision was made to isolate and remove the quenched material. The remediation plan addressed issues relating to community safety, controlled access, media involvement, worker safety and waste disposal (Gacke, Lee and Boyd 1997).

Chips from scrap tires have also been evaluated as an insulating layer for gravel-surfaced roads that experience frost heave (Humphrey and Eaton 1995). Test sections were constructed and the results showed that significant reductions in depth of frost penetration and the amount of heave experienced by the rubber insulated sections were comparable to that observed in the control sections. The favorable results of the behavior of the rubber insulated sections make the use of scrap tire rubber in this manner a realistic use.

Rubber modified asphalt can be used in railroad trackbeds. Currently, the noise associated with railways poses a major concern especially in major metropolitan areas. The use of CRM mixes is expected to provide major benefit in controlling noise for railroad trackbeds. Laboratory tests examined the shear stiffness and damping ratio of CRM mixes compared to conventional asphalt mixes and unsaturated subgrade soils (Zhong, Zeng, and Rose 2002). Results show that the damping ratio for the CRM mixes was nearly twice that of the conventional asphalt mix and nearly three times that of the unsaturated subgrade soil. The high damping ratio of the CRM makes it an attractive potential choice for reducing vibration attenuation of railroad trackbeds. Also the high shear modulus of the CRM mix ensures that it has the needed stiffness characteristics for use in railroad track structures.

CRM has also shown potential in helping remove petroleum from water. Research has shown that many rubber polymers can absorb a variety of solvents, including aromatic hydrocarbons such as benzene, toluene, ethylbenzene, and xylene compounds (BTEX) in gasoline. Using the CRM as a component in a variety of remediation techniques has shown potential. However, further research including a cost analysis of the use of such material is needed (Pamukcu and Kershaw 1996).

Transportation Products

Transportation officials around the country are reporting that recycled-content safety cones, traffic barricades, traffic control devices, and parking stops deliver high performance and reduce installation and maintenance costs. The U.S Environmental Protection Agency (EPA) updates comprehensive Procurement Guidelines (CPG) every two years. Through the CPG, EPA designates items that must contain recycled products when purchased by federal, state, and local agencies. EPA also issues non regulatory companion guidance-the Recovery Material Advisory Notice (RMAN)-that recommends levels of recycled content for items as follows:

Traffic Cones	(Crumb Rubber)	50-100%
Parking Stops	(Plastic/or Rubber)	100%
Channelizers (Base Only)		100% (post consumer)
Delineators (Rubber base only)		100% (post consumer)

Tire Derived Fuel

The use of tires as a fuel supplement in cement kilns and cogeneration facilities constitutes a large market for waste tires, both nationally and in California. For example, of the 34 million waste tires generated in 2002, approximately five million were used as Tire Derived Fuel (TDF) in various cement kilns in California. These kilns produce cement, which is used to manufacture concrete incorporated in many

construction projects. Caltrans use of cement has decreased relative to previous years due to the reduction of large construction projects in the program. In a number of states, the primary use of scrap tire rubber is as TDF. Burning scrap tires for fuel is not considered to be a value-added application, because the rubber is consumed. However cost and supply fluctuations of petroleum-based fuels and issues related to use of coal make this an attractive alternative. The US is currently experiencing a shortage of portland cement due to overseas demands, so methods to increase cement production would help improve supply and control costs.

CRM in Portland Cement Concrete

Arizona State University and the Arizona Department of Environmental Quality are evaluating the use of CRM as a light-weight aggregate substitute in PCC materials. A range of rubber contents have been evaluated in the laboratory with some promising results. Using CRM does affect compressive strength in proportion to the amount used, but at low concentrations of a few pounds per cubic yard losses are relatively small.

As indicated by the scope of the literature reviewed, there a wide variety of ways to use scrap tire rubber that continue to be investigated as means of reducing the stockpiling of this waste material.

2.4 SPECIFICATIONS

The development of specifications to control the design, production, and placement of CRM asphalt paving materials is important to help standardize and control the quality of these types of materials. State specifications relating to the use of CRM in asphalt paving materials have evolved as their experience has grown. Specifications for wet process high viscosity binders evolved from research by champions of CRM-modification and subsequent validation and refinement by the respective state DOTs. Appendix B includes a detailed summary of practices for Arizona, California, Florida and Texas. It includes information not only on the types of materials used, but also structural design and construction.

A good example of an independent specification development process is provided by FDOT's approach. FDOT used three demonstration projects to evaluate the constructability and short-term field performance of different amounts and sizes of ground tire rubber, i.e. CRM, in plant-produced FDOT mixes in order to incorporate the results into specifications and procedures for its use. Research into the development of mix properties focused on the use of fine CRM (passing the 300 μm (No. 50) sieve) at relatively low percentages, from 5 to 15% CRM by weight of binder (Page, Ruth, and West 1992).

The first demonstration project resulted in a dense graded mix with 5.3% passing the 300 μm (No. 50) sieve CRM by weight of asphalt cement appearing to be the most appropriate proportion. The second demonstration project, which focused on developing an open-graded friction course, indicated that 10 to 15% CRM by binder weight seemed to be an effective amount used in combination with binder contents of less than 8% by mix weight used in the project. The last demonstration project used 10% CRM passing the 300 μm (No. 50) sieve by binder weight to determine whether asphalt rubber could be blended and incorporated into an open-graded friction course mix using a prototype continuous production blending unit. The project was constructed without any major problems. However, blending times were longer than expected because the prototype provided the asphalt cement at a lower-than-anticipated temperature.

Findings from these experiments indicated that appropriate proportions for blending with the asphalt cement were 5% of passing the 300 μm (No. 50) sieve CRM by binder weight for dense-graded friction course mixes, and 12% of passing the 600 μm (No. 30) sieve CRM for open-graded friction courses. CRM also proved feasible for providing SAMIs to seal the underlying pavement from surface moisture

and help retard reflective cracking. The appropriate CRM proportion for the spray application was found to be 20% of passing the 2.0 mm (No. 10) sieve. Current FDOT rubber gradation specifications are presented in Table 2.2 in this report.

Cost estimates by the Florida State Materials Office indicated that the cost of including CRM in the asphalt pavements in Florida would increase the cost by 15 %. The third demonstration project was let through the normal bidding process, at a cost of 31% more than for an equal thickness of conventional DGAC. The report provides specifications for the general, physical, chemical, and packaging and identification requirements for the CRM. Specifications were also developed to control the production of asphalt-rubber in terms of materials, equipment, and method of measurement (Page, Ruth, and West 1992). As the use of CRM continued throughout the state of Florida, a study was initiated in 2002 by FDOT to compile the findings regarding the use of the modifiers in the state. This on-going study will also provide a summary of the issues related to the use of the modifiers along with a review of the performance of materials. Based upon the results, guidelines for the use of modifiers within the state of Florida will be provided (Florida Department of Transportation 2002).

For ease of comparison several tables are presented which contain specification parameters for the four user states (AZ, CA, FL and TX). These include information on the following: CRM gradation; CRM binders, with separate tables for high viscosity and no agitation binders; and aggregate gradations used in dense, gap and open-graded RAC mixes.

Crumb Rubber Modifier (CRM)

Table 2.2 presents CRM gradations currently specified by Caltrans, ADOT, FDOT and TxDOT for use in CRM binders (both high viscosity and no agitation) for asphalt concrete, chip seals and/or interlayers.

Table 2.2: CRM Gradation Specifications

Sieve Size % Passing	Caltrans Scrap Tire (Green- book)	Caltrans High Nat'l (Green- book)	TxDOT Grade A	TxDOT Grade B	TxDOT Grade C	ADOT Type A	ADOT Type B	FDOT Type A	FDOT Type B	FDOT Type C
2.36 mm (#8)	100	100	100			100				
2.00 mm (#10)	98-100	100	95-100	100		95-100	100			
1.18 mm (#16)	45-75	95-100		70-100	100	0-10	65-100			100
600 µm (#30)	2-20	35-85		25-60	90-100		20-100		100	70-100
425 µm (#40)					45-100					
300 µm (#50)	0-6	10-30	0-10				0-45	100	40-60	20-40
150 µm (#100)	0-2	0-4						50-80		
75 µm (#200)	0	0-1		0-5			0-5	--	--	--

Caltrans uses the same gradation of scrap tire and high natural rubber content CRM materials for hot mixes, chip seals and interlayers. The Standard Specifications for Public Works Construction “Greenbook” lists the same CRM gradation requirements for wet process CRM-modified binders as Caltrans. The Greenbook is used by a number of counties and municipalities particularly in southern California. TxDOT uses CRM Grade B in binders for SAMIs, and a finer grind of CRM, Grade C, in hot mixes. ADOT uses Type A CRM in binders for chip seals and SAMIs, and finer Type B CRM in gap- and open-graded hot mixes. FDOT also follows the trend of using coarser rubber in SAMIs (Type C) than in CRM binders for hot mixes (Types A and B), but specifications allow the CRM producer to use Types A and B in binders for SAMIs. Each agency has similar limits for moisture content (a safety requirement to prevent splash and splatter during blending with hot asphalt cement) and metal contaminants. Although FDOT includes chemical requirements in its specification with the intent of limiting CRM to scrap tire rubber, it has not made a practice of requiring chemical analysis testing as Caltrans has.

CRM-Modified Binder

Table 2.3 presents specifications for high viscosity wet process CRM binders with minimum viscosity of 1.500 Pa•sec (1500 cPs). The table shows considerable similarity among the users. TxDOT uses the properties in Table 1 of ASTM D 6114, Specification for Asphalt Rubber Binder.

For high viscosity wet process binders, Caltrans requires the use of extender oil and high natural rubber content CRM (Type 2). These components are not required by FDOT or TxDOT, and ADOT does not allow extender oil in such binders. However these three states use the SHRP performance-graded (PG) system for asphalt cement, which allows much more control over the properties of the virgin asphalt cement than does the aged residue (AR) system used in California. The PG system allows control and selection of appropriate grades of asphalt cement for CRM without forcing the use of another asphalt modifier such as extender oil. High natural rubber content CRM has been shown to enhance chip retention of CRM chip seals, but the practices of these three DOTs indicate that it is not necessary for HMA. The primary reason to use extender oil and high natural rubber content CRM is to ensure compatibility and promote interaction of the CRM and asphalt cement. The Greenbook allows Type 1 (CRM and asphalt only) and Type 2 binder.

Table 2.4 presents specifications for no agitation wet process CRM-modified binders with minimum viscosity less than 1.5 Pa•sec (1,500 cPs) for ADOT, Caltrans, FDOT, TxDOT and the Greenbook. Comparison of the specifications presented indicates common elements among all but the Caltrans MB materials. Both the Greenbook and TxDOT require that the CRM be completely digested; the other specifications do not include this requirement.

The MB specification is unique in that it is based on the shear susceptibility of the phase angle, δ , and the shear susceptibility of the viscosity of the modified binder. Although the Caltrans MB specification lists high natural CRM as the rubber component, there is no minimum CRM content requirement. The specified physical properties could be obtained without adding CRM, by use of various polymers and other additives. Comparison with the other specifications for wet process no agitation CRM-modified binders shows no clear relationship to the MB property requirements.

Table 2.5 presents aggregate gradations for CRM asphalt concrete mixes for ADOT, Caltrans, FDOT, and TxDOT. For TxDOT, only the open- and gap- (SMAR) gradations used with wet process high viscosity binders are shown. Wet process no agitation binders can be used in any TxDOT dense-graded mix as a substitute for a performance-graded or viscosity-graded binder. FDOT does not use CRM in gap-graded mixes, but does use it in both open-graded and dense-graded friction (surface) courses. Caltrans has a moratorium on use of high viscosity binders in DGAC, but does use these binders in gap and open-graded mixes. Caltrans has used MB in some DGAC and gap-graded mixes, but is awaiting results of HVS, field performance, and laboratory performance testing before continuing use of MB. ADOT has allowed use of PG 76-22 TR+ as a substitute for high viscosity binders in some gap-graded mixes, but considers the no agitation binder to be a very different material from the high viscosity binders, that results in as much as a 2% decrease in binder content when used as a substitute.

Table 2.3: Specifications for High-Viscosity Wet Process CRM Modified Binders with Minimum Viscosity = 1.5 Pa•sec, 1500 cPs

Agency	ADOT ¹	ADOT ¹	ADOT ¹	Caltrans ² (Greenbook)	Greenbook ³	FDOT ⁴	TxDOT ¹	TxDOT ¹	TxDOT ¹
Binder Type	1	2	3	2	1	ARB 20	I	II	III
CRM Type: Scrap tire (ST) High Natural (HN)	ST ---	ST ---	ST ---	75±2% ST 25±2% HN	ST --	ST ---	ST ---	ST ---	ST ---
Minimum CRM by total weight of binder, %							15	15	15
Minimum CRM by weight of asphalt cement, %	20	20	20	18	18	20			
Base Asphalt Cement Grade	PG 64-16	PG 58-22	PG 52-28	AR-4000	AR-4000	Seal Coat (SAMI) PG 64-22	AC-10 or AC-20 (PG 58-28/ PG 64-22)	AC-10 or AC-20 (PG 58-28/ PG 64-22)	AC-10 or AC-20 (PG 58-28/ PG 64-22)
Asphalt Modifier (extender oil) by weight of asphalt cement, %	Not Allowed	Not Allowed	Not Allowed	2.5-6.0	0	Allowed but not used	Allowed but not used	Allowed but not used	Allowed but not used
Minimum Interaction Temperature	163°C/325°F	163°C/325°F	163°C/325°F	190°C/375°F	190°C/375°F	170°C/335°F	---	---	---
Maximum Interaction Temperature	190°C/375°F	190°C/375°F	190°C/375°F	218°C/425°F (226°C/440°F)	226°C/440°F	190°C/375°F	---	---	---
Minimum Interaction Time	60 minutes	60 minutes	60 minutes	45 minutes	45 minutes	30 minutes	---	---	---
Rotational Viscosity range in Pa•sec, specified measurement temperature	1.5-4.0 177°C/350°F	1.5-4.0 177°C/350°F	1.5-4.0 177°C/350°F	Seal Coat 1.5-3.0 AC 1.5-4.0 190°C/375°F	1.5-4.0 190°C/375°F	Seal Coat Min 1.5 175°C/350°F	AC 2.5-5.0 175°C/347°F	Seal Coat 1.5-5.0 AC 2.5-5.0 175°C/347°F	Seal Coat 1.5-5.0 175°C/347°F
Needle Penetration @ 4°C/39.2°F, 200g, 60 sec, 0.1 mm	Min 10	Min 15	Min 25						
Cone Penetration @ 25°C/77°F, 150g, 5 sec, 0.1 mm				25-70	25-70				
Needle Penetration @ 25°C/77°F, 100g, 5 sec, 0.1 mm								25-75	50-100
Softening Point, °C/°F, minimum	57°C/135°F	54°C/130°F	52°C/125°F	52°C/125°F	52°C/125°F		57°C/135°F	54°C/130°F	52°C/125°F
Softening Point, °C/°F, maximum				74°C/165°F	74°C/165°F				
Resilience @25°C/77°F, % Rebound	Min 25	Min 20	Min 15	Min 18	Min 18	25-75	Min 25	Min 20	Min 10
Tests on residue from Thin Film Oven Test: Retained penetration ratio@ 4°C/39.2°F, % of original							Min 75	Min 75	Min 75

¹ADOT and TxDOT specifications are published in English units; for this table, temperature values were converted from °F to °C and rounded.

²Caltrans dual units specifications are presented in this table.

³Greenbook allows use of either Type 1 and Type 2 binders; requirements follow Caltrans unless indicated (otherwise)

⁴FDOT provides respective values for °C and °F that are not exact conversions of each other; temperature limits presented in this table are as shown in the FDOT Standard Specifications and have not been adjusted.

Table 2.4: Specifications for No Agitation Wet Process CRM Modified Binders with Minimum Viscosity Less Than 1.5 Pa•sec, 1500 cPs

Agency	ADOT	FDOT	FDOT	TxDOT	Greenbook	Caltrans			
Binder Designation	PG 76-22 TR+	ARB 5	ARB 12	AC-20-5TR	MAC-10TR	MB-4	MB-5	MB-6	MB-7
Original Physical Properties									
CRM by total weight of binder				Min 5%					
CRM by weight of asphalt cement	Min 9%	Min 5%	Min 12%		Min 10%				
Base Asphalt Cement Grade	PG 76-22	PG 67-22	PG 67-22	AC-20					
Rotational Viscosity, Pa•sec, °C/°F		Min 0.4 @ 150°C/300°F	Min 1.0 @ 150°C/300°F						
Viscosity AASHTO 202, poise @ 60°C/140°F/ 135°C/275°F				Min 2000/ Max 10.0	Min 5000/ Max 10				
Interaction Temperature		150-170°C 300-335°F	150-175°C 300-350°F						
Minimum Interaction Time		10 minutes	15 minutes						
G*/sin δ @ 76°C @ 10 rad/sec	Min 1.0 kPa								
Phase angle, δ	Max 75°								
G*/sin δ @ 64°C @ 10 rad/sec				Min 1.0 kPa					
Needle Penetration @ 25°C/77°F, 100g, 5 sec, 0.1 mm				75-115	40-60				
Softening Point, °C/°F, min	60°C/140°F			49°C/120°F	53°C/127°F				
Elastic Recovery, 10°C, %	Min 55%			Min 55%					
Needle Penetration @ 4°C/39.2°F, 200g, 60 sec, 0.1 mm					Min 20				
Shear Susceptibility of δ and Viscosity						SSD ≥ 30(0.6 + SSV) ³ @ 25°C, CT 381			
Tests on TFOT Residue									
Retained penetration ratio @ 25°C/77°F, % of original				60-100	RTFO Min 50%				
Tests on RTFO Residue									
G*/sin δ @ 76°C @ 10 rad/sec	Min 2.20 kPa								
δ ≤ 97-6(log G*) and G*/sin δ ≥ 4.0kPa @ 10 rad/sec, @°C						@ 64°C	@ 64°C	@ 64°C	@ 70°C
Needle Penetration @ 4°C/39.2°F					Min 14				
Needle Penetration @ 25°C/77°F					20-40				
Dynamic Viscosity 60°C/140°F, Poise					Min 20000				
Kinematic Viscosity 135°C/275°F, cSt					Max 1500				
Tests on RTFO/PAV Residue									
G*/sin δ @ 31°C @ 10 rad/sec	Min 5,000 kPa								
Creep Stiffness, S @ -12°C, 60 sec	Max 300 MPa								
Creep Stiffness, S @ -18°C				Max 300 MPa					
m-value @ -12°C, 60 sec	Min 0.300								
m-value @ -18°C				Min 0.300					
S ≤ 300 MPa, m ≥ 0.30, 60 sec, @ °C						@ -8°C	@ -19°C	@ -30°C	@ -8°C
Shear Susceptibility of δ and Viscosity						SSD ≥ -115 SSV - 50.6 @ 25°C, CT381			

Table 2.5: Aggregate Gradation Specifications for CRM-modified Asphalt Concrete Mixes

Sieve Size mm (in)			Caltrans						Greenbook			FDOT			TxDOT		
	Gap	Open	19 mm D-MB	19mm RAC-G G-MB	12.5mm RAC-G G-MB	9.5mm G-MB	12.5mm RAC-O	9.5mm RAC-O	ARHM GG-B	ARHM GG-C	ARHM GG-D	FC-5 Open	FC-9.5 Dense	FC- 12.5 Dense	PFC Open	SMAR Coarse	SMAR Fine
25 mm (1")	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
19 mm (3/4")	100	100	95-100	95-100	100	100	100	100	90-100	100	100	100	100	100	100	100	100
12.5 mm (1/2")	80-100	---	---	83-87	90-100	100	95-100	100	---	90-100	100	85-100	100	90-100	95-100	72-85	100
9.5 mm (3/8")	65-80	---	65-80	65-70	83-87	78-92	78-89	90-100	60-75	78-92	78-92	55-75	90-100	<90	50-80	50-70	95-100
4.75 mm (# 4)	28-42	30-45	49-54	33-37	33-37	33-37	28-37	29-36	28-42	28-42	28-42	15-25	<90	---	0-8	30-45	40-50
2.36 mm (# 8)	14-22	4-8	36-40	18-22	18-22	18-22	7-18	7-18	15-25	15-25	15-25	5-10	32-67	22-58	0-4	17-27	17-27
1.18 mm (# 16)	---	---	---	---	---	---	0-10	0-10	---	---	---	---	*	*	---	12-22	12-22
600 µm (# 30)	---	---	18-21	8-12	8-12	8-12	---	---	5-15	5-15	5-15	---	*	*	---	8-20	8-20
300 µm (# 50)	---	---	---	---	---	---	---	---	---	---	---	---	*	*	---	6-15	6-15
75 µm (# 200)	0-2.5	0-2.5	3-8	2-7 MB 3-7	2-7 MB 3-7	3-7	0-3	0-3	0-5	2-7	2-7	2-4	2-10	2-10	0-4	5-9	5-9

*Excludes Superpave restricted zone

2.5 SUMMARY

An extensive body of literature is available on the various uses of CRM which cover a wide range of approaches and extensive experience. The primary focus of this review is the value-added use in asphalt paving applications of CRM produced from scrap tires, and related issues and concerns. Examples of other uses and applications are described to provide an overview and some perspective.

The use of CRM-modified binders in asphalt concrete mixes has yielded variable results for a number of reasons already discussed. These materials have been shown to have great potential for use in engineering pavements to resist fatigue, rutting, and reflective cracking, which works to enhance durability and reduce needs for maintenance and repairs. There have been successes, some of which are described herein. However there have also been failures which seem to have much greater impact on the overall perception of the performance and quality of these materials than any report of a successful application.

The four states where crumb rubber modification has become routine are Arizona, California, Florida, and Texas. It is no coincidence that these are the locations where the materials were championed by local suppliers, or by state DOTs. FDOT's use of CRM was adapted to cause as little disruption to existing procedures and costs as possible. In Arizona, California and Texas, suppliers strongly championed the use of these materials and provided considerable technical and engineering support to the respective DOTs to help develop and optimize CRM paving materials and systems. In-state mobilization costs were also generally more reasonable. Where the modified materials were fostered, they succeeded on a regular basis; any failures were typically quickly remedied. Standard specifications were developed and used on a regular basis, and contractors had the opportunity to become proficient in handling and constructing the CRM materials.

It is somewhat of a coincidence that the routine users are all Sunbelt states, which has led to a common misunderstanding that CRM materials only work in hot climates. Both California and Arizona include the seven SHRP climatic zones ranging from low desert to high alpine where there really is winter and plenty of cold and snow. The literature indicates that CRM pavements have provided excellent service in high mountain areas with extremely cold climates, including the Donner Summit in California and I-40 near Flagstaff, AZ. The landmark Ravendale experiment which changed Caltrans approach to the use of CRM materials is located in an area that is subject to winter storms, snow and tire chains.

It appears that the technical barriers to use of CRM materials have been surmounted. There is sufficient experience available to facilitate use in nearly any climate. Moreover, paving mixes can be designed and placed with conventional equipment. Instructional materials are readily available through the California Rubberized Asphalt Concrete Technology Centers, and the Caltrans "Asphalt Rubber Usage Guide" is available on the Internet. The remaining barriers to use of CRM paving materials are primarily cost and perceptions.

3.0 USAGE SURVEYS

3.1 INTRODUCTION

To determine Caltrans use of CRM in paving applications relative to its counterparts nationwide, two surveys were conducted.

1. List Server Survey: a blanket survey utilizing the American Association of Highway Transportation Officials (AASHTO) List Server. The survey results are shown in Appendix D.
2. Usage Survey: a focused survey of state agencies known to routinely use scrap rubber in paving applications. Survey results are shown in Appendix E.

In addition, data from California local agencies known to use CRM in paving applications were compiled. These data were extracted from several sources including the following: California Integrated Waste Management Board (CIWMB) and the Rubberized Asphalt Technology Center (RACTC) 2002-2003 usage survey, and phone interviews. This chapter presents the results of these surveys. Copies of the “list server” and “usage” questionnaires are provided in Appendix F.

3.2 LIST SERVER SURVEY

To assess the use of CRM in paving applications the AASHTO List Server was used to survey the 50 state DOTs, the District of Columbia, Puerto Rico and the Canadian province of Ontario. The survey questioned the agency’s use of CRM in hot mix asphalt concrete, microsurfacing or spray applications.

Compilation of the responses revealed the following with respect to use of CRM in paving applications: 7 departments currently use it (AZ, CA, FL, NE, RI, PA, TX); 39 do not currently use it; 7 did not respond. The results of the survey are shown graphically in Figure 3.1. Complete survey results and contact information are shown in Appendix D.

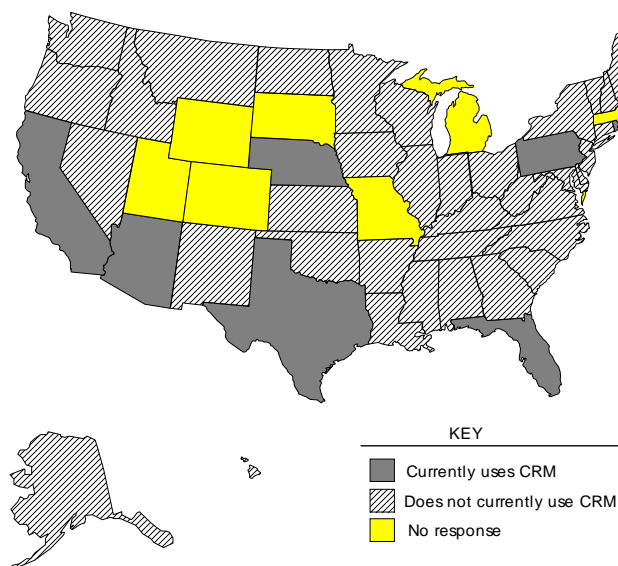


Figure 3.1: Use of CRM by State DOTs

While the majority of DOTs do not currently use CRM, there is a significant number that have used CRM in the past and/or have specifications that allow for its use. The most commonly cited reason for not using CRM was cost.

The results of the AASHTO List Server Survey provided a national perspective on CRM use in paving applications. To assess Caltrans use relative to those states currently using CRM, a second, more focused survey was sent to primary user state DOTs in Arizona, Florida and Texas. Nebraska, Pennsylvania and Rhode Island reported using CRM, but in such small quantities that it could best be described as “experimental,” i.e., these states do not routinely use CRM. Accordingly, these states were not included in the follow-up “Usage Survey.” Additionally, through the List Server Survey it was discovered that California, Florida and Texas produce annual reports that categorize and quantify the end-use of scrap tires. The most recent year for which reports were available was 2002.

3.2.1 Scrap Tire Use – Annual Reports

As noted above, California, Florida and Texas produce annual reports outlining the end-use of scrap tires (CIWMB, 2003; Florida Department of Environmental Protection, 2004; Texas Commission on Environmental Quality, 2004). Each report summarizes scrap tire end-use data by category. Table 3.1 outlines the application categories and quantities for 2002. The state of Arizona does not publish a similar document, i.e., the California, Florida or Texas equivalent of a “tire report.” Although the nomenclature varies slightly, all three states have general end-use categories pertaining to crumb rubber, energy, civil engineering and disposal. Both California and Florida note the number of tires exported, whereas Texas does not. Note also that California tracks retreaded and imported tires. Texas, on the other hand accounts for scrap tires in land reclamation and on-site septic use. Disposal accounts for nearly 24% in California, 15% in Florida and 4% in Texas.

Table 3.1: Estimated Waste Tire Usage by State, 2002

CA		FL		TX	
Application Category	Waste Tires Used (PTE x 100,000)*	Application Category	Waste Tires Used (PTE x 100,000)*	Application Category	Waste Tires Used (STU x 100,000)**
Crumb Rubber	58	Crumb Rubber	49.4	Crumb Rubber	3.4
Tire-Derived Fuel (TDF)	61	Energy Use	89.7	Tire-Derived Fuel (TDF)	116.3
Civil Engineering	30	Civil Engineering	24.8	Civil Engineering	38.1
Exported	20	Exported	2.5	Land Reclamation	78.5
Retreaded	23			On-site Septic	5.0
Imported	15			Disposal	10.4
Disposal	84	Disposal	28.6	Other	8.3
Other	59			Total Waste Tires	260
Total Waste Tires	350	Total Waste Tires	195	Total Waste Tires	260
Percent of Tires Used in Transportation-Related Applications					
16.6		25		4.5	
$58 \div 350 \times 100$		$49.4 \div 195 \times 100$		$(3.4 + 8.3) \div 260 \times 100$	

*Passenger Tire Unit (PTU) = 20 lb of scrap tire rubber

**Standard Tire Unit (STU) = 20 lb of scrap tire rubber

Tire Derived Fuel (TDF) and Civil Engineering

In 2002 nearly one-half the scrap tires in Florida (46%) and Texas (45%) were used as a source of energy, i.e. Tire Derived Fuel (TDF). In contrast, only 17% of scrap tires in California were used for TDF. Another primary end-use of scrap tires is in civil engineering applications. In 2002 these practices

accounted for 9% in California, 13% in Florida and 15% in Texas. Although considered separate from civil engineering, the “land reclamation” category accounts for a substantial 30% of end-use in Texas.

Transportation-Related Applications

Transportation-related applications include transportation-related products and paving applications. Transportation-related products are those *other* than paving materials that contain CRM. These items vary in form from barrels and lane delineators to parking stops, barricades, traffic cones and anti-vegetation mats. All key user states reported the use of some of these products, though none rigorously track the quantities used. These products are, instead, included in the value for “crumb rubber” for California and Florida, and in “other” for Texas. For paving applications California, Florida and Texas include CRM in the “crumb rubber” category. Based on the data and descriptors provided in the annual reports, the percent of waste tires used in transportation-related applications was computed as shown in Table 3.1. For California and Florida the quantities in the “crumb rubber” category of Table 3.1 were used. For Texas, transportation-related products are included in the “other” category whereas paving applications are included in the “crumb rubber” category. Accordingly, for Texas the quantities in the “other” and “crumb rubber” categories were combined. The formula for computation of percent of waste tires used in transportation-related applications is shown in Table 3.1. The result is shown graphically in Figure 3.2. Scrap tire use in transportation-related applications accounts for 16.6% in California, 25% in Florida and 4.5% in Texas.

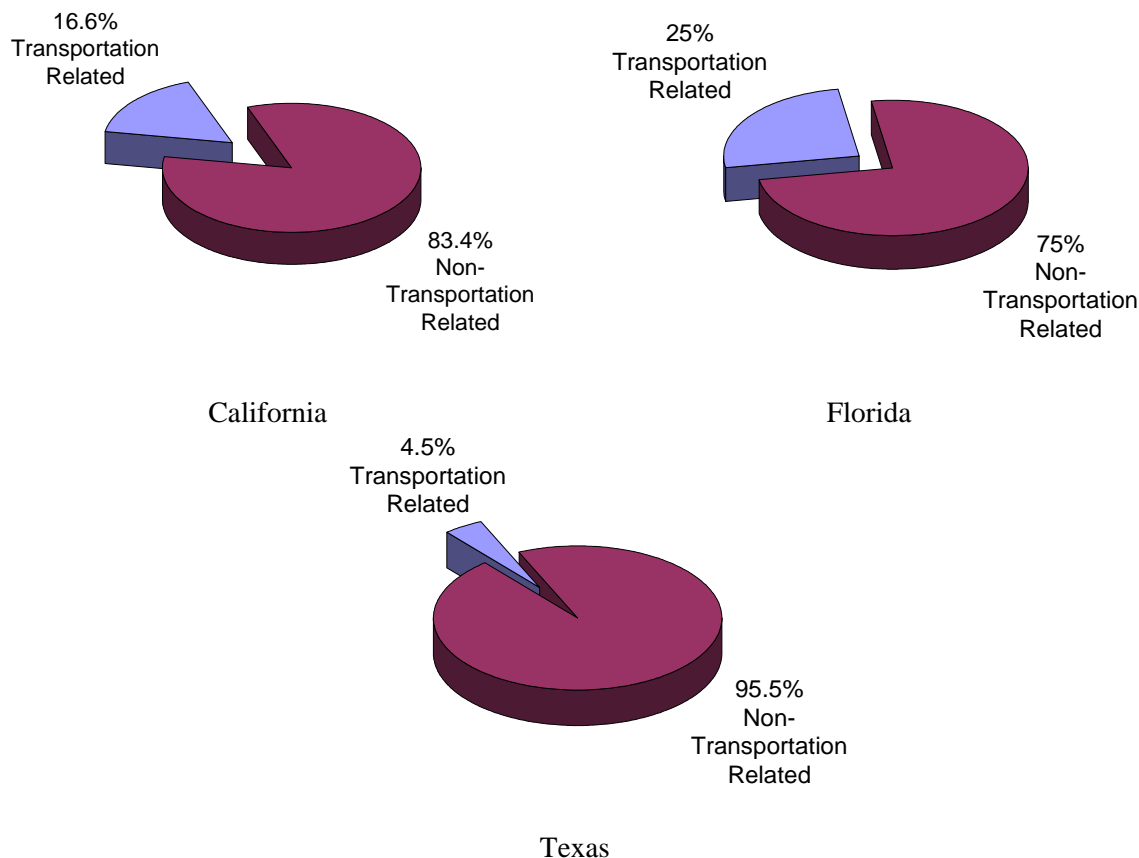


Figure 3.2: Tire Reuse Applications by California, Florida and Texas in 2002

3.3 USAGE SURVEY OF STATE AGENCIES

This survey solicited quantitative as well as qualitative information from four state DOTs: Arizona, California, Florida and Texas. The survey topics included the following:

- use of CRM;
- technologies used for incorporating CRM into paving materials;
- quantities of CRM hot mix asphalt used annually from 1999-2003;
- quantities of CRM spray application used annually from 1999-2003;
- typical CRM content;
- typical in-place material costs; and
- environmental regulations affecting the use of CRM.

The survey results are addressed in the following sections.

3.3.1 Annual DOT use of CRM in HMA

The primary user state DOTs provided summaries of CRM used in HMA from 1999 to 2003. It is important to note that DOTs in Arizona, Florida and Texas consider CRM to be a “value-added” product such that they do not rigorously monitor quantities. The data provided by DOT staff in Arizona, Florida and Texas are “best estimates.” DOT estimates of average annual CRM use in HMA were as follows: Arizona, 0.5 million tonnes/yr; Florida, 1.2 million tonnes/yr; and Texas, 0.1 million tonnes/yr.

Caltrans CRM use from 1999 to 2003 varied from 0.3 to 1.5 million tonnes/yr (Caltrans, 2003). Fluctuations in annual use are affected by funding to specific programs. For example, in 2000 Caltrans placed 1.5 million tonnes compared to 0.6 million tonnes in 2001. This dramatic reduction in the use of CRM over the course of one year was, reportedly, the result of funding earmarked for maintenance and rehabilitation, i.e. Transportation Congestion Relief Program of 2000.

3.3.2 Tires Consumed in CRM HMA

Rather than comparing annual CRM use in HMA, a more revealing picture of the DOTs’ strategy emerges by computing the number of scrap tires used per tonne of hot mix. Assuming 10 lb of CRM per scrap tire (Heitzman, 1992), and typical parameters for open-graded mixes, the data in Table 3.2 were used to compute scrap tire use per tonne of HMA. According to the job mix formula provided by DOT materials staff for typical open-graded mixes, scrap tires used per tonne of HMA ranged from 1.9 (FDOT) to 4.9 (TxDOT).

The Caltrans CRM open-graded mix “recipe” consumes nearly twice the number of scrap tires as does FDOT’s “recipe:” 3.3 tires/tonne for Caltrans vs 1.7 tires/tonne for FDOT. Using DOT estimates of CRM HMA tonnage and the data from Table 3.2, scrap tire use for 2003 was computed as shown Table 3.3. Comparisons of CRM in HMA based on absolute (tonnage) or relative (percent CRM-HMA placed as a percent of total HMA placed) terms can be misleading. Accordingly, comparisons between/among agencies should account for differences in strategies (mix types) and job mix formulae (CRM and binder content) to “normalize” the data and allow computation of scrap tires used per tonne of HMA.

Table 3.2: Tires Consumed/Ton of Rubber Modified HMA

Arizona			Florida		
Mix Type	AC (%)	Tires/Tonne 20% CRM	Mix Type	AC (%)	Tires/Tonne 12% CRM
Open Graded	9.9	4.4	Open Graded	7.3	1.9
California			Texas		
Mix Type	AC (%)	Tires/Tonne 20 % CRM	Mix Type	AC (%)	Tires/Tonne 20% CRM
Open Graded	7.5	3.3	Open Graded	11.1	4.9

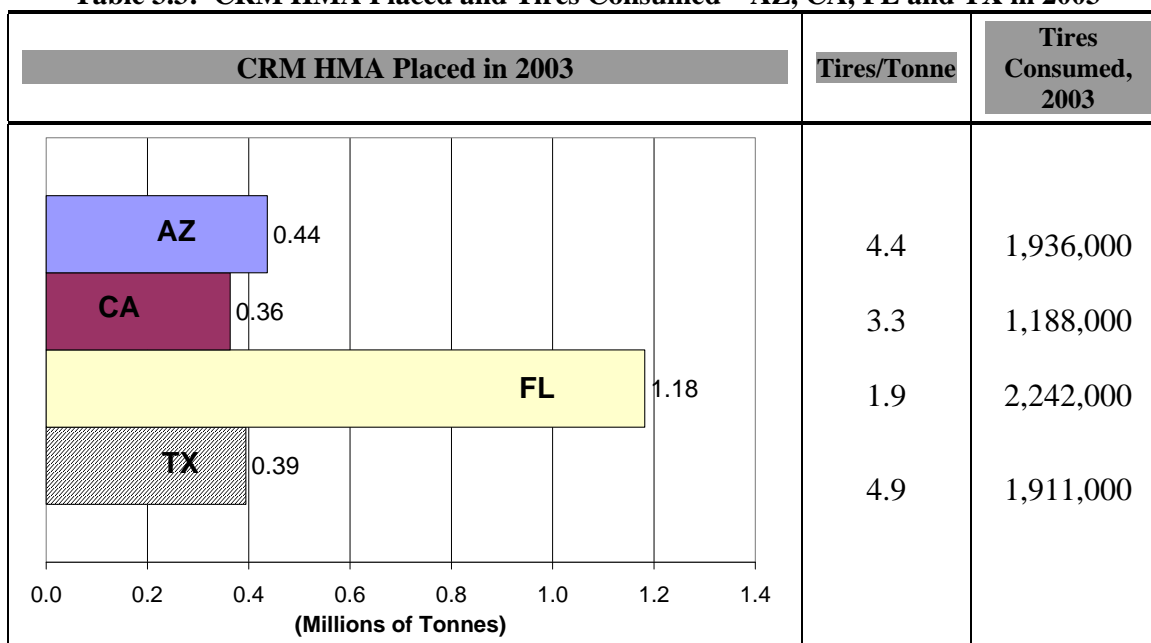
The equation used to determine the number of tires used per ton of HMA:

$$\text{Tires/Tonne} = \text{AC (\%)} \times \text{CRM (\%)} \times (2200 \text{ lb/tonne}) \div (\text{lb of rubber reclaimed per tire})$$

Assumptions:

- Asphalt content (AC %) is percent based on dry weight of aggregate.
- Tires/Tonne based on 10 lb of rubber reclaimed per scrap tire.
- Crumb rubber modifier (CRM) is 100% recycled tires.

Table 3.3: CRM HMA Placed and Tires Consumed – AZ, CA, FL and TX in 2003



Tires/Tonne values based on values for CRM and AC content for open graded mix (Table 3.2).

The equation used to determine the number of tires:

$$\text{Tires Consumed} = \text{Tires/Tonne (Table 3.2)} \times \text{Tonnes of CRM HMA Placed for 2003 (Figure 3.3)}$$

Figure 3.3 shows Caltrans historical and projected use of CRM HMA through 2006. Florida DOT reported that it will reduce its use of CRM HMA by nearly 50%, replacing it with polymer modified HMA. Assuming the Caltrans projections are accurate, FDOT reduces its use of CRM as reported, and

there is no significant change in ADOT or TxDOT use, Caltrans will lead the nation in not only tons of CRM HMA placed but also in terms of tires consumed, as shown in Table 3.4. If Caltrans 2005 projections are accurate it would consume more than double the number of scrap tires as its nearest state DOT counterpart: approximately 3.9 million for Caltrans vs. 1.9 million for ADOT.

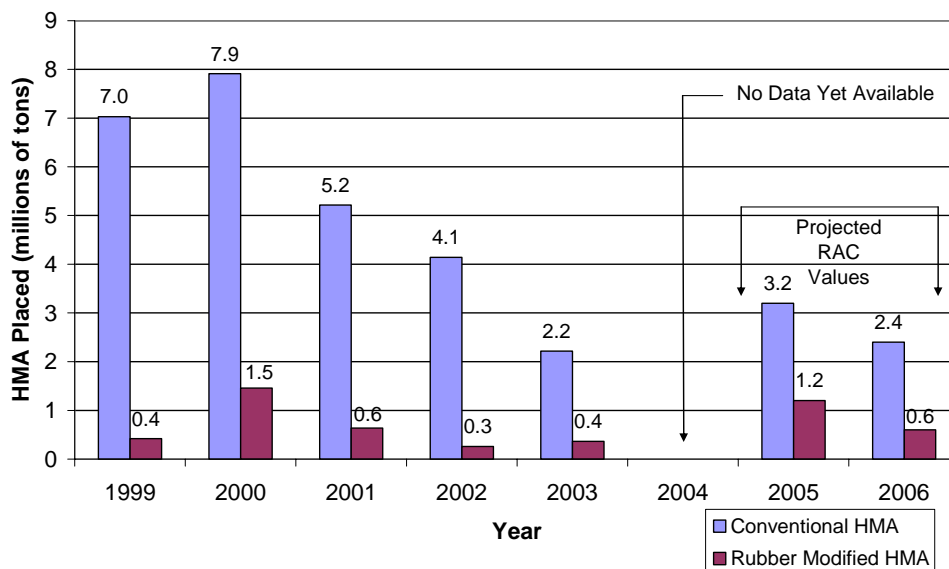


Figure 3.3: Conventional HMA vs. CRM HMA Placed & Projected by Caltrans, 1999-2006

Table 3.4: Projected CRM HMA Usage and Tires Consumed – AZ, CA, FL and TX in 2005

CRM HMA Placed for 2005 (Millions of Tonnes)	Tires/Tonne	Tires Consumed, 2003
AZ: 0.44	4.4	1,936,000
CA: 1.20	3.3	3,960,000
FL: 0.59	1.9	1,121,000
TX: 0.39	4.9	1,911,000

Tires/Tonne values based on values for CRM and AC content for open graded mix (Table 3.2).
 The equation used to determine the number of tires: Tires Consumed = Tires/Tonne (Table 3.2) x Tonnes of CRM HMA Placed for 2005 (Figure 3.3).

3.3.3 Caltrans Usage

Historically, about 18% of HMA placed by Caltrans has been rubber modified. Its projected use of CRM HMA, as computed from the data shown in Figure 3.3 is 27% and 20%, in 2005 and 2006, respectively. Caltrans District use of CRM HMA from 1999 to 2003 is summarized in Table 3.5. Note that during this survey period District 1 had not used CRM HMA due to restraints imposed by three Air Quality Management Districts (AQMD): North Coast, Mendocino and Lake Counties. More recent partnering discussions involving District 1, industry and AQMD staff indicate a genuine interest in reevaluating the technical and environmental aspects of CRM HMA. A project is scheduled for construction in District 1 in late Spring 2005. Currently, the Route 20 project in Mendocino County will incorporate at least 4 types of rubberized asphalt concrete as well as an unmodified asphalt concrete control section. Approximately 18,610 tonnes of CRM HMA will be placed as well as nearly 5,920 tonnes of conventional hot mix. The CRM HMA placed by district between 1999 and 2003 is shown graphically in Figure 3.4.

From figure 3.4 one may observe that Caltrans use of CRM HMA is concentrated in districts 4, 6, 7, 8, 10, 11 and 12. Districts 4, 6, 7 and 11 placed 374,360 to 695,815 tonnes while districts 8, 10 and 12 placed 199,210 to 287,244 tonnes. High-use districts share some of the following characteristics: moderate climate; proximity to or encompassing large cities such as San Francisco, Los Angeles and San Diego; and proximity to local CRM producers/ suppliers and experienced contractors. Location of the 11 CRM producers/suppliers in California, as reported by the RACTC, is shown in Figure 3.5 and supports this high-use trend.

Table 3.5: CRM HMA Usage by District (tonnes), 1999-2003

District	Year					Total
	1999	2000	2001	2002	2003	
01	0	0	0	0	0	0
02	0	99,700	0	0	23,616	123,316
03	0	17,540	48,190	53,695	0	119,425
04	7,960	238,354	286,450	0	46,530	579,294
05	0	10,400	55,200	0	0	65,600
06	75,400	206,100	10,300	33,320	49,190	374,360
07	8,150	341,840	77,332	48,810	27,280	503,412
08	0	62,480	40,710	76,700	19,320	199,210
09	0	8,000	0	0	0	8,000
10	188,700	60,750	19,940	7,460	10,394	287,244
11	130,090	375,735	29,880	0	160,110	695,815
12	9,860	37,900	69,270	38,812	77,720	233,571
Total	420,160	1,458,799	637,272	258,797	414,160	

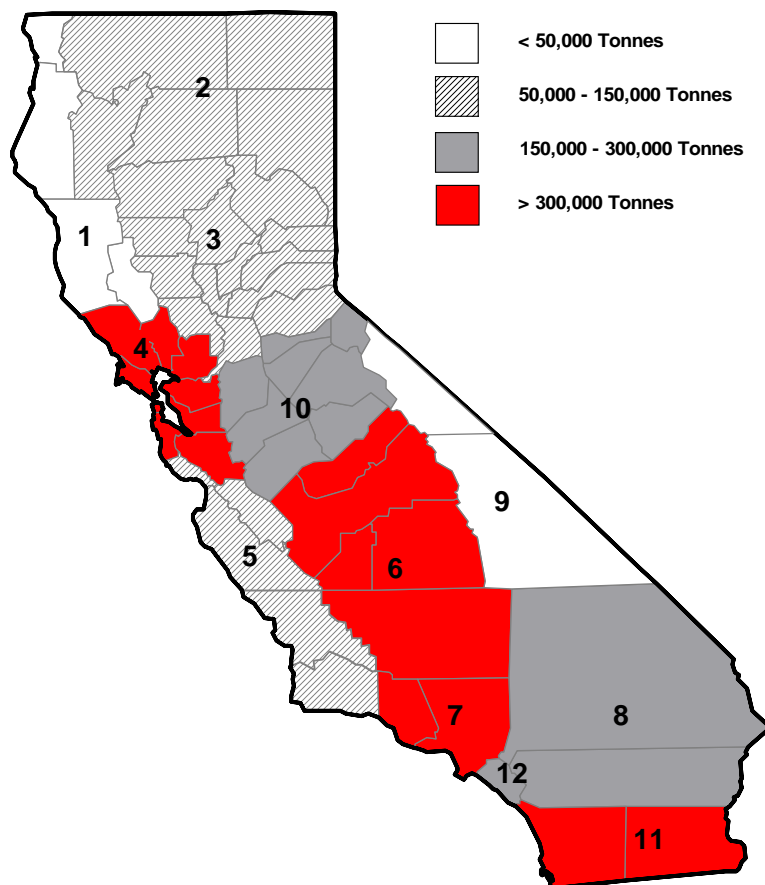


Figure 3.4: Caltrans RAC Usage 1999-2003

3.3.4 Annual use of CRM Spray Applications

Similar to CRM HMA usage, ADOT, FDOT, Caltrans and TxDOT provided summaries of annual use of CRM spray applications in construction and maintenance activities from 1999 to 2003. Spray applications are those processes where asphalt is applied directly to the surface and aggregate is applied separately. These processes typically include chip seals and SAMI-R (stress absorbing membrane inter-layer – rubberized).

Construction Applications

Only Florida and California estimated quantities of rubber modified spray materials used in construction applications. Arizona and Texas reported that negligible quantities were used such that these data were not monitored. FDOT estimated using 5.3 million yd²/year of rubber modified spray application. Caltrans use varied annually but averaged 880,000 yd²/year over the five year survey period. The CRM used in spray applications for the key user states is summarized in Table 3.6.

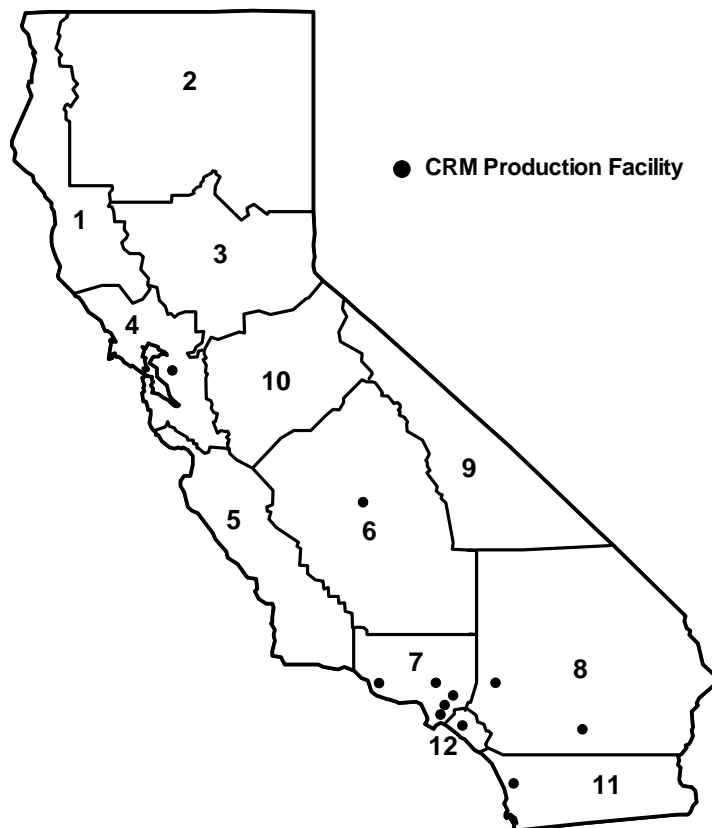


Figure 3.5: California CRM Producers by District

Table 3.6: CRM Spray Application for Construction, 1999-2003 (millions of yd²)

Year	AZ	CA	FL	TX
1999	None	0.0	5.3	None
2000		0.0	5.3	
2001		1.7	5.3	
2002		0.7	5.3	
2003		2.0	5.3	

Maintenance Applications

Only Texas and California reported using CRM spray applications for maintenance activities. Over the 5 year survey period, Texas DOT’s average annual use was 54 million yd² whereas Caltrans averaged nearly 1 million yd². Arizona DOT reported negligible use such that the quantities are not monitored. Florida DOT reported that no rubber modified spray asphalt was used in maintenance applications. These data are summarized in Table 3.7

Table 3.7: CRM Spray Application for Maintenance, 1999-2003 (millions of yd²)

Year	AZ	CA	FL	TX
1999	None	0.0	None	21.2
2000		0.0		52.6
2001		1.8		58.0
2002		0.6		78.2
2003		2.4		60.1

3.3.5 Typical In-place Material Costs

The cost of CRM HMA is affected by several factors including demand, material costs and availability, labor, project size, and haul distance.

Rubber Modified Hot Mix Applications

Survey results compiled for 2004 showed that CRM HMA prices varied from \$58.00/tonne in Texas to \$83.00/tonne in Florida. The cost data for specific materials are summarized in Table 3.8.

Table 3.8: Reported Cost of CRM HMA, 2004

State DOT	Cost (\$/Tonne)	Material Type
AZ	62 – 66	Open and Gap Graded
CA	68 – 72	Open and Gap Graded
FL	66 – 83	Open and Dense Graded
TX	58 – 65	Open and Gap Graded

Rubber Modified Spray Applications

The cost of CRM spray applications in 2004 ranged from \$2.00/yd² in Florida to \$4.25/yd² in California as shown in Table 3.9. The cost data include aggregate and rubber modified asphalt.

Table 3.9: Reported Cost of CRM Spray Application, 2004

State Department of Transportation	Cost - \$/yd ²	Material Type
AZ	Not Available	---
CA	3.75 – 4.25	Asphalt Rubber Chip Seal
FL	2.00 – 2.25	Asphalt Rubber Membrane Interlayer (ARMI)
TX	Not Available	---

3.3.6 Environmental Regulations Affecting the Use of CRM

Agency personnel from Arizona, Florida and Texas reported that there were no explicit environmental regulations limiting the use of CRM HMA or spray applications. Since 1994 restrictions imposed by California Air Quality Management Districts (AQMD) in District 1 have precluded the use of CRM HMA due to air quality concerns. More recently, however, a series of partnering meetings involving Caltrans, industry and AQMD, has yielded positive results. As noted previously a project using CRM HMA on Route 20 east of Ukiah is scheduled for construction in late Spring 2005.

3.4 CALIFORNIA CITY AND COUNTY USE OF RAC

Faced with the challenge of diverting or safely managing more than 33 million reusable and waste tires generated in the state each year, the California Integrated Waste Management Board (CIWMB) oversees the Rubberized Asphalt Concrete Technology Centers (RACTC). The RACTCs' function is to promote the use of crumb rubber from scrap tires in roadway rehabilitation projects by providing education, training and consultation services to local agencies within California. The RACTC maintains offices in Sacramento and Los Angeles. The northern region, serviced by the Sacramento office, stretches from the state's northern border to mid state. The southern portion of the state is serviced by the Los Angeles office.

Of California's 58 counties, 15 used CRM HMA in the period 1992 to 2003. Of the approximately 1500 cities in California it is estimated that 55 have used CRM HMA over the same period. The CIWMB reported that 1,384,678 tonnes of CRM HMA were placed from 1992 to 2003. Cumulative county RAC use as reported by the CIWMB, is shown in Table 3.10 and Figure 3.6. As expected, California city and county use of CRM tends to mirror that of Caltrans; i.e., it is concentrated in moderate climates near large cities, producers/suppliers and experienced contractors.

Table 3.10: Summary of CRM HMA Use by County: Cumulative 1992 – August 2004

County	Tonnes
Alameda	116,278
Alpine County	9,545
Contra Costa	12,205
Los Angeles	514,078
Monterey	1,418
Orange	11,818
Riverside	177,341
Sacramento	366,426
San Bernardino	44,227
San Diego	23,695
Santa Barbara	11,490
Santa Clara	28,218
Santa Cruz	27,823
Stanislaus	2,660
Ventura	37,450
Total	1,384,678

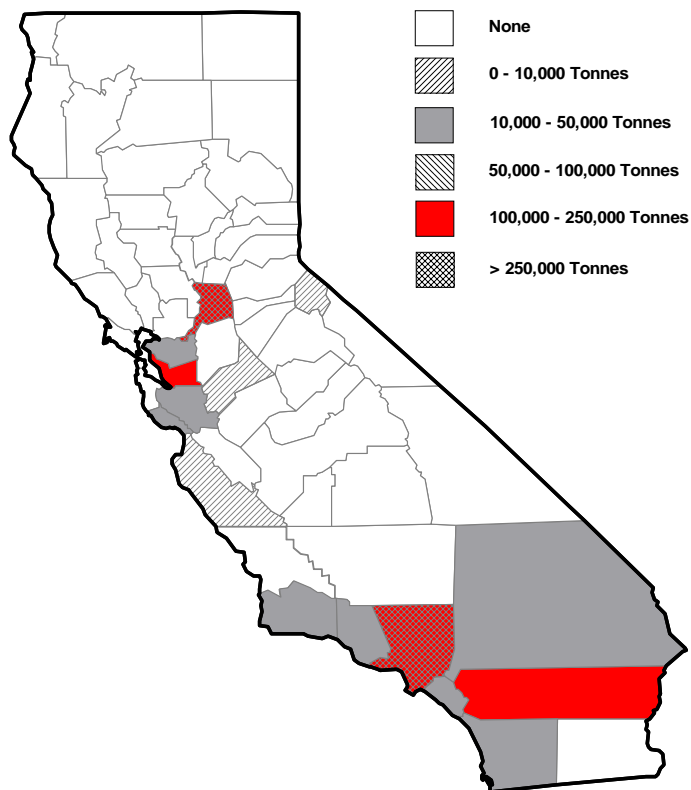


Figure 3.6: California RAC Usage – Tonnage by County

The largest county users, as shown in Table 3.10, Sacramento and Los Angeles reported that more than 366,426 and 514,078 tonnes, respectively, of CRM HMA have been placed since 1993. More recent data for Sacramento County and Los Angeles County are shown in Tables 3.11 and 3.12.

For Sacramento county both the tonnage and percent of CRM HMA placed (as a percent of total HMA placed) have decreased over the 5-year period. In 1999, 45,934 tonnes of CRM HMA were placed, about 50% of the total HMA placed. In 2001 more CRM HMA was placed than conventional HMA. In contrast the 12,675 tonnes of CRM HMA placed in 2002 represented only 10% of the total HMA placed. Still, use of CRM HMA appears to be on the rise as the tonnage placed in 2003 (32,127 tonnes) is nearly three-fold that placed in 2002 (12,675 tonnes).

In Los Angeles County tonnage of CRM HMA decreased by almost an order of magnitude from 2001 to 2003: 266,241 tonnes to 20,389 tonnes. Similarly, the tonnage of conventional HMA placed over that same time frame decreased from 265,529 tonnes to 46,625 tonnes. The percentage of CRM HMA placed over that same period decreased from 50% to 30%.

Although no explanation was readily available from RACTC staff, the authors speculate that the fluctuations are related to funding rather than technical issues or environmental concerns related to CRM.

Typical In-place Material Costs

Typical costs collected for the twelve year period ranged from a low of \$53.35/tonne in 1994 to a high of \$80.64/tonne in 2002 with an average price of \$62.54/tonne. This average was slightly lower than the average price of \$68.20/tonne reported by Caltrans.

Table 3.11: Sacramento County HMA Use, 1999-2003

Year	CRM HMA Placed (tonnes)	Conventional HMA (tonnes)	CRM as % Total HMA
1999	45,934	45,454	50%
2000	26,670	45,454	37%
2001	21,124	18,990	59%
2002	12,675	113,910	10%
2003	32,127	93,770	26%

Table 3.12: Los Angeles County Public Works HMA Use, 2001-2004

Fiscal Year	CRM HMA Placed (tonnes)	Conventional HMA (tonnes)	CRM as % Total HMA
2001-2002	266,241	265,529	50%
2002-2003	64,210	57,345	53%
2003-2004	20,389	46,625	30%

Table 3.13: CIWMB 2003-2004 Grant Recipient Data

County Recipients	Tonnes/Year	Number of Projects
Alpine	9,545	3
Los Angeles	94,938	16
Sacramento	97,831	12
City Recipients		
Folsom	5,636	1
Saratoga	2,545	1
Ontario	44,227	11
Lakewood	33,636	2
Riverside	29,972	4
Covina	21,818	3
Thousand Oaks	18,181	1
Temple City	16,500	3
Palm Desert	13,636	1
San Clemente	11,818	4
Rancho Mirage	8,636	1
Gardena	6,454	2
Mirada	6,363	2
West Hollywood	6,191	1
Palm Springs	2,331	1
Ojai	2,272	1
Totals	432,530	70 Projects

Legislative Influences

Introduced in 2002, Senate Bill 1346 authorized the CIWMB to implement a program to award grants (up to \$2.75 per tonne) to cities, counties, districts, and other local governmental agencies for partial funding of public works projects that use RAC. Grant recipient data provided by the CIWMB is shown in Table 3.13. From the number of projects it is difficult to draw any conclusions with respect to CRM HMA “market penetration.” A more revealing indicator for the grant recipients would be percent CRM HMA tonnage placed (as a percent of total HMA placed). This type of data was not available.

3.5 SUMMARY

The results of the surveys indicate that Caltrans is one of only four state DOTs that consistently use significant quantities of CRM in paving applications. Other DOTs making extensive use of CRM in paving applications are those in Arizona, Florida and Texas. From a more global perspective, the surveys revealed that only California, Florida and Texas produce an annual report documenting the end-use of scrap tires.

Although the nomenclature varies slightly, all three states (CA, FL and TX) have general end-use categories pertaining to crumb rubber, energy, civil engineering and disposal. Noteworthy statistics with respect to scrap tire end-use from the 2002 “tire reports” are as follows:

- Disposal accounts for nearly 24% in California, 15% in Florida and 4% in Texas.
- Tire Derived Fuel (TDF) accounts for 46% in Florida, 45% in Texas and 17% in California.
- Civil Engineering applications account for 15% in Texas, 13% in Florida and 9% in California.
- The broad category of transportation-related applications account for 25% in Florida, 16.6% in California and 4.5% in Texas.

Returning to scrap tire use in paving applications, estimates of annual CRM HMA placed by primary user DOTs between 1999 and 2003 were as follows:

- Arizona: 0.5 million tonnes
- California: 0.3 to 1.5 million tonnes
- Florida: 1.2 million tonnes
- Texas: 0.1 million tones

Comparisons of CRM in HMA based on absolute (tonnage) or relative (percent CRM-HMA placed as a percent of total HMA placed) terms can be misleading. To account for differences in strategies (mix types) and job mix formulae (CRM and binder content) the data may be “normalized” in terms of scrap tires per tonne of HMA. Using this approach with typical DOT “recipes” for an open-graded mix, scrap tire use per tonne of hot mix is as follows:

- Arizona: 4.4
- California: 3.3
- Florida: 1.9
- Texas: 4.9

Arizona and Texas DOT staff report that projected use of CRM in hot mix asphalt is likely to remain relatively constant. Florida DOT staff, on the other hand, report that it will reduce its use of CRM HMA by nearly 50%, replacing it with polymer modified HMA. In contrast, Caltrans projects increased use of CRM HMA. Based on the information provided, Caltrans will very likely lead the nation in not only tonnes of CRM HMA placed but also in terms of tires consumed. By 2005, Caltrans could consume more than double the number of scrap tires of its nearest state DOT counterpart: approximately 3.9 million for Caltrans vs. 1.9 million for ADOT.

California city and county use of CRM tends to mirror that of Caltrans; i.e., it is concentrated in moderate climates near large cities, producers/suppliers and experienced contractors.

4.0 CONCLUSIONS AND RECOMMENDATIONS

This report is a survey and analysis of the state of the technology of using scrap tire rubber in roadway construction and maintenance. An extensive literature search and review was conducted to identify and evaluate past and current research conducted throughout the U.S. A detailed materials survey was completed by representatives of the four primary user state DOTs (ADOT, Caltrans, FDOT, and TxDOT) to identify best practices based on their strategies and methods for successful use of crumb rubber modification. Findings were referenced to specific topic areas, among which some overlap was unavoidable, and summarized in Chapter 2. Other civil engineering applications for scrap tire rubber were also outlined in Chapter 2 for information. Chapter 3 presented detailed survey information on the amounts of CRM-modified paving materials and scrap tire rubber used in California, including Caltrans, city and county use, and limited data supplied by ADOT, FDOT and TxDOT. The conclusions presented herein are based on analysis of the information included in this report.

4.1 CONCLUSIONS

Only four states (Arizona, California, Florida, and Texas) routinely use significant quantities of scrap tires in paving applications, and they make nearly exclusive use of the “wet process” technology of crumb rubber modification. These four states are where industry and DOT “champions” fostered the technology through research and experimentation, and local suppliers were available to provide CRM-modified materials as needed. Each has developed successful applications of relatively thin (≤ 60 mm, approximately 2.3 inches thick) surface lifts of CRM-modified asphalt concrete pavements that provide improved performance with reduced rutting, fatigue, and reflective cracking compared to conventional DGAC. The improved resistance to these common modes of pavement distress provides increased durability that reduces the frequency and extent of repairs needed and extends the service life of CRM-modified pavements.

ADOT, Caltrans, and TxDOT consider CRM materials to be “special use” materials for specific applications, typically for thin overlays, surface courses, or surface treatments of distressed pavements that are essentially structurally sound. Where additional structure is required, an appropriate thickness of DGAC is placed, followed by application of the selected CRM material(s), which may include a SAMI. CRM materials are more expensive than unmodified or polymer-modified materials such that their use is limited to the most effective application, in the upper and surface layers of the pavement structure.

Many states experimented with use of CRM in paving materials as a result of the 1991 ISTEA legislation. Review of the referenced studies indicates that the performance of CRM paving mixes was highly variable not only from state to state, but also among respective projects constructed by a single agency. However, overall field and laboratory results for a wide variety of mix types (dense-, gap-, and open-graded) and crumb rubber modification processes (wet high viscosity, wet no agitation, and dry with various CRM gradations) tested by various organizations and researchers, indicate that mixes made with wet-process binders are more consistent at providing better performance than dry-process mixes.

4.1.1 Asphalt Concrete Mix Types

Overall, gap-graded CRM mixes made with wet and dry processes respectively seem to perform better and more consistently than dense-graded CRM mixes with respect to DGAC control mixes. The gap-gradation provides sufficient void space to accommodate CRM particles passing the 2.0 mm (No. 10) sieve (wet and dry) and higher binder contents, particularly when using wet process high viscosity

materials. Higher binder contents typically improve durability and resistance to reflective cracking and fatigue of HMA in general, whether CRM or conventional.

Dense-graded mixes can accommodate only limited CRM due to limited void space in the aggregate matrix/structure, and are sensitive to minor changes in binder content and CRM gradation. CRM modification (wet or dry process) of dense-graded mixes is best accomplished using fine CRM gradations (passing the 300 µm (No. 50) sieve). Field performance of properly designed dense-graded CRM mixes typically differs little from that of conventional DGAC.

Open-graded CRM mixes appear to perform well when they retain sufficient binder (without excessive drain-down) to avoid raveling. Although open-graded mixes include sufficient void space to use coarse CRM gradations (retained on the 4.75 mm (No. 4) sieve), findings for dry process mixes indicate that use of coarse CRM increased the frequency and severity of raveling, pop-outs, and cracking (particularly along construction joints) compared to mixes made with finer CRM (passing the 2.0 mm (No. 10) sieve).

Wet process binders for AC mixes use CRM that passes the 2.36 mm (No.8) sieve, or finer CRM gradations as shown in Table 2.2. High viscosity binders minimize drain-down and permit binder contents for open-graded mixes to be increased to 9.5 or 10% by total weight of mix (much higher than the amount of no agitation binder that can be retained) which has provided very pavement good performance and durability.

4.1.2 Membranes – Surface and Interlayers

ADOT and Caltrans also use wet-process high viscosity CRM binders in surface treatments (chip seals) and stress absorbing membrane interlayers (SAMIs) to reduce reflective cracking from distressed in-place conventional pavements. FDOT and TxDOT use the high viscosity binders in SAMIs only; TxDOT uses no agitation CRM binders or polymer-modified asphalt cement for chip seals.

High viscosity binders allow heavier application rates than for no agitation binders, but the aggregate chips need to be sized accordingly (nominal ½-inch to 5/8-inch maximum) to avoid flushing and bleeding. Heavier binder application rates appear to promote durability and increase the service life of chip seals, but such seals should not be applied to pavements that are flushing or bleeding. Chip seal construction is sensitive to a number of factors and good practices are required when working with highly modified materials to achieve a good finished product.

Although both Arizona and Florida have observed good performance of membrane layers, the experience of other states (including California) since the mid-1990s has been mixed. How much of the reported variability is due to materials or to construction issues is still not clear.

CRM-modified SAMIs have proved effective as crack interruption layers in reducing the onset and severity of reflective cracking. Based on field performance data, Caltrans has assigned a minor structural and reflective cracking equivalency of 0.05 ft (15 mm) of RAC-G to SAMI-R. SAMIs have been widely used in Florida and have performed well.

4.1.3 Materials Selection and Design

Review of the various studies of RAC mixes shows that a wide range of combinations of CRM gradations, CRM concentrations, types of CRM-modification (wet or dry), grades of asphalt cement, and aggregate gradation (dense-, gap-, and open-graded) have been evaluated by many researchers and state DOTs. The materials utilized and tested for RAC mixes have been dependent upon the desires of the agency sponsoring the research. A number of different approaches have been tried with varying success,

of which more than one has been successful. However wet process crumb rubber modification has proved to be the most reliable approach.

The literature review revealed a glaring lack of data on the basic physical properties of the various wet process binders used in many of the laboratory and field evaluations. Very few of the reports reviewed indicated that any type of specification compliance type testing was performed on the subject CRM binders, and only rarely were any of those test results included. This lack of fundamental information makes it difficult to assess the value of many of the studies reviewed, as it is rarely clear whether the CRM binders used in specific studies would have been considered suitable for the use to which they were put. Inferences were made regarding which CRM binders would have been high viscosity or no agitation, based on CRM content and gradation. However the omission of such basic property information indicates that many of the researchers did not understand the important effects of CRM binder properties on the performance of the resulting CRM modified mixes, chip seals or interlayers.

There are some common factors among the four primary users that have resulted in successful use of CRM, and also some fundamental differences in approaches and practices, as follows.

Common Factors

ADOT, Caltrans, FDOT and TxDOT have specifications for wet process high viscosity binders and for wet process no agitation binders. ADOT, FDOT and TxDOT consider the no agitation binders to be very different materials than the high viscosity binders (or polymer-modified binders) and use the two types of wet process binders differently.

CRM

Coarser CRM gradations (passing the 2.0 mm (No. 10 sieve)) may be used in high viscosity binders than in no agitation binders, which typically require nearly 100% of CRM particles passing the 600 μm (No. 30) sieve.

High Viscosity Binders

High viscosity wet process binders are suitable for use and seem to provide the best performance in gap- and open-graded mixes where their high viscosity and corresponding resistance to drain-down allow increased binder contents of up to 2% greater by weight of mix than can be accommodated in dense-graded mixes. The high binder contents promote durability and resistance to fatigue and reflective cracking. Caltrans, ADOT, and TxDOT use such binders in gap- and open-graded mixes, primarily in the upper and surface layers of the pavement structure, but not in dense-graded mixes. Florida uses high viscosity wet process binders only for SAMIs, and not in hot mixes. High viscosity binders are generally not suitable for use in dense-graded mixes.

No Agitation Binders

No agitation CRM binders are suitable for use in dense-graded mixes. TxDOT allows such binders as substitutes for Superprave PG binders, and FDOT uses them routinely. Caltrans has an SSP for Type D MB which is currently under evaluation. These may be used in gap- or open-graded mixes, but caution must be used to minimize drain-down. Such binders do not have sufficient viscosity to permit significant increases in binder content from the optimum content for un-modified asphalt cement. FDOT routinely uses such binders in open-graded mixes. TxDOT requires that fibers and lime be added to reduce drain-down when no-agitation binders are used in PFCs (porous, i.e. open-graded, friction courses). ADOT has allowed substitution of no agitation binders for high viscosity binders in gap-graded mixes for low

tonnage projects and patching of CRM pavements, but treats the mixes differently and requires evaluation of drain-down. ADOT does not allow the use of no agitation binders in open-graded mixes.

Differences

Only Caltrans requires the use of extender oil and high natural rubber content CRM in high viscosity wet process binders for paving mixes.

No Agitation Binders

Caltrans specifications for MB binders are based on completely different physical properties than the no agitation CRM-modified binders used in Arizona, Florida and Texas. The differences in measured and calculated properties provide no basis for direct comparison with MB materials.

4.1.4 Structural Design

The literature review indicates that several methods have been used in an attempt to establish parameters for RAC mix for the structural design purpose. These methods included a mechanistic-empirical method used by ADOT based on the finite element modeling, laboratory testing and field performance monitoring of pavement sections; the thickness reduction method used by Caltrans by designing a required DGAC overlay thickness based on deflection, traffic index, and existing pavement structure and then reducing the DGAC thickness to near half of its thickness when RAC is used; and the AASHTO structural layer coefficient approach attempted by several agencies based on layer properties. The results of the literature review indicate that there is no standard consensus for how each agency handles the structural design of rubber-modified asphalt concrete mixes.

However, based on the experience of the four primary user DOTs, ADOT, Caltrans, FDOT and TxDOT, it appears that assigning the same structural coefficient or credit to gap and dense-graded RAC mixes as is used for conventional DGAC is not unreasonable. FDOT assigns a structural coefficient of 0.44 to their dense-graded 9.5 and 12.5 mm RAC mixes. TxDOT treats gap-graded RAC mixes as conventional DGAC in structural designs for new construction, rehabilitation, and maintenance. ADOT's structural design methodologies for gap-graded RAC mixes are the same as for conventional dense-graded mixes regardless of application.

ADOT, FDOT, TxDOT, and Caltrans do not assign any structural value to OGAC during the pavement structural design. However, Caltrans does consider small structural and reflective crack retardation credits of 15 mm of RAC-G for SAMIs.

4.1.5 Performance

The field performance studies reviewed showed that the performance of CRM mixes, particularly dry process mixes, was highly variable among and within respective agencies. A wide range of materials were tested among the various studies. There are a number of reasons for the observed variability in the performance of the CRM materials studied, including but not limited to the following:

- Differences among specifications
- Differences among the processes of rubber-modification used
- Differences among binder and mix design procedures
- Appropriateness of the application for the intended use
- Changes in materials from those used in the original design

- Experience of contractors and paving crew with highly modified paving materials
- Willingness to modify production, handling, and/or construction procedures to accommodate modified materials
- Level of quality control exercised during material production (modified binders and mixes)
- Temperature control of paving mixes for placement and compaction
- Quality of construction, including placement and compaction equipment and procedures

A number of DOTs found crumb rubber modification to be feasible, but found that the performance benefits (if realized) did not justify the increase in cost. Those states and local jurisdictions with good experiences have continued to develop and use these products. Those that experienced poor performance and/or high costs have chosen to use other modifiers to improve the properties of their asphalt binders and HMA. In spite of the variability in performance results, the following conclusions can be made:

- Results of studies reviewed indicate that crumb rubber modification has greater potential to resist reflective cracking, rutting, and fatigue than does conventional DGAC.
- Although some dry process mixes have performed very well under traffic in a variety of environments, their performance is generally less reliable than that of wet process mixes. Coarse CRM seems to make dry process mixes more susceptible to raveling, cracking, and pop-outs. Use of CRM passing the 2.0 mm (No. 10) sieve or very fine CRM (passing the 300 µm (No. 50 sieve)) seems to improve the performance of dry process mixes.
- Wet process mixes typically perform better than dry process mixes at resisting rutting, fatigue, reflective cracking, and raveling.
- Gap-graded and open-graded CRM mixes typically perform best for both wet and dry process CRM modification.
- Mixes with high viscosity CRM binders seem to be more effective in resisting rutting, fatigue and reflective cracking than mixes with no agitation binders or conventional DGAC, in part because of the higher binder contents that can be used. Performance is further enhanced when relatively high contents of high viscosity binder can be accommodated in the mix. High viscosity binders are not well-suited for use in dense-graded mixes.
- Although laboratory tests indicate that wet process mixes are not as stiff as conventional DGAC (i.e. typically have lower modulus and stability values), a number of field performance tests show that such mixes (when properly designed) exhibit increased resistance to rutting and cracking.
- Improved resistance to such common modes of pavement distress improves the overall durability of the resulting pavement. Improved durability would be expected to reduce the extent and frequency of maintenance and repairs needed over the life of the pavement.

4.1.6 Cost

California Contract Cost Data from 2003 indicate that the weighted average cost of RAC mixes is about 16% higher than that of the conventional AC mixes. These are average initial costs, which also depend on the size of the project, i.e. the amount of tonnage of CRM material to be produced. Initial costs of CRM mixes in Arizona, Florida and Texas are also higher than for conventional DGAC by varying amounts. However, these agencies find that the overall performance (and social) benefits of such value-added use of CRM generally offset the increase in initial costs over the life of the resulting pavements. Life cycle cost analyses by ADOT have indicated that there are cost offsets for reduced maintenance and extended service life of CRM-modified pavements. However, for small quantities of CRM materials, the initial unit costs may increase more than can be offset. A 1998 Caltrans analysis indicates that projects with three days of paving or less are likely to have significantly higher unit costs than larger projects, and may not be cost-effective. For projects with less than 2,250 tonnes (2,500 tons) of RAC, the increased cost of

CRM materials is probably not justifiable unless there are special circumstances. In such cases, the initial costs should be evaluated with respect to the expected benefits of using CRM materials.

To provide improved LCCA to determine the “break-even” point for cost of CRM materials, more information is needed regarding the frequency and type of maintenance and repair activities required, and the life of the repairs. Additional information regarding actual serviceable life of CRM pavements is also needed.

4.1.7 Recycling

Literature related to recycling is reviewed in a separate report, “Feasibility of Recycling Rubber-Modified Paving Materials.” The recycling of CRM mixes for use as Reclaimed Asphalt Pavement (RAP) has been an area of interest since CRM was first used in asphalt paving materials. Some agencies have used CRM-modified materials in limited recycling experiments or demonstration projects.

The results indicate that a wide range of CRM paving materials can apparently be successfully recycled. Due to the concerns regarding possible emissions from recycling CRM paving materials, many of the studies of recycling CRM materials include an assessment of the emissions. The overall results of emissions assessments indicate little difference and no apparent increase in risk from conventional HMA production.

4.1.8 Environmental Issues

A variety of studies have been conducted to assess possible environmental impacts of the use of CRM in a number of locations through the United States. There are clearly environmental benefits to using scrap tire rubber in paving materials, but there have also been some concerns regarding emissions from CRM-modified asphalt binder and mix production and paving operations. Concerns have also been expressed regarding the possibility of groundwater contamination as a result of potential leachate from the CRM materials.

There are a number of social benefits of using CRM that is ground from recycled scrap tires to engineer and build pavements, including but not limited to the following: reducing tire stockpiles, improved pavement durability, and pavement noise reduction.

Benefit of Noise Reduction

A number of studies in Europe and the US have indicated reduction in pavement noise due to crumb rubber modification of open- and gap-graded mixes, including studies in California and Arizona. A 6-year Sacramento study on RAC-G type pavements that showed noise reduction persisted for 6 years. ADOT and Caltrans are currently involved in a joint FHWA study to measure and document pavement noise over a 10-year period to assess the noise generated by CRM pavements for possible incorporation of pavement surface type into the FHWA noise models.

Air Quality

Concerns have been expressed regarding the effects of CRM-modified paving materials on air quality, particularly related to AC plant emissions and worker health and safety. CRM consists mostly of various types of rubber and other hydrocarbons, carbon black, extender oils, and inert fillers. Most of the chemical compounds in CRM are also present to some extent in paving grade asphalt, although the proportions are likely to differ. CRM does not include exotic chemicals that present any new health risks. A number of stack emissions have been performed throughout the U.S. that have not indicated any increased risk due to CRM-related emissions.

The literature review indicated that numerous studies of worker exposure to potentially hazardous compounds in asphalt rubber fumes have also been performed. Fumes generated by CRM-modified materials at elevated temperatures often have increased concentrations of a number of compounds of interest compared to conventional asphalt materials, but these rarely exceed established permissible exposure limits. Thus there is no pattern of evidence that CRM-modified materials present greater health hazards than conventional asphalt materials.

Water Quality

Water quality is another area of concern regarding the use of CRM. A limited number of studies were conducted. A study for Rhode Island DOT recommends further research before final conclusions are reached, but concludes that the conducted research does not show evidence that the use of CRM will pose a problem to the environment or human health. A Texas study that tested leachate from a stockpile of reclaimed CRM HMA concluded that levels of detectable leachates were too low to be environmentally significant or dangerous.

4.1.9 Other Uses of Scrap Tire Rubber

The use of scrap tires for transportation-related activities is not limited to CRM paving materials. The literature reviewed indicates that there a number of value-added ways to use scrap tire rubber that continue to be investigated as means of reducing the stockpiling of this waste material. In fact, the use of scrap tire rubber for various other value-added applications has been assessed through differing field trials and laboratory experiments. A number of civil engineering applications are being explored, including spray application on concrete sound barriers, lightweight embankment fills, insulating layers to prevent frost heave of gravel-surfaced roads, railroad track bed paving, and rubber soils. CRM is also included in traffic control devices including traffic cones, parking stops, channelizers and delineators. The Arizona Department of Environmental Quality is investigating use of CRM as an aggregate substitute in PCC.

However, the primary use of scrap tire rubber in the US is not a value-added use, but as a fuel supplement in cement kilns and power cogeneration facilities.

4.1.10 Specifications

The development of specifications to control the design, production, and placement of CRM-modified paving materials is important to help standardize and control the quality of these types of materials. State specifications relating to the use of CRM in asphalt paving materials have evolved within each state as its experience has grown. Specifications for wet process high viscosity binders evolved from research by champions of crumb rubber modification and subsequent validation and refinement by the respective state DOTs.

The specifications presented in Tables 2.2 through 2.5 should be considered to represent the current state of the art and best practices for ADOT, Caltrans, FDOT, and TxDOT. These include requirements for CRM gradation, high viscosity wet process CRM binders, no agitation wet process CRM binders, and aggregate gradations for CRM HMA. There are a number of similarities which have been discussed. There are also clearly some differences, the most notable of which are the Caltrans MB specifications for no agitation binders which relate to none of the other materials requirements. The other distinct differences are Caltrans requirements to include extender oil and high natural rubber in high viscosity binders.

Specifications are periodically updated, but none of the four primary user states indicate any major changes are planned. Most of the continuing refinement at this time seems to be focused on mix design methods, according to reported activities in Texas and Arizona.

4.2 RECOMMENDATIONS

The following recommendations with respect to refining, broadening and increasing Caltrans use of scrap tires in paving applications are as follows:

- Learn from the experiences of ADOT, FDOT and TxDOT regarding the important differences between wet process high viscosity and no agitation (i.e. terminal blend) CRM binders. There are suitable applications for both types of wet process binders, but they are distinctly different types of material that are not equivalent to each other and should not be used interchangeably. The fact that both types can be used in gap-graded mixes or chip seals and SAMIs does not mean that they can be substituted for each other on a one-to-one basis. ADOT and TxDOT both indicate that using high viscosity binders typically results in up to a 2% increase in design binder content by weight of mix over no agitation binders and asphalt cement. Direct substitution of a no agitation binder would result in severe bleeding and flushing. This is also true for membrane applications such as chip seals and SAMIs, where the no agitation binders are applied at rates similar to paving grade asphalt cement and thus use relatively fine aggregate chips, but high viscosity binders are applied very heavily and larger (nominal ½ inch or 5/8 inch) chips are necessary to keep from being “swallowed” by the binder membrane.
- Develop/finalize construction reports for all RAC Warranty projects and the Firebaugh project. Continue laboratory testing on materials obtained from all RAC Warranty projects and the Firebaugh project. Continue to monitor performance and develop evaluation reports. Use the results to update specifications and guidelines for design and construction.
- Continue HVS testing and companion laboratory testing to evaluate performance and provide structural data for refining structural design with CRM-modified materials.
- Develop RAC gravel factor for use in Caltrans structural design methodology and update/modify Caltrans overlay design procedure to include the use of RAC on various pavement structures.
- Initiate laboratory testing to quantify effect of binder type on pavement performance. This is a critical step in the direction of performance related specifications.

- Proceed with evaluating the feasibility of recycling CRM paving materials to remove one of the potential barriers to increased use of CRM. Incorporate recycling RAC in the proposed District 1 project scheduled for construction in 2005.
- Consider eliminating Type 2 recipe requirements for high viscosity wet process CRM binders in HMA at least on a trial basis, and particularly for emissions-sensitive projects. It is not necessary to eliminate the use of Type 2 binders, but consider that it may no longer be necessary to make a distinction between Type 1 and Type 2 binders if Caltrans allows, but does not require, use of extender oil and high natural CRM in binders for HMA. Maintain or tighten existing Caltrans specifications for minimum total CRM content, viscosity, resilience, softening point, and penetration to assure appropriate properties of the resulting binders. In addition, timely submittal of 24-hour binder design profiles should be required and enforced to verify suitability and specification compliance. Consider adopting climate-related aspects of ASTM D 6114, Standard Specification for Asphalt-Rubber Binder, which was developed to cover both Type 1 and Type 2 high viscosity binders, although this may be complicated by the aged residue (AR) asphalt cement grading system used in California. Allowing use of a proven alternate method of CRM-modification that does not require either extender oil or high natural CRM would allow some savings to contractors and Caltrans. Operations are simplified when only two materials are blended rather than four, and extender oil is expensive. Savings would be expected not only in reduced materials costs, but also due to reduced materials tracking, handling, sampling, and QC/QA testing activities and related costs.
- Use of high natural rubber is still recommended in binders for chip seals and SAMIs, as it has been proven to improve chip retention. However use of extender oil should become an option rather than a requirement for chip seal binders, too avoid softening the binder too much.
- Use the findings of current research and evaluations in progress (RAC Warranty projects, Firebaugh test sections, HVS and companion lab testing) to refine Caltrans specifications and guidelines for CRM binders and RAC products. In the meantime, follow the recommendations in the Caltrans AR Usage Guide including use of best practices for CRM HMA production and construction.
- Increase the use of RAC-O and RAC-O HB, which has been very effective in Arizona and in Texas in providing smooth ride, improving safety through reduced water spray and potential for hydroplaning, and reducing pavement noise. Open-graded mixes can be made binder rich and thus can use relatively high quantities of CRM, although adjustments to the RAC-O mix design method may be required to optimize binder content and performance.
- Provide periodic training on the design and construction of rubber modified hot mix and chip seals to ensure Caltrans staff understand the benefits and limitations of these products. Completion of on-going and planned studies and implementation of findings will position Caltrans as a leader in the use of CRM technology.

5.0 REFERENCES

- Abdelrahman, M.A. and S.H. Carpenter. 1999. "Mechanism of Interaction of Asphalt Cement with Crumb CRM." *Transportation Research Record 1661*. Transportation Research Board, Washington D.C.
- Albritton, G.E., W.F. Barstis, and G.R. Gatlin. 1999. *Construction and Testing of Crumb CRM HMA Asphalt Pavement*. Report No: FHWA/MS-DOT-RD-99-115. Federal Highway Administration, Washington D.C.
- Almaguer, Daniel, A.K. Miller, K.W. Hanley. 1996. NIOSH Health Hazard Evaluation Report 95-0118-2565 Martin Paving Co. Yeehaw Junction Florida. NIOSH Hazard Evaluation and Technical Assistance (HETA) Branch.
- American Association of State Highway and Transportation Officials (AASHTO). 1993. *Guide for Design of Pavement Structures*. American Association of State Highway and Transportation Officials, Washington, DC.
- American Society of Testing and Materials. 2004. "D 6114 Standard Specification for Asphalt-Rubber Binder" in *Vol. 4.03, Road and Paving Materials; Vehicle-Pavement Systems*, Annual Book of ASTM Standards 2004, ASTM, West Conshohocken, PA.
- Amirkhanian, S.N. 1993. "Utilization of Scrap Tires in Flexible Pavements – Review of Existing Technology." In *Use of Waste Materials in Hot-Mix Asphalt*. American Society for Testing and Materials, STP 1193, pp 233-250.
- Arizona Department of Transportation. 1999. An Environmentally Sound Noise Reduction System. *Research in Progress as noted on the Transportation Research Board website*. <http://rip.trb.org/>.
- Arizona Department of Transportation. 2000. *Standard Specifications for Road and Bridge Construction*. Phoenix, AZ.
- Anderson, K.W. and N. C. Jackson. 1992. *Rubber-Asphalt Pavements in the State of Washington*. Washington State Department of Transportation, Olympia, WA.
- Ayres, M. and M.W. Witzak. 1995. "Resilient Modulus Properties of Asphalt Rubber Mixes from Field Demonstration Projects in Maryland." *Transportation Research Record 1492*. Transportation Research Board, Washington D.C.
- Baker, R.F. and E. Connolly. 1995. "Mix Designs and Air Quality Emissions Tests of Crumb Rubber Modified Asphalt Concrete." *Transportation Research Record 1515*. Transportation Research Board, Washington D.C.
- Baker, T. 1993. "Production of Crumb Rubber Modifier (CRM) Material," Session 3, Workshop Notes, FHWA Crumb Rubber Modifier Workshop, Atlanta, GA, February 1993.
- Burr, G. A. and A. K. Miller. 1996. *Health Hazard Evaluation Report HETA 96-0072-2603, Staker Construction Company, Casa Grande, Arizona*. National Institute for Occupational Safety and Health, Cincinnati, OH.

California Integrated Waste Management Board, California Waste Tire Generation, Markets and Disposal, Staff Report, October 2003.

Caltrans, “2003 Contract Cost Data,” Division of Engineering Services – Office Engineer, Office of Contract Awards and Services, Caltrans, Sacramento, CA 2003.

Charania, E, J.O. Cano, and R.H. Schnormeier. 1991. “Twenty Year Study of Asphalt-Rubber Pavements in the City of Phoenix, Arizona.” *Transportation Research Record 1307*. Transportation Research Board, Washington D.C.

Chen, N.J., J.A.DiVito, and G.R.Morris. 1982. “Finite Element Analysis of Arizona’s Three-Layer System of Rigid Pavements to Prevent Reflective Cracking.” Arizona Department of Transportation, presented at 1982 AAPT Meeting

Choubane, B., G.A. Sholar, J.A. Musselman, and G.C. Page. 1999. “Ten-Year Performance Evaluation of Asphalt-Rubber Surface Mixes.” *Transportation Research Record 1681*. Transportation Research Board, Washington D.C.

Couret, C. 2000. “Thin Treatments Extend Road Life and Budget.” *American City and County, Volume 115, Issue 5*. Intertec, Atlanta, GA.

Crockford, W.W., D. Makunike, R.R. Davison, T. Scullion and T.C. Billiter. July 1995. “Recycling Crumb Rubber Modified Pavements.” Texas Transportation Institute Research Report 1333-1F. Texas A&M University, College Station, TX.

DeLaubenfels, L. 1985. “Effectiveness of Rubberized Asphalt in Stopping Reflection Cracking of Asphalt Concrete (Interim Report). Caltrans Report No. FHWA/CA/TL-85/09, Sacramento, CA.

Doty, R.N., “Flexible Pavement Rehabilitation Using Asphalt-Rubber Combinations: Progress Report,” *TRR 1196*, Transportation Research Board, 1988.

Eaton, R.A., R.J. Roberts, and R.R. Blackburn. 1991. “Use of Scrap Rubber in Asphalt Pavement Surface.” Special Report 91-27, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

Edgar, R. 1998. *Ten Year Performance of Asphalt Additive Test Sections: Lava Butte Road – Freemont Highway Junction Section*. Oregon Department of Transportation, Salem, OR.

Emery, J. 1994. “Evaluation of Rubber Modified Asphalt Demonstration Projects.” Ontario Ministry of Environment and Energy, Ontario, Canada

Emery, J. 1995. “Evaluation of Rubber Modified Asphalt Demonstration Projects.” *Transportation Research Record 1515*. Transportation Research Board, Washington D.C.

Emery, J. 1997. *Final Report -Performance Monitoring of Rubber Modified Asphalt Demonstration Projects*. Ontario Ministry of the Environment, Ontario, Canada.

Esch, David C. 1984. *Asphalt Pavements Modified With Coarse Rubber Particles Design, Construction, and Ice Control Observations*. Final Report. Alaska Department of Transportation, Juneau, AK.

Fager, G.A. 2001. *Asphalt Rubber: A Summary of the Use of Crumb Rubber in Hot Mixes: Kansas Experience 1990-2000*. Report No. FHWA-KS-01-1, Kansas Department of Transportation, Topeka, KS.

FHWA. 1998 “Life Cycle Cost Analysis in Pavement Design Demonstration Project 115: Participant Notebook, FHWA-SA-98-400, FHWA.

FHWA/USEPA. June 1993 “Study Of The Use Of Recycled Paving Material - Report To Congress.” Final Report No. FHWA-RD-93-147, USDOT/FHWA, Washington, D.C.

Flintsch, G.W., L.A. Scofield, and J.P. Zaniewski. 1994. “Network-Level Performance Evaluation of Asphalt-Rubber Pavement Treatments in Arizona.” *Transportation Research Record 1435*. Transportation Research Board, Washington D.C.

Florida Department of Environmental Protection. March 2004. “Waste Tires in Florida, State of the State.”

Florida Department of Transportation. 2002. Guidelines for Use of Modified Binders. *Research in Progress as noted on the Transportation Research Board website*. <http://rip.trb.org/>.

Florida Department of Transportation. 2004. *Standard Specifications for Road and Bridge Construction*. Tallahassee, FL.

Freeman, T.J., D.A. Pinchott, H. Ren, and C.H. Spiegelman. 2003. *Analysis and Treatment Recommendations from the Supplemental Maintenance Effectiveness Research Program (SMERP)*. Texas Transportation Institute, College Station, TX.

Gacke, S., M. Lee, and N. Boyd. 1997. “Field Performance and Mitigation of Shredded Tire Embankment.” *Transportation Research Record 1577*. Transportation Research Board, Washington, D.C.

Green, E.L. and W.J. Tolonen. 1977 “Chemical and Physical Properties of Asphalt-Rubber Mixes Final Report Part 1 –Basic Material Behavior”. Report: ADOT-RS-14 (162) Arizona DOT

Gunkel, K. O’C. 1994. Evaluation of Exhaust Gas Emissions and Worker Exposure from Asphalt-Rubber Binders In Hot Mix Asphalt Mixes. Wildwood Environmental Engineering Consultants, Inc. for Michigan Department of Transportation.

Haggerty, E.J. 1994. Industrial Hygiene Monitoring During Paving Operations Utilizing A Crumb Rubber Modified (CRM) Asphalt (Caltrans Contract No. 11-172504) Jobsite: Highway 115, Holtville, CA from November 30, 1994 through December 1, 1994 (for Granite Construction, El Centro, CA)

Hanley, K.W. and A.K. Miller. 1996. NIOSH Health Hazard Evaluation Report 94-0408-2564 Granite Construction Co. Sacramento, California. NIOSH Hazard Evaluation and Technical Assistance (HETA) Branch. Cincinnati OH.

Hanley, K.W. and A.K. Miller. 1996. 1996. NIOSH Health Hazard Evaluation Report 94-0365-2563 Spartan Paving Co. Lansing Michigan. NIOSH Hazard Evaluation and Technical Assistance (HETA) Branch. Cincinnati OH.

Hansen, K.R. and G. Anderton. 1993. “A Laboratory Evaluation of Recycled Tire Rubber in Hot-Mix Asphalt Paving Systems.” In *Use of Waste Materials in Hot-Mix Asphalt*. American Society for Testing and Materials, STP 1193, pp. 69-83.

Harmelink, D. 1999. *Using Ground Tire Rubber in Hot Asphalt Pavements*. Colorado Department of Transportation, Denver, CO.

Harvey, J.T. and L. Popescu. 2000. “Accelerated Pavement Testing of Rutting Performance of Two Caltrans Overlay Strategies.” *Transportation Research Record 1716*. Transportation Research Board, Washington, D.C.

Harvey, J.T. and M.O. Bejarano. 2001. “Performance of Two Overlay Strategies under Heavy Vehicle Simulator Trafficking.” *Transportation Research Record 1769*. Transportation Research Board, Washington, D.C.

Heitzman, M. 1992. “Design and Construction of Asphalt Paving Materials with Crumb CRM.” *Transportation Research Record 1339*. Transportation Research Board, Washington, D.C.

Heitzman, M. 1992. “State of the Practice – Design and Construction of Asphalt Paving Materials with Crumb CRM,” FHWA-SA-92-202, Federal Highway Administration, Washington DC.

Henderson, M.P. and S.A. Kalevela. 1996. *A Comparison of Traffic Noise From Asphalt Rubber Concrete Friction Courses (ARACFC) and Portland Cement Concrete Pavements (PCCP)*. Arizona Department of Transportation, Phoenix, AZ.

Herritt, K. 2001. “Rubber Pavements: A Caltrans Success Story.” *California Department of Transportation Journal, Volume 1, Issue 3*. California Department of Transportation, Sacramento, CA.

Hicks, R.G. and G. Holleran. 2002. “Rubber Modified Binder- Pilot Projects Review 2001.” California Department of Transportation, Sacramento, CA.

Hicks, R.G., J.R. Lundy, R.B. Leahy, D. Hanson, and J. Epps. 1995. *Crumb CRM (CRM) in Asphalt Pavements: Summary of Practices in Arizona, California, and Florida*. Report FHWA-SA-95-056. Federal Highway Administration, Washington, D.C.

Hicks, R.G. and J.A. Epps, “Life Cycle Costs for Asphalt-Rubber Paving Materials,” Asphalt Rubber 2000, Proceedings Vilamoura, Portugal, November 2000. pp. 569-589.

Hildebrand, Gary and Van Kirk, Jack L. 1996. “Asphalt Rubber Performance Evaluation.” Internal Caltrans Report. Caltrans, Sacramento, CA.

Hossain, M. and A. Habib. *Development of Structural Layer Coefficients of Crumb Rubber Modified Asphalt Mixes from In-Situ Deflection Tests*. Report No: K-TRAN: KSU-96-2. Kansas Department of Transportation, Topeka, KS.

Huang, B., L.N. Mohammand, P.S. Graves, and C. Abadie. 2002. “Louisiana Experience with Crumb Rubber-Modified Hot-Mix Asphalt Pavement.” *Transportation Research Record 1789*. Transportation Research Board, Washington, D.C.

Humphrey, D.N. and R.A. Eaton. 1995. “Field Performance of Tire Chips as Subgrade Insulation for Rural Roads.” *Proceedings from the Sixth International Conference on Low-Volume Roads, Volume 2*. Transportation Research Board, Washington, D.C.

Humphrey, D.N. 1996. “Tire Chips: A New Road-Building Geomaterial. *TR News, Issue 184*. Transportation Research Board. Washington, D.C.

Hunt, E.A. 2002. *Crumb Rubber Modified Asphalt Concrete in Oregon*. Oregon Department of Transportation, Salem, Oregon.

Kandhal, P.S. 1993. “Waste Materials in Hot Mix Asphalt – An Overview.” In *Use of Waste Materials in Hot-Mix Asphalt*. American Society for Testing and Materials, STP 1193, pp. 3-16.

Kinnes, G. M., A. K. Miller, and G. A. Burr. 1996. *Health Hazard Evaluation Report HETA 96-0130-2619, The Sim J. Harris Company, San Diego, California*. National Inst. for Occupational Safety and Health, Cincinnati, OH.

Loh, S.W., S. Kim, and H.U. Bahia. 2000. *Characterization of Simple and Complex Crumb Rubber Modified Binders*. Wisconsin Department of Transportation, Madison, WI.

Lundy, J.R., R.G. Hicks and H. Zhou. 1993. “Ground Rubber Tires in Asphalt-Concrete Mixes – Three Case Histories.” In *Use of Waste Materials in Hot-Mix Asphalt*. American Society for Testing and Materials, STP 1193, pp 262-275.

Madapati, R.R., K.W. Lee, F.J. Manning, and C.A. Franco. 1996. “Feasibility of Crumb Rubber Use for Asphalt Pavement Construction.” *Transportation Research Record 1530*. Transportation Research Board, Washington, D.C.

Miller, A. K. and G. A. Burr. 1996. *Health Hazard Evaluation Report HETA 95-0307-2602, Koester Equipment Company, Evansville, Indiana*. National Inst. for Occupational Safety and Health, Cincinnati, OH.

Murphy, K.H. and C.F. Potts. 1980. “Evaluation of Asphalt-Rubber as a Stress-Absorbing Membrane Interlayer and as a Binder for Seal Coat Construction (SR-60 Hillsborough County).” Demonstration Project 37, FHWA-DP-27-14.

Nebraska Department of Roads. 2003. Pavement Quality Indicators. *Research in Progress as noted on the Transportation Research Board website*. <http://rip.trb.org/>.

Page, G.C. 1992. “Florida’s Initial Experience Utilizing Ground Tire Rubber in Asphalt Concrete Mixes.” *Journal of the Association of Asphalt Paving Technologists, Vol. 61*. Association of Asphalt Paving Technologists, St. Paul, MN.

Page, G.C., B.E. Ruth, and R.C. West. 1992. “Florida’s Approach Using Ground Tire Rubber in Asphalt Concrete Mixes.” *Transportation Research Record 1339*. Transportation Research Board, Washington, D.C.

Pamukcu, S. and D. Kershaw. 1996. “Using CRM to Remove Petroleum from Water.” *TR News, Issue 184*. Transportation Research Board. Washington, D.C.

Pavlovich, R.D, T.S. Shuler & J.C. Rosner. 1979. “Chemical and Physical Properties of Asphalt-Rubber Mixes Phase II- Product Specifications and Test Procedures” FHWA/AZ-79/121, Arizona DOT

Peterson, D. E. 1985. *Life-Cycle Cost Analysis of Pavements*. NCHRP Synthesis of Highway Practice 122. Transportation Research Board, Washington, DC.

Public Works Standards, Inc. 2000. “Greenbook” Standard Specifications for Public Works Construction. BNi Building News, Anaheim, CA.

Raad, L., S. Saboundjian, and J. Corcoran. 1993. “Remaining Fatigue Life Analysis: Comparison between Dense-Graded Conventional Asphalt Concrete and Gap-Graded Asphalt-Rubber Hot Mix.” *Transportation Research Record 1388*. Transportation Research Board, Washington, D.C.

Raad, L. and S. Saboundjian. 1998. “Fatigue Behavior of Rubber-Modified Pavements. *Transportation Research Record 1639*. Transportation Research Board, Washington, D.C.

Radian Corporation. 1993. *Asphalt/Rubber Fume Pilot Study (Final)*. Radian Corporation, Sacramento, CA.

Rebala, S.R. and C.K. Estakhri. 1995. “Laboratory Evaluation of Crumb Rubber Modified Mixes Designed Using TxDOT Mix Design Method.” *Transportation Research Record 1515*. Transportation Research Board, Washington, D.C.

Recycled Materials Resource Center. 2001. A Life-Cycle Analysis Model and Decision-Support Tool for Selecting Recycled versus Virgin Materials for Highway Applications. *Research in Progress as noted on the Transportation Research Board website*. <http://rip.trb.org/>.

Rinck, G; D.Napier and D. Null. 1991. Exposure of Paving Workers to Asphalt Emissions (When Using Asphalt-Rubber Mixes). Asphalt Rubber Producers Group, Phoenix, AZ.

Roberts, F.L., L.N. Mohammad, H. Qin, and B. Huang. *Comparative Performance of CRM HMA Asphalt under ALF Loading*. Louisiana Department of Transportation and Development, Baton Rouge, LA.

Rosner, J.C. and Chehovits, J.G. “Chemical and Physical Properties of Asphalt-Rubber Mixes – Phase III,” Vols. 1-5, *FHWA/AZ-82-159*, Arizona DOT, June 1982.

Ruth, B.E, S. Sigurjonsson, and C.L. Wu. 1989. *Evaluation of Experimental Asphalt-Rubber, Dense-Graded, Friction Course Mixes: Materials and Construction of Test Pavements in N.E. 23 Avenue, Gainesville, Florida*. University of Florida, Gainesville, FL.

Sacramento County DERA and Bollard & Brennan, Inc. 1999. *Report on the Status of Rubberized Asphalt Traffic Noise Reduction in Sacramento County*. Sacramento, CA.

Schnormeier, R.H. 1986. *Fifteen-Year Pavement Condition History of Asphalt Rubber Membranes in Phoenix, Arizona*. Asphalt Rubber Producers Group, Tempe, AZ.

Scofield, L. and P.R.Donovan. 2003. “Development of Arizona’s Quiet Pavement Research Program.” *Proceedings Asphalt Rubber 2003 Conference*.

Sebaaly, P.E., G.M. Bazi, and Y. Vivekanathan. 2003. *Evaluation of New Pavement Technologies in Nevada*. Nevada Department of Transportation, Carson City, Nevada.

Shatnawi, Shakir, “Fatigue Performance of Asphalt Concrete Mixes Using a New Repetitive Direct Tension Test.” Internal Caltrans report, October 1997.

- Shatnawi, S. and G. Holleran, "Asphalt Rubber Maintenance Treatments in California," Proceedings, Asphalt Rubber 2003, Brazil, December 2003. pp. 35-47.
- Shatnawi, S. and B. Long, "Performance of Asphalt Rubber as Thin Overlays," Proceedings, Asphalt Rubber 2000, Portugal, November 2000. pp. 53-71
- Sousa, J.B, J.C. Pais, R. Saim, G.B. Way, and R.N. Stubstad. 2002. "Mechanistic-Empirical Overlay Design Method for Reflective Cracking." Transportation Research Record 1809. Transportation Research Board, Washington, D.C.
- State of California Department of Transportation. 1999. *Standard Specifications*. Sacramento, CA.
- State of California Department of Transportation. June 2001. *Flexible Pavement Rehabilitation Manual*. Sacramento, CA.
- Stout, D. and D. Carlson. 2003. "Stack Emissions with Asphalt Rubber A Synthesis of Studies." *Proceedings Asphalt Rubber 2003 Conference*
- Stroup-Gardiner, M., B. Chadbourn, and D.E. Newcomb. 1996. "Babbitt, Minnesota: Case Study of Pretreated Crumb Rubber Modified Asphalt Concrete." *Transportation Research Record 1530*. Transportation Research Board, Washington, D.C.
- Swearington, D.L., N.C. Jackson, and K.W. Anderson. 1992. "Use of Recycled Materials in Highway Construction." Paper No. WA-RD 252.2, Washington State Department of Transportation, Olympia, Washington.
- Tahmoressi, M. 2001. *Evaluation of Asphalt Rubber Pavements in Texas*. PaveTex Engineering and Testing for Rubber Pavements Association, Tempe, AZ.
- Texas Commission on Environmental Quality and the Texas Department of Transportation, 2004 Progress Report on Using Scrap Tires and Crumb Rubber in Texas Highway Construction Projects, 2004.
- Texas Department of Transportation (TxDOT). 2003. Mix Design and Performance Testing of Crumb CRM HMA Asphalt Concrete (CRM-HMAC). *Research in Progress as noted on the Transportation Research Board website*. <http://rip.trb.org/>.
- Texas Department of Transportation (TxDOT). 2004. *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges*. Austin, TX.
- Trepanier, J. 1995. *Evaluation of Reclaimed Rubber in Bituminous Pavements*. Report No: FHWA/IL/PR-117. Illinois Department of Transportation, Springfield, IL.
- Van Bramer, T.F. 1997. *Rubber-Modified Asphalt Concrete Overlays: A Summary of Field Performance*. Special Report 125, Report No. FHWA/NY/SR-97/126. Transportation Research and Development Bureau, New York State Department of Transportation, Albany NY
- Tahmoressi, M. 2001. "Evaluation of Asphalt Rubber Pavements in Texas.", Dripping Springs, TX.
- Van Kirk, J.L. 1992. "An Overview of Caltrans Experience with Rubberized Asphalt Concrete," prepared for presentation at the 71st Annual Meeting of the Transportation Research Board, January 1992
- Volle, T. H. 2000. *Performance of Rubberized Asphalt Pavements in Illinois*. Report No: FHWA/IL/PRR-136. Illinois Department of Transportation, Springfield, IL.

Walls, J., Smith M.R., “Life Cycle Cost Analysis in Pavement Design,” Report, FHWA-A-SA-98-079, FHWA, September 1998.

Walls, J. and M. R. Smith. 1998. *Life-Cycle Cost Analysis in Pavement Design—Interim Technical Bulletin*. Federal Highway Administration, Washington, DC.

Way, G.B. 2000. “Flagstaff I-40 Asphalt Rubber Overlay Project: Nine Years of Success.” *Transportation Research Record 1723*. Transportation Research Board, Washington, D.C.

Witczak, M.W. 1991. *State of the Art Synthesis Report-Use of CRM in Hot Mix Asphalt*. Maryland Department of Transportation, Baltimore, MD.

Witczak, M.W. and Xicheng Qi. 1995. “Executive Summary Field Performance of Asphalt Rubber Test Sections in the State of Maryland.” Department of Civil Engineering, University of Maryland, College Park, MD.

Wright, R.M., K.W. Lee, J.T Quinn, P. Vashisth, and C. Reddy. 1999. *Assessment of Water Pollutants from Asphalt Pavements Containing Recycled Rubber in Rhode Island*. Rhode Island Department of Transportation, Providence, RI.

Zhong, X.G., X. Zeng, and J.G. Rose. 2002 “Shear Modulus and Damping Ratio of Rubber-Modified Asphalt Mixes and Unsaturated Subgrade Soils. *Journal of Materials in Civil Engineering, Volume 14, Issue 6*. American Society of Civil Engineers, Reston, VA.

Appendix A

GLOSSARY

Asphalt rubber – is used as a binder in various types of flexible pavement construction including surface treatments and hot mixes. According to the ASTM definition (ASTM D 8, Vol. 4.03, “Road and Paving Materials” of the Annual Book of ASTM Standards 2001) asphalt-rubber is “a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 % by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles”. By definition, asphalt-rubber is prepared using the “wet process”. Caltrans specifications for asphalt-rubber physical properties fall within the ranges listed in ASTM D 6114, “Standard Specification for Asphalt-Rubber Binder,” also located in Vol. 4.03. Recycled scrap tire rubber is used for the reclaimed rubber and is currently referred to as crumb CRM (CRM). The asphalt-rubber is formulated at elevated temperatures and under high agitation to promote the physical interaction of the asphalt cement and CRM constituents, and to keep the CRM particles suspended in the blend. Various petroleum distillates or extender oil may be added to reduce viscosity, facilitate spray applications, and promote workability. (See **Wet Process**.)

Automobile tires – tires with an outside diameter less than 660 mm (26 in.) used on automobiles, pickups, and light trucks.

Crumb CRM (CRM) – general term for scrap tire rubber that is reduced in size for use as modifier in asphalt paving materials. Several types are defined herein. A variety of processes and equipment may be used to accomplish the size reduction as follows.

TYPES OF CRM

Ground crumb CRM – irregularly shaped, torn scrap rubber particles with a large surface area, generally produced by a crackermill.

High Natural Rubber (Hi Nat) – scrap rubber product that includes 40-48 % natural rubber or isoprene and a minimum of 50 % rubber hydrocarbon according to Caltrans requirements. Sources of high natural rubber include scrap tire rubber from some types of heavy truck tires, but are not limited to scrap tires. Other sources of high natural rubber include scrap from tennis balls and mat rubber.

Buffing waste – high quality scrap tire rubber that is a byproduct from the conditioning of tire carcasses in preparation for re-treading. Buffings contain essentially no metal or fiber.

Tread rubber – scrap tire rubber that consists primarily of tread rubber with less than approximately 5 % sidewall rubber.

Tread peel – pieces of scrap tire tread rubber that are also a by-product of tire re-treading operations, that contain little if any tire cord.

Whole tire rubber – scrap tire rubber that includes tread and sidewalls in proportions that approximate the respective weights in an average tire.

CRM PREPARATION METHODS

Ambient grinding - method of processing where scrap tire rubber is ground or processed at or above ordinary room temperature. Ambient processing is typically required to provide irregularly shaped, torn particles with relatively large surface areas to promote interaction with the paving asphalt.

Cryogenic grinding – process that uses liquid nitrogen to freeze the scrap tire rubber until it becomes brittle and then uses a hammer mill to shatter the frozen rubber into smooth particles with relatively small surface area. This method is used to reduce particle size prior to grinding at ambient temperatures.

Granulation – produces cubical, uniformly shaped, cut crumb rubber particles with a low surface area.

Shredding – process that reduces scrap tires to pieces 0.023 m² (6 in.²) and smaller prior to granulation or ambient grinding.

Dense-graded – refers to a continuously graded aggregate blend typically used to make hot-mix asphalt concrete pavements with conventional or modified binders.

Devulcanized rubber – rubber that has been treated by heat, pressure, or the addition of softening agents after grinding to alter physical and chemical properties of the recycled material.

Diluent – a lighter petroleum product (typically kerosene or similar product with solvent-like characteristics) added to asphalt rubber binder just before the binder is sprayed on the pavement surface for chip seal applications. The diluent thins the binder to promote fanning and uniform spray application, and then evaporates over time without causing major changes to the asphalt rubber properties. Diluent is not used in asphalt rubber binders that are used to make asphalt concrete, and is not recommended for use in interlayers that will be overlaid with asphalt concrete (AC) in less than 90 days due to on-going evaporation of volatile components.

Dry process – any method that includes scrap tire CRM as a substitute for 1 to 3 % of the aggregate in an asphalt concrete paving mixture, not as part of the asphalt binder. This method applies only to production of CRM-modified AC mixtures. A variety of CRM gradations have been used, ranging from coarse rubber (1/4" to + No. 8) to "Ultrafine" minus 180 µm (No. 80) sized CRM. Caltrans has a special provision for RUMAC which includes an intermediate CRM gradation specification. Care must be taken during the mix design to make appropriate adjustments for the low specific gravity of the CRM compared to the aggregate material to assure proper volumetric analysis. Several methods have been established for feeding the CRM dry with the aggregate into hot plant mixing units before the mixture is charged with asphalt binder. Although there may be some limited interaction of the CRM with the asphalt cement during mixing in the AC plant, silo storage, hauling, placement and compaction, the asphalt cement is not considered to be modified in the dry process.

Extender oil – aromatic oil used to promote the interaction of the asphalt binder and the crumb CRM.

Flush coat – application of diluted emulsified asphalt onto a pavement surface to extend pavement life, and that may also be used to prevent rock loss in chip seals or raveling in AC.

Gap-graded – aggregate that is not continuously graded for all size fractions, but is typically missing or low on some of the finer size fractions (minus 2.36 mm (No. 8) or finer). Such gradations typically plot below the maximum density line on a 0.45 power gradation chart. Gap grading is used to promote stone-to-stone contact in hot-mix asphalt concrete and is similar to the gradations used in stone matrix asphalt, but with relatively low percentages passing the 75 μm (No. 200) sieve size. This type of gradation is most frequently used to make rubberized asphalt concrete-gap graded (RAC-G) paving mixtures.

Interaction – the physical exchange between asphalt binder and crumb CRM when blended together at elevated temperatures. It is a physical interaction in which the crumb rubber absorbs aromatic oils and light fractions (small volatile or active molecules) from the asphalt binder, and releases some of the similar oils used in rubber compounding into the asphalt binder. The interaction is more appropriately defined as polymer swell. It is not a chemical reaction.

Lightweight aggregate – porous aggregate with very low density such as expanded shale, which is typically manufactured. It has been used in chip seals to reduce windshield damage.

Open-graded – aggregate gradation that is intended to be free draining and consists mostly of 2 or 3 nominal sizes of aggregate particles with few fines and 0 to 4 % by mass passing the 0.075 mm (No. 200 sieve). Open grading is used in hot-mix applications to provide relatively thin surface or wearing courses with good frictional characteristics that quickly drain surface water to reduce hydroplaning, splash and spray.

Reaction – commonly used term for the interaction between asphalt binder and crumb CRM when blended together at elevated temperatures. (See **Interaction**)

Recycled tire rubber – rubber obtained by processing used automobile, truck, or bus tires (essentially highway or “over the road” tires). The Caltrans chemical requirements for scrap tire rubber are intended to eliminate unsuitable sources of scrap tire rubber such as solid tires; tires from forklifts, aircraft, and earthmoving equipment; and other non-automotive tires that do not provide the appropriate components for asphalt rubber interaction. Non-tire rubber sources may be used only to provide High Natural Rubber to supplement the recycled tire rubber.

Rubberized asphalt - asphalt binder modified with CRM that may include less than 15 % CRM by mass and thus may not comply with the ASTM definition of asphalt rubber (ASTM D 8, Vol. 4.03). In the past, wet process no agitation CRM-modified binders including Rubber Modified Binder (RMB) have typically fallen in this category.

Rubberized asphalt concrete (RAC) – material produced for hot mix applications by mixing asphalt rubber or rubberized asphalt binder with graded aggregate. RAC may be dense-, gap-, or open-graded.

RUMAC – generic type of dry process RAC mixture that has taken the place of proprietary dry process systems such as PlusRide.

Stress-absorbing membrane (SAM) – a chip seal that consists of a hot asphalt-rubber binder sprayed on the existing pavement surface followed immediately by an application of a uniform sized cover aggregate which is then rolled and embedded into the binder membrane. Its nominal thickness generally ranges between 9 and 12 mm (3/8 and 1/2 in.) depending on the size of the cover aggregate. A SAM is a surface treatment that is used primarily to restore surface frictional characteristics, seal cracks and provide a waterproof membrane to minimize the intrusion of surface water into the pavement structure. SAMs are used for pavement preservation, maintenance, and limited repairs. Asphalt-rubber SAMs minimize reflective cracking from an underlying distressed asphalt or rigid pavement, and can help maintain serviceability of the pavement pending rehabilitation or reconstruction operations.

Stress-absorbing membrane interlayer-Rubber (SAMI-R) – SAMI-R is an asphalt-rubber SAM that is overlaid with an asphalt paving mix that may or may not include CRM. The SAMI-R delays the propagation of the cracks (reflective cracking) through the new overlay.

Stress-absorbing membrane interlayer (SAMI) - originally defined as a spray application of asphalt-rubber binder and cover aggregate. However, interlayers now may include asphalt-rubber chip seal (SAMI-R), fabric (SAMI-F), or fine unbound aggregate.

Terminal blend – see **Wet Process-No Agitation**

Truck tires – tires with an outside diameter greater than 660 mm (26 in.) and less than 1520 mm (60 in.); used on commercial trucks and buses.

Viscosity – is the property of resistance to flow (shearing force) in a fluid or semi-fluid. Thick stiff fluids such as asphalt rubber have high viscosity; water has low viscosity. Viscosity is specified as a measure of field quality control for asphalt-rubber production and its use in RAC mixtures.

Vulcanized rubber – crude or synthetic rubber that has been subjected to treatment by chemicals, heat and/or pressure to improve strength, stability, durability, etc. Tire rubber is vulcanized.

Wet Process - the method of modifying asphalt binders with crumb rubber produced from scrap tire rubber and, if required, other components. The wet process requires thorough mixing of the crumb CRM (CRM) in hot asphalt cement (176°C to 226°C) and holding the resulting blend at elevated temperatures (163°C to 218°C) for a designated minimum period of time (typically 45 to 60 minutes) to permit an interaction between the rubber and asphalt. Other components may be included, depending on applicable specifications. The interaction (also referred to as reaction) includes swelling of the rubber particles and development of specified physical properties of the asphalt and CRM blend to meet requirements. Typical specification requirements include an operating range for rotational viscosity, and minimum values of softening point, resilience, and penetration (needle or cone, cold and/or room temperature). Requirements for components, minimum temperatures for the asphalt cement at CRM addition and for interaction of the asphalt and CRM blend, interaction periods, and resulting physical properties of the blend vary among agencies that use this process (e.g. Arizona, California, Florida, and Texas).

Some agencies, such as Caltrans, require use of asphalt modifiers such as extender oils, and addition of high natural CRM, which includes a higher natural rubber content than typical scrap tire CRM made from passenger vehicle tires, and may be manufactured from scrap tennis balls, mat rubber, or heavy truck tires. Other agencies such as TxDOT have allowed use of various modifiers (extender oil for use in asphalt concrete, diluent for spray applications) but do not require these modifiers. For spray applications, Florida allows but does not require extender oil and diluent; neither is used in AC mixes. Arizona DOT does not allow use of extender oils or diluent in asphalt rubber binders.

The wet process can be used to produce a wide variety of CRM modified binders that have corresponding respective ranges of physical properties. However the most important distinctions among the various blends seem to be related to rotational viscosity of the resulting CRM-asphalt cement blend at high temperature (threshold is 1,500 cPs or 1.5 Pa•sec at 177°C or 190°C depending on governing specification) and whether or not the blend requires constant agitation to maintain a relatively uniform distribution of rubber particles. Viscosity is strongly related to the size of the scrap tire CRM particles and relative tire rubber content of the CRM-modified blend. CRM gradations used in the wet process are minus 2 mm (No. 10) sieve size or finer (see Table 2.2). CRM-modified binders with viscosities $\geq 1,500$ cPs at 177°C or 190°C should be assumed to require agitation.

Wet Process-No Agitation - rubber-modified binders that do not require constant agitation to keep discrete rubber particles uniformly distributed in the hot asphalt cement. The term “terminal blend” is often used to describe such materials, which may include some MBs. However such binders may be produced in the field or at an asphalt concrete plant as well, so calling them terminal blends may be misleading and is unnecessarily restrictive. The preferred description for this type of binder is therefore “**wet process-no agitation**”. Such binders are typically modified with CRM particles finer than 300 μm (No. 50) sieve size that can be digested (broken down and melted in) relatively quickly and/or can be kept dispersed by normal circulation within the storage tank rather than by agitation by special augers or paddles. Polymers and other additives may also be included. In the past, rubber contents for such blends have generally been $\leq 10\%$ by mass of asphalt or total binder (which does not satisfy the ASTM D 8 definition of asphalt-rubber), but current reports indicate some California products now include 15% or more CRM. Although such binders may develop a considerable level of rubber modification, rotational viscosity values rarely approach the minimum threshold of 1500 centipoise (cPs) or 1.5 Pa•s at 177°C or 190°C, that is necessary to significantly increase binder contents above those of conventional AC mixes without excessive drain-down. This product is used in Arizona, California, Texas and Florida with various concentrations of CRM.

Wet Process-High Viscosity - rubber-modified binders that maintain or exceed the minimum rotational viscosity threshold of 1500 centipoise (cPs) at 177°C or 190°C over the interaction period should be described as “**wet process-high viscosity**” binders to distinguish their physical properties from those of wet process-no agitation materials. These binders require agitation to keep the CRM particles evenly distributed. They may be manufactured in large stationary tanks or in mobile blending units that pump into agitated stationary or mobile storage tanks. Wet process-high viscosity binders include asphalt rubber materials that meet the requirements of ASTM D6114. Wet process-high viscosity binders typically require at least 15% scrap tire rubber to achieve the threshold viscosity. However CRM-modified binders that meet Caltrans asphalt rubber recipe requirements for minimum total CRM content and relative proportions of scrap tire and high natural CRM with less than 15% tire rubber generally achieve sufficient viscosity to be included in this category and should be assumed to require agitation.

Appendix B

DETAILED SUMMARY OF PRACTICES FOR AZ, CA, FL AND TX

Materials Survey Questionnaire	California			Arizona			Texas			Florida		
	Application			Application			Application			Application		
1. Scrap Tire Rubber as a Binder Modifier (Wet process)												
a. Binder Constituents	Asphalt Concrete	Spray		Asphalt Concrete	Spray		Asphalt Concrete	Spray		Asphalt Concrete	Spray	
Asphalt Cement (Grade)	AR 4000			(For AC) PG64-16,PG58-22; PG52-28(rare)			AC-10 or AC-20			PG 67-22	PG 64-22	
Scrap Tire Rubber Content Range, %	Min 18% by total weight of binder; 25% HN & 75% ST			min 20% by wt of asphalt			15 to 20%			5%, 12%	20%	
(Identify if by weight of asphalt or total binder)										By weight of AC		
Other Type of Rubber Required? Yes/No				no			Yes					
Identify Type, content range, %							5% Tire Rubber	AC-20-5TR				
Extender Oil Required? Yes/No (Content Range)	2.5– 6% by weight of base asphalt			no, not allowed			No			No	Allowed	
Diluent Required? Yes/No (Content Range)				no, not allowed			No			No	Allowed	
Other Additives Required? Yes/No (Identify) (Content Range)				no			No			Liquid antistripping, 0.5%	No	
b. Binder Specifications												
Standard Specifications or Special Provisions?	SSP			(For AC) Std specs with some updates in specials (contained in stored specifications. Same used in all specials. Until spec book update)			Item 300			Standard		
Recipe requirements? Yes/No	Yes			yes			No			Yes		
Physical property requirements? Yes/No	Yes			yes			Yes	No		Yes		
Is rotational viscosity used as field criterion for adding binder to mix or spraying? Yes/No	hand held hake viscometer			yes			Yes			Yes		
If so, what is the specified minimum viscosity, at what temperature?	1500cPs - 4000cPs @ 190°C			1.5 Pa sec@350°F			1500-5000cP @ 347°F			4.0 Poise @ 300F, 10 P @ 300F	15 P @ 350F	
2. Asphalt Concrete Mixes												
a. Mix Design	Wet Process	Dry Process		Wet Process	Dry Process		Wet Process	Dry Process		Wet Process	Dry Process	
Standard Specifications or Special Provisions?	SSP	Pilot projects		(For AC) Std specs with some updates in specials (contained in stored specifications. Same used in all specials. Until spec book update)			Items 342 & 346	None		Standard	N/A	
Compaction Method												
• Marshall (indicate blows-per-face)				75			N/A			N/A		
• Hveem	Hveem			n/a			N/A			N/A		
• Texas Gyrotory				n/a			N/A			N/A		
• Superpave Gyrotory (indicate number of gyrations)				n/a			(For wet process) Item 342 – 50 gyrations; Item 346 – 75 or 100 gyrations			75/NA	N/A	
• Other, Specify				n/a			N/A					
Requirements	Yes/No	Yes/No		Yes/No	Yes/No		Yes/No	Yes/No		Yes/No	Yes/No	
• Air Voids, %	3-6% depend on region			yes			Yes			4		
• VMA, %	18% all agg. (not for MB-D)			yes			Yes/No			15/14 (min)		
• VFA, %	No			yes			No			65-75		
• Minimum Stability? (Yes/No)	Hveem 23 min (28 min for RUMAC)			no			No			No		
Identify and list Hveem or Marshall value							N/A			N/A		
• Other strength test?	No			no			(For wet process) Item 342 – Cantabro Loss (20% max); Item 346 – Hamburg Wheel Test (1/2 inch @ 20,000 passes)			N/A		
• Resistance to Moisture Damage? (Yes/No)	No			no			Yes			T-283		
Identify test method & requirement							(For wet process) Item 342 - Boil Test; Item 346 – Boil Test & Hamburg Wheel Test (1/2 inch @ 20,000 passes)			TSR 0.8 min; dry 100 psi min	N/A	
Binder Content												
Mix Type. Binder Content Range, %*												
• Dense-Graded	6-8.5% weight dry agg.			n/a			N/A			6.2% (Total mix)		
• Gap-Graded	7-9% weight dry agg.			7-8			7-10% (total mix)			N/A		N/A
• Open-Graded	moratorium not used			9-9.7			8-10%			N/A		6.8% (Total mix)
*Specify if by weight of Dry Aggregate or Total Mix												
Is There Minimum Percentage of CRM for Dry Process? (Yes/No)	Yes	Pilot 18% ±2% mass binder		n/a						N/A		
Are aggregate requirements different from conventional dense-graded asphalt concrete? (Yes/No). If Yes, please specify the following:	Scrap Tire Modified AC	Conventional DGAC		Scrap Tire Modified AC	Conventional DGAC		Scrap Tire Modified AC	Conventional DGAC		Scrap Tire Modified AC	Conventional DGAC	
• Crushed particle, %, min.	two face or more 90		One face or more 90				Yes			N/A		
• Los Angeles abrasion, %, max.	500 rev 40% max		500 rev 45%				Yes			N/A		
• Sand Equivalent, %, min.	No						No			N/A		
b. Construction												
Typical Lift Thickness, specify inch or mm (indicate typical range and specification limits)	Maintenance	Rehabilitation	Construction	Maintenance	Rehabilitation	Construction	Maintenance	Rehabilitation	Construction	Maintenance	Rehabilitation	Construction
• Dense-graded	30mm	35 -60mm		no rubber dense grade						N/A		
• Gap-Graded	30mm	35 -60mm		2 in						2" (Fine 1 1/2 -3"; Coarse 2-4")		
• Open-Graded	30mm			0.5-1 in						1-2 inch (none)		
Compaction Requirements (% of Rice)												
• Dense-graded	moratorium not used			n/a						N/A		
• Gap-Graded	96% to lab density, not RICE (only for 60 mm max thick lifts)			rolling method						94.0-96.5%		
• Open-Graded	Method spec			rolling method						<82%		
Compaction Equipment (Vibratory, static-steel, pneumatic, combo)												
• Dense-graded - breakdown	moratorium not used			no dense graded asphalt rubber						N/A		
• Gap-Graded - breakdown	Steel			vibratory						N/A		
• Open-Graded - breakdown	Steel			static						N/A		
• Dense-graded - intermediate/finish	moratorium not used			no dense graded asphalt rubber						N/A		
• Gap-Graded - intermediate/finish	Steel	Not Pneumatic		vibratory/static						N/A		
• Open-Graded - intermediate/finish	Pneum. (not for finish)	Steel		static						N/A		

Temperature Requirements											
• Mix discharge at plant, range, °C					350°F			<177°C (350°F)	149-154 (DGFC)	160 (OGFC)	
• Ambient at paving site, minimum, °C	13°C (the following temperatures apply to RAC-G)			(For rehab) gap-graded; 65°F and rising; stop @ 70°F and falling; open graded no ambient specified				N/A	7	18	
• Pavement surface (if overlay) minimum, °C	13°C			(For rehab) gap-graded 65°F; open graded 85°F				>21°C (70°F)	N/A		
• Placement minimum, °C	138-163 depending on atmospheric & surface temperature			275°F				138°C (280°F)	138-149	150-155	
• Compaction minimum, °C	135°C breakdown; 121°C finish (depends on air & surf. Temps.)			220°F				N/A	70	100 (Guess)	
Acceptance Tests											
Type, Frequency	For all of phases testing is required for Binder; Mix (asphalt content) Agg (gradation); Density if applicable			(For rehab) aggregate gradation, 1/500ton of aggregate; binder content 4x per day, aggregate properties (sand equivalent, flakiness, etc) 1x per day			(For construction) Laboratory Modeled density, 1-4 per lot. In-place air voids, 4/lot			Va, Pb, P200, P8, density; 1 set/4000 tons (DGAC)	Pb, P3/8, P4, P8; 1 set/2000 tons (OGFC)
3. Spray Applications											
Chip Seals											
	Application Rate Range			Application Rate Range			Application Rate Range			Application Rate Range	
Maximum Chip Size (mm)	Binder, gal/yd ²	Stone, lb/yd ²		Binder, gal/yd ²	Stone, lb/yd ²		Binder, gal/yd ²	Stone, lb/yd ²		Binder, gal/yd ²	Stone, lb/yd ²
12.5	0.55 - 0.65	25-40					0.50-0.55	90-95		N/A	
9.5	0.55 - 0.65	25-40					0.50-0.55	90-95		N/A	
Other							N/A	N/A		N/A	
Stress-Absorbing Membrane Interlayer (SAMI)											
Maximum Chip Size (mm)											
12.5	0.55 - 0.65	25-40					0.50-0.55	90-95		N/A	
9.5	0.55 - 0.65	25-40					0.50-0.55	90-95		N/A	
Other							N/A		0.6-0.8 gal/yd ² (19 mm)	0.26-0.33 ft ³ /yd ²	
Is use of spray applications limited to maintenance and rehabilitation activities? Yes/No. If No, describe other uses.	Yes						Yes			Yes	
4. Recycling											
Has your agency recycled any asphalt concrete paving materials that include scrap tire rubber in the mix, as an interlayer or surface seal? If so, please describe	No			We did a very short proof of concept type test for hot in-place recycling of our open-graded mix (no addition of new aggregate). It was successful. We have plans to do a project in which we hot-in-place recycle 14 year old open-graded mix and also on the same project we will be trying using open-graded mix as RAP for a new open-graded mix.			Yes, one project on I-10 in San Antonio using 30% (~ 1994).			Yes. We have milled and recycled pavements with asphalt rubber in them.	
• The method of mix design used to incorporate the recycled mixture or membrane layer							TxDOT Hveem Hot Mix Asphalt Mixture Design Method (Tex-204-F)			Superpave	
• Mix production methods											
o Is rubber-modified RAP added by the same method as conventional RAP? Yes/No							Yes			Yes	
o Were any problems encountered with blue smoke or fumes?							No			No	
• Construction methods							Hot-Central-Plant			Hot-Central-Plant	
o Hot-Central-Plant; Hot-In-Place; Cold-In-Place; Other							None			The solution to pollution is dilution. (ARB only in top 1/2"-1" typically we mill 1-1/2"-2" then only use ~30% or less RAP in the recycled mixture). We do not recycle AR SAMI. We mill it & give it to FDOT maintenance for misc. use.	
• Issues and/or problems encountered and solutions developed							N/A			Yes	
• Were solutions effective?							Same as conventional			Perfect	
• Quality of resulting finished pavement											
5. Structural Design											
What structural design considerations and methodologies are used for rubber-modified asphalt concrete and spray applications for:				Structural design methodologies for rubber-modified asphalt concrete are the same as for conventional dense-graded mixtures, regardless of application.							
• New construction?	Yes						No different from conventional pavement designs			For pavement design purpose, layer coefficients are:	
• Rehabilitation?	Yes						No different from conventional pavement designs			OGFC - 0	
• Maintenance?	Yes						No different from conventional pavement designs			DGFC - 0.44	
• Is any structural credit assigned to open-graded mixes? (Yes/No)	Yes			No			No			No	
• Is any structural credit assigned to SAMIs? (Yes/No)	Yes			N/A			No			No	
• What kind of structural credit is assigned to gap-graded mixes relative to dense-graded mixes?				No dense-graded rubber mixes used			No difference			N/A	
6. Cost Considerations											
• Initial Costs											
o Agency costs (Yes/No)	Yes						Yes			Yes	
o Highway user costs (Yes/No)	Yes						No			No	
o How do scrap-tire modified mixtures compare with dense-graded asphalt concrete and/or SMA?	We do not use SMA. We use half thickness when we use Modified mixture compare to Type D in maintenance and re-hab jobs										
§ Typical cost range for scrap tire modified mixtures	Type O:\$ 59-\$133 avg: \$74; Type G: \$58-\$12,500 avg: \$60.02			gap-graded \$48/ton; open graded \$51/ton			\$40-80/ton			OGFC 77\$/ton; DGFC 65\$/ton	
§ Typical cost range for conventional dense-graded asphalt concrete	Type A:\$53-\$200 avg: \$56.79; Type B:\$48.8-\$220 avg: \$58.69			_ \$34/ton			\$30-50/ton			56\$/ton	
§ Typical cost range for SMA				N/A			\$45-55/ton			N/A	
o Can you provide a copy of the cost data for typical scrap-tire modified asphalt concrete, conventional dense-graded asphalt concrete and/or SMA? Yes/No	Yes except for SMA			Yes depending on exactly what you want			No			Yes	
• Life Cycle Costs											
o Do you conduct life cycle cost analysis? Yes/No	Yes						No			No	
o How do scrap-tire modified mixtures compare with dense-graded asphalt concrete and/or SMA?	We do not use SMA. In revalidation and maintenance jobs we use half thickness with modified mixture compare to Type D						Subjective estimate scrap-tire modified mixtures last 30-50% longer, no objective data available. No data for SMA comparison				

Appendix C

LIFE CYCLE COST TECHNIQUES AND ANALYSIS

LIFE CYCLE COST TECHNIQUES

There are a number of different techniques that are used to equate the value of costs incurred at various points in time. Most commonly, these present and future costs are expressed in terms of a present worth (PW) cost or an equivalent uniform annual cost (EUAC). Using the PW method, all future costs are adjusted to a PW cost using a selected discount rate. The costs incurred at any time in the future can be combined with the initial construction costs to give a total PW cost over the analysis period. This is shown in equation 1. The present worth method is typically used to compare the costs of different alternatives over the same analysis period.

$$PW = C * \frac{1}{(1+i)^n} \quad (1)$$

where:

- PW = Present worth of future costs, \$.
- C = Future cost at time t = n, \$.
- i = Discount rate, expressed as a decimal.
- n = Time at which future cost incurred; also analysis period, years.

The EUAC method expresses present and future costs in terms of an equalized, annual payment using a selected discount rate. This method is used to compare the costs of alternatives when they have different analysis periods. The formula used to calculate EUAC is shown in equation 2.

$$EUAC = PW * \left[\frac{i}{1 - (1+i)^{-n}} \right] \quad (2)$$

where:

- EUAC = Equivalent uniform annual cost, \$.

There are several variables need to be considered when performing the life cycle cost analysis as described below.

Analysis Period

The analysis period refers to the time over which the economic analysis is to be conducted, which is not necessarily the same as the “life” of the treatment. Suggested analysis periods for new pavement design are 20 years to 50 years for high volume roadways, and 15 years to 25 years for low volume roadways (AASHTO 1993). For rehabilitation work, the analysis period will usually be shorter, such as 10 to 20 or more years, depending on the future use of the facility, the need for geometric improvements, and other factors. The analysis period should at least be long enough to force a rehabilitation of every rehabilitation alternative being analyzed, and should be the same for all rehabilitation alternatives.

Discount Rate

The discount rate, defined as the interest rate used in calculating the present value of expected yearly benefits and costs represents the time value of money. It is often approximated as the difference between the commercial interest rate and inflation rate as given by the consumer price index (hence the term *discount* rate since it is an interest rate that has been *discounted* for inflation).

The difference between interest rates and inflation rates does not remain constant over time and for that reason no specific discount rate will always be correct. However, the selection of the appropriate rate should not be based on short-term economic conditions but should be based on the longer term average condition.

The selection of the appropriate discount rate for a LCC analysis is critical to the selection of the preferred rehabilitation alternative since it can have a significant effect on the outcome. The use of a low discount rate (for example, 2 to 3 %) favors projects with large initial costs, whereas the use of a high discount rate (say, 6 to 8 %) favors projects that have lower initial costs but higher future (maintenance or rehabilitation) costs. A 4 % discount rate may be appropriate to use in the life cycle cost analysis.

LIFE CYCLE COST ANALYSIS

Life cycle cost analysis (LCCA) should be conducted as early in the project development cycle as possible. The level of detail in the analysis should be consistent with the level of investment. Basically, the analysis involves the following steps:

- Develop rehabilitation and maintenance strategies for the analysis period
- Establish the timing (or expected life) of various rehabilitation and maintenance strategies
- Estimate the agency costs for construction, rehabilitation, and maintenance
- Estimate user and non-user costs
- Develop expenditure streams
- Compute the PW or EUAC
- Analyze the results
- Reevaluate strategies and develop new ones as needed

Establish alternative design strategies

The primary purpose of a LCCA is to quantify the long-term economic implications of initial pavement decisions. Various rehabilitation and maintenance strategies can be employed over the analysis period as shown in Figure 1a. This first step is to identify alternate strategies over the analysis period, typically 40 years. Figure 1b shows a comparison of two alternatives over a certain pavement life.

Determine expected life of rehabilitation and maintenance strategies

The next step is to obtain estimates of expected lives for the various rehabilitation and maintenance strategies. Very often the expected life of a rehabilitation or maintenance strategy is difficult to determine; the low, average, and high values represent the 10, 50 and 90 %ile values for expected life may be used. It should be emphasized that reliable estimated lives for asphalt rubber pavement have not been established yet and many asphalt rubber pavements are still performing well; therefore, the expected life for asphalt rubber strategies are at best an estimate.

Estimate agency costs

Agency costs include all costs incurred directly by the agency over the life of the project. These costs typically include expenditures for preliminary engineering, contract administration, construction, including construction supervision, and all future maintenance (routine and preventive), resurfacing and rehabilitation. The low, average and high values represent the 10, 50 and 90 percentile values for expected costs may be used in the LCCA.

Salvage value represents the value of an investment alternative at the end of the analysis period. The method used to account for salvage value may be prorated-based on the cost of final rehabilitation activity, expected life of rehabilitation, and time since last rehabilitation activity as shown below:

$$SV = \left(1 - \frac{L_A}{L_E} \right) C \quad (3)$$

where:

- L_E = the expected life of the rehabilitation alternate
- L_A = portion of expected life consumed
- C = cost of the rehabilitation strategy.

Estimate user and non-user costs

In simple terms, user costs are those incurred by the highway user over the life of the project. They include vehicle operating costs (VOC), user delay costs, and accident costs. For most pavements on the National Highway System (NHS), the VOC are considered to be similar for the different alternatives. However, slight differences in VOC rates caused by differences in roughness could result in huge differences in VOC over the life of the pavement.

Delay cost rates have been derived for both passenger cars and trucks. These can range from \$10-13/veh-hr for passengers cars and \$17-24/veh-hr for trucks [WAL 98]. Because these costs require project specific information for inclusion in LCCA and the value of delay costs is often questioned, the authors opted to use a simpler approach using lane rental fees. Typical values for lane rental fees might vary with traffic volume as follows [HIC 99]:

<u>Type of Facility</u>	<u>\$/Lane-km/Day</u>
Low volume	620
Moderate volume	3100
High volume	7200

These values are estimates only, but allow the effect of delays to be accounted for indirectly. Accident and non-user costs may also vary with type of rehabilitation and maintenance strategy.

Develop expenditure streams

Expenditure streams are graphical or tabular representations of expenditures over time. They are generally developed for each pavement design strategy to visualize the extent and timing of expenditures. Figure 2 is an example of an expenditure stream. Normally, costs are depicted as upward arrows and benefits are reported as negative cost (or downward arrows). The only benefits, or negative cost, included herein are the costs associated with the salvage value.

Compute PW or EUAC

Knowing the design strategies, expected life of rehabilitation and maintenance strategies, agency cost, and/or user costs, the present worth and equivalent uniform annual cost can be calculated using equations 1 and 2. The project with the lowest equivalent uniform annual cost is the most economical.

Analyze results

Once completed, all LCCA results should be subjected to a sensitivity analysis to determine the influence of major input variables. Many times the sensitivity analysis will focus on inputs with the highest degree of uncertainty (i.e., life) in an attempt to bracket outcomes. For example, if a conventional project lasts 10 years, how long must an asphalt rubber design last for it to be cost effective?

Reevaluate design strategy

Once the PW or EUAC has been computed for each alternative, the analyst needs to reevaluate competing design strategies. Questions to be considered include:

- Are the design lives and maintenance and rehabilitation costs appropriate?
- Have all costs been considered (e.g., shoulder and guard rail)?
- Has uncertainty been adequately treated?
- Are there other alternates that should be considered?

Many assumptions, estimates, and projections feed the LCCA process. The variability associated with these inputs can have a major influence on the results.

Appendix D

AASHTO LIST SERVER SURVEY SUMMARY

STATE	CONTACT	EMAIL	USE CRM	COMMENTS
ALABAMA	Randy Mountcastle	Mountcastler@mail.dot.state.al.us	No	Years ago, when FHWA was debating mandating CRM recycling, we laid a short test section using CRM. We currently use traditional (elastic) modifiers like SBR, SBS, etc. simply because they are cheaper than CRM in Alabama at this time.
ALASKA	Newt Bingham	newt_bingham@dot.state.ak.us	No	Not currently using CRM in HMA applications. Research currently being performed on studded tire wear resistance, pilot projects expected in the future.
ARIZONA	Jim Delton	jdelton@dot.state.az.us	Yes	See website (quietroads.com)
ARKANSAS	Jerry R. Westerman	Jerry.Westerman@ahd.state.ar.us	No	Arkansas has used recycled tire rubber in asphalt concrete hot mix. Currently it is not being used. Materials price has been a factor in the decision to not use crumb rubber. Considerable more use of crumb rubber was in stress absorbing membrane interlayers.
CALIFORNIA	Phil Stolarski	phil_stolarski@dot.ca.gov	Yes	Caltrans currently uses CRM in Gap and Open Graded mixes as well as asphalt rubber chip seals.
COLORADO				No Response
CONNECTICUT	Keith Lane	keith.lane@po.state.ct.us	No	Currently placing 2 experimental sections of fine mix (#4) with approx. 10% rubber. Intended to be used as a wearing/maintenance layer on bridge applications.
DELAWARE	Jim Pappas	JPappas@mail.dot.state.de.us	No	Currently, Delaware does not use crumb rubber in any of the applications you referenced.
DISTRICT OF COLUMBIA				No Response
FLORIDA	Jim Musselman	jim.musselman@dot.state.fl.us	Yes	The Florida DOT currently uses crumb rubber in two HMA applications (fine graded friction courses and open graded friction courses), as well as one spray application (an asphalt rubber SAMI). Please let me know if you need anything else.
GEORGIA	Peter Wu	Peter.Wu@dot.state.ga.us	No	Georgia is NOT using crumb rubber in asphalt paving applications. We use only SBS/SB polymers as asphalt modifier.
HAWAII	No Contact Given	Garret.Okada@hawaii.gov	No	No experience in using rubber.
IDAHO	Bob Schumacher	BSchumac@itd.state.id.us	No	Idaho Transportation Department does not currently use CRM in an applications.
ILLINOIS	Eric E. Harm	HARMEE@dot.il.gov	No	Illinois DOT does not use CRM in any applications. During the Federal mandate period we looked CRM in HMA (2 projects) in the traditional wet method. We did a number of projects demonstrating putting in 1,2,4,5 pounds per ton in the dry method as a more cost efficient way of getting rid of tires than the wet method.
INDIANA	Mark Miller	MMILLER@indot.state.in.us	No	Indiana did a couple of trial projects in the 1980s. One used the dry mixing process and there were several problems with the production and performance of that mix. The job using the wet mixing process performed adequately. Indiana has not continued any work in this area due to concerns with the cost and ability to recycle these mixes. We are working with the use of tire shreds as embankment material.
IOWA	James Berger	James.Berger@dot.iowa.gov	No	We have, but it is not cost effective and we haven't used it recently.
KANSAS	Lon Ingram	Lingram@ks.dot.org	No	Kansas has used CRM in hot mix in the past. We are not currently specifying CRM because of performance concerns and cost issues. We have use CRM as in interlayer in the past. We are not using this product now. We do have a specification that allows CRM in our chip seals. We bid the product as an alternate to polymer modified emulsion chip seals.
KENTUCKY	Allen H. Myers	Allen.Myers@dot.ky.gov	No	Kentucky has very little experience with recycled-tire rubber or CRM. We constructed one resurfacing project in 1993 that involved ground-tire rubber added to the asphalt binder. We also completed an asphalt membrane interlayer placed directly on the subgrade and covered with conventional asphalt pavement in 1995. This project involved a spray application of asphalt binder covered with a mixture of recycled-tire chips and aggregate. Please advise if you need more details.
LOUISIANA	Doug Hood	doughood@dotd.state.la.us	No	Does not currently use CRM in HMA applications.
MAINE	Richard L. Bradbury	Richard.Bradbury@maine.gov	No	Maine DOT did an experimental project in the '80s using crumb rubber. Currently, we do not use it in any process.
MARYLAND	Larry Michael	lmichael@sha.state.md.us	No	Maryland DOT is not currently using CRM in HMA applications. Specifications do allow its use.
MASSACHUSETTS				No Response
MICHIGAN				No Response
MINNESOTA	Roger Olson	Roger.Olson@dot.state.mn.us	No	I am responding on behalf of Minnesota DOT (Mn/DOT). Mn/DOT, like most States did several test sections before and during the time of the ISTEA mandate in 1992. Test sections included plus ride for ice control, and several variations of crumb rubber modified HMA. Some of the projects are still intact, several had premature failures. At the present time, crumb rubber modified HMA mixes are not a part of our program. We also constructed a few test sections of spray applied applications, both SAM and SAMI's. We have not constructed any additional sections for some time. If you would like any further information, please let me know.
MISSISSIPPI	Richard H. Sheffield	rsheffield@mdot.state.ms.us	No	Mississippi DOT allows crumb rubber as an asphalt modifier. To my knowledge, it has only been used once as a contractor's option, and that was in 1997 on an I-20 overlay in Lauderdale County. We had problems on that project with the contractor controlling the amount of crumb rubber that went into the binder - it was kind of "hit or miss" (mostly miss). However, the project has held up well, rut-wise, although we have a good bit of longitudinal cracking related to sections where too much crumb rubber was in the binder.
MISSOURI				No Response
MONTANA	Kent Barnes	kbarnes@state.mt.us	No	Montana doesn't currently use this material. We did a little work with it when there was a mandate for it. We are interested in using crumb rubber in some applications but it hasn't appeared economically workable in Montana.
NEBRASKA	Robert C. Rea	rrea@dot.state.ne.us	Yes	We are using crumb rubber as a modifier, on a research and development basis. We currently build 2 to 3 projects per year and are evaluating their effectiveness and we continue to modify the designs and specifications as needed. Projects so far have been: 3 Gap Graded Hot Mix (Interstate, Expressway, and Low Volume) 1 Spray Applied Chip Seal. This year we are placing 2 Gap graded hot mix and 1 Open graded hot mix. We also have a local asphalt terminal interested in trying to make some terminal blend CRM.

STATE	CONTACT	EMAIL	USE CRM	COMMENTS
NEVADA	Dean C. Weitzel	dweitzel@dot.state.nv.us	No	Phil the Nevada DOT does not use crumb or tire rubber in any of the applications you noted below. We have tried CRM in hot mix concrete however the results were poor. Phil, I received this same question from Magdy Mikhail of the TXDOT. I do not know if there is a connection or not.
NEW HAMPSHIRE	Alan Perkins	APerkins@dot.state.nh.us	No	NHDOT has used (does not currently use) recycled tire rubber or crumb rubber modifier (CRM) in hot mix asphalt concrete and in stress absorbing interlayers.
NEW JERSEY	Eileen Sheehy	Eileen.Sheehy@dot.state.nj.us	No	In New Jersey we did about 6 trial projects in the early '90's. Only one fell apart immediately (It was a dry process called Plus Ride). The remainder are continuing to perform well.
NEW MEXICO	John H. Tenison, Jr.	John.Tenison@nmshtd.state.nm.us	No	Due to the additional cost to use CRM and still questioned "better performance" over not using CRM, we presently do not use CRM.
NEW YORK	Zoeb G. Zavery	ZZAVERY@dot.state.ny.us	No	In 1990, we did use the crumb rubber as a fine aggregate which was added to the Hot Mix Asphalt. Unfortunately, we did not have very good success with this process. In 1994, we used the wet process on few projects where the fine crumb rubber was added to the liquid asphalt as a modifier. We had better success with this process but it was a bit costly. At this time, we are looking into constructing two or three pilot projects next year by using PG binder modified with a chemically extracted tire rubber. As for other applications, no we have not use it.
NORTH CAROLINA	Jack Cowsert	icowsert@dot.state.nc.us	No	North Carolina does not currently specify crumb rubber in any application.
NORTH DAKOTA	Ron Horner	rhorer@state.nd.us	No	North Dakota does not currently use crumb rubber in HMA at this time.
OHIO	Dave Powers	David.Powers@dot.state.oh.us	No	Ohio used CRM about 10 years ago at too great a cost/ benefit. Ohio does not use CRM today.
OKLAHOMA	Danny Gierhart	dgierhart@fd9ns01.okladot.state.ok.us	No	We had some unsuccessful attempts using CRM before the government mandates of the mid-1990's. After those attempts, we tried sprinkling 1% in enough projects to meet the mandate requirements. We do not currently use any CRM in our dense-grade mixes. We do have a spec for AC-15TR for chip seals, however.
OREGON	Bruce Patterson	Bruce.M.PATTERSON@odot.state.or.us	No	Oregon does not currently use CRM or recycled tire rubber in HMA but it has been used. A number of test projects have been done in the 80's and early 90's. The last one was in 1994. We have had mixed success. The best performers have been mixes with terminal blended ground tire rubber (about 10% by weight of asphalt) which have performed as well as or a little better than control mixes. Other methods of introducing rubber have not performed very well. A hot asphalt containing 5% rubber has been marketed in our state for hot asphalt chip seals. Some counties have used this in place of emulsified chip seals and a few have been applied to state highways. We have not been using them extensively. If you are interested a March 2002 report titled "Crumb Rubber Modified Asphalt in Oregon" is available on our web site under Research Reports at www.oregon.gov/ODOT/publications.html
PENNSYLVANIA	Dean Maurer	demaurer@dot.state.pa.us	Yes	PENNDOT has long-term evaluated recycled rubber from tires; dating back to the mid 1960's with products such as "Ramflex" & "Flo-mix". We constructed pavement sections with "sam's & "sami's" using the McDonald "wet" processing in the 70's & 80's & developed a crack sealing specification for maintenance. Beginning in the 90's, due mostly to the political pressure of ISTEA legislation, we continued experiments in HMA, including "dry" processing as well other proprietary processes, such as, "Tyrsoiv" & most recently additives, such as, "Vestenamer". However, only crack sealing applications have proved to be cost effective from a cost/benefit viewpoint. Even crack sealing using "field mixing" has changed significantly since the 80's, such that most approved suppliers provide "pre-packaged" sealants, eliminating the need to field blend. I am confident PENNDOT will continue to evaluate crumb-rubber in asphalt applications as new processing methods are introduced and tires remain as a waste issue. However, it continues to remain experimental, until such time as a cost effective application is found in Pennsylvania.
PUERTO RICO	Orlando Quirindongo	OQuirindongo@act.dtop.gov.pr	No	The Puerto Rico Hwy.& Transportation Authority does not use recycled rubber or CRM in its hot mix asphalt concrete etc.
RHODE ISLAND	Colin Franco	cfranco@dot.state.ri.us ; mfelag@DOT.STATE.RI.US	Yes	RIDOT has been using crumb rubber successfully for the last 6/7 years. It is being used in our crack seal program (With fibers added!). In our thin mix overlays (PG 70-40 and PG 76-34 in 1 inch lifts) for pavement preservation , and in our chip seals which has proved extremely effective in stopping reflective cracks coming through. We are now moving towards using crumb rubber modified asphalt Pg 76-34 in our modified friction mixes with a mix scheduled to go down this summer. Our next step is to used the same on OGFC on high speed roads and SMA's at intersections. WE have developed our specs and expertise over the last few years working with the HUDSON Asphalt Co. and the university of Massachusetts at Dartmouth. We are fortunate that we are allowed to try new mixes and binders via our pavement preservation program. Should you need any further info pl feel free to contact me.
SOUTH CAROLINA	Chad Hawkins	HawkinsCW@dot.state.sc.us	No	South Carolina is presently researching and placing a few test sections using recycled tire rubber in hot mix and as a stress absorbing interlayer. Not enough data has been generated to make any conclusions. You may wish to contact Clemson University's Asphalt Rubber Technology Services (ARTS) Center at 864-656-6799 and ask to speak with Ms. Mary Corley or Dr. Serji Amirkhanian. Please let me know if I can be of further assistance.
SOUTH DAKOTA				No Response
TENNESSEE	Brian Egan	Brian.Egan@state.tn.us	No	The Tennessee DOT currently does not use CRM in hot mix applications. We placed 2 HMA concrete projects in 1998 and 3 projects in 1993, but none since.
TEXAS	Magdy Mikhail	MMIKHAI@dot.state.tx.us	Yes	The Texas Department of Transportation uses Asphalt Rubber with seal coats Item 318. We use Asphalt rubber with Permeable Friction Course(PFC) mixes item 342. We also use Asphalt rubber with Stone Matrix asphalt mixtures (SMAR) item 346.
UTAH				No Response
VERMONT	Donald H. Lathrop	Don.Lathrop@state.vt.us	No	The Vermont Agency of Transportation paved two projects with crumb rubber modifier in hot mix in the 1993-1995 time frame. The wet-blend or terminal-blend was used. It has not been used since.

STATE	CONTACT	EMAIL	USE CRM	COMMENTS
VIRGINIA	William R. Bailey III	Bill.Bailey@VirginiaDOT.org	No	Virginia experimented with crumb rubber in asphalt pavements about 10 -12 years ago. This was around the time it was mandated by TEA (Late 80's early 90's). These were research projects. Virginia does not currently use recycled tire rubber or crumb rubber in HMA, microsurfacing, chip seals or stress absorbing layers.
WASHINGTON	Thomas E. Baker	BakerT@wsdot.wa.gov	No	We use performance graded asphalts (PG) that specify performance rather than method. Asphalts modified with crumb rubber can meet the performance specifications; however, we see almost no use due to the inability of crumb rubber modified asphalts to compete on the open market.
WEST VIRGINIA	Roy Capper	rgenthner@dot.state.wv.us , RCAPPER@dot.state.wv.us	No	WV does NOT use any rubber.
WISCONSIN	John Volker	john.volker@dot.state.wi.us	No	We tried various uses some years back but we are not using any at this time. Our specifications allow it use but it has to comply the same tests and qualities as our more conventional mixes.
WYOMING				No Response
ONTARIO, CANADA	Kai Tam	Kai.Tam@mto.gov.on.ca	No	We placed the first two sites using CRM in hot mix in 1980, and constructed further projects between 1990 and 1994 on an experimental basis. Also, we tried crumb rubber mix for the "stress absorbing interlayer" over concrete in the early 80's. We did not used CRM in other applications, and are not currently using CRM in any of our mixes.

Appendix E

USAGE SURVEY RESULTS FOR AZ, CA, FL AND TX

Survey Topics	Arizona	California	Florida	Texas
	Az Dot	Caltrans	Fl Dot	Tx Dot
Scrap Tire Rubber Usage				
Paving applications				
Chip Seals	✓			✓
Stress Absorbing Membranes (SAMI's)			✓	✓
Thin Hot Mix Overlays (<60mm)	✓		✓	✓
Structural Overlays (>60mm)	✓		✓	
In recycled asphalt pavements (RAP mixes)				
Other paving applications				Permeable friction course, Stone matrix asphalt
Transportation applications				
Barrels, Drums				✓
Delineators				✓
Parking stops				
Barricades				✓
Cones				✓
Other transportation applications				Molded rubber products-guard rail spacer blocks, delineator posts, anti-vegetation mats
Other applications				
Tire derived fuel		✓		✓
Embankment fill		✓		✓
Marine structures (reefs)				✓
Lechate fields				
Additional applications				
Scrap Tire Rubber Technology				
Wet Process				
Field Blend	✓		✓	✓
Terminal Blend	✓		✓	✓
Dry Process				
How Much Rubber Modified Hot Mix is Placed Annually				
Construction applications (tons)				
1999	687,900	420,210	1.3mil	82,065
2000	478,500	1,458,799	1.3mil	133,568
2001	451,400	637,272	1.3mil	96,539
2002	450,570	258,806	1.3mil	51,932
2003	480,260	363,060	1.3mil	433,615
Maintenance applications (tons)				
1999	0	0	0	0
2000	0	0	0	0
2001	0	0	0	0
2002	0	0	0	0
2003	0	0	0	0
How Much Rubber Modified Spray Application is Placed Annually				
Construction applications (yd ²)				
1999	0	0	5.3mil	0
2000	0	0	5.3mil	0
2001	0	1,724,800	5.3mil	0
2002	0	718,080	5.3mil	0
2003	0	2,013,440	5.3mil	0
Maintenance applications (yd ²)				
1999	0	0	0	44,208 tons
2000	0	0	0	109,482 tons
2001	0	\$7,322,000.00	0	120,830 tons
2002	0	\$2,276,000.00	0	162,869 tons
2003	0	\$9,482,000.00	0	125,120 tons
Typical Scrap Tire Rubber Content				
Hot mix applications				
% by weight of binder	18.5 (16.7min)	8-22	5-12	8-10
% by dry weight of aggregate (dry process only)				
Spray applications				
% by weight of binder	9	20	20	5 (min)
Typical Range in Cost				
Hot mix (\$/ton)	275.00 (AR-ACFC)		60.00 - 75.00	53.33 - 58.80 (\$53.33 CRM HMA, \$58.80 A-R PFC)
Spray application (\$/yd ²)		4.25	2.00 - 2.25	
Environmental Regulations that Affect the Use of Scrap Tire Rubber				
Organization	No additional regulations			Texas Commission on Env. Quality (TCEQ)
Contact				Blake Stewart (512) 239-6931

Appendix F

LIST AND USAGE QUESTIONNAIRES

6. What is the typical **range in cost** of scrap tire modified

hot mix? _____\$/ton

spray applications? _____\$/yd²

7. If there are ANY **environmental regulations** (eg, air quality, health & safety) that affect the use of scrap tire rubber in paving applications in your state, please provide the name and contact information of the individual who can provide some insight on these regulations:

Name _____ E-Mail _____ Phone/Fax _____

SCRAP TIRE RUBBER – LIST SURVER SURVEY

From: phil_stolarski@dot.ca.gov [mailto:phil_stolarski@dot.ca.gov]

Sent: July 6, 2004 1:40 PM

To:

Cc:

Subject: Question on recycled tire rubber or crumb CRM (CRM)

Has your agency used (or does it currently use) recycled tire rubber or crumb CRM (CRM) in hot mix asphalt concrete, microsurfacing, or spray applications such as chip seals or stress absorbing interlayers? Please respond by July 19.

Thanks

Appendix G

CALTRANS DISTRICT RAC USE

Year	RAC Usage by District (tons)											
	1	2	3	4	5	6	7	8	9	10	11	12
1999	None	None	None	7,960	None	75,450	8,150	None	None	188,700	130,090	9,860
2000	None	99,700	17,540	238,354	10,400	206,100	341,840	62,480	8,000	60,750	375,735	37,900
2001	None	None	48,190	286,450	55,200	10,300	77,332	40,710	None	19,940	29,880	69,270
2002	None	None	53,695	None	None	33,320	48,810	76,700	None	7,460	None	38,821
2003	None	23,616	None	46,530	None	49,190	27,280	19,320	None	10,394	160,110	77,720
Total:	0	123,316	119,425	579,294	65,600	374,360	503,412	199,210	8,000	287,244	695,815	233,571