ASPHALT RUBBER USAGE GUIDE




Prepared by

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

Revised September 30, 2006

ABSTRACT

This Asphalt Rubber Usage Guide is intended for use by Caltrans design, construction, and maintenance managers and engineers, as well as by field personnel involved in placement of asphalt rubber paving materials including hot mixes and surface treatments. The purpose of this Guide is to provide state-of-the-practice information regarding product selection and use, design, production, construction, and quality control and assurance of the asphalt rubber binder, paving materials and spray applications. The intent is to enable Caltrans to optimize the use of asphalt rubber materials to obtain the advertised benefits. This Guide provides an overview of asphalt rubber (AR) materials, components and binder design, and of the benefits and limitations of these materials. This Guide describes the various types of asphalt rubber products available for use in hot mixes and spray (membrane) applications, and presents criteria for selection and use. It also presents information on:

- Mix design criteria,
- Similarities and differences between asphalt rubber and corresponding conventional bituminous applications,
- Cost and environmental considerations related to asphalt rubber materials, and
- Guidelines for construction and inspection considerations for asphalt rubber pavements and surface treatments.

This Guide does not address maintenance, repair, or rehabilitation of asphalt rubber products. Such information can be found in Chapter 600 of the Caltrans Highway Design Manual and in the Caltrans Maintenance Technical Advisory Guide.

DISCLAIMER

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY OF TERMS

Asphalt rubber binder (ARB) – is used 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 2006) asphalt rubber is "a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent 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 binder is prepared using the "wet process". Caltrans specifications for ARB physical properties fall within the ranges listed in ASTM D 6114, "Standard Specification for Asphalt Rubber Binder," also located in Vol. 4.03. Recycled tire rubber is used for the reclaimed rubber and is currently referred to as crumb rubber modifier (CRM). The asphalt cement and CRM are mixed and interacted at elevated temperatures and under high agitation to promote the physical interaction of the asphalt cement and CRM constituents. During ARB production and storage, agitation is required 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 26 inches (660 mm) used on automobiles, pickups, and light trucks.

Crumb rubber modifier (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 rubber modifier – 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 percent natural rubber or isoprene and a minimum of 50 percent 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 percent 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 asphalt cement.

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 6 in.^{2} (0.023 m^2) and smaller prior to granulation or ambient grinding.

CRM PROCESSING EQUIPMENT

Cracker mill – apparatus typically used for ambient grinding, that tears apart scrap tire rubber by passing the material between rotating corrugated steel drums, reducing the size of the rubber to a crumb particle generally No. 4 to No. 40 (4.75 mm to 425 μm) sieve size.

Granulator – apparatus that shears apart the scrap tire rubber, cutting the rubber with revolving steel plates that pass at close tolerance, reducing the rubber to cubicle particles generally 3/8 in. to No. 10 sieve (9.5 mm to 2.0 mm) in size.

Micro-mill – process that further grinds crumb rubber particles to sizes below the No. 40 (425 μm) sieve size.

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

Devulcanized rubber – rubber that has been subjected to treatment 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 ARB to make HMA, and is not recommended for use in interlayers that will be overlaid with HMA 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. The CRM acts as a rubber aggregate in the paving mixture. 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 in. to plus No. 8 (6.3 to 2.36 mm) sieve sizes) to "Ultrafine" minus No. 80 (180 µm) 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 cement. 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 reaction of the asphalt cement and the crumb rubber modifier.

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

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 No. 8 (2.36 mm) 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 HMA and is similar to the gradations used in stone matrix asphalt (SMA), but with relatively low percentages passing the No. 200 (75 µm) 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 cement and CRM when blended together at elevated temperatures which includes swelling of the rubber particles and development of specified physical properties of the asphalt and CRM blend to meet requirements. Although often referred to as reaction, interaction is not a chemical reaction but rather a physical interaction in which the CRM absorbs aromatic oils and light fractions (small volatile or active molecules) from the asphalt cement, and releases some of the similar oils used in rubber compounding into the asphalt cement. The interaction may be more appropriately defined as polymer swell.

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 percent by mass passing the No. 200 (0.075 mm) 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 cement and crumb rubber modifier 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). 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 cement modified with CRM that may include less than 15 percent CRM by mass and thus may not comply with the ASTM definition of asphalt rubber (ASTM D 8, Vol. 4.03). In the past, terminal blends (wet process, no agitation CRM-modified asphalt binders including Modified Binder (MB) materials) 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 3/8 and 1/2-inch (9 and 12 mm) 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 (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.

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.

Terminal blend – See **Wet Process – No Agitation**

Truck tires – tires with an outside diameter greater than 26 inches (660 mm) and less than 60 inches (1520 mm); 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 binder with CRM produced from scrap tire rubber and other components as required before incorporating the binder into the asphalt paving materials. Caltrans requires the use of extender oil and addition of high natural CRM. The wet process requires thorough mixing of the crumb CRM in hot asphalt cement (375ºF to 435ºF, 190ºC to 224ºC) and holding the resulting blend at elevated temperatures (375ºF to 425ºF, 190ºC to 218ºC) for a designated minimum period of time (typically 45 minutes) to permit an interaction between the CRM and asphalt. Caltrans specification requirements include an operating range for rotational viscosity and cone penetration, and minimum values of softening point and resilience,.

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 centipoises (cPs) or 1.5 Pa•sec at 375ºF (190ºC) 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 tire rubber content of the CRM-modified blend. CRM gradations used in the wet process are typically minus No. 10 (2 mm) sieve size or finer. CRM-modified binders with viscosities ≥ 1,500 cPs at 375ºF (190ºC) should be assumed to require agitation.

Wet Process-No Agitation - a form of the wet process where CRM is blended with hot asphalt cement at the refinery or at an asphalt storage and distribution terminal and transported to the HMA mixing plant or job site for use. This type of rubberized asphalt (which includes Rubber Modified Binder, RMB) does not require subsequent agitation to keep the CRM particles evenly dispersed in the modified binder. The term "terminal blend" is often used to describe such materials, although they may also be produced in the field. Therefore, calling them terminal blends is unnecessarily restrictive and the preferred description for this type of binder is "**wet process-no agitation**". Such binders are typically modified with CRM particles finer than the No. 50 (300 µm) 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 ≤ 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 (cPs) or 1.5 Pa•s at 375ºF (190ºC), that is necessary to significantly increase binder contents above those of conventional HMA mixes without excessive drain-down.

Wet Process-High Viscosity - CRM-modified binders that maintain or exceed the minimum rotational viscosity threshold of 1500 cPs at 375ºF (190ºC) 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. Caltrans requires a minimum total CRM content of 18%.

1.0 INTRODUCTION AND OVERVIEW

The purpose of this Usage Guide is to provide the California Department of Transportation (Caltrans) with state-of-the-practice information regarding product selection and use, design, production, construction, and quality control and assurance of asphalt rubber binder, paving materials and spray applications. It also contains some generally accepted best practices for asphalt rubber binder preparation and mixture placement. The intent is to enable Caltrans to optimize the use and handling of asphalt rubber materials in order to obtain the many advertised benefits including increased durability and reduced maintenance.

1.1 WHAT IS ASPHALT RUBBER?

According to the ASTM definition, asphalt rubber (AR) is "a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent 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." Physical property requirements are listed in ASTM D 6114, "Standard Specification for Asphalt Rubber Binder," located in Vol. 4.03 of the Annual Book of ASTM Standards 2006, and in Caltrans Standard Special Provisions for Rubberized Asphalt Concrete (RAC). The asphalt rubber is produced at elevated temperatures (≥ 350°F, 177°C) and under high agitation to promote the physical interaction of the asphalt binder and rubber constituents, and to keep the rubber particles suspended in the blend. Various petroleum distillates or extender oil may be added to reduce viscosity, facilitate spray applications, and promote workability.

Recycled tire rubber is used for the reclaimed rubber and is called crumb rubber modifier (CRM). Tire rubber is a blend of synthetic rubber, natural rubber, carbon black, anti-oxidants, fillers, and extender type oils that is soluble in hot paving grade asphalt.

In California, asphalt rubber is specified to include 18 to 22 percent CRM by total mass of the asphalt rubber blend. The CRM must also include 25 ± 2 percent high natural rubber content scrap rubber by mass of the CRM that may come from scrap tires or other sources. Caltrans requires use of extender oil as an asphalt modifier in asphalt rubber. Caltrans specifications for ARB physical properties fall within the ranges listed in ASTM D 6114.

Asphalt rubber should not be confused with other rubberized asphalt products such as the "dry process" in which crumb rubber is substituted for a small proportion of the aggregate and is not reacted with the asphalt binder prior to mixing, or with "terminal blends" (no agitation CRM-modified binders). Terminal blends are made by the wet process, but historically have included no more than 10 percent ground tire rubber along with other additives. Such low CRM content blends do not achieve sufficient viscosity to perform in HMA mixtures in the same manner as high viscosity ARB. However, new terminal blends with up to 15 percent CRM have been developed. Terminal blends must meet the Caltrans requirements for Rubber Modified Binder (RMB).

Rubberized asphalt concrete (RAC) may be produced using a variety of CRM-modified binders, including asphalt rubber, rubberized terminal blends, RMB materials, or by the dry process. Caltrans uses MB and dry process HMA (RUMAC) mixes on a limited basis. Anecdotal reports indicate a wide range of performance, but relatively little conclusive data is available regarding their performance on rehabilitation projects in the California State Highway System. Both types of mixes have been included as test sections in recent Caltrans projects in order to follow their performance over time and compare with performance of typical Caltrans RAC-G mixes. *Consequently, the information presented in this Usage Guide is limited to asphalt rubber paving materials made with high viscosity ARB and may not be appropriate for other rubber modified binder or dry process materials.*

1.2 BRIEF HISTORY OF ASPHALT RUBBER

Development of asphalt rubber materials for use as joint sealers, patches, and membranes began in the late 1930s**.** In the early 1950s, Lewis and Welborn of the Bureau of Public Roads (BPR) conducted an extensive laboratory study to evaluate "The Effect of Various Rubbers on the Properties of Petroleum Asphalts." They used 14 types of rubber powders and three asphalts, including "a California asphalt of low-gravity, low-sulfur, low-asphaltenes type." The results were published in the October 1954 issue of *Public Roads* along with results of a companion "Laboratory Study of Rubber-Asphalt Paving Mixtures," conducted by Rex and Peck at BPR. The mixtures study looked at a wide range of vulcanized and unvulcanized rubber materials including tread from scrap tires, styrene-butadiene rubber (SBR), natural rubber, polybutadiene, and reclaimed (devulcanized) rubber and at both wet and dry methods of adding them to AC mixtures. Interest and work in this area continued to grow, as did the number of patent applications. In March 1960, the Asphalt Institute held the first Symposium on Rubber in Asphalt in Chicago, IL. It consisted of five paper presentations and discussion.

Charles H. McDonald of the City of Phoenix Arizona worked extensively with asphalt and rubber materials in the 1960s and 1970s and was instrumental in development of the "wet process" (also called the McDonald process) of producing asphalt rubber. He was the first to routinely use asphalt rubber in hot mix patching and surface treatments for repair and maintenance. Asphalt rubber chip seals served effectively as the City's primary pavement maintenance and preservation strategy for arterial roadways for nearly twenty years, until traffic volumes forced a change to thin AC overlays. Gap-graded asphalt rubber concrete mixtures were developed as a successful substitute.

In 1975, Caltrans began experimenting with asphalt rubber chip seals in the laboratory and small test patches located at 03-Yol-84-PM 16+ and 03-Sac-99-PM 20+, with generally favorable results. In 1978, the first Caltrans dry process rubber-modified AC pavement was constructed on SR 50 at Meyers Flat. It included one percent ground rubber by mass added to the dry aggregate prior to mixing with the paving asphalt. Performance was rated good. The first Caltrans rubberized asphalt concrete (RAC) pavements made with early versions of "wet-process" asphalt rubber 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 2.4-inch (0.2 ft, 60 mm) layer of dense-graded HMA to restore structural capacity, under the thin (1.2 inches, 0.1 ft, 30

mm) RAC wearing course. 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 chain abrasion and reflective cracking.

The Ravendale project (02-Las-395) constructed in 1983 significantly changed Caltrans' approach to the use of asphalt rubber. This project presented a typical dilemma. The cost of rehabilitation by overlaying with dense-graded HMA 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 SAMI (4 sections), wet and dry RAC at 1.8 inches (0.15 ft, 46 mm) thick without SAMI (2 sections), four control sections with different thicknesses of dense-graded HMA from 1.8 to 6 inches (46 to 152 mm), two sections surfaced only by double asphalt rubber chip seals, and one section surfaced with a single asphalt rubber chip. The test sections were monitored over time. 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. By 1987, it was clear that the thin RAC pavements were performing better than thicker conventional dense-graded HMA. Caltrans built more RAC projects and continued to study the performance of RAC constructed at reduced thickness relative to dense-graded HMA structural requirements.

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 that ranged from 1 inch (25 mm) for open-graded to 3 inches (75 mm) for RAC-D. Some projects included pavement reinforcing fabric (PRF) and/or a leveling course, and some others included asphalt rubber stress absorbing membrane interlayer (SAMI) under the asphalt rubber mixes.

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 presented structural and reflection crack retardation equivalencies for gap-graded asphalt rubber mixtures (now designated RAC-G) with respect to dense-graded HMA, and with and without SAMI. These equivalencies were considered to be field validated and were incorporated in Chapter 6 (Tables 3 and 4) of the Caltrans Flexible Pavement Rehabilitation Manual (June 2001). Caltrans considered that RAC-G could generally be substituted for dense-graded HMA at about one-half the 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 mixtures.

The Caltrans review indicated that asphalt rubber materials can perform very well when properly designed and constructed, and that Caltrans should continue using and studying asphalt rubber. 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 dense-graded HMA 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 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.

Caltrans was also instrumental in developing specifications for modified binders containing crumb rubber. The Modified Binder (MB) specification was developed in the early 1990s as part of a continuing movement towards performance-based specifications from method type or "recipe" specifications. It has been suggested that the specification be renamed as "RMB," Rubber Modified Binder. 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 mixtures placed over a range of structural sections. These projects were reviewed in 2002 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. However findings to date are limited and use of MB products has been limited to test sections and a warranty project. Heavy vehicle simulator (HVS) trials are being conducted at the University of California Berkeley Richmond Field Station but have not yet been completed.

By mid-2001, over 210 Caltrans RAC projects had been constructed throughout California. 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 continued to arise. Districts 7 and 8 reportedly experienced several major RAC failures.

From 2002 through 2004, Caltrans built five pilot RAC overlay projects through its rehabilitation program that include a 5-year warranty on the RAC materials, workmanship, and performance. Warranty conformance is determined by periodic distress surveys of designated performance evaluation sections. The special provisions list specific distress triggers for repairs. The overall objective of these RAC warranty pilot projects was to provide a "level playing field" for wet process (field-produced high viscosity and terminal blend no agitation CRM-modified asphalt binders) and for dry process (CRM as an aggregate substitute) rubber-modified mixes that contain a minimum of 15% CRM (by total mass of binder). No dry process mixes were bid, and only one project used a terminal blend binder in the mix. Performance evaluations to date indicate the overlays are generally in good condition.

Test sections for CRM-modified paving materials were subsequently incorporated by change order into two Caltrans projects constructed in 2004 and 2005. The primary purpose was to assess relative field and laboratory performance of dense-graded HMA control mixes, gap-graded RAC and RUMAC mixes, and dense- and gap-graded MB mixes. Constructability of the respective types of CRM-modified mixes was also evaluated. Both projects are to be monitored over a 5-year period. Field and lab performance will be compared with findings from the HVS study for similar CRM-modified mixtures.

The Firebaugh project was constructed in 2004 on SR 33 in Fresno County just north of the town of Firebaugh. It included a full-thickness (3.5 inches, 90 mm) control section of conventional dense-graded HMA and eight test sections as follows:

- RAC-G (wet process high viscosity field blend, gap-graded) at full (3.5 inches, 90 mm) and half (1.75 inches, 45 mm) thickness
- RUMAC (dry process, gap-graded) at full (3.5 inches, 90 mm) and half (1.75 inches, 45 mm) thickness
- MB-G (wet process terminal blend, no agitation, gap-graded) at full (3.5 inches, 90 mm) and half (1.75 inches, 45 mm) thickness
- MB-D (wet process terminal blend, no agitation, dense-graded) at full (3.5 inches, 90 mm) and half (1.75 inches, 45 mm) thickness

The District 1 RAC experimental project on State Route 20 in Mendocino County consisted of a control and three test sections:

- Dense-graded HMA Control (4.13 inches,105 mm)
- RAC-G mix (wet process high viscosity field blend, 2.36 inches (60 mm))
- RUMAC-G mix (dry process, 2.36 inches (60(mm))
- MB-D mix (wet process, no agitation terminal blend, 2.36 inches (60 mm))

Emission tests were performed at the District 1 project to determine pollutant emission rates for each mix as requested by the North Coast Mendocino and Lake County Air Quality Management Districts. No problems were reported during mix production or construction.

Research was conducted in 2005 on the structural equivalency of RAC-G to dense-graded HMA. Although reflective cracking was not the subject of the research, the study indicated that the practice of using a reduced RAC-G overlay thickness to retard reflective cracking is still warranted. Limited laboratory test results indicate that the gravel factor (G_f) for RAC-G is similar to but slightly lower than that of dense-graded HMA. Mechanistic-empirical analysis indicates that these two very different types of mixes are structurally similar at thicknesses ranging from 1.2 to 2.4 inches (30 to 60 mm). **Therefore, RAC-G should not be used at half thickness when it is intended to provide a structural equivalent to dense-graded HMA.** The research indicates that as the thickness of RAC-G increases above 2.4 inches (60 mm), the gravel equivalency of RAC-G begins to decrease relative to dense-graded HMA.

These research findings have been adopted by Caltrans. For new construction, Caltrans recommends that RAC-G should not be thicker than 2.4 inches (60 mm) and should be placed on

a layer of conventional HMA rather than directly on an unbound base course. RAC-O should not be thicker than 1.8 inches (45 mm) and should be used only as a surface course. Up to 1.8 inches (45 mm) of RAC-O may be placed on top of 2.4 inches (60 mm) of RAC-G. Also for new construction, the overall pavement thickness may not be reduced when RAC is used (Caltrans, 2006b).

1.3 HOW IS ASPHALT RUBBER USED?

Asphalt rubber is used as a binder in various types of asphalt pavement construction including surface treatments and hot mixes (HMA). It is also used in crack sealants, which are not a subject of this Guide. For hot mixes, asphalt rubber has been found to be most effective and is most commonly used in gap-graded and open-graded mixes, particularly for surface courses and for thin overlays that are 1.2 to 2.4 inches (30 to 60 mm) thick. It may be used in new construction or to rehabilitate an existing pavement Terminal blends and MB have been used in dense- and gap-graded mixes. The most common spray application is a chip seal, also called a stress absorbing membrane (SAM). Chip seals are primarily used for maintenance and pavement preservation. Asphalt rubber chip seals may also be overlaid with hot mix, making them interlayers, typically called SAMI-R. SAMIs are used primarily for pavement rehabilitation. Chapter 2 provides more detailed information on product selection, usage, and design.

1.4 WHERE SHOULD ASPHALT RUBBER PRODUCTS BE USED?

Asphalt rubber products can be used wherever conventional asphalt concrete or bituminous surface treatments would be used, but provide better resistance to reflective cracking and fatigue than standard dense-graded HMA. Asphalt rubber hot mixes are typically most effective as thin rehabilitative overlays of distressed flexible or rigid pavements. Arizona has had well-documented success with long-term performance of asphalt rubber overlays of rigid pavements (I-17 Durango Curve in Phoenix, I-19 near Tucson, I-40 near Flagstaff), but California's experience with this application has been limited.

Caltrans' reflection crack retardation equivalencies for RAC-G generally allow substitution for dense-graded HMA at about one-half the thickness (as referenced in 1.2). The reduced thickness encourages the use of RAC-G mixtures where there are vertical geometric constraints such as curb-and–gutter alignment or underpass clearance.

Temperature is critical for compaction of RAC mixtures. Because asphalt rubber is stiffer than asphalt cement, higher placement and compaction temperatures are usually required. Temperature guidelines for construction operations are presented in Section 4.0. Because RAC-G is placed in thin layers, ambient temperature, pavement surface temperature and wind have considerable impacts on mat temperature during compaction. Asphalt rubber products should thus be used only where and when weather conditions are favorable for placement. This does not prevent their use at high elevations, but means that paving in such locations requires placement practices and temperature requirements tailored to these more demanding conditions. Asphalt rubber products have been used with success in most of the geographical and climate zones in California and Arizona, from low desert through the mountain/alpine climate zones.

However there are coastal areas in California where favorable conditions for asphalt rubber paving operations may not occur often.

1.5 WHERE SHOULD ASPHALT RUBBER PRODUCTS NOT BE USED?

Problems that have been documented typically have been construction issues related to cold temperature paving or late season construction. This indicates that temperature was a major contributing factor. Temperature also affects placement and compaction of conventional mixtures, but is more critical when working with materials that have been modified to increase high temperature stiffness such as asphalt rubber and are typically being placed in thin lifts. Asphalt rubber paving materials should not be placed in the following conditions:

- During cold or rainy weather with ambient or surface temperatures <55°F (13°C).
- Over pavements with severe cracks more than 0.5 inch (12.5 mm) wide.
- Where traffic and deflection data are not available.
  NOTE: Traffic and deflection data are basic requirements for Caltrans structural pavement design and rehabilitation. In some cases it may be necessary to add a layer of dense-graded HMA before overlaying with RAC to provide sufficient pavement structure.
- Areas where considerable handwork is required.
- Where haul distances between AC plant and job site are too long to maintain mixture temperature as required for placement and compaction.

1.6 BENEFITS OF ASPHALT RUBBER

The primary reason for using asphalt rubber is that it provides significantly improved engineering properties over conventional paving grade asphalt. Asphalt rubber binders can be engineered to perform in any type of climate as indicated in ASTM D 6114. Responsible asphalt rubber binder designers usually consider climate conditions and available traffic data in their design to provide a suitable asphalt rubber product. More information on asphalt rubber binder design is presented in Chapter 2.

At intermediate and high temperatures, ARB physical properties are significantly different than those of neat paving grade asphalts such as PG 64-16. The rubber stiffens the binder and increases elasticity (proportion of deformation that is recoverable) over these pavement operating temperature ranges, which decreases pavement temperature susceptibility and improves resistance to permanent deformation (rutting) and fatigue with little effect on cold temperature properties. The benefits of asphalt rubber are summarized in Table 1-1.

Table 1-1 Summary of Benefits of Asphalt Rubber Paving Materials

ARB has:

- Increased viscosity that allows greater film thickness in paving mixes without excessive drain down or bleeding.
- Increased elasticity and resilience at high temperatures.

RAC pavements have:

- Improved durability.
- Improved resistance to surface initiated and fatigue/reflection cracking due to higher binder contents and elasticity.
- Reduced temperature susceptibility.
- Improved aging and oxidation resistance due to higher binder contents, thicker binder films, and anti-oxidants in the tire rubber.
- Improved resistance to rutting (permanent deformation) due to higher viscosity, softening points and resilience (stiffer, more elastic binder at high temperatures).
- Lower pavement maintenance costs due to improved pavement durability and performance.

In addition, RAC and asphalt rubber binders can result in:

- Reduced construction times due to thinner lifts.
- Better chip retention in chip seals due to thick films of highly modified asphalt.
- Improved safety due to better long-term color contrast for pavement markings because carbon black in the rubber acts as a pigment that keeps the pavement blacker longer.
- Savings in energy and natural resources by using waste products.

1.7 LIMITATIONS OF ASPHALT RUBBER

Asphalt rubber materials are useful, but they are not the solution to all pavement problems. The asphalt rubber materials must be properly selected, designed, produced, and constructed to provide the desired improvements to pavement performance. Pavement structure and drainage must also be adequate. Limitations on the use of asphalt rubber include:

- Higher unit costs due to mobilization of asphalt rubber production equipment. For large projects, these unit costs can be spread over enough tonnage so that they can generally be offset by increased service life, lower maintenance costs, and reduced lift thickness. For small projects, mobilization cost is the same, resulting in relatively high unit prices because mobilization costs may not be fully offset.

- Asphalt rubber is not best suited for use in dense-graded HMA. There is not enough void space in the dense-graded aggregate matrix to accommodate sufficient ARB content to enhance performance of dense-graded mixes enough to justify the added cost of the ARB.
- Construction may be more challenging, as temperature requirements are more critical. Asphalt rubber materials must be compacted at higher temperatures than dense-graded HMA because, like polymers, rubber stiffens the binders at high temperatures. Also, coarse gap-graded mixtures may be more resistant to compaction due to the stone-on-stone nature of the aggregate structure.
- Potential odor (see 1.9 for further information).
- If work is delayed more than 48 hours after blending the asphalt rubber, some binders may not be usable. The reason is that the CRM has been digested to such an extent that it is not possible to achieve the minimum specified viscosity even if more CRM is added in accordance with specified limits.
- For chip seals in remote locations, hot and/or pre-coated aggregate may not be available because there may not be a hot-mix plant within reasonable haul distance of the job site.

1.8 COST CONSIDERATIONS

The unit costs of asphalt rubber products are typically higher than those of conventional or polymer modified products. The initial cost is one of the reasons that usage of asphalt rubber hot mixes has been limited to thin lifts, but costs of hot mixes are now converging. Asphalt rubber is generally cost effective when used as thin gap- or open-graded surface courses or overlays of 1.2 to 2.4 inches (30 to 60 mm) compacted thickness, chip seals and interlayer applications.

Asphalt rubber products have been proven to be very useful tools to rehabilitate severely deteriorated pavements with some remaining structural integrity that experience heavy traffic loadings. In many cases, the reduced thickness of RAC overlays (half of dense-graded HMA thickness, with 1.2 inch (30 mm) minimum) offsets much of the increase in initial cost. The added benefits of reduced maintenance demand and longer service life provided by asphalt rubber materials generally offset any remaining cost difference. Using a SAMI-R in place of a layer of HMA or RAC can also save money and speed construction, and provide additional savings.

Cost effectiveness should be evaluated using Life Cycle Cost Analysis (LCCA), for which Caltrans has developed a procedure for implementation in 2006. It includes typical maintenance and rehabilitation (M&R) schedules for California by climate region (coastal, valley, low/high desert, low/high mountain), District, surface type, and M&R treatment design life. It also includes construction unit costs for various rehabilitation strategies.

Costs of construction materials and petroleum products have increased since the year 2000 as illustrated in Table 1-2. The Caltrans Contract Cost Data Summary is the source of the cost data for binders and hot mixes for 2004 and 2005. Caltrans Maintenance provided current costs for chip seals and thin overlays in terms of dollars per lane mile, which have been converted to dollars per square yard.

Table 1-2 Caltrans Cost Data

Item Description	Year		
CALTRANS CONSTRUCTION ITEMS	**2000**	**2004**	**2005**
Conventional Type A HMA (dense-graded), $/ton	30-34	50-64	61-78
Conventional HMA (open-graded), $/ton		44-61	73-74
Polymer Modified HMA(dense-graded), $/ton	34-40		
Polymer Modified HMA(open-graded), $/ton		63	71
RAC-G, $/ton	44-50	53-65	73-76
RAC-O, $/ton		64-67	69-78
CALTRANS MAINTENANCE ITEMS			
Chip Seals			
Emulsion Chip Seal, $/yard^2	1.20-1.50		---
Polymer Modified Emulsion Chip Seal, $/yard^2	1.50-1.80		2.55-3.40
Asphalt Rubber Chip Seal, $/yard^2	3.00-3.60		9.25
Thin Overlays			
Conventional HMA (dense-graded), $/yard^2			6.40
Polymer Modified HMA, $/yard^2			7.10-9.25
RAC-O, RAC-G, $/yard^2			8.50
RAC-O-HB, $/yard^2			9.25

The difference in costs of RAC hot mixes compared to conventional HMA and polymer-modified HMA dropped somewhat in 2004 and 2005 from the customary difference of about $16/tonne. It is not clear if this is a function of job size, more routine use of RAC, or higher costs of other materials and products.

In 1998 Caltrans conducted an analysis of RAC and dense-graded HMA unit prices versus mix quantity based on data from 1996 and 1997 Caltrans projects. The results were reported in a July 7 memorandum that indicated that unit costs escalate considerably for jobs with less than 2,500 tons (2250 tonnes) of RAC. Mobilization and set up of the asphalt rubber binder production equipment cost as much for small jobs as for big ones, but large projects spread mobilization costs over more RAC tonnage. The memo suggests that smaller RAC projects may not be cost effective with respect to initial cost. Although the break point for project size may have changed since then, unit costs of small projects (three days RAC paving or less) should be evaluated by LCCA during the design phase.

The costs of RAC-O and RAC-O (HB) overlays are higher than conventional OGAC because of the asphalt rubber binder content is 1.2 to 1.6 times higher than for conventional AR-4000 or PG binders. Since open-graded mixtures are not considered as structural elements, there is no reduction in thickness compared to conventional. However, improved durability, particularly resistance to reflective cracking and related reduced maintenance needs, should substantially reduce the overall life cycle costs and help offset the difference in initial cost.

1.9 ENVIRONMENTAL CONSIDERATIONS

1.9.1 Benefits

There are a number of social benefits of using rubber that is ground from recycled scrap tires to build pavements.

1.9.1.1 Not Contributing to Tire Stockpiles. The primary benefit is putting newly generated waste tires into a secondary use instead of contributing to tire stockpiles. The California Integrated Waste Management Board (CIWMB) stated in its 2004 Staff Report that over 40 million reusable and waste tires are generated in California and approximately 2 million more waste tires are imported into the State each year, of which about 75% (30 million) are recycled. This yields a surplus of about 10 million tires per year and does not account for tires that have been stockpiled legally or otherwise in the past, although CIWMB reports that stockpiles have been substantially reduced. CIWMB reported in 2004 that "Over the past few years, California has used nearly ten million waste tires in RAC paving projects, saving them from disposal."

1.9.1.2 Value-Added Use of Waste Tires. Burning waste tires for fuel is an effective method of disposal that helps to conserve other energy resources, but the value of the rubber is consumed while disposal of incinerator ash and residues remains an issue. Asphalt rubber paving products provide a "value-added" means of reutilizing the waste rubber material. The rubber enhances the physical properties of the resulting paving materials over the life of the pavement, and thus provides a long-term benefit to tax payers and the motoring public. Estimates indicate that RAC-G uses about 1,000 tires per lane mile per 1-inch (≈ 620 tires per lane kilometer per 25 mm) of thickness.

1.9.1.3 Noise Abatement. 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, Netherlands), Canada, Arizona (Quiet Pavements Program), and California (Orange, Los Angeles and Sacramento Counties). Significant reductions in traffic noise, ranging from 40 to 88 percent, have been measured not only for open-graded but also for gap-graded RAC. However there are unanswered questions about how long the noise abatement would continue. The Sacramento County Department of Environmental Review and Assessment and a consultant specializing in acoustics and noise control conducted a six-year study on RAC pavements that was finished in 1999. Their results supported the findings of other similar studies referenced within their report. The Sacramento study showed that the RAC continued to keep the traffic noise level down after six years, while noise measured on the conventional dense-graded HMA was back up to pre-paving levels within four years. California and Arizona are participating in a 10-year FHWA project to study noise levels of a variety of pavements including RAC-G, RAC-O, and RAC-O-HB.

1.9.2 Emissions

The high temperatures and the highly aromatic extender oils involved in asphalt rubber binder and mixture production would be expected to increase the amount of emissions (fumes and smoke) generated by production and construction of asphalt products. This is not necessarily true as evidenced by a number of emissions studies that have been performed during the last 20

years. Study results generally indicate little if any difference from emissions of conventional HMA materials, and no identifiable increase in risk to health or safety of hot plant or paving personnel or the public.

However, the distinctive odor of asphalt rubber continues to trigger concerns about emissions, because people have a natural tendency to think that strong odors indicate a hazard.

1.9.2.1 Hot Plant Tests. Plant "stack tests" were performed during asphalt rubber hot mix production in New Jersey (1994), Michigan (1994), Texas (1995), and California (1994 and Bay Area in 2001). The results generally indicate that emissions measured during asphalt rubber production at HMA plants remain about the same as for conventional hot mix and that amounts of any hazardous components and particulates remain below mandated limits. The Bay Area emissions tests showed that measured emissions rates of particulate and toxic compounds were consistently lower than the EPA's AP-42 emission factors for conventional HMA plants. Raising HMA plant operating temperatures typically increases emissions. Plant emissions generally appear to be more directly influenced by plant operating temperature, burner fuel and the base asphalt cement than by CRM.

CRM does not include exotic chemicals that present any new health risks when mixed with asphalt cement or asphalt concrete. It consists mostly of various types of rubber and other hydrocarbons, carbon black, oils, and inert fillers. Most of the chemical compounds in CRM are also present in asphalt cement, although the proportions are likely to differ.

The asphalt rubber binder manufacturing plant does require an air quality permit, but emissions levels are low due to the essentially sealed nature of the process. Only some minimal filtered venting is required.

1.9.2.2 Exposure of Paving Personnel. Use of asphalt rubber does not appear to increase health risks to paving personnel, including paver operators, screed person, rakers, roller operators, bootmen on distributor trucks, and other workers. A 2-1/2 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, before fume exhaust capture and ventilation 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 the results "clearly demonstrated that risks associated with the use of asphalt rubber products were negligible". "Emission exposures in asphalt rubber operations did not differ from those of conventional asphalt operations".

The National Institute for Occupational Safety and Health (NIOSH) in cooperation with FHWA has performed evaluations of possible differences in the occupational exposures and potential health effects of crumb rubber modified hot mixes and conventional AC mixes. NIOSH Health Hazard Evaluations were performed at seven paving projects located in Michigan, Indiana, Florida, Arizona, Massachusetts, and at two in California from 1994 through 1997. 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. These reports

indicated that increasing operating temperatures of AC plants seemed to have a greater effect on emissions quantity and content than did adding CRM. However the December 2000 NIOSH report on Health Effects of Occupational Exposure to Asphalt (No. 2001-110) that references these seven projects does not present any of the findings for asphalt mixtures containing CRM. This latest 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.

Additional information on studies related to asphalt rubber emissions and worker health and safety is compiled in the Caltrans report "Use of Scrap Tire Rubber State of the Technology and Best Practices," dated February 8, 2005. This report is posted on the Caltrans website for Materials Engineering and Testing Services (METS) and can be downloaded.

2.0 ASPHALT RUBBER PRODUCT DESIGN, SELECTION, AND USE

Asphalt rubber binders can be used in hot mixes and for spray applications as surfaces or interlayers. To aid evaluation of project submittals including asphalt rubber binder designs and quality control plans for binder production, this chapter summarizes the state-of–the–practice of asphalt rubber binder design. It also presents guidance to assist project and pavement designers with selecting the appropriate type of high-viscosity (field blend) asphalt rubber product for the intended use, for maintenance, rehabilitation, or construction.

2.1 ASPHALT RUBBER BINDER (ARB) DESIGN

Asphalt rubber binders must be properly designed and produced to comply with specifications and provide a quality product suitable for the expected climate and traffic conditions. Individual components that comply with specifications may be combined and interacted in proportions that also fully comply, but may yield a binder that is not usable. The interaction between asphalt cement and CRM materials is material-specific and depends on a number of factors, including:

- Asphalt Cement Source and Grade
- Rubber Type
- Rubber Source
- Amount of Rubber
- Gradation of Rubber
- Interaction Time
- Interaction Temperature

Therefore, an appropriate asphalt rubber binder design must be developed using the designated source and grade of asphalt, asphalt modifier (extender oil), and CRM materials (scrap tire and high natural) that will be used for the subject project(s).

Caltrans Standard Special Provisions (SSPs) for asphalt rubber binder require that at least 2 weeks prior to start of construction the Contractor must supply to the Engineer, for approval, an asphalt rubber binder formulation (design or "recipe") that includes results of specified physical property tests, along with samples of all of the component materials. Samples of the prepared asphalt rubber binder must also be submitted to the Engineer at least 2 weeks before it is scheduled for use on the project.

2.1.1 Caltrans Specification Requirements

Caltrans SSPs for ARB and rubberized asphalt concrete (RAC) mixes are currently being updated to reflect implementation of the performance graded (PG) asphalt binder system and will be incorporated into Section 39 of the Standard Specifications. This section discusses current SSP requirements and recommended changes developed by a Caltrans-Industry working group.

For each project, a detailed review of the special provisions and other contract documents is recommended to assure compliance with the project requirements.

The Aged Residue (AR) system of asphalt binder grading is being replaced by the performance graded (PG) system. AR-4000 will no longer be specified as the base asphalt cement for asphalt rubber binders. Instead, PG 58-22 is specified as the base asphalt cement for use in asphalt rubber binders for the high mountain and high desert climate areas where resistance to cold temperature cracking is critical to long term performance. A stiffer grade, PG 64-16, is specified for use in asphalt rubber in the rest of California (coastal, valley, low or southern mountains, low desert). PG asphalt has been proven capable of making good quality asphalt rubber binders in Arizona, Texas, Florida, and other locations. The change in grading systems should not present any major obstacles to asphalt rubber binder design. However, the base asphalt cement shall not be polymer-modified.

The current specifications for Asphalt Rubber Binder call for 20 ± 2 percent crumb rubber modifier (CRM) content by total binder mass. The CRM must include 25 ± 2 percent by mass of high natural rubber CRM and 75 ± 2 percent scrap tire CRM. No changes have been recommended to the types of CRM or relative proportions thereof. The scrap tire CRM consists primarily of No. 10 to No. 30 sized particles (2 mm to 600 μm sieve sizes). The high natural rubber CRM is somewhat finer, mostly No. 16 to No. 50 (1.18 mm to 300 μm sieve sizes).

The extender oil dosage for chip seals will remain at a range of 2.5 to 6 percent by mass of the asphalt cement. However, the minimum extender oil content for use in RAC mixes may be reduced to one percent to minimize potential for flushing and bleeding for hot climate, high traffic index (TI) locations.

Extender oils and high natural CRM are used to enhance the asphalt rubber interaction. Extender oils act as “compatibilizing” agents for the asphalt rubber interaction by supplying light fractions (aromatics, small molecules) that swell the rubber particles and help disperse them in the asphalt. High natural CRM has also been found to aid chip retention in chip seal applications, even at concentrations as low as 3 percent by asphalt rubber binder mass. Use of high natural CRM appears to improve the bond between cover aggregate and the asphalt rubber membrane.

It is important to understand that just mixing together proportions of arbitrarily selected asphalt, CRM and extender oil components within the specified ranges will not necessarily yield a binder that complies with the physical property requirements in the special provisions. Properties of asphalt rubber binders depend directly on the composition, compatibility and relative proportions of the component materials, as well as on the interaction temperature and duration. There are many combinations of suitable materials within the recipe proportions that simply do not provide an appropriate or even usable asphalt rubber binder. That is why binder design and testing procedures are essential to develop satisfactory asphalt rubber formulations.

2.1.2 Design Considerations

Most high viscosity asphalt rubber binders are produced in the field just prior to use, but may be stored at elevated temperatures for 24 hours or more if construction is delayed. It is important that the ARB properties, particularly the primary field control of viscosity, remain in compliance with specifications when mixed with aggregate or spray-applied. It is desirable for the asphalt rubber binder properties to remain relatively stable over time. Uniformity of binder properties also facilitates RAC production, placement and compaction operations. For this reason, some contractors prefer that the different asphalt rubber binders that they use be formulated to remain within a relatively narrow viscosity range, such as 2,000 to 3,000 cPs, so that other critical construction operations can be performed in a consistent manner from job to job.

Careful consideration should be given to the amount of extender oil included in the asphalt rubber binder. Although it is used for other purposes, extender oil also softens most asphalt cement materials to some extent while the CRM acts to stiffen the binder. The high-temperature stiffening effects of CRM do have limits, and in some low desert regions it is not unusual for exposed AC pavement temperatures to reach 180°F (82°C). In such cases, consideration should be given to limiting the amount of extender oil used. Conversely, extender oil dosage may be increased for locations where cold temperature performance, i.e. resistance to thermal cracking, is the issue. It might also be appropriate to increase extender oil content (within limits) for asphalt rubber binders for low volume roadways, where cracks are not exposed to the kneading action of tires and experience little healing from traffic.

Established asphalt rubber industry best practices for laboratory binder design develop a profile of the asphalt rubber interaction over a period of 24 hours by measuring the physical properties of the asphalt rubber binder sampled at specific time intervals. The current specification allows compliance to be documented with test results of one set of samples taken after 45 minutes of interaction.

Therefore, one of the most important changes to the asphalt rubber binder specifications requires that the binder design includes testing to develop and present a design profile of each specification property value measured at intervals over a 24-hour interaction period. The design profile indicates the compatibility of the components and the quality and stability of the resulting ARB properties over time.

The profile will include, at a minimum, results of specification compliance tests after an initial interaction period of 45 minutes, 4 hours later, and simulated over night cool down and reheat. Viscosity should also be measured and recorded at 2 and 3 hours after addition of the CRM to identify the expected trends for field production. Cool down is simulated by reducing oven temperature to 275ºF (135ºC) for a period of approximately 16 hours starting at 6 hours after CRM addition and ending 22 hours after CRM addition. After the cool down, the ARB is reheated to the appropriate temperature for viscosity testing (375ºF, 190ºC) at the end of the 24-hour interaction period.

Table 2-1 presents an example of a state-of–the-practice asphalt rubber binder design profile. Please note that this is one example and other interactions may follow very different patterns.

The asphalt rubber design profile is based on laboratory testing of the specific sources and grades of asphalt, asphalt modifier, and CRM identified for use in asphalt rubber binder production for specific project(s). The design profile must identify the specific component materials (source or supplier and grade) and proportions thereof used in the design and it does not apply to any combinations of different component materials. Due to differences between laboratory and field production, the ARB design profile shall serve only as a guide to indicate expected trends in asphalt rubber viscosity during asphalt rubber binder production and shall not be interpreted as a specification.

Table 2-1 Example Asphalt Rubber Binder Design Profile

Test Performed	**Minutes of Reaction**					**45 minutes Specification Limits*** **
	45	**90**	**240**	**360**	**1,440**	
Viscosity, Haake at 190°C, Pa·s, (10^{-3}), or cP (*See Note)	2400	2800	2800	2800	2100	1500 – 4000
Resilience at 25°C, % Rebound (ASTM D5329)**	27	--	33	--	23	18 Minimum
Ring & Ball Softening Point, °C (ASTM D36)	59.0	59.5	59.5	60.0	58.5	52 – 74
Cone Pen. at 25°C, 150g, 5 sec., 1/10 mm (ASTM D217)	39	--	46	--	50	25 – 70

Notes regarding specified test procedures for Asphalt Rubber Binder

* *The viscosity test shall be conducted using a hand-held Haake viscometer ….or equivalent.*
** *ASTM D 5329 has replaced ASTM D3407*
*** *Per Caltrans specifications as of September 2006*

2.1.3 Design Procedure and Criteria

Because asphalt rubber interactions are highly material-specific, the first step an asphalt rubber producer must take in the design process is to obtain samples of the base asphalt binder (unmodified PG 58-22 or PG 64-16 depending on project location), CRM, and any other additives that will be used for the subject project(s). Use of extender oil and high natural CRM can help compensate for variability in the other components to some extent, but changes in source or grade of the asphalt cement or CRM can have major impacts on binder properties and would require a new design.

The ARB designer blends trial proportions of the designated components within specification requirements, based on practical experience. The asphalt rubber interaction is then conducted at the specified temperature. Samples of the asphalt rubber binder are taken after various intervals of interaction time as shown in Table 2-1 and tested for specification compliance. This provides a profile of how the asphalt rubber properties behave over time and a reasonable indicator of what to expect during field production, though field data may vary from the lab design. If results of the first trial are not adequate, additional interactions are performed as needed.

Caltrans has specified ranges of particular physical properties for asphalt rubber binders that are indicators of the relative amount of modification achieved by CRM interaction. The properties are rotational viscosity, resilience, ring-and-ball softening point, and cone penetration. The specification limits are shown in Table 2-1.

Viscosity and resilience are the most meaningful indicators of asphalt rubber field performance and are expected to vary as the asphalt rubber interaction proceeds. Viscosity should remain above the minimum 1,500 cPs value throughout the interaction and should not manifest drastic drops. There is no maximum value for resilience. High resilience typically indicates that the binder should perform well in resisting fatigue and reflective cracking. Submittal of the high viscosity binder design profile should be required for both hot mix and spray applications.

Best practice indicates that the asphalt rubber interaction properties (particularly softening point and resilience) should be examined to evaluate whether the extender oil content is appropriate for project environmental and traffic conditions. ASTM D 6114, "Standard Specification for Asphalt Rubber Binder," lists three types of asphalt rubber binder with varying limits on softening point and resilience. The Appendix provides corresponding suggested climate guidelines for type selection that may be used as a reference for such evaluation. Hot, moderate, and cold climate ranges are defined in terms of average monthly minimum and maximum temperatures. Some states have specified asphalt rubber properties based on climate and/or traffic considerations.

2.2 RUBBERIZED ASPHALT CONCRETE (RAC) HOT MIXES

Use of asphalt rubber in hot mixes is typically limited to gap and open gradations because these are most effective with respect to performance and cost. Use of high viscosity (field blend) asphalt rubber binder is not recommended in dense-graded mixtures because there is insufficient void space to accommodate enough of the high viscosity asphalt rubber binder to significantly improve performance of the resulting pavement. However dense gradations are well suited for use with terminal blend (no agitation) binders such as Caltrans MB, and should provide similar structural capacity to conventional dense-graded HMA mixes.

Gap and open-graded RAC mixes are most often used as overlays for maintenance and/or rehabilitation of existing asphalt concrete and portland cement concrete pavements. RAC is also used as surface (wearing) courses for new pavement construction, most often in areas where traffic noise is a consideration. Structural design is performed as for conventional dense-graded HMA pavements. Thickness reductions for resistance to reflective cracking may be applied when gap-graded asphalt rubber surface courses are substituted for dense-graded HMA for use as an overlay of structurally adequate pavement.

According to Section 631.3 of the recently updated Caltrans Highway Design Manual, "When all factors (including cost) are the same, RAC should be used as a preferred material for surface layer instead of HMA."

2.2.1 Gap-Graded Hot Mix

The most commonly used asphalt rubber product in California is gap-graded rubberized asphalt concrete (RAC-G) hot mix. RAC-G acts as a structural layer in the pavement and is most

effective at compacted thicknesses ranging from 1.2 inches (30 mm) to 2.4 inches (60 mm) according to recent structural analysis and modeling. This supports and corresponds to current practice based on empirical experience and economic considerations.

Should an increase in structural capacity greater than 2.4 inches of RAC-G be required, an intermediate layer of dense-graded HMA should be placed first to provide sufficient total pavement thickness. The pavement deflection study determines the structural requirements, which the designer uses to develop alternative structural sections for LCCA.

2.2.1.1 Purpose of RAC-G. RAC-G mixes provide a durable, flexible pavement surface with increased resistance to reflective cracking, rutting and oxidation, good surface friction characteristics due to the texture provided by the gapped aggregate grading, and often reduced traffic noise. RAC-G acts as a structural layer in the pavement.

2.2.1.2 Appropriate Use. RAC-G can be used for overlay or new construction for a wide range of traffic volumes and loadings. RAC-G can also be used in urban areas where there is considerable stop-and-go traffic for which open-graded mixes would not be suitable. Such areas include numerous signalized intersections and driveways. However, RAC-G mixtures are not recommended for parking areas as the surface of these low modulus mixes are likely to scuff when subjected to simultaneous low speed braking and turning movements that are typical in such areas.

2.2.1.3 RAC-G Overlay Thickness Design. Current Caltrans rehabilitation policy is to design an overlay so as to extend the service life of the pavement for ten years, although other design periods can be used. Overlay thickness design is based on the Traffic Index (TI) for the design period and the following three items:

- Structural adequacy upgrade;
- Reflective crack retardation; and
- Ride quality improvement.

Designing a RAC-G overlay involves determining the overlay thickness for a conventional dense-graded HMA overlay based on measured pavement deflection and traffic, then adjusting the thickness according to structural equivalencies between dense-graded HMA and RAC-G. Thickness of dense-graded HMA needed to retard reflective cracking and to restore ride are also evaluated. Reductions to RAC thickness are made when reflective cracking is the primary distress mode in the existing pavement.

Recent research from a limited laboratory test indicates that RAC-G has a gravel factor similar to conventional HMA but slightly lower. For purely structural considerations, RAC-G may be considered equivalent to conventional HMA up to a thickness of about 2.4 inches (60 mm). Mechanistic-empirical (M-E) structural models indicate that RAC-G is most effective when used as a thin surface overlay less than 2.4 inches (60 mm) and use as lower layers in a pavement system provides no added benefit.

2.2.1.4 RAC Overlay Systems. RAC overlays may also be placed as two- and three-layer systems, surfaced with either gap- or open-graded RAC. A two-layer system is typically RAC

placed directly on a SAMI-R which provides additional resistance to reflective cracking. When a leveling course (typically HMA) is placed prior to application of the SAMI-R, a three-layer system is created as shown in Figure 2-1. A finished RAC-G pavement is shown in Figure 2-2.

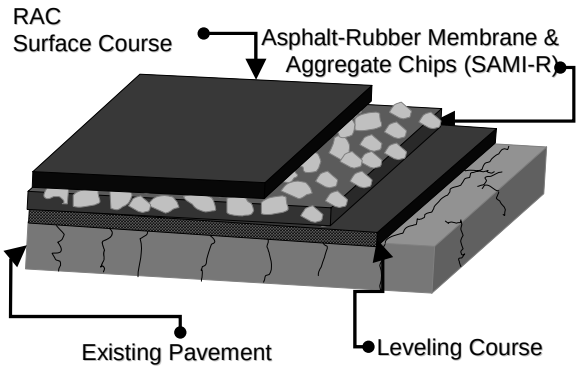

Figure 2-1 Three-Layer System

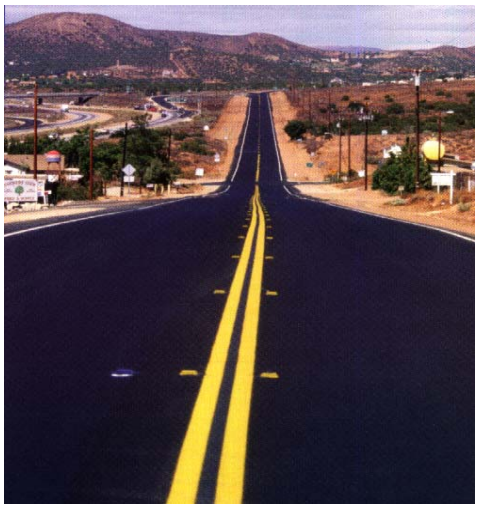

Figure 2-2 Finished RAC-G Pavement

2.2.1.5 RAC-G Mixture Design. Existing California Tests, including CT 367 with Hveem compaction, are used with some modifications as indicated in the updated specifications for RAC-G. These include allowances for lower Hveem stability (minimum 23), requirements for voids in mineral aggregate (VMA) of 18 to 23 percent and a significantly higher binder content than conventional HMA with a minimum requirement of 7.0 percent by mass of dry aggregate. Air voids content requirements are similar to dense graded HMA, and are specified within a range of 3.0 to 5.0 percent based on climate and traffic. Typical mix designs target 4.0 percent air voids. For locations with heavy truck traffic (high TI values) and/or high ambient temperatures, target design air void content should be increased to 5.0 percent to enhance resistance to bleeding and rutting. For rural highways with relatively little traffic, design air void

content may be reduced to between 3.0 and 4.0 percent to enhance durability. Recommended modifications to the RAC-G mix design method include using the average of test results for three briquettes at each binder content, use of Caltrans Laboratory Procedures for volumetric calculations, and reporting voids filled and dust proportion for information.

2.2.2 Open-Graded Hot Mix

Open-graded asphalt concrete (OGAC) pavements provide good surface frictional characteristics. OGAC is also called open-graded friction course (OGFC), and is essentially a hot mix version of a chip seal. OGFC pavements are intended to be free draining so that surface water can quickly travel through the mat to drain out along the edges of the pavement structure. This reduces splash, spray, and hydroplaning during and immediately after rains and thus improves visibility and safety. Conventional OGFC also reduces traffic noise, although reports of long term effectiveness of the reduction vary. Open-graded RAC mixes are designated as RAC-O and RAC-O-HB (High Binder).

Caltrans has used asphalt rubber open graded mixes (RAC–O and RAC-O-HB) primarily as maintenance blankets and as overlays for rehabilitation to restore surface friction. These mixes are highly resistant to reflection of cracks and joints in PCC pavements, and to reflection of severe cracks from underlying AC pavements. RAC-O may be considered one of the "new generation" friction course materials that use highly modified binders to address performance and durability issues of conventional open-graded asphalt concrete, but RAC-O has been in use much longer.

The thicker film coating of the high viscosity ARB increases durability of open-graded pavements. One of the reasons that RAC-O mixtures are durable is that these are relatively low modulus materials, which means that they have lower stress to strain ratios than stiffer materials like dense-graded HMA. They move more in response to the same level of loading, and function by flexing and recovering (relaxing, creeping, rebounding, etc.) rather than by being stiff like HMA. The high asphalt rubber binder contents render these materials very resilient and resistant to fatigue, but they are not stiff layers and are typically placed as thin lifts about 1 to 1.2 inches (24 to 30 mm) thick. Neither RAC-O nor RAC-O (HB) is considered to be a structural element; these materials are considered to be sacrificial and no thickness reduction is applied.

Caltrans continues to evaluate RAC-O-HB which uses higher asphalt rubber binder contents of 8 to 10 percent by mass of dry aggregate. Extensive experience in Arizona has shown that asphalt-rubber binder contents can be increased to 10 percent or more by mass of dry aggregate without excessive drain-off because of the high viscosity of the asphalt rubber binder. Such rich open-graded mixtures have generally provided excellent performance in a variety of climate zones in Arizona, where they are placed at a nominal compacted thickness of ½-inch over asphalt concrete pavements and 1-inch thick over portland cement concrete (PCC) pavements. Although the high binder content mixes are not as free draining as RAC-O, the thicker film coating of the ARB provides improved resistance to fatigue and reflective cracking, as well as to stripping and oxidative aging. These factors increase the durability of open-graded pavements.

2.2.2.1 Advantages of RAC-O. These include:

- The thicker asphalt rubber binder film provides improved resistance to stripping and oxidative aging.
- RAC-O mixes are highly resistant to reflection of cracks and joints in PCC pavements, and to reflection of severe cracks from underlying HMA pavements.
- Reduced traffic noise. Noise reduction over time is currently being studied by Caltrans, Arizona DOT, and the Federal Highway Administration (FHWA).

2.2.2.2 Purpose. The primary reasons for using RAC-O include:

- Provide a durable, highly flexible pavement surface with enhanced drainage and frictional characteristics
- Reduce splash and spray to improve visibility during wet weather
- Reduce hydroplaning in wet conditions to reduce potential for skidding (see Figure 2-3)
- Provide increased resistance to reflective cracking and oxidation
- Provide a smooth ride
- Use as an alternative to chip sealing because hot mixes are less sensitive to construction operations and essentially eliminate threat of windshield breakage

2.2.2.3 Appropriate Use. RAC-O is a surface course (for overlay or new construction) for roadways where traffic flow is essentially uninterrupted by signalization, such as some freeways, rural and secondary highways. It is highly effective as an overlay of PCC and HMA pavements in locations where potential for reflection of joints and/or cracks is severe. RAC-O is also used as a maintenance blanket to restore surface frictional characteristics and to help preserve the underlying pavement. Caltrans does not use RAC-O in snow country due to concerns about possible damage from tire chains and snowplows.

According to the Caltrans April 24, 2006 Memorandum on Use of RAC, RAC-O may also be used as a surface for new HMA pavement construction at a maximum thickness of 1.75 inches (45 mm), and may be placed directly on up to 2.4 inches (60 mm) of RAC-G. According to the Draft Caltrans OGFC Usage Guide, November, 2005, Caltrans has also placed thin overlays of RAC-O and RAC-O-HB directly on portland cement concrete pavement (PCCP) and these pilot projects are reportedly performing well.

Use of RAC-O-HB has been limited to date, but may increase in the future. While the higher binder content of the RAC-O-HB improves durability, it also makes the resulting pavement surface less free draining than RAC-O. Therefore, RAC-O-HB is best used where resistance to reflective cracking is most critical.

Open graded mixes should not be used where there is a significant amount of stop and go traffic or turning vehicles, such as city streets or in parking lots, because the porous low modulus pavement is susceptible to damage from leaking vehicle fluids and to tire scuffs from simultaneous braking and turning motions.

Figure 2-3 Free-Draining RAC-O Next To Dense-Graded HMA

2.2.2.4 RAC-O Mixture Design. Mixture design is performed according to California Test 368, with asphalt rubber binder content set at 1.2 times the optimum PG binder content with a check test for drain off. RAC-O-HB is designed according to the same procedure, but the multiplier for asphalt rubber binder content is increased to 1.6. If long hauls are anticipated, drain off should also be checked for the expected haul time. If excessive, adjustments may be required. For long hauls, reducing mixture temperature for hauling may not be appropriate for complying with minimum requirements for placement temperature.

2.3 ASPHALT RUBBER SPRAY APPLICATIONS

Asphalt rubber spray applications may be used as surface treatments or interlayers. Such applications are typically used for maintenance or rehabilitation of existing pavements, and are very effective at resisting reflective cracking.

2.3.1 Chip Seals (SAMs)

Chip seals are used by Caltrans for preventative and corrective maintenance to:

- Correct surface deficiencies.
- Seal raveled pavement surfaces.
- Seal off and protect the pavement structure against intrusion of surface water.
- Protect the pavement surface from oxidation.

In many jurisdictions, chip seals are called stress-absorbing membranes (SAMs). Chip seals do not add structural strength or correct profile or ride problems. Where traffic volumes allow, they may be used as an alternate to OGAC to restore surface frictional characteristics.

To construct a chip seal, the hot ARB is sprayed on the roadway surface at a rate determined by the Engineer depending on the surface condition. Typical application rates are 0.55 to 0.70 gallons per square yard which provide a relatively thick membrane. The binder is immediately covered with a layer of hot pre-coated chips that must be quickly embedded into the binder by rolling before the membrane cools. Best results are achieved with clean nominal 3/8 to 1/2-inch

(9.5 to 12.5mm) single-sized chips. The standard chip size for Caltrans asphalt rubber seals is 3/8-inch (9.5 mm); 1/2-inch (12.5 mm) chips are used by Caltrans only where ADT is less than 5,000 per lane. Lightweight aggregates may be substituted to minimize windshield breakage by loose chips in areas where traffic is heavy or fast. Pre-coating the aggregate with asphalt cement improves adhesion by removing surface dust and "wetting" the chips. Caltrans requires that the aggregate chips be delivered to the job site precoated and hot. To further aid chip retention after the chips have been embedded and swept, a fog seal of asphalt emulsion (diluted 1:1 with water) is sprayed over the chips at a typical rate of about 0.05 to 0.1 gal/yd^2 (0.14 to 0.27 l/m^2). A light dusting of sand, about 2 to 4 lbs/yd^2 (1 to 2 kg/m^2) is then applied as blotter as directed by the Engineer. Figure 2-4 shows an asphalt rubber chip seal train.

Figure 2-4 Chip Seal Train

Note: *All chip seals are very sensitive to construction operations and site environmental conditions. With hot-applied seals, the thin binder membrane cools very quickly regardless of its composition. Embedment and adhesion must be accomplished while the membrane is still hot.*

Although some references indicate that asphalt rubber seals can be applied at colder temperatures than emulsion seals due to use of hot precoated chips, placement when the ambient temperature is less than 60ºF is not recommended. The potential for problems with embedment and adhesion increases as ambient and surface temperatures decrease.

2.3.1.1 Advantages. Asphalt rubber chip seals provide the same benefits as conventional chip seals, but also provide the following additional advantages:

- Significantly longer service life than conventional chip seals.
- Superior long-term performance in resisting reflective cracking.

2.3.1.2 Purpose. Asphalt rubber chip seals provide a flexible, waterproof, skid resistant and durable surface that resists oxidation and is highly resistant to reflective cracking. A chip seal is not a structural layer and provides no profile adjustment.

2.3.1.3 Appropriate Uses. These include:

- Rehabilitation of structurally sound pavements which are cracked or raveled

- Restoration of surface frictional characteristics (corrective maintenance)
- Routine preventative maintenance to extend the life of AC pavements

Chip seals have been used to restore some serviceability to functionally failed (aged and badly cracked) pavements with relatively sound structural capacity until rehabilitation can be performed. However they are too thin to correct pavement profile, and the aggregate surface may be somewhat noisy and rough to ride on. Appearance may also be an issue, although use of hot precoated chips and flush coat may improve appearance as well as durability. Noise and roughness generated are related to aggregate particle size. Larger cover aggregate is noisier and presents a rougher surface appearance.

Caltrans Maintenance Manual (Volume 1) includes criteria for use of chip seals and cover aggregate size based on speed limits and average daily traffic. The maximum ADT limit for chip seals is 30,000. Use of chip seals is not encouraged in areas with heavy trucks or stop-and-go traffic, at signalized intersections, or in locations where speed limits are ≥45 mph (72.4 kph).

2.3.1.4 Asphalt Rubber Binder Design. The specifications for ARB referenced in 2.1 also apply to asphalt rubber binders for chip seals, except that maximum viscosity is 3,000 cPs rather than 4,000. In the future, minimum extender oil content requirements may also differ. The asphalt rubber binder design profile and materials submittals requirements, including test results that verify compliance with ARB physical property specifications over a 24-hour period, are the same for chip seals as for hot mixes.

2.3.1.5 Application Rates. According to Caltrans standard special provisions for asphalt rubber seal coat, SSP37-030, target application rates for asphalt rubber chip seals are:

- Asphalt rubber binder at 0.6-0.7 gal/yd^2 (2.5-3 l/m^2)
- Hot precoated chips (nominal 1/2 or 3/8" size) at 30-44 lbs/yd^2 (15-22 kg/m^2)

However, the exact rate is to be determined by the Engineer. A number of factors should be considered in determining appropriate application rates for asphalt rubber binder and cover aggregate, including:

- Surface texture of the existing pavement: severely aged, oxidized and open-textured surfaces will absorb more binder than newer tighter surfaces.
- Traffic volumes: typically use smaller chips for higher volumes to reduce potential for vehicle damage by loose chips. Binder application rates can be increased for low traffic volume areas.
- Seasonal temperature ranges: thicker membranes may be used in areas with cool climates.
- Aggregate size: large stone requires more asphalt rubber binder (thicker membrane) to achieve 50 to 70 percent embedment. The standard chip size for Caltrans asphalt rubber seals is nominal 3/8-inch, which may be too small for heavy binder applications. However Caltrans policy is to use ½-inch chips only where ADT is less than 5,000 per lane.

- Aggregate gradation: single-sized materials require more ARB than do graded aggregates.

There are methods by which the specified aggregate application rate can be evaluated prior to the start of construction. The easiest is to simply lay the aggregate one-stone deep on a measured area, weigh the amount of stone required to cover that area and convert to appropriate units (lbs/yd^2, kg/m^2).

To verify if application rates are appropriate, also check the embedment of the cover stone. The stone should be embedded to a depth of about 50-70 percent after seating in the lab or by rollers and traffic in the field. Excess chip application interferes with embedment and adhesion.

Excess asphalt rubber application can literally submerge or swallow the chips, which results in flushing/bleeding. Loose stones along the roadway edge after sweeping may indicate excessive chip application and wasted stone, that the asphalt rubber application is too light, or that the binder cooled before embedment and adhesion were achieved.

2.3.2 Asphalt Rubber Stress Absorbing Membrane Interlayers (SAMI-R)

A SAMI-R is simply an asphalt rubber chip seal that is overlaid with conventional HMA or RAC. Interlayers are used under corrective maintenance overlays and as a pavement rehabilitation tool, but would not be included in new construction. SAMI-R acts to interrupt crack propagation and has been shown to be highly effective in delaying reflective cracking in overlays of existing distressed asphalt and jointed portland cement concrete (PCC) pavements.

SAMI-R material is very flexible and elastic and has a low modulus; it flexes and creeps to relieve stresses and to heal many of the cracks that do occur. The membrane also provides a seal that minimizes further infiltration of surface water through the pavement structure. In cases where reflective cracking is expected to be the primary distress mode and structural capacity is deemed sufficient, interlayers may be used to reduce the required thickness of the overlay.

Chip retention is not an issue unless the interlayer will be opened to traffic prior to overlay. Otherwise, the aggregate chips are sandwiched in. They are keyed into the overlay during compaction and prevent formation of a slippage plane along the relatively thick asphalt rubber membrane. No fog seal or sand should be applied over an interlayer because it could interfere with bonding of the overlay.

SAMIs may be applied to any type of rigid (PCC) or asphalt pavement, and have proved very effective at minimizing reflection of PCC joints. However the Caltrans Maintenance Manual states that if the surface irregularities (rutting in AC or faulting of PCC) exceed 1/2-inch (12.5 mm) then either a leveling course should be placed or grinding and crack filling are required prior to placing SAMI-R.

2.3.2.1 Advantages. These include:

- Highly effective in minimizing reflective cracking in overlays of existing distressed asphalt and jointed portland cement concrete pavements.
- Minimize overlay thickness when reflective cracking is expected to be the primary distress mode and structural capacity is deemed sufficient.
- May contribute to reduced overlay thickness based on reflective cracking equivalency, which fabric does not.

2.3.2.2 Purpose. SAMI-R is a low modulus (non-structural) layer that is used to retard and minimize reflective cracking in overlays placed on it, and to minimize further infiltration of surface water through the pavement structure.

2.3.2.3 Use. SAMIs are used under thin maintenance overlays and are a pavement rehabilitation tool. A SAMI would not be included as part of new construction. Based on "the cost effectiveness and enhanced performance of sealing the pavement and overlaying" of SAMI-R in the Yolo 16 Esparto Test, the Caltrans Division of Maintenance recommended implementing two-layer pavement strategies as part of the Capital Outlay Preventative Maintenance (CAPM) program (Holland and Brown, 2005).

2.3.2.4 Design. Design of the ARB is the same as for chip seal. Determination of appropriate binder and cover aggregate application rates is also the same. SAMIs have been assigned an equivalency factor in rehabilitation projects when reflection cracking is the governing distress mode for overlay design.

3.0 PRODUCTION OF ASPHALT RUBBER BINDERS AND MIXES

This chapter presents information and procedures for production of asphalt rubber binder and how the use of ARB affects HMA mixture production.

3.1 ASPHALT RUBBER BINDER PRODUCTION

Asphalt rubber binder production methods are essentially the same for both hot mix and spray applications. The primary difference is the importance of coordination of asphalt rubber and hot mix production to assure that enough ARB is available to provide the desired RAC mix production rate.

Field production of high viscosity ARB is a relatively straightforward process for which Figure 3-1 shows a schematic. Equipment for feeding and blending may differ among asphalt rubber types and manufacturers, but the processes are similar. The component materials are metered into high shear blending units to incorporate the correct proportions of extender oil and CRM into the paving grade asphalt. The blending units thoroughly mix the CRM into the hot asphalt cement and extender oil, and the blend is pumped into a heated tank where the asphalt rubber interaction proceeds.

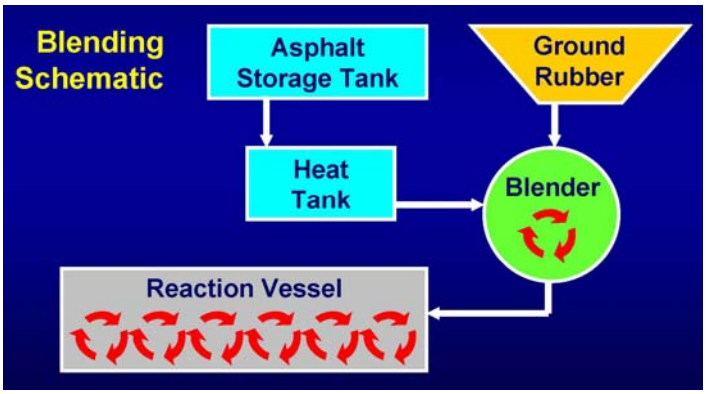

Figure 3-1 Asphalt Rubber Blending Schematic

The quality of the resulting asphalt rubber binder depends on proportioning, temperature, agitation, and time. ***Temperature is critical for process control*** and temperature gauges or thermometers should be readily visible. Tanks that store the asphalt cement and the asphalt rubber between initial blending and use are heated to temperatures from 375°F to 435° F (190°C to 226°C) and insulated. Asphalt rubber production equipment and storage tanks generally include retort heaters or heat exchangers to heat the asphalt cement and/or asphalt rubber binder. It is reasonable to assume some heat will be lost in any transfers, but this can be reduced by wrapping transfer lines with insulation.

Figure 3-2 shows an example of a typical asphalt rubber production set up at an HMA plant. Binders for spray applications are typically produced close to the job site, not necessarily at an HMA plant, and must also be coordinated with application operations.

Figure 3-2 Asphalt Rubber Production Set Up at HMA Plant

CRM is usually supplied in one ton (0.91 tonne) super sacks (Figure 3-3) that are fed into a weigh hopper for proportioning (Figure 3-4). The containers should be clearly labeled and stored in an acceptable manner. Caltrans' acceptance sampling should be coordinated with asphalt rubber personnel to assure that all CRM lots can be sampled as appropriate.

Figure 3-3 CRM Super Sacks

Figure 3-4 Blending from CRM Weigh Hopper

Augers are needed to agitate the asphalt rubber inside the tanks (Fig. 3.5) to keep the CRM particles well dispersed; otherwise the particles tend either to settle to the bottom or float near the surface. Agitation can be verified by periodic observation through the top hatch or the port where the auger control is inserted

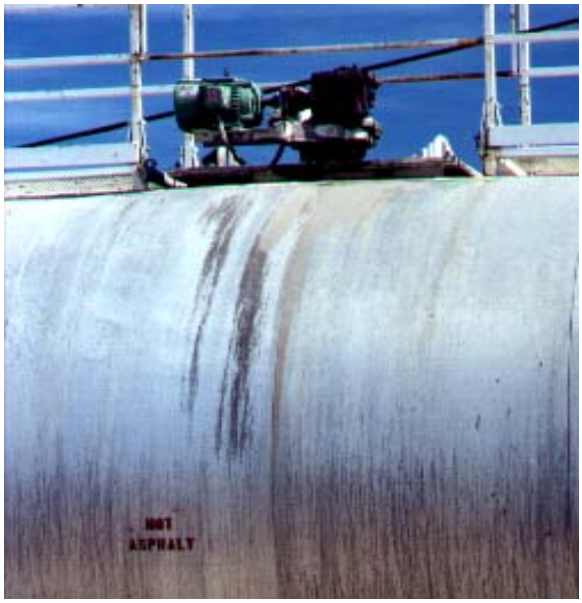

Figure 3-5 Auger for Agitating Asphalt Rubber Storage Tank

The asphalt rubber binder must be interacted with agitation for a minimum of 45 minutes at temperatures from 375 to 425°F (190 to 218°C) to achieve the desired interaction between asphalt and rubber. In order to maintain the reaction temperature within the specified range, the asphalt cement must be hot, 204 to 224°C (400 to 435°F) before the design proportions of scrap tire and high natural CRM are added. This is because the CRM is added at ambient temperature (not heated) and reduces the temperature of the blend.

The component materials are metered into blending units to incorporate the correct proportions of CRM into the asphalt cement, and are thoroughly mixed. The asphalt rubber producer is allowed to add the extender oil while adding the rubber, although in some cases the asphalt cement may be supplied with the extender included. If the asphalt rubber producer adds the extender oil, use of a second meter is recommended to best control the proportioning. The meter for the extender oil should be linked to that for the asphalt cement.

An ARB interacted at lower temperatures will never achieve the same physical properties as the laboratory design, although it may achieve the minimum specification values for use. Hand held rotational viscometers (Haake or equivalent as referenced in Table 2-1) are used to monitor the viscosity of the asphalt rubber interaction over time for quality control and assurance. Before any asphalt rubber binder can be used, compliance with the minimum viscosity requirement must be verified using an approved rotational viscometer. As long as the viscosity is in compliance and the interaction has proceeded for at least 45 minutes, the asphalt rubber may be used.

3.1.1 Hold-Over and Reheating

Caltrans requires that heating be discontinued if ARB material is not used within 4 hours after the 45-minute reaction period. The rate of cooling in an insulated tank varies, but reheating is required if the temperature drops below 375°F (190°C). A reheat cycle is defined as any time an asphalt rubber binder cools below and is reheated to 375 to 425°F (190 to 218°C). Caltrans allows two reheat cycles, but the asphalt rubber binder must continue to meet all requirements, including the minimum viscosity. Sometimes the binder must be held overnight. The asphalt and rubber will continue to interact at least as long as the asphalt rubber remains liquid. The rubber breaks down (is digested) over time, which reduces viscosity. Up to 10 percent more CRM by binder mass can be added to restore the viscosity to specified levels. The resulting asphalt rubber blend must be interacted at 375 to 425°F (190 to 218°C) for 45 minutes and must meet the minimum viscosity requirement before it can be used.

3.1.2 Documentation

3.1.2.1 Certificates of Compliance. According to Caltrans requirements, a certificate of compliance (COC) is required for every binder constituent as well as for the finished asphalt rubber binder. The COCs must include test results that show conformance of all of these materials to the respective special provisions, including chemical composition of the scrap tire and high natural CRM materials and asphalt modifier (extender oil). COCs for each of the component materials delivered to site of the asphalt rubber blending operation should be provided to the Engineer, inspector and/or project staff. It is current policy for Caltrans representatives to sample components and blended asphalt rubber materials at the mixing site for testing and acceptance.

3.1.2.2 Asphalt Rubber Binder Design. A copy of the approved ARB Design Profile that includes results of specified laboratory tests and proportions of each component must be available at the asphalt rubber blending site.

3.1.2.3 Asphalt Rubber Binder Production Log. A Log of ARB Production shall also be maintained for each project. For each batch of asphalt rubber produced, the log should list the weights of each component used, the reaction start time, and results of all viscosity tests performed, including the time and asphalt rubber binder temperature, and the time when the batch was metered into the HMA plant. Figure 3-6 presents an example of an asphalt rubber Binder Viscosity Log. The production log should also include all holdover and reheat cycle information including the time that heating was discontinued, the time that reheating began and corresponding ARB temperature, amount and time of CRM addition if applicable, and subsequent viscosity test results. These data should be recorded on the Asphalt Rubber Binder Viscosity Testing Log shown in Figure 3-6.

Project Name/Number	
Asphalt Rubber (AR) Blender/Supplier	
Location of AR Blending Plant	
RAC Mix Supplier	

ASPHALT RUBBER BINDER FORMULATION **Blend Proportions**

Asphalt Cement PG Grade and Supplier		
Asphalt Modifier Type and Supplier		% by AC mass:
Asphalt Cement and Modifier		% by Asphalt Rubber Binder mass:
Scrap Tire CRM Type & Supplier		% by Asphalt Rubber Binder mass:
High Natural CRM Source & Description		% by Asphalt Rubber Binder mass:

Asphalt Rubber Binder (ARB) material must be tested to verify compliance with minimum viscosity requirement of 1,500 Pa•s (x 10^{-3}) at 375± 3°F before it can be used.

*Cycle Start Date & Time	AR Batch #	Temperature In ARB Tank (°F)	Temp. During Viscosity Test (°F) (375 ± 3°F)	Measured Viscosity** Pa•s(x10^{-3})	Date and Time Sampled	Date and Time Tested	Comments

Viscometer Make, Model and Serial #:_____

Rotor Designation:_____

Test Operator:_____

** The cycle begins when the asphalt rubber tank is fully loaded and temperature in the tank is 375±3°F.*

*** Measure viscosity at 375±3°F according to Caltrans LP-XX. Viscometer may read in units of centipoises (cPs) or dPa•s. Unit conversions are as follows:*

1Pa•s = 1,000 cPs
1dPa•s = 0.1Pa•s = 100 cPs
1mPa•s = 0.001Pa•s = 1 cPs

Figure 3-6 Example Asphalt Rubber Binder Viscosity Testing Log

3.1.3 Sampling and Testing Requirements

For quality control, sampling and testing frequencies for all components of ARB are listed in Table 3-1. Quality Assurance testing requirements may vary, but sampling requirements typically should not exceed the frequencies shown below.

Tests for CRM gradation and chemical composition may take more time to conduct than for conventional paving materials. Failures to meet these requirements should be evaluated on a case-by-case basis and results of physical property tests of the asphalt rubber binder should also be considered. For RAC-G mixes, volumetric mix properties should also be evaluated.

Table 3-1 QC Sampling and Testing Frequency

Material	QC Sampling and Testing Frequency*
CRM	Chemical composition Each 250 tons (225 tonnes about)
CRM	Gradation and physical properties Each truckload: Each 20 tons (18 tonnes)
Asphalt Rubber Binder	Viscosity: Test every hour during RAC production. Retain 1 gallon (4 liters) /batch
Asphalt Cement	Each 200 tons (180 tonnes) Sample at point of origin or at mixing site.
Asphalt Modifier	Each 25 tons (23 tonnes) Sample at point of origin or at mixing site.

**Minimum frequency is once for each project.*

3.1.3.1 CRM Sampling and Testing. CRM consists of graded particles of ground rubber that tend to agglomerate (clump) in the presence of moisture and may segregate by size. Although CRM manufacturers certify CRM gradation at the plant, segregation may occur during storage and shipping. Segregation is not an issue when the entire container is added to the asphalt rubber blend, but it can affect the small samples (approximately 100 grams) obtained for purposes of gradation testing for acceptance. Caltrans has developed a standard method to obtain representative samples of CRM from shipping containers using tube samplers such as grain probes. It is included in a draft Laboratory Practice (LP-10) for Sampling and Testing CRM which is currently under review by Caltrans and has not yet been implemented.

3.1.3.2 Asphalt Rubber Sampling and Testing. Caltrans requires the Contractor (typically the ARB producer) to sample the asphalt rubber from an appropriate sample valve or the feed line into the AC plant and measure the viscosity at least every hour during AC production. At least 1 gallon of ARB should be wasted to assure that the sampling valve is clear, and the sample to be tested should be poured into a clean, dry container that can be sealed and clearly labeled. At least one viscosity test is required for each asphalt rubber batch, with subsequent hourly measurements during mix production. The Engineer is to be notified when the tests will be performed. Caltrans requires that results of all viscosity tests performed, including the time and ARB temperature, be submitted to the Engineer on a daily basis. Figure 3-6 presents an example Asphalt Rubber Binder Viscosity Testing Log.

Viscosity depends on temperature. It is essential to have a controllable heat source (hot plate, gas stove/burner, etc.) to maintain asphalt rubber sample temperature at 375 ± 3°F (190 ± 1°C) during viscosity measurement.

The Caltrans Laboratory Procedure for testing asphalt rubber binder viscosity (LP-11) with a hand-held rotational viscometer (analog or digital) is still in development and is not yet available. A description is presented below for information, but the actual procedure adopted may differ. The original field test procedure can be obtained from the Transportation Laboratory, Pavement Branch by request.

The open ARB sample container should be set on or over the heat source as appropriate, and the sample should be stirred to prevent scorching or burning. The No. 1 viscometer spindle should be inserted in the hot binder sample near the edge of the can for about one minute to acclimate, without plugging the vent holes. This is longer than the Caltrans test method requires, because 10 seconds is not enough time to raise the spindle temperature by 300°F (167°C). While acclimating, the sample can be thoroughly stirred and the temperature measured. The probe should then be moved to the center of sample to make the viscosity measurement. The analog viscometers have a level bubble for proper orientation (probe shaft perpendicular to binder surface and viscometer level) and an immersion depth mark on the shaft. Bubbles need to be added to the digital models. Once leveled, begin probe rotation. The peak viscosity value is read from scale labeled with the corresponding spindle number (see Figures 3-7 and 3-8 for analog models, and Figure 3-9 for digital model).

Figure 3-7 Hand Held Viscometer Testing (Analog Model)

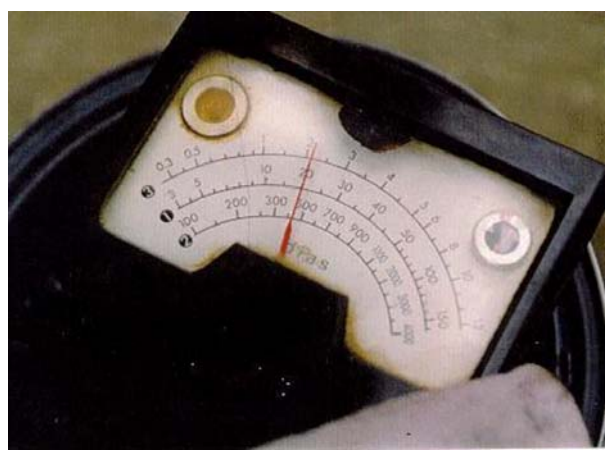

Figure 3-8 Analog Viscometer Reading – Scale No. 1

The peak measurement represents the viscosity of the asphalt rubber binder system and that is typically the value that should be reported and logged. However, for some binders, there is a noticeable pause in the reading immediately after it begins to drop from the peak value before the drop continues. If this occurs, substitute the lower value where the reading paused. As the probe continues to turn, it "drills" into the sample, (i.e., spins rubber particles out of its measurement area) and the apparent viscosity drops to reflect only the liquid phase of the asphalt rubber. Three measurements should be taken and averaged to determine the viscosity. Between

measurements, the viscometer probe should be moved away from the center (without removing it from the asphalt rubber binder sample) and the sample should be thoroughly stirred again.

Figure 3-9 Digital Readout Rotational Viscometer (per manufacturer)

During ARB production, field viscosity measurements may vary from the laboratory design but should follow a similar pattern of increase and/or decrease over the duration of the asphalt rubber interaction. Larger differences than ± 500 centipoises (cPs) or different patterns can indicate that a change may have occurred in component materials since the original design and testing was performed. In such cases, samples of the reacted asphalt rubber binder should be obtained and tested immediately for specification compliance. As long as the asphalt rubber binder viscosity complies with specification limits, the Contractor may elect to use that batch of binder. However in such cases, there is a risk that the test results may show that the sample does not comply with other specified physical property requirements. Complete and well-maintained asphalt rubber production logs can help limit areas of penalty and/or removal and replacement by recording when and/or where the reject material was used.

Upon request or as agreed during the pre-paving conference, asphalt rubber producer personnel should provide to the Engineer or Inspector samples of reacted asphalt rubber binder for quality assurance and acceptance testing for compliance with the specified property limits.

3.1.3.3 Terminal Blend Products. Terminal blend products may be manufactured by different methods and are governed by different specifications and tested with different equipment than the high viscosity asphalt rubber binders described in this Asphalt rubber Usage Guide. **These products are not within the scope of this Guide.**

CAUTION: Remember that the two families of CRM-modified binders, high viscosity asphalt rubber and terminal blend (no agitation) are not interchangeable. Neither type should be directly substituted for the other in a hot mix without laboratory testing to determine appropriate adjustments in binder content and possibly aggregate gradation.

3.2 ASPHALT RUBBER HOT MIXES (RUBBERIZED ASPHALT CONCRETE, RAC)

3.2.1 Mix Production

Using asphalt rubber binder has relatively little effect on hot plant operations, for either batch or continuous HMA plants, except that it may be necessary to increase the plant operating temperature in order to provide the higher mixing and placement temperatures typically required for RAC mixtures.

The asphalt rubber production equipment is independent of the HMA plant, but is usually set up as close to the mixing unit as feasible to minimize the length of the heated and/or jacketed binder feed lines.

The asphalt rubber producer provides special heavy-duty pumps to transfer the asphalt rubber binder, because most HMA plant pumps cannot handle such viscous materials without risk of damage. A two- or three-way valve can be installed in the asphalt feed line that allows the plant to switch between using the ARB or the regular paving asphalt in the HMA plant tanks, according to demand for various HMA products. For drum plants, the asphalt rubber producer is required to use a flow meter that interlocks the ARB feed with the plant aggregate feeds.

RAC production rates may be slightly reduced from dense-graded HMA rates due to higher binder content (increased mixing time) and asphalt rubber binder production rate. Planning and coordination between the asphalt rubber binder producer and the HMA plant operator are important to minimize impacts on RAC production. The binder supplier can in many cases arrange to use more or larger storage and reaction tanks, and schedule materials deliveries and asphalt rubber blending operations to expedite asphalt rubber and mix production. Because of the relatively high mixing temperatures, there is potential for increased emissions of smoke and/or fumes. Reducing the mix production rate usually reduces visible emissions.

3.2.1.1 Inspection and Troubleshooting of the RAC Mixture. Both the plant and field inspectors should visually inspect the RAC in the haul truck bed for signs of any problems with the mix and check mix temperature. Surface readings are not an accurate indicator. Measure the temperature of the RAC mix with a thermometer that has a probe at least 6 inches (152 mm) long, by sticking the full depth of the probe into the mix. If only a heat gun is available, it will be necessary to measure temperature of the RAC as it is flows out of the plant discharge chute into the haul truck.

Whenever any type of RAC mixture problem is suspected, the Inspector should obtain samples immediately and have them tested for gradation and ARB content. In some cases, it may be necessary to check voids properties of compacted hot mix specimens. The Inspector should enter a full description of the problem observed and subsequent activities in the project daily log, and immediately report these observations to the Resident Engineer (RE). Test results should be relayed to the RE immediately upon receipt. Some of the potential “trouble” signs to watch for in the mix are as follows.

- Segregation: Particle size segregation may be difficult to identify in some coarse gap-graded mixtures. There are few fines present and that can sometimes make the RAC appear segregated even if it is not. Identify the affected truckloads and corresponding placement areas, take samples and test gradation and binder content to verify. It is also recommended that, if possible, samples of RAC that do not appear segregated should be taken from the same truckload, for comparison. Temperature segregation (hot or cold spots) may be checked with a heat gun or with an infrared camera. The primary concern is differences rather than exact values.
- Blue smoke: Mix is too hot.
- White smoke: Steam – too much moisture. This means that the aggregate was not dried enough prior to mixing with asphalt rubber binder. This may cause the RAC mix to become tender and may contribute to compaction problems.
- Stiff appearance: Mix may be too cool – check temperature.
- Dull, flat appearance: Indicates low asphalt rubber binder content and/or excessive fines (minus No. 200 (0.075 mm) sieve size). Localized areas of dullness may indicate insufficient mixing of the asphalt rubber binder and aggregates, or mix segregation. Take samples and test for gradation and binder content.
- Slumped and shiny: High ARB content. RAC-O, and especially RAC-O (HB) mixtures, may look this way and still meet SSP requirements, so this is not always a problem. An old descriptive term for this is "wormy," because the mix seems to almost crawl when watched. Look in the truck bed for binder drain down, take and test samples for asphalt rubber binder content and gradation.

The only change to the plant Inspector's normal duties is the addition of monitoring the asphalt rubber production and viscosity results and sampling the ARB and its components. The Asphalt Rubber Binder Production Log and Testing Log should contain all of the pertinent information, and should be available for inspection. The Inspector should obtain at least one 1-gallon (4 liter) sample from each batch of ARB produced for the project to test for compliance with specification limits.

The normal activities related to plant inspection for conventional HMA production remain the same and include the following items, along with close attention to temperature:

- Observing aggregate storage and handling and plant operations
- Basic sampling and testing procedures for checking aggregate and RAC characteristics;
- Verifying that the correct mixture is being produced according to the design and in compliance with specifications, etc.

3.2.2 Importance of Temperature

The key to quality in producing asphalt rubber materials and constructing asphalt rubber pavements is temperature control in all aspects of the work. Asphalt rubber materials need to be produced and handled at somewhat higher temperatures than conventional bituminous materials and mixtures because they are stiffer than these conventional materials at the typical mixing and compaction temperatures.

Temperature is critical to:

- ARB manufacture
- RAC hot mix production
- RAC delivery
- RAC placement
- RAC compaction

It is therefore important to closely monitor temperature of the materials during all phases of asphalt rubber binder and mixture production and construction. The Inspector should have appropriate equipment for checking temperature of asphalt rubber binder and hot mix, including surface and probe type thermometers that can also measure ambient air temperature, and a heat gun. The asphalt rubber blending and storage tanks should also be equipped with readily visible thermometers.

3.2.3 Safety

Safety is always a consideration when working with hot materials. Conventional HMA mixtures are hot enough to cause burns, and so are asphalt rubber binders and RAC materials. Personnel should wear appropriate protective gear including but not limited to gloves made for handling hot samples and suitable eye protection.

4.0 CONSTRUCTION AND INSPECTION GUIDELINES

This chapter presents information and procedures for construction and inspection of asphalt rubber pavements, chip seals and interlayers, including placement, compaction and finishing.

4.1 HOT MIX (RAC) PAVING EQUIPMENT

Conventional equipment is used to place and compact RAC materials. The field inspector should confirm that the necessary paving equipment is on site before any RAC mix is shipped from the HMA plant. Any equipment-related questions or issues should have been resolved in the pre-paving conference. Availability and paving capability may be affected by unanticipated mechanical problems or logistics.

4.1.1 Haul Trucks

Any type of trucks that are customarily used for transporting HMA may be used, including conventional end or bottom dumps, or horizontal discharge (live bottom). Trucks hauling RAC mix should be tarped to retain heat during transport.

4.1.2 Material Transfer Vehicle (MTV)

Use of this type of equipment is optional and typically limited to large projects. MTVs have been described as "surge bins on wheels" and are most often used when smoothness, segregation, or mixture delivery rate are concerns.

4.1.3 Pavers

Conventional mechanical self-propelled pavers are used to place RAC mixes. Pavers should be equipped with vibratory screed and screed heaters, automatic screed controls with skid, and comply with all of the pertinent Caltrans specification requirements.

4.1.4 Rollers

Rubber tired rollers are not appropriate for compacting RAC mixes because of excessive pick up of the mixture by the tires. Rollers for RAC must be steel-wheeled (drum), and must be equipped with pads and a watering system to prevent excessive pick-up. It may sometimes be necessary to add a little soap to the watering system.

RAC-G mixtures are likely to require more compaction effort than dense-graded HMA. Minimum recommended roller weight is 8 tons (7.3 tonnes); pup rollers cannot provide sufficient compaction. The types of rollers normally include the following:

- **Breakdown roller with vibratory capability**. Two breakdown rollers should be used, especially if paving width exceeds 12 feet (3.65 m).

- **Intermediate roller.** If not of equal or greater width than the breakdown roller(s), two intermediate rollers should be required.
- **Finish roller.** May be vibratory or static, but use the static mode for finishing
- **Standby roller.** One with vibratory capability should be on site and would be required if only one breakdown roller is available.

4.1.5 Sand Spreader

Any Caltrans approved spreader with uniform distribution capabilities to provide a sand blotter for opening the RAC surface to traffic.

4.2 FINAL PREPARATIONS FOR PAVING

Surface preparation must be completed prior to RAC production or spray application. This includes customary items such as removal and replacement of failed pavement, pothole repair (patching), milling or grinding for smoothness and/or to restore or adjust profile, crack filling and/or sealing, etc. Patching should be performed using standard good practice and conventional HMA. Do not overfill cracks, as excess sealer/filler will cause bumps in the overlay, and may migrate up through the RAC mat during compaction and to create "fat spots." Fill ruts as necessary. If a leveling course is required, use a fine dense-graded HMA material. Immediately prior to mixture delivery, the surface should be swept and tack coat applied.

4.2.1 Tack Coat (Paint Binder)

A tack coat should generally be uniformly applied so as to lightly cover the entire pavement surface to be overlaid. Tack coat may consist of paving grade asphalt or emulsified asphalt. Area of tack application should be limited to what will be paved over on that day. However, tack coat is not required when a SAMI-R will be placed prior to overlaying, and is not recommended when RAC will be placed directly on a new pavement.

4.2.1.1 Emulsified Asphalt. Recommended application rate is 0.05 to 0.1 gal/square yard residual, depending on the condition of the existing surface. Caution should be used when ambient and pavement temperatures are marginally cool and emulsion tack coats are to be used. Emulsion must "break" (i.e. turn from dark brown to black as the suspended asphalt droplets separate from the water) and the water must evaporate prior to paving. Otherwise, the remaining water in the emulsion will turn to steam and rise up through the mat. This prevents the tack from establishing the intended bond with the new pavement and the excess moisture may also cause a tender spot in the mix during compaction. Water trapped between pavement layers may cause stripping. Cold or damp conditions and lack of sun slow evaporation and may delay paving operations.

4.2.1.2 Asphalt Cement. Unmodified PG asphalt cement can also be used as tack for RAC mixes and is preferred for use where site conditions are marginal. Asphalt tack must be hot enough (300 to 350°F, 149 to 176°C) to spray an overlapping fan pattern that provides a uniform application. The distributor truck must have a heater to maintain asphalt temperature and

consistency for spray application. The application rate must be properly controlled to avoid bleeding (too high) or delamination (too low). Any defective or plugged nozzles must be corrected immediately.

4.3 HOT MIX DELIVERY

The same good practices recommended for conventional hot mix delivery should be applied to RAC materials, along with special attention to temperature. Any type of conventional HMA haul truck can be used to transport RAC. However, use of bottom dumps and windrows is not recommended when air and pavement surface temperatures are marginally cool. It is critical that the RAC does not cool below the minimum laydown temperature (290ºF,143ºC) during transport. Tarps are needed to maintain acceptable mixture shipment temperatures ranging from 290º to 325ºF.

4.3.1 Release Agents

No solvent based release agents or diesel fuel should be used in haul truck beds because of adverse effects on the asphalt rubber binder. Soapy water (dish or laundry soap) is recommended; it is effective and cheap. Dilute silicone emulsions may also be used.

4.3.2 Coordinating Mix Delivery and Placement

Coordination and balance of binder and mix production with mix delivery, placement, and compaction operations is essential to achieving a smooth finished pavement with a pleasing appearance, the two factors that motorists reportedly consider the most important indicators of pavement quality. The paver should never have to stop due to lack of material. If it stops on the new mat, the result is either a bump or depression that is not removable by rolling. If the paver pulls off the mat, it may be necessary to construct a transverse joint. A long line of haul trucks waiting to access the paver usually means that some loads will cool too much to be used. Material transfer vehicles can be used to reduce adverse impacts of irregular mix delivery, but these large heavy machines are generally used only for large projects.

4.3.2.1 Unloading RAC Mix into a Paver Hopper. As for conventional HMA, the haul truck should be centered and backed up to the paver, but should stop just short of contacting the push rollers on the front of the paver (Figure 4-1). After the truck releases its brakes, the paver should move forward to pick up and push the truck forward, instead of the truck bumping the paver. This method helps to minimize screed marks and roughness. End dumps and if used, live bottom trucks, should raise their beds slightly so that the mix slides up against the closed tailgate, then open the gates to discharge the mix in a single mass. This "floods" the paver hopper and helps to minimize potential for mix segregation.

4.3.2.2 Unloading Hot Mix Into A Material Transfer Vehicle. This is easier, because MTVs also have a front hopper to receive the mix, but eliminate the problem of bumping the paver. The same method of discharge should be used to flood the MTV hopper as a paver hopper.

4.3.2.3 Load Tickets. Load tickets should be collected when the mix is discharged from the haul truck. Yield calculations are typically used to verify overall thickness based on total tonnage and

area paved. However in-place thickness of randomly selected cores should also be measured as a check.

Figure 4-1 Unloading RAC-G into Paver Hopper

4.4 HOT MIX PLACEMENT

Placement of asphalt rubber materials or any HMA materials requires good paving practices. Examples of good paving practices are listed in Table 4-1. Temperature is critical for proper placement of all HMA materials and particularly for RAC. Asphalt rubber binders are stiffer than conventional paving asphalt at the customary placement and compaction temperatures, so time available for compaction of modified materials is typically shorter than for conventional dense-graded HMA mixtures. How much shorter depends on a number of variables that are discussed in section 4.5 on Compaction.

Caltrans special provisions for RAC-G specify minimum atmospheric and pavement surface temperatures of 55°F (13°C) for mixture placement. When atmospheric and pavement surface temperatures are between 55°F and 64°F (18°C), spread (lay down) temperature for RAC-G is specified as 290 to 325°F (143 to 163°C). For site temperatures ≥ 64°F (18°C), the lower limit of RAC spread temperature drops to 280°F (138°C).

Placement at minimum ambient temperatures is not recommended, because time available for compaction is very limited and leaves no margin for circumstance or error, which often results in inadequate compaction. When feasible, it is recommended that the minimum ambient temperature requirement for RAC placement be increased to 65ºF. Because of the importance of temperature in achieving adequate RAC compaction, operating in the mid to upper end of specified temperature ranges is strongly recommended.

Asphalt rubber paving materials should not be placed during rain or when rain is imminent. If site conditions are wet, windy, or too cold, placement should be delayed until environmental conditions improve. Otherwise, expect significant problems in achieving adequate compaction. Weather conditions may change during the paving operation. If necessary, paving should be stopped until conditions improve.

Table 4-1 Examples of Good Paving Practices

- Use appropriate and properly maintained equipment operated by responsible, well-trained personnel.
- Comply with plans and specifications, and pay attention to details.
- Handle the mix so as to minimize segregation by particle size or temperature.
- Maintain mix temperature by using tarps and, if available, insulated beds on haul trucks.
- Deliver the mixture as a free flowing, homogeneous mass without segregation, crusts, lumps, or significant binder drain-off.
- Coordinate mix production, delivery, placement and paving operations to provide a smooth uninterrupted flow of material to the paver.
- Ideally, the paver should never stop on the new mat.
- Use good workmanship in constructing and compacting cold and hot, longitudinal and transverse joints. Allow appropriate overlap and thickness of hot material for roll-down, and roll from the hot side.
- Do not lute joints.
- Use enough rollers to achieve adequate breakdown and intermediate compaction and to complete finish rolling within the temperature limits for these operations.

4.4.1 Paver Operations

Paver operations for RAC should not differ from those commonly used for conventional HMA, except perhaps for paying closer attention to the temperature of the mix in the hopper. It is important to the quality of the finished product that the paver be operated so as to minimize starting and stopping. The importance of coordinating mix delivery with placement cannot be overemphasized. A consistent paver speed, even if relatively slow, helps maintain a uniform head of material and to control thickness. Care should be taken to dump (fold) the paver wings before mix collected in the corners cools enough to form chunks. However, wings should *never* be dumped into an empty hopper. Slat conveyors should not be allowed to run empty or nearly so.

4.4.2 Raking and Handwork

RAC mixtures are not particularly amenable to raking or handwork, so these activities should be minimized and performed immediately before the mix has time to cool. The relatively coarse RAC-G aggregate gradation and stiffer binder make handwork a problem, and may affect the appearance of joints. The higher asphalt rubber binder content of RAC-O-HB may make raking and handwork a little easier until the binder cools and stiffens.

The lack of fines in the gap and open graded mixes can create a somewhat rough and open-looking texture, even when placed by machine. RAC placed by hand may not provide a pleasing appearance even if the workmanship is excellent and the best practice is applied.

4.4.3 Joints

AC joints are typically defined as longitudinal or transverse, cold or hot. Butt joints are most typical and the practices presented apply to those. Some agencies have adopted wedge joints and/or skewed joints that are not discussed in this Guide; there may be some issues with using wedge joints for thin lifts of RAC, since there are few fines in RAC mixes. Broadcasting of the mix at joints is not good practice and should not be done.

4.4.3.1 Longitudinal Joints are most likely to be cold joints. To provide a good bond with the adjacent pavement, remove any loose material and tack the vertical edge prior to placing hot mix. To minimize need for raking, it is important to set both the screed overlap and height carefully on the adjacent pass. The screed should overlap the cold material by only about 1 to 1.5 inches (25 to 38 mm). The screed should be set above the elevation of the cold side by approximately 1/8 to 1/4 inch for each inch (3 to 6 mm for each 25 mm) of compacted pavement thickness being placed. Compacted thickness of RAC is 1.2 to 2.4 inches (30 to 60 mm) so the differences in height would range from about 0.2 to 0.6 inch (5 to 14.4 mm). This is relatively small compared to maximum stone size in the mix. Since it is difficult to feather RAC mixtures, some raking may be unavoidable. Extra material should be raked onto the hot side, not the cold. Roll from the hot side, not the cold side, to make a tight joint.

If the mix is placed by hand rather than machine, the height difference for compaction should be increased to ¼ to 3/8 inch for each inch (6.3 to 9.5 mm for each 25 mm). The height difference may vary among mixes, so experience and engineering judgment should be used as appropriate.

4.4.3.2 Transverse Joints. These may be hot or cold. Hot joints should be treated the same as for conventional dense-graded HMA, but the RAC mix will stiffen more quickly. Cold joints should be treated as described for longitudinal joints. Most often, transverse joints are constructed at the end of the paving day or when a lane is finished, using a bulkhead or Kraft paper to provide a vertical butt joint. If the paver runs out the mix, the joint should be constructed where the full compacted thickness is available, and the rest of the mix placed past that point should be removed and wasted. Ideally, transverse joints should be rolled in a transverse direction. This is rarely feasible and they are generally rolled longitudinally.

4.5 HOT MIX COMPACTION

Compaction is essential to the performance of any asphalt pavement. Although asphalt rubber mixtures are very forgiving materials, even they require adequate compaction to achieve the desired performance and durability. The best materials, mix designs, and placement techniques cannot compensate for adverse effects resulting from poor compaction during construction.

The coarse aggregate structure and stiff asphalt rubber binders in RAC-G mixes often require more compaction effort than conventional HMA. Compaction depends primarily on temperature and compactive effort. Breakdown compaction of RAC-G mixtures must be performed in the vibratory mode, and it is advisable to obtain at least 95% of the required density during breakdown rolling. Caltrans plans to implement density requirements for RAC-G mixes, including penalties for inadequate compaction.

However, vibratory compaction is not used for open-graded mixtures. There are no compaction requirements for open-graded mixes. These are typically placed as surface courses in thin lifts about 1 to 1.2 inches thick. Compaction is achieved with a few passes by rollers operating in the static mode.

4.5.1 Temperature Requirements

According to the Special Provisions for RAC-G, when atmospheric and pavement surface temperatures are less than 64°F (18°C), breakdown compaction must be completed before the mat temperature drops below 260°F (127°C). For site temperatures ≥18°C (64°F), breakdown compaction must be completed before the mat temperature drops below 250°F (121°C). ***It is strongly recommended that breakdown compaction of RAC-G should be completed before the temperature of the RAC mat drops below 280°F (138°C) in order to achieve adequate compaction.***

Mat temperature should be closely monitored during placement and compaction, and adjustments should be made as needed to speed up the compaction process. It may be necessary to add a second breakdown roller. Inability to perform breakdown rolling within the temperature range specified may be cause to terminate paving operations and reject loads. Also, vibratory rolling below the minimum breakdown rolling temperature should not be allowed, nor should vibratory rolling be permitted after static (finish) rolling.

4.5.2 Factors That Affect RAC and HMA Compaction

Compaction is affected by many factors including:

- Layer thickness,
- Air temperature,
- Pavement/ base temperature,
- Mix temperature,
- Wind velocity, and
- Sunlight or lack thereof.

Thin lifts, cool temperatures and wind reduce the time available for compaction because of temperature loss. Therefore, it is often easier to compact thick lifts (more than 2 inches (50 mm) thick) than thin ones. The rule of thumb is that the compacted thickness should be at least twice the maximum aggregate size, or three times the nominal maximum aggregate size. Otherwise, there may be problems with compaction due to a tendency for stones to stack and to catch under

the screed and be dragged through the mat. When stones stack, they tend to reorient with each paver pass, or to break.

When placing RAC mixtures, it is important for the breakdown roller to follow immediately behind the paver in order to achieve 95 percent of the required compaction during the vibratory breakdown while the mix is still hot. The number of vibratory coverage required may vary depending on the mix and site conditions during placement. The anticipated roller coverages may need to be adjusted based on temperature and wind conditions. Therefore, it is advisable to use two breakdown rollers to keep up with the paver and to obtain sufficient compaction. Intermediate rolling provides relatively little increase in density of RAC mixes.

4.5.3 Test Strips and Rolling Patterns

California Test Method 113 is required for pavements with thickness ≥ 60 mm (2.4 inches) to establish the engineer's approval of equipment and rolling pattern based on achieving a minimum of 95 percent compaction relative to the mix design bulk density. Since 60 mm is the upper limit of RAC thickness, CT 113 may not be required for most RAC pavements. However if CT 113 is used, the temperature ranges for the test must be modified for RAC-G. Test strips for thinner RAC lifts are recommended when feasible to indicate what level of compaction effort is needed to achieve adequate in-place density. During test strip compaction, both Contractor and agency representatives should correlate their respective nuclear gauge(s) on the test strip according to CT 375. Gauge data should then be correlated with core results in order for nuclear density to provide accurate data for quality control during paving.

A Paving Check List is included in Appendix A. This handout should be delivered to the contractor for distribution to all members of the construction staff as well as to the Inspector.

4.5.4 Opening New RAC Pavement to Traffic

4.5.4.1 Sand Blotter: RAC mixes are relatively binder-rich and the surface may be tacky until the new mat has a chance to cure. To prevent tracking and pickup of the newly placed mat upon opening to traffic, a light dusting of clean sand may be spread on the surface of RAC pavement at a rate of about 2 to 4 pounds per square yard to act as a blotter. However applying sand does not cool the pavement. Sand shall be free from clay or organic material. Excess sand shall be removed from the pavement surface by sweeping.

4.5.4.2 Water: In order to open to traffic according to schedule, it may be necessary to cool the new RAC pavement with water. If environmental regulations allow it, application of water shall conform to the provisions in Section 17, "Watering" of the Standard Specifications. If environmental regulations allow, a dilute solution of lime water consisting of a minimum of 50 pounds of hydrated lime per 3,000 gallons of water, may be sprayed on the pavement surface to cool the mat and stiffen the exposed surface of the asphalt rubber binder.

4.6 CHIP SEAL CONSTRUCTION

Chip seals are surface treatments that are extremely sensitive to the effects of construction operations and site conditions, including temperature (ambient air temperature and temperatures

of the cover aggregates, and underlying pavement). There are only minor practical differences in construction of conventional hot chip seals versus asphalt rubber chip seals. The primary difference is that the asphalt rubber membrane is thicker and chips must be large enough so as not to be "swallowed" by the membrane. The other is that the distributor nozzles may have a greater tendency to clog due to the presence of discrete rubber particles. This is addressed by appropriate nozzle sizing.

Temperature is critical to successful chip seal construction whether the binder is conventional paving grade asphalt or high viscosity asphalt rubber. Clean or precoated chips are also critical and, for use with ARB, are required to be hot (260 to 325ºF). Embedment and adhesion of the chips must be accomplished by rolling while the asphalt rubber membrane is still hot. Caltrans guidance indicates that the higher temperatures of the asphalt rubber binder and use of hot precoated chips allow placement of asphalt rubber chip seal at cooler temperatures than emulsion binders and at night. However is not advisable to place chip seals when ambient or pavement temperature is less than 60º. Such cool conditions leave little margin for variability in materials, application or site temperature conditions. A reasonable production rate is about 5 to 7 lane miles per day.

4.6.1 Chip Seal Equipment

The equipment required to place a chip seal includes:

- Distributor truck with fume catcher to spray apply asphalt rubber membrane.
- Chip Spreader.
- Haul trucks for chips.
- Roller(s): Because the surface of the chip seal is the cover aggregate, rubber tired rollers may be used to embed the aggregate and are recommended for their kneading action. Steel wheeled rollers may also be used, but may not be as effective for embedding the aggregate.
- Hand tools (broom, shovels, etc.)
- Power broom.
- Distributor truck to apply a flush coat (typically diluted emulsion) -not required for SAMI-R.

4.6.2 Asphalt Rubber Spray Application

The distributor must be properly adjusted and operated to apply the proper amount of asphalt rubber binder uniformly over the surface. As for the tack coat, fanning and overlap is necessary to apply the membrane. The nozzle (snivy) size, spacing, and angle in relation to the spray bar help determine the height of the bar. Streaking may occur if the asphalt rubber binder is too cold, when its viscosity is too high, or the spray bar too low. The person who monitors the application for uniformity and nozzle problems is protected from fumes by a pollution hood over the spray bar. Application rate according to Caltrans special provisions is 0.6 to 0.7 gallons per square yard (2.5 to 3.0 l/m^2) and the Resident Engineer determines the exact rate.

Each spray application should start and end on paper (tar paper or roofing felt if possible) to ensure uniformity for the entire application. The application width should be adjusted so that the longitudinal joint (meet-line) is not in the wheel path, but on the centerline or in the center or edge of the driving lanes. After each application, the distance, the width, and the amount of asphalt rubber should be determined to verify the application rate.

4.6.3 Chip Application

The hot pre-coated chips should be applied immediately behind the asphalt rubber binder spray; the chip spreader should follow at a maximum distance of about 65 to 100 feet (20 to 30 meters). The asphalt rubber binder must be fluid so the rock will be embedded by the displacement of the asphalt, preferably to 50 to 70 percent embedment. Embedment should be checked after start up and application rates adjusted as necessary. A chip seal train consisting of binder distributor truck, chip spreader, and roller is shown in Figure 4-2.

Figure 4-2 Chip Seal Train

The standard chip application rate is about 28 to 44 pounds per square yard (15 to 22 kg/m^2) with the exact rate to be determined by the Engineer. Trucks should back into the spreader box and should not cross over any exposed asphalt rubber membrane. This is illustrated in Figure 4-3; the chip spreader is in the foreground of the photo, and the raised bed of the haul truck can be seen behind the spreader. The speeds and loads of the trucks hauling the chips should be regulated to prevent damage to the new seal. They should turn as little as possible on the new seal.

The chip spreader should be operated at a speed that will prevent the cover aggregate from being rolled as it is being applied. The aggregate supply should be controlled to assure a uniform distribution across the entire box. If an excess of aggregate is spread in some areas, it should be distributed on the adjacent roadway surface or picked up. Excess application usually interferes with embedment and adhesion and may lead to future problems with chip loss. Areas that do not get enough aggregate cover (about 85 percent of the total membrane area is a reasonable target) should be covered with additional aggregate (normally by hand), but problems with adhesion may occur, because by then the asphalt rubber has cooled.

Figure 4-3 Spreading Precoated Aggregates

Loose stones along the roadway edge after sweeping may indicate excessive chip application and wasted stone, that the asphalt rubber application is too light, or that the binder cooled before embedment and adhesion were achieved. Excess asphalt rubber application can literally submerge or swallow the chips, and results in flushing/bleeding.

4.6.4 Rolling Asphalt Rubber Chip Seals

Pneumatic rollers are normally used for rolling chip seals because the kneading action of the rubber tires promotes embedment. The tires do not bridge across surface irregularities and depressions, as do steel drums.

Skirts around the tires can help maintain elevated tire temperature to aid compaction and minimize any pickup. Rolling of a chip seal is done to orient and embed the rock (get the flat sides down). Rollers should be operated at slow speeds of 4 to 6 mph (6 to 10 kph) so that the rock is set, not displaced. The number of rollers required depends on the speed of operation, as it takes 2 to 4 passes of the roller to set the rock (Figure 4-4).

Figure 4-4 Rubber-Tired Rollers with Skirts on Chip Seal

4.6.5 Sweeping

Sweeping (brooming) is done at the completion of chip sealing to remove surplus aggregate from the surface of the new chip seal to minimize flying rocks. Sweeping can be done shortly after chip application, usually within 30 minutes. It is desirable to sweep during the cool period of the day using a rotary power broom (Figure 4-5).

Figure 4-5 Sweeping Chip Seal to Remove Loose Cover Aggregate

Figure 4-6 shows the surface of a finished asphalt rubber chip seal after sweeping, before application of flush coat and sand. For interlayers, no flush coat or sand is applied.

4.6.6 Flush Coat

The flush coat consists of an application of fog seal over the new asphalt rubber chip seal followed by a sand cover.

Figure 4-6 Finished Chip Seal Before Applying Fog Seal and Sand

4.6.6.1 Fog seals are applied over chip seals to help retain the cover aggregate and provide a more uniform appearance. Fog seals are not applied over SAMI-R because it will be covered with an overlay. Fog seals typically consist of grade CSS-1, CSS-1h, or CQS-1 asphalt emulsion diluted with 50 percent added water. The standard application rate over asphalt rubber chip seals is 0.14 to 0.27 l/m^2 or as determined by the Engineer.

4.6.6.2 Sand cover is applied immediately after application of the fog seal to prevent pick up and tracking of the chip seal material by vehicle tires. The sand must be clean (free of clay fines or organic material). It is spread in a single application of 1 to 2 kg/m^2, or at a rate determined by the Engineer.

4.6.7 Traffic Control

Some form of traffic control is required to keep the initial traffic speed below about 25 mph (40 kph). Flag persons or signs help, but the most positive means is a pilot car. The primary purpose of the pilot car is to control the speed of the traffic through the project. This traffic will also supply some additional pneumatic tire rolling and kneading action.

5.0 REFERENCES

American Society of Testing and Materials, 2001. "D 6114 Standard Specification for Asphalt rubber Binder," in *Vol. 4.03, Road and Paving Materials; Vehicle-Pavement Systems*, Annual Book of ASTM Standards 2006, ASTM, West Conshohocken, PA, 2001.

American Society of Testing and Materials, 2001. "D 8 Standard Terminology Relating to Materials for Roads and Pavements," in *Vol. 4.03, Road and Paving Materials; Vehicle-Pavement Systems*, Annual Book of ASTM Standards 2006, ASTM, West Conshohocken, PA, 2001.

Asphalt Rubber Producers Group, 1989. "Rubber Used in Asphalt-Rubber Applications," Proceedings, National Seminar on Asphalt-Rubber, Kansas City, MO, October 1989.

Bahia, Hussain and Robert Davies, 1994. "Effect of Crumb Rubber Modifiers (CRM) on Performance-Related Properties of Asphalt Binders," *Journal*, AAPT, 1994, pp. 414-441.

Baker, Tim, 1993. "Production of Crumb Rubber Modifier (CRM) Material," Session 3, Workshop Notes, FHWA Crumb Rubber Modifier Workshop, Atlanta, GA, February 1993.

Caltrans, 1998. "Maintenance Manual - Volume 1," (out of print, but available on Caltrans Website), Caltrans, Sacramento, CA June 1998.

Caltrans, 2001. "Flexible Pavement Rehabilitation Manual," Sacramento, CA June 2001.

Caltrans, 2005a. "Draft Open Graded Friction Course Usage Guide," November 2005.

Caltrans, 2005b. "Use of Scrap Tire Rubber-State of the Technology and Best Practices," Office of Flexible Pavement Materials, February, 2005.

Caltrans, 2005c. "Feasibility of Recycling Rubber-Modified Paving Materials," Office of Flexible Pavement Materials, Sacramento, February 2005.

Caltrans, 2005d. "Rubberized Asphalt Concrete Firebaugh Project Volume 1 - Construction Report," Office of Flexible Pavement Materials, March, 2005.

Caltrans, 2005e. "Rubberized Asphalt Concrete District 1 Project Volume 3 - Construction Report," Office of Flexible Pavement Materials, October 2005.

Caltrans, 2005f. "Synthesis of Caltrans Rubberized Asphalt Concrete Projects," Office of Flexible Pavement Materials, October, 2005.

Caltrans, 2005g. "Rubberized Asphalt Concrete Warranty Pilot Projects Volume 1 - Construction Report," Office of Flexible Pavement Materials, September 2005.

Caltrans, 2005h. "Recommendations for Using RAC in New Pavements and for Structural Overlays," Office of Flexible Pavement Materials, December, 2005.

Caltrans, 2006a. "Highway Design Manual 2006 Update Chapter 630 Flexible Pavement," Caltrans, Sacramento, CA, 2006.

Caltrans, 2006b. "Use of Rubberized Asphalt Concrete for New Construction," Memorandum, Caltrans, Sacramento, CA, April 24, 2006.

Charania, E., Joe O. Cano, and Russell Schnormeier, 1991. "A Twenty Year Study of Asphalt-Rubber Pavements in the City of Phoenix, Arizona," Asphalt Rubber Producers Group 1991.

Chehovits, J.G. and Hicks, R.G., "Mix Design Procedures, 1993. "Session 10, Workshop Notes, FHWA Crumb Rubber Modifier Workshop, Atlanta, GA, February 1993.

Chehovits, J.G., 1993. "Binder Design Procedures," Session 9, Workshop Notes, FHWA Crumb Rubber Modifier Workshop, Atlanta, GA, February 1993.

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

Epps, Jon A., 1994. "Uses of Recycled Rubber Tires in Highways," *NCHRP Synthesis 198*, Transportation Research Board, 1994.

FHWA, 1993. "Crumb Rubber Modifier Workshop Notes, Design Procedures and Construction Practices," FHWA-SA-93-011, Federal Highway Administration, 1993.

FHWA, 1996. "National Highway User Survey," Federal Highway Administration, May 1996.

Heitzman, M., 1992. "State of the Practice – Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier," *FHWA-SA-92-202*, Federal Highway Administration, May 1992.

Hicks, R.G. and Epps, Jon A., 1999. "Evaluation of Caltrans Modified Binder Specifications," Final Report to RPA, March 1999.

Hicks, R.G. and Epps, Jon A., 2000. "Quality Control for Asphalt Rubber Binders And Mixes," Proceedings, Asphalt Rubber 2000, Portugal, November 2000.

Hicks, R.G., 2001. "Asphalt Rubber Design and Construction Guidelines," Final Report to NCRACTC, May 2001.

Hicks, R.G., J. Lundy, R. B. Leahy, D. Hanson, and J. Epps, 1995. "Crumb Rubber Modifier in Asphalt Pavements," *FHWA-SA-95-056*, Federal Highway Administration, September 1995.

Hildebrand, Gary and Van Kirk, Jack, 1996. "Asphalt Rubber Performance Evaluation," Internal Caltrans Report, April 18, 1996.

Holland, T. Joseph and Brown, Lance, 2005. "Caltrans Pavement Maintenance Using Rubberized Asphalt Concrete", Caltrans Division of Maintenance, Sacramento, CA, December 2005.

Holleran, Glynn and Van Kirk, Jack, 2000. "Reduced Thickness Asphalt Rubber Concrete Leads To Cost Effective Pavement Performance", *Proceedings*, Asphalt Rubber 2000, Portugal, November 2000.

Holleran, Glynn, 2000. "Emulsification of Asphalt Rubber Blends", Proceedings, Asphalt Rubber 2000, Portugal, November 2000.

Martignoni, Beatrix, Leni Mathias Leite and Romulo Santo Constantino, 2000. "Studies of Asphalt Rubber Using Various Sources of Ground Tire Rubber", Proceedings, Asphalt Rubber 2000, Portugal, November 2000.

McDonald, C. H., 1981. "Recollections of Early Asphalt-Rubber History," Proceedings, National Seminar on Asphalt-Rubber, October 1981.

Nevada DOT, 1998. "A Report on the Performance of Crumb Rubber Asphalt Plant Mix Bituminous Surfacing in Nevada," December 4, 1998.

Nicholson, Lynn, 1997. "Inspection of Rubberized Asphalt Concrete," (County of Los Angeles). 1997.

Nokes, W.A., et al, 1997. "Caltrans Accelerated Pavement Testing (CAL/APT) Program – Test Results: 1993-1996," Proceedings, 8th International Conference on Asphalt Pavements, Seattle, WA, August 1997.

Oliver, J.W.H., 1981. "Modification of Paving Asphalts by Digestion with Scrap Rubber," *TRR 821*, Transportation Research Board, 1981, pp. 37-44.

Raad, Lutfi, Saboundjian, Steve and Minassian, George, 2001. "Field Aging Effects on the Fatigue of Asphalt Concrete and Asphalt-Rubber Concrete," presented at Annual Meeting of Transportation Research Board, January 2001.

Rinck, Grace and Napier, Dan, C.I.H., 1991. "Exposure of Paving Workers to Asphalt Emissions (When Using Asphalt-Rubber Mixes)", Asphalt Rubber Producers Group, Washington D.C., 1991.

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

Rostler, F.S., 1971. "An Annotated Bibliography on Use of Rubber in Asphalt Pavement," *FHWA-RD-72-1*, Federal Highway Administration, May 1971.

Sacramento County Department of Environmental Review and Bollard & Brennan, Inc., 1999. "Report on the Status of Rubberized Asphalt Traffic Noise Reduction in Sacramento County," Sacramento County Department of Environmental Review and Bollard & Brennan, Inc., November 1999.

Sebaaly, Peter E., et al., 1998. "Laboratory Evaluation of Rubber-Modified HMA Mixtures," U. of Nevada-Reno, May 6, 1998.

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

Shatnawi, Shakir, 2000. "Performance of Asphalt Rubber Mixes as Thin Overlays," *Proceedings*, Asphalt Rubber 2000, Portugal, November 2000.

Takallou, H. Barry, Bahia, Hussain U., Perdomo, Dario and Schwartz, Robert, 1997. "Use of Superpave Technology for Design and Construction of Rubberized Asphalt Mixtures," *TRR 1583*, Transportation Research Board, 1997, pp. 71-81.

Transportation Research Board, 2000. "Hot-Mix Asphalt Paving Handbook 2000," National Research Council, Washington, D.C., 2000.

Troy, Kenneth, Sebaaly, Peter E., and Epps, Jon, 1996. "Evaluation System for Crumb Rubber Modified Binders and Mixtures," *TRR 1530*, Transportation Research Board, 1996, pp. 3-10.

Van Kirk, Jack L. and Holleran, Glynn, 2000. "Reduced Thickness Asphalt Rubber Concrete Leads to Cost Effective Pavement Performance," Proceedings, Asphalt Rubber 2000, Portugal, November 2000.

Van Kirk, Jack 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.

Van Kirk, Jack L., 1997. "Caltrans Pavement Rehabilitation using Rubberized Asphalt Concrete," Rubber Division, American Chemical Society, Anaheim, CA, May 1997.

Way, George B., 2000. "Flagstaff I-40 Asphalt-Rubber Overlay Project Nine Years of Success," presented at the 78th Annual Meeting of the Transportation Research Board, January 2000.

USEFUL ASPHALT RUBBER WEBSITES:

Caltrans home page < http://www.dot.ca.gov/>
Caltrans RAC Reports
<http://www.dot.ca.gov/hq/esc/Translab/fpmlab/CALTRANS_CIWMBPROJECTT021DELIVERABLES.htm>

American Chemical Society Rubber Division <http://www.rubber.org/index.htm>
Asphalt Emulsion Manufacturers Association (AEMA) <http://www.aema.org/>
Asphalt Institute <http://www.asphaltinstitute.org/>
Asphalt Recycling & Reclaiming Association <http://www.arra.org/>
Asphalt Rubber Technology Service <http://www.ces.clemson.edu/arts/index.html>
California Integrated Waste Management Board <http://www.ciwmb.ca.gov/>
Federal Highway Administration <http://www.tfhrc.gov/pubrds/spring97/crum.htm>
Federal Highway Administration <http://www.fhwa.dot.gov/pavement/index.cfm>
Federal Highway Administration <http://www.fhwa.dot.gov/pavement/topics.cfm>
National Asphalt Pavement Association (NAPA) <http://www.hotmix.org/>
National Center for Asphalt Technology (NCAT) <http://www.eng.auburn.edu/center/ncat/>
Rubberized Asphalt Concrete Technology Center <http://www.rubberizedasphalt.org/>
The Rubber Pavement Association <http://www.rubberpavements.org/>

APPENDIX A

Checklists

CHECKLIST OF MATERIALS SUBMITTALS

I. BINDER

A. Binder Formulation ❑

1) Paving Asphalt and Modifiers - % of Total Binder
   a) % Asphalt of Paving Asphalt
   b) % Extender Oil of Paving Asphalt
2) Crumb Rubber Modifier (CRM) - % of Total Binder
   a) % Scrap tire rubber of total rubber
   b) % Natural rubber of total rubber, based on
      i) Specification, and
      ii) Chemical Analysis of natural rubber

B. Rubber Test Documentation ❑

1) Chemical analysis of natural rubber
2) Chemical analysis of scrap tire rubber
3) Fiber content for both types
4) Gradations of tire rubber
5) Gradations of natural rubber

C. Certification of Compliance/Specific Product and Project ❑

1) Asphalt Cement incl. Source and Grade
2) Extender Oil incl. Source and Type ID
3) Scrap Tire Rubber including Source and Type ID
4) Natural Rubber including Source and Type ID

D. Rubber Samples (Needed for matching with materials at plant) ❑

1) Scrap Tire rubber
2) Natural rubber

E. Asphalt Rubber Binder 24-Hour Design Profile & Test Results ❑

1) Penetration
2) Resilience
3) Softening Point
4) Viscosity

F. Two binder samples ❑

II. AGGREGATE ❑

A. LA Rattler
B. Crushed Faces
C. Sand Equivalent*
D. K_c and K_f *

III. MIX DESIGN ❑

A. Target gradations within specification
B. Binder content vs. air voids plot (Form TL-306)*
D. Selected binder content (corresponding to specified air voids)
E. Show recommended range (+0%/-.3%)*
G. Stabilometer value*
H. VMA*
I. Target Gradations for specified sieves
J. Bin percentages and sieve analyses for each

** Not applicable to chip seals.*

CHECKLIST FOR PAVING AND CHIP SEALS

I. HOT MIX

A. Pre-Spread ❑

1. Functional heater element for hot asphalt tack.
2. Uniform application of tack, at agreed rate of _____.

C. Joints at proper locations (traffic lane lines or clear of wheel paths in center of lane).

D. Proper thickness at 0" grind point (screed break at grade break).

B. Compaction Equipment (Steel drum) ❑

1. Vibratory roller for (breakdown) and another vibratory for backup
2. Intermediate roller of the same or greater width than the breakdown roller
3. Finish roller

C. Compaction Process

4. No vibratory mode when mat temperature is below 121°C (250° F)
5. Intermediate roller operating at all times during paving?

D. Post Compaction ❑

1. Sand cover is required, but cannot be applied until compaction is complete except as authorized by Caltrans in special circumstances.

II. CHIP SEALS

A. Pre-Spread ❑

1. Pavement is clean and dry.
2. Pavement temperature in shade above 13° C (55°)
3. Air temperature above 16°C (60°).
4. Hot asphalt coated rocks on site
5. Nominal size chip size 9.5 mm (3/8") or 12.5 mm (1/2")
6. Trucks lock onto hitch of aggregate spreader
7. 3 rubber tire rollers (two if equivalent coverage), all functional
8. One functional 8-10 ton steel wheel roller
9. Sweeper functional
10. Joints are positioned to avoid wheel paths

B. Spread ❑

1. Binder application temperature
2. Binder application rate
3. Chip spreader following immediately behind (20-30 m) distributor truck
4. Chip application rate
5. Lead roller follows immediately behind (20-30 m) chip spreader
6. Number of coverage's by rubber tire rollers
7. Joints thoroughly swept 150 mm (6") from edge prior to overlapping application
8. Overlapping nozzle angled to cut back application rate at joints
9. Overlap at longitudinal joints, 102 mm (4") maximum

C. Post-Spread ❑

1. Sweep loose aggregate

**Falling out of compliance with these parameters will be cause to halt paving operations until reconciled.*