Rubber Modified Asphalt Technical Manual

Prepared for the Ontario Tire Stewardship
Toronto, Canada

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Abstract:

Rubber modified asphalt including asphalt rubber and terminal blend has been widely used in many countries. In order to promote sustainability and utilize recycled waste tires, Ontario Tire Stewardship would like to develop a comprehensive technical manual to support the technology transfer of utilizing rubber modified asphalt in Ontario, Canada.

This manual contains the knowledge and practices of various experienced agencies around the world, as well as Ontario's local experiences of utilizing crumb rubber in pavement. An international survey was conducted and its results were utilized in this manual. A specification report combining the knowledge around the world was generated and recommendations were provided for Ontario. The manual also includes the knowledge from recent field trials by the Ministry of Transportation, Ontario, and laboratory testing on rubberized asphalt cement.

This manual was developed to provide guidance to agencies, contractors and consulting engineers in Ontario who are using or plan to use crumb rubber modifier (CRM) in hot mix asphalt, chip seals, or interlayers. The major contents of the manual include an introduction and definitions of CRM and rubber modified asphalt, various applications and a guide for using rubberized asphalt cement, design and specification guidelines, production and construction considerations of rubber modified asphalt, inspections of rubber modified asphalt paving projects, and a summary of key points for successfully implementing the rubber modified asphalt concrete.

Keywords: Ground Tire Rubber, Asphalt Rubber, Terminal Blend, Rubber Modified Asphalt, Chip Seals and Interlayers

Foreword

The Ontario Ministry of Transportation (MTO) has experimented with rubber modified asphalt for several years. The rubberized binders have been used in both gap- and dense-graded mixes. In gap-graded mixes, the product known as asphalt rubber has been used. This product requires the use of specialized blending equipment to react the binder. Terminal blend rubber modified binders have been used in dense-graded mixes. The product is produced at a terminal where the fine crumb rubber is blended into the asphalt forming a product similar to polymer modified asphalt. Specifications for both products are now available from the MTO.

The Ontario Tire Stewardship (OTS) is working with industry and agencies to increase the use of recycled tires in asphalt pavements. They have been working closely with the MTO to place pilot projects throughout the Province and to increase the awareness of the benefits of using recycled tires in the pavement. New tire processors have been installed in Ontario to help recycle Ontario's tire population. The Province is now positioned to use rubberized asphalt products in many of their roads.

This manual was developed for use by agencies, contractors and consulting engineers in Ontario who plan on using crumb rubber modifier (CRM) in hot mix asphalt, chip seals, or interlayers. This manual has been developed by Dr. Susan Tighe (Consultant), Dr. Gary Hicks (Consultant), and Dr. DingXin Cheng for the Ontario Tire Stewardship in Toronto, Canada. The manual consists of the following chapters:

- Chapter 1. Introduction to Rubber Modified Asphalt
- Chapter 2. Application and Usage Guide for Asphalt Rubber Cement
- Chapter 3. Design and Specification Guide
- Chapter 4. Production and Construction Considerations
- Chapter 5. Inspection Guide
- Chapter 6. Summary of Key Points

In addition, it contains several appendices which include:

- Appendix A. Glossary
- Appendix B. Summary of survey
- Appendix C. Specifications for asphalt rubber field blends and terminal blends
- Appendix D. Mix design procedures for rubberized asphalt mixes
- Appendix E. Project experiences with 2011 rubberized asphalt mixes
- Appendix F. Crumb rubber sample examination performed by the MTO

Copies of the manual can be obtained from:

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Disclaimer

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ontario Tire Stewardship or the Ontario Ministry of Transportation.

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1.0 Introduction to Rubber Modified Asphalt

1.1 Introduction

This guide is a comprehensive resource for the usage of rubber modified asphalt (RMA) in Canada. Various material, design and construction aspects of RMA are presented herein with an emphasis on Canadian specifications and best practices. RMA usage is of interest to many Canadian transportation agencies based on the potential technical, economic and environmental benefits. Furthermore, as resources, namely aggregate and asphalt cement, become scarcer and more expensive, the opportunity to reuse rubber tires in asphalt pavements becomes even more attractive. The ability to reuse the crumb rubber in an engineered manner not only provides technical benefits but also potential environmental savings.

RMA can be incorporated into Hot Mix Asphalt (HMA) and placed using conventional asphalt equipment and procedures. Some slight modifications may be required and these are further discussed in this document. However, these modifications can be easily accommodated with proper training and inspection. The RMA pavements can be designed in the same manner as conventional HMA and would be expected to provide similar structural numbers. As long as quality is achieved, there should be little change in the performance of the RMA in the field as compared to conventional HMA. In fact, experiences in California, Texas and Arizona have shown that performance of these mixes is superior. In Canada, performance has not been historically as good; however, with proper material testing, RMA should show similar performance to that observed in the United States. This manual provides design and construction guidelines for the construction of quality RMA pavements with long lasting performance.

1.2 Rubber Modified Cement Types

The inclusion of crumb rubber in asphalt concrete mixes is done by either a wet or dry process. The wet process develops a range of rubber modified binders from a high viscosity type to no agitation types. There are three types of RMA and these are dependent on the process in which they are mixed into the HMA. The first type is a wet process-high viscosity which involves mixing, while the second type is also a wet process with no mixing. Finally the third type is a dry process. All three types are described below.

The crumb rubber can be produced either through ambient grinding, cryogenic grinding, or a combination of the two. Definitions for the types of processing are given in Appendix A. The type of processing can have an effect on the performance of the paving mixture as will be discussed later in the manual.

1.2.1 Wet Process – High Viscosity (Asphalt rubber)

The wet process or field-blended asphalt rubber incorporates the crumb rubber modifier (CRM) directly into the asphalt cement (AC) before it is mixed into the RMA. When the CRM is mixed into the hot asphalt cement, it must be maintained between 205 and 220^{o}C. Once the mixing process is complete, the CRM-AC blend should be maintained between 165 and 220^{o}C for at least 45 minutes to one hour. This is important to ensure the CRM-AC blend is completely mixed. During this time, other extenders, asphalt modifiers and/or high natural CRM may be added depending on the specific material requirements for the pavement. It is also important to note that during the mixing of the CRM-AC, the CRM will swell and various chemical reactions may occur. When the material is stable, it is then ready for addition to the HMA. Typically, the high viscosity type of asphalt rubber contains approximately 18-22% crumb rubber, with particle sizes of 2.00 mm (Sieve No. 10) to 2.36 mm (Sieve No. 8). The wet process or field-blended asphalt rubber is typically used in gap- or open- graded mixes and chip seal applications.

Photo of Crumb rubber used in asphalt rubber in California

Photo of Crumb rubber used in Ontario

1.2.2 Wet Process – No Agitation (Terminal Blends)

The second type of RMA also involves a wet process, but in this case the CRM is not mixed with the AC. It is instead produced without mixing and is often referred to as a ***terminal blend.*** In this case, the CRM particle size is less than 600µm (Sieve No. 30) and is blended with hot asphalt cement at the terminal. It can then be transported to the asphalt plant for mixing. This type of RMA does not require agitation to keep the CRM particles evenly distributed in the asphalt cement. The no agitation type binder generally contains a maximum of 15 to 25 % crumb rubber.

Terminal blends can be used in all paving and maintenance applications requiring crumb rubber content. They have been used in dense-graded, open-graded and gap-graded mixes, but are best for dense-graded mixes. They can also be used in chip seal applications, slurry seal applications, and tack coat applications. Terminal blends can be used with rubber contents as low as 5% and as high as 25%, depending on the application and the project's requirements [AI 2008].

Photo of High Viscosity (left) vs. terminal blend (right) rubberized binders used in California

1.2.3 Dry Process

The third process for adding the CRM into the HMA to make RMA involves addition of the CRM in dry form. The CRM is used as an aggregate substitute in the HMA. The CRM is added to the mix and replaces between one and three percent of aggregate. The CRM in this case acts more as an aggregate instead of an asphalt cement.

The CRM usage in a dry process mixture is not intended to alter the asphalt cement; although, it is recognized that some interactions do occur over time in the form of light absorption of the asphalt cement into the CRM in the mix. Gradations of the CRM aggregate range from slightly larger than 50mm in size to as small as 0.180mm sieve size. This type of product is not widely used in either the USA or Canada.

1.3 Asphalt Rubber Cement Components

The materials and their respective proportions are determined in accordance with the local specifications. The asphalt rubber binder must meet all of the asphalt specifications for the intended pavement design.

1.3.1 Crumb Rubber Modifier

Crumb rubber modifier (CRM) is composed of ground scrap tires, tread buffing and other waste or excess rubber products. Currently, there are a number of available processes and equipment used to produce the required gradations of CRM material to be used in RMA. The list of current CRM suppliers in Ontario is provided below:

Liberty Tire Recycling

Contact: Jeff Bateman
Phone: 1-519-752-7696 / 1-800-387-8473 (mobile: 1-519-590-7070)
E-mail: jbateman@libertytire.com
Website: www.libertytire.com
Location: 300 Henry Street, Brantford, Ontario

CRM Co ULC
Contact: Christie Newmeyer
Phone: 949.263.9100 (mobile: 949.529.6444)
E-mail: CNewmeyer@CRMRubber.com
Website: www.crmrubber.com
Location: 150 Garden Ave, Brantford, Ontario

For additional information on crumb rubber suppliers, please contact:

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(o) 416-626-9185
(m) 416-428-7702

1.3.2 Asphalt Cements

Asphalt cement specifications are well established in Canadian transportation agencies and industry suppliers are very experienced with meeting the required quality parameters for use in asphalt pavement. Conventional asphalt specifications were developed to define physical properties such as penetration, viscosity and ductility. A criticism of these conventional physical property tests was that they were performed at standard temperatures, regardless of the environmental characteristics of the intended area of use. In an effort to address the shortcomings of the traditional conventional asphalt grading subsystems, such as ASTM and AASHTO, the Strategic Highway Research Program (SHRP) in the United States and the Canadian counterpart (C-SHRP) undertook, as a primary objective, the development of performance based grading specifications for asphalt cements [TAC 2012].

Testing protocols were developed to represent field performance. The resultant performance grade asphalt cement (PGAC) specification classifies asphalt cements based on the temperature environment for their intended use. Asphalt cements are performance graded and required to comply with specified requirements at both the low and high pavement in-service temperatures which must be determined on a project specific basis [AASHTO 2010, TAC 2012].

DSR test use by the MTO

BBR test used by the MTO

In Canada, the majority of agencies use PGACs which are specified by AASHTO M 320 [AASHTO 2010]. Very few agencies use penetration grade specifications. In southern Canada, the asphalt cements tend to be harder or stiffer to withstand higher traffic volumes, while in the northern part of Canada, softer asphalt cements tend to be used. In general, when CRM is added to the asphalt cement, softer grade asphalt cement is more desirable to achieve a better quality RMA.

In California, the Performance Graded Terminal Blended Rubberized Asphalt (PG-TR) grades are specifically targeted for use in the same applications for which Performance Graded Polymer Modified Asphalt (PG-PMA) cements are used, including dense-graded mixes for thick structural sections [Caltrans 2008, AI 2008]. Typical terminal blended grades are PG64-28TR, PG70-22TR, and PG76-22TR. These grades can have varying rubber contents from as low as 5% to as high as 25% by weight. Caltrans, Nevada Department of Transportation (NDOT), and the Pacific Coast Conference on Asphalt Specifications (PCCAS) have adopted the PG terminal blends and have accepted them as an alternative to PMA materials. In 2008, Nevada DOT built a six-mile project with PG64-28TR as a replacement for their PG64-28NV specification [AI 2008]. Several projects have been placed in California using this product for both chip seals and in HMA.

In Canada, typical PG binders would include: PG 52-34 (northern, cold climate areas), PG 58-34 (moderate climate areas) and PG 58-28 (southern, warmer climate areas). It is important to note that these grades are often bumped due to both higher traffic levels and static or slow moving levels. This can result in PG 64-28 and/or possibly PG 70-28 for areas where there is extensive truck traffic that is slow moving or stopped [OHMPA 1999]. When CRM is added to the asphalt cement, it should meet the final PG grade specified for the pavement design. Thus, the base PG asphalt cement prior to addition of rubber may be different from the final rubber asphalt PG. One of the challenges with this is that the blended rubber materials, especially field blend, may not be suitable for testing using the standard PG asphalt cement test such as the AASHTO M320 [AASHTO 2010].

1.3.3 Additives

Use of additives with the asphalt cement in HMA is often related to enhancing the mixture workability and compatibility. Various modifiers have been developed, mainly to reduce the temperature susceptibility of asphalt materials. This can be accomplished by improving the critical stiffness properties of the asphalt cement at both the low and high service temperature extremes. With the adoption of PGAC by most agencies in Canada, specific engineered asphalt specifications are becoming obsolete as the PGAC specifications set the performance requirements. Possible additives used with CRM can include: extender oils, high natural rubber (HNR), polymers (mainly in no agitation binders) and/or mineral admixtures [Caltrans MTAG 2008].

Samples of high natural rubber and crumb tire rubber. The HNR is on the bottom

1.4 History of Asphalt Rubber

The earliest application of asphalt rubber was during the 1930s as a joint sealer, in patches and in membranes. The effects of the application of rubber in asphaltic paving material were investigated in the 1950s by the Bureau of Public Records of the State of California using a number of different rubber powders and asphalt combinations. By the 1960s, the first symposium on rubber in asphalt was held by the Asphalt Institute and included a number of paper presentations and discussions on the innovative inclusion of rubber in asphalt paving material [Sacramento 1999].

Photos of Caltrans projects placed in 1983 and taken in 1993. Pavement was placed in northeast California in a cold dry climate where thermal cracking is prevalent.

1.4.1 International History and Experience

Since the 1960s, rubber material has been used by government jurisdictions mainly in chip seals, interlayers and HMA. In the United States, it has been used in California, Arizona, Florida and Texas. As noted, these states exhibit warmer climates. This usage has been documented and it has been shown that RMA does provide noise reducing benefits [Sacramento 1999]. Since the early days, its use has expanded to colder regions in the United States, China, and Scandinavia [Cheng and Hicks, 2012]

Terminal blended asphalt rubber technology has been used since the mid-1980s in many states. In the terminal blending of rubberized asphalt, tire rubber is blended into the asphalt cement at the asphalt terminal or refinery and shipped to the hot mix production plant as a finished product with no additional handling or processing. The tire rubber is completely digested into the asphalt to provide styrene, butadiene, carbon black and aromatic oils yielding a homogeneous material that exhibits excellent storage stability and compatibility with the finished binder formulation [AI 2008]. This product is very similar to polymer modified asphalt cement.

Terminal blended rubberized asphalt (TR) was first used in Texas in the mid-1980s. It was initially used in Texas and Louisiana in dense-graded hot mix. A modified, hot-applied chip seal was adapted in Texas about the same time. Not long after, TR was used in open- and gap-graded surface courses in Texas, Florida, Louisiana, New York, Arizona, California and Nevada [AI 2008]. The Wright process of terminal blending is used by many of these states.

In addition, in Belgium, research involving open-graded rubberized asphalt has also been shown to reduce noise pollution at traffic speeds of 50km/h in the range of 2.1 to 3.2 dBA. Similar studies have been conducted in the United States, France, Austria and Germany on the noise reducing effect of rubberized asphalt concrete with similar results [Sacramento 1999].

1.4.2 Canadian History

Rubber modified asphalt has had limited application in Canada, though several agencies are in the process of investigating the inclusion of RMA in current transportation infrastructure.

Ontario

The province of Ontario has over 30 years of experience with rubber asphalt projects. During the first trials, between 1980 and 1995, the objectives included determining whether the addition of scrap tires into asphalt was environmentally acceptable, identifying if rubber asphalt pavements could be recycled, and determining rubberized asphalt's economic feasibility. The majority of these trials adopted a dry process mix, where the rubber is added as a portion of the aggregate content. Performance of these test sections was generally moderate to poor [Tabib 2009]. One significant trial was built in two phases on Highway 2 in Thamesville, Ontario to evaluate feasibility and performance of RMA [Lawrence 1991]. In Phase 1 of construction, advances were made especially in the areas of worker safety, as the additional hazards of working with rubber asphalt became understood [Lawrence 1991]. With the benefits of recycling asphalt already known, and following the successful completion of Phase 1, the objective of Phase 2 was to determine the recyclability of rubber asphalt pavements [Aurilio 1993]. The test sections were successfully removed, recycled, and repaved. Results of the recycled pavement were similar to the original results, with stone loss noted as the only major issue [Aurilio 1993]. A 1994 review of 11 Ontario rubber asphalt projects noted that roller pick up had been a serious construction issue [Emery 1994].

A comparative study, conducted in 1995 examined the differences between moist-process (similar to dry process, but using crumb rubber particles smaller than 600 μm in size) and wet-process asphalt mixes. A City of Brantford project was chosen as the representative moist design. A 500 m test section was paved in Brantford in 1994. Initial testing determined that the pavement performed acceptably in every area [Carrick 1995]. The Town of Kirkland project was chosen as the wet-process representative. A 300 m test section was constructed in 1994. No significant problems were noted and the project is considered a technical success [Carrick 1995]. However, the wet process mix was associated with an additional initial cost 40% greater than the moist process mix [Carrick 1995].

Following these initial trials, the Ministry of the Environment (MOE) and the Ministry of Transportation (MTO) sponsored a 1997 study to evaluate the performance of 15 test sections. Visual inspections, distress surveys, deflection and frictional properties testing, and pavement profile measurements were conducted [Tabib 2009]. The report from this project included several key findings. First, sections constructed using the dry process generally performed worse than sections constructed of conventional HMA, while sections constructed using the moist process were somewhat comparable to conventional pavement sections. Wet-process test sites exhibited superior performance to other rubber asphalt mixes, and were generally similar to conventional pavements [Tabib 2009].

A continuum to the 1997 study was performed by the MTO in 2003, to evaluate the long-term performance of rubber asphalt sections within the province. The 2003 survey collected information on the current traffic volume, the date of resurfacing and the pavement condition prior to resurfacing, as well as other general comments. The findings from this survey indicated that many of the pavements had been resurfaced in 2003. However, due to limited information, no firm conclusions could be drawn regarding performance [Tabib 2009].

The Regional Municipality of Waterloo (RMOW), Ontario, Canada, in partnership with the University of Waterloo Centre for Pavement and Transportation Technology (CPATT), investigated three types of noise reducing pavements: Rubberized Open Graded Friction Course Asphalt Pavements (rOFC and rOGC) and Stone Mastic Asphalt Pavement (SMA). The two types of open friction course asphalt pavements had a similar mix design, but were different in the quality of the aggregate. Two types of field sound level measurements were conducted in this study: Close-Proximity Method and Controlled Pass-By Method. Laboratory testing including impedance tube testing was utilized to determine the pavement sound absorption properties [Leung 2006]. The study found that vehicle noise increases when the vehicle speed or size increases for both test methods. The SMA pavement type did not provide any noise reductions for light sized vehicles and for vehicle speeds of 60 km/h and 70 km/h in both test methods. rOFC and rOGC provide the highest amount of noise reduction in both testing methods. The highest noise reduction amounts for rOFC and rOGC pavement were 3.3 dBA in the CPX results. For the pass by method results, the highest noise reduction amounts were 2.5 dBA and 2.8 dBA for rOFC and rOGC pavement, respectively. Also, both rOFC and rOGC could reduce a larger amount of noise in a medium vehicle category. Although rOGC contained local aggregate, it performed slightly better than rOFC which contained premium aggregate at all testing vehicle speeds.

Most recently in Ontario, the MTO constructed two 500 m test sections on Highway 15 north of Smiths Falls. The sites, constructed in 2008, used a moist process and two types of CRM: ambient and cryogenic. These two sections are the first rubber modified Superpave mixes in Ontario. Several construction issues were noted, including slight segregation, visible fumes, increased coring difficulty, and air void inconsistencies. A longer evaluation period is needed to provide any conclusive results [Tabib 2009]. Results from projects constructed in 2011 are summarized in Appendix E

Saskatchewan

Saskatchewan's early experience with rubber asphalt was in the form of seal coats. In the summer of 1978, eight test sections were constructed using rubber binder seal coats [Scott 1979]. Despite several construction difficulties associated with rubber asphalt's first time use, the project was implemented successfully [Scott 1979]. A five-year review of the 1978 project determined that the only issue present in the test sections was stone loss in the seal coat [Scott 1984]. However, the quality of the product and the success rate had improved each year since the implementation [Scott 1984].

In July 2005, Saskatchewan's Ministry of Highways and Infrastructure (MHI) constructed three rubberized asphalt test sections along Highway 11 between Regina and Saskatoon. The purpose of the project was to evaluate the effectiveness of rubberized asphalt as an overlay treatment in the rehabilitation of conventional asphalt concrete pavements [Anthony 2008]. Prior to the 2005 trials, the province's experience with asphalt rubber was limited to its use in graded aggregate seals and crack filling [Anthony 2008]. While conventional asphalt mixes in Saskatchewan typically incorporate 26% natural aggregate materials, the rubber test sections contained only manufactured aggregates. Following the recommendations of Caltrans, the MHI adopted a reduced layer thickness of 40%, from the conventional required thickness of 120 mm to a total constructed thickness of 70 mm in the constructed asphalt rubber [Anthony 2008].

The contractor noted several challenges associated with constructing asphalt rubber. Required temperatures of both the asphalt cement and asphalt concrete required onsite storage and heating and resulted in increased fume levels, resulting in crew discomfort. Additionally, consistency of the asphalt rubber binder was more difficult to achieve, and proper mixing and viscosity were essential to proper construction [Anthony 2008].

Through both field observations and laboratory tests, several conclusions were drawn from the trials. After three years in service, the asphalt rubber performed comparably to conventional sections. The surface texture of the rubberized asphalt was observed to be rougher than the conventional mix. It was also observed that reflective cracking was slowed in the asphalt rubber sections. Laboratory testing indicated there were no major differences in material behaviour between conventional and rubber asphalt at 20ºC [Anthony 2008].

Alberta

Alberta Infrastructure and Transportation (AIT) has conducted trials with rubberized asphalt since the late 1970s. Poor performance of initial tests halted rubber trials for several decades. Beginning in 2002, trial projects were launched to further investigate the use of rubber asphalt within the province. A total of 7 asphalt rubber projects were constructed between 2002 and 2006 [Juhasz 2007], including one chip seal project and one employing a high binder friction course. Initially, lower volume roads were chosen so the impact of any potential failures would be minimized [Juhasz 2007]. Initial lab testing was used to aid in the construction of projects located in Lethbridge. Testing determined the optimal proportion of rubber in the mix design, along with several other expected physical properties [MacLeod 2007]. Over the course of these 5 years, Alberta was able to adapt early requirements to best suit the needs of the province and of contractors. For instance, after initially adopting the Arizona Department of Transportation's method specifications for all rubberized projects, AIT was able to develop its own specifications for rubber asphalt, using the preferred product specifications [Juhasz 2007]. The construction specifications have been revised several times during the trial period. Additionally, advances to mix design and requirements, tendering and costs, and quality assurance have been achieved within the province.

Many performance metrics have been observed and collected from the field. First, it has been observed that rubber asphalt has not reduced low temperature transverse cracking on Alberta roads. According to AIT, literature indicates that rubber asphalt will not prevent thermal reflective cracking, the main source of the province [Juhasz 2007]. Secondly, moderate noise reduction was observed in the sections paved with rubber modified asphalt, although the improvement was shown to decrease after several years [Juhasz 2007]. Skid resistance was slightly higher in the rubberized sections compared to conventional asphalt. Additionally, laboratory testing has yielded favourable results for rubber asphalt samples [Juhasz 2007]. In general, AIT concluded that rubber asphalt did not outperform comparative conventional asphalt, and actually performed worse in some cases. Under the current process, AIT predicts very limited continued use of rubberized asphalt within the province [Juhasz 2007].

British Columbia

The province of British Columbia (BC) began rubber asphalt trials in 1992, with three trials. The success of these early trials prompted 4 additional full-scale projects in 1994 and 1995 in the Vancouver area. These projects were implemented primarily to aid with rutting and reflective cracking and employed reduced thicknesses of rubber asphalt. One construction issue noted by all 4 projects was pick-up of the sticky rubberized hot mix [Johnson 1995]. Contractors used soapy water, diesel fuel-water mixture, or an environmentally friendly solvent on the rollers to manage the issue, with varying degrees of success. Conclusions from this study included the potential to manufacture rubber binder for a wide range of climates or customer requirements. Additionally, the rubberized asphalt was shown to be more flexible than conventional asphalt, even at sub-zero temperatures [Johnson 1995].

The previous trials within the province culminated in a full-scale demonstration project that began in 2004. The project was constructed on Highway 6 in southeastern BC. The selection of location allowed the Ministry of Transportation (MoT) to compare rubber asphalt to conventional surface mix, two thicknesses of rubber asphalt, and rubber asphalt subjected to high and low traffic volumes [Johnston 2005]. The project experienced similar construction issues to those that were experienced during the 1990s. Roller pick-up was alleviated with a detergent-based agent. To assist in the evaluation of the project, an extensive performance monitoring program was developed. The program included reflective cracking assessment, structural performance, and surface characteristics such as ride quality, skid resistance, and noise assessments [Johnston 2005]. Based on initial results, the greatest benefits of asphalt rubber were in the areas of noise reduction (rubber asphalt initially reduced noise by 5 dB or more compared to conventional sections) and rutting resistance [Johnston 2005].

1.5 Types of Applications

Rubberized asphalt has a number of uses, including spray and hot mix applications. Each of these is briefly discussed in the following sections.

1.5.1 Chip Seals

A chip seal spray application is a surface treatment where an application of aggregate is applied directly to an asphalt film sprayed on the subgrade or base course or surface. Single-sized seals consist of a uniform stone chip and a rapid setting (RS) emulsion. These seals are widely used in eastern Canada and are for the most part double seals [TAC 2012]. The first layer of a double seal usually uses larger aggregates, with the second application of smaller-sized aggregates interlocking with the first layer .

Chip seal operation

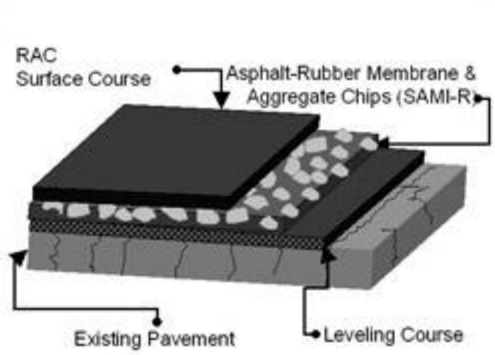
When adding rubber to the chip seal, it is necessary to use a distributor with a large enough nozzle to mitigate the risk of clogging due to rubber particles in the membrane. The use of clean or pre-coated aggregate chips is standard in all chip seal mixtures and they must be raised to the appropriate temperature when used in an asphalt rubber cement. The chips are to be included into the asphalt rubber membrane through rolling while the membrane is hot. The inclusion of chip seals in the asphalt rubber membrane at cooler temperatures (less than 15°C) may discourage the surface treatment from meeting the quality requirements of the project.

Photo of chip seal operation before sweeping

1.5.2 Interlayers

Interlayers are required for the maintenance and rehabilitation of existing pavement infrastructure. Both chip seals and interlayers use the same equipment and application procedures. Structurally sound pavements are usually repaired using high viscosity rubberized binders over severe cracks. The application of rubberized binders in interlayers and chip seals provides a longer service life than conventional asphalt binders and longer performance in resisting reflective cracking.

Photo of an interlayer



Schematic of an interlayer

1.5.3 Hot Mix Asphalt

HMA includes a wide range of aggregate mix types including gap-graded, open-graded, open-graded high binder and dense-graded. The gap- and open- graded mixes can be successfully placed using the wet process high viscosity rubber binder in surface courses while dense-graded mixes tend to use the wet process terminal blends or no agitation binders. These are the applications which have been used normally by agencies in the USA and Canada. However, the rubber used in the United States for the field blended products tends to be coarser than that used in Ontario.

1.6 Overview of Asphalt Rubber Binder Production

Both HMA and spray applications can use the wet process high viscosity asphalt rubber binders. They are produced using the same method. However, the primary difference is related to the interaction between the CRM and the asphalt cement to successfully produce enough asphalt rubber cement to create RMA at the specified rate. For spray applications, asphalt cement is usually produced near the job site and must be coordinated with application operations. For HMA applications, the asphalt cement is produced at the plant site.

The quality of an asphalt rubber cement is dependent on the proportion of the ingredients, the temperature at production, the degree of agitation and the time it takes to complete the production. Temperature is an especially critical component of binder production and temperature gauges and/or thermometers must be visible and monitored frequently. The tanks that store the asphalt rubber binder between the initial blending and the application of the material must be heated and insulated to maintain the appropriate temperature for application. Transfer lines should also be insulated to maintain heat. The equipment used to produce and store the asphalt-rubber should be equipped with a heater or heat exchangers to heat the asphalt cement and/or asphalt-rubber cement. This is especially important in Canada due to the large change in temperatures that can occur during the day and over the course of a number of weeks.

While the equipment used to feed and blend the components of the RMA mixes may vary slightly based on its type and manufacturer, the general process is the same. The materials are divided into high shear blending units to include the required proportions of the crumb rubber modifier into the paving grade asphalt. The blending units mix the CRM into the hot asphalt cement resulting in a blend that is pumped into a heated tank to allow for the asphalt-rubber interaction to occur.

Typical blending unit used for the field blended projects

To thoroughly agitate the high viscosity asphalt rubber, augers are used to keep the CRM particles from settling or floating to the surface. Agitation should be monitored periodically to maintain sufficient dispersion of CRM particles. To monitor the viscosity of the asphalt rubber interaction, a hand held rotational viscometer is used. The asphalt rubber binder must meet the minimum viscosity specification and the interaction time should be at least 45 minutes before it can be included in a hot mix or spray application [ASTM 2006a].

Photo of a Haake Viscometer measuring the viscosity of the binder

1.6.1 Holdover and Preheating Issues

There are four main areas of concern when working with asphalt rubber binders since the temperature of the cement has a strong influence on the quality of the product. First, the heating period for the asphalt rubber should be discontinued 4 hours after the 45 minute reaction period. Second, the rubber asphalt cement can only be reheated twice before the quality is compromised. Third, the asphalt rubber cement must meet all specified quality requirements. Finally, if the viscosity of the rubber asphalt has to be restored, additional CRM can be added up to a maximum of 10% of the binder mass. In short, if holdover is required, it is important that the aforementioned procedures are implemented to ensure the quality is maintained.

1.6.2 Required Documentation

When using RMA pavement, quality control and assurance procedures must be followed to ensure the material and application are in accordance with the local agency specifications. The asphalt rubber cement production log should be submitted as required documentation during the project. In addition, laboratory test results related to the specification including the chemical composition of the scrap tire and natural rubber used as CRM and the asphalt modifier, if included in the cement, should be documented. All documentation should be provided to the contract administrator when the materials are delivered. Samples of the components and the cement are typically tested by the owner to ensure specification compliance. These are in accordance with the agency specification requirements.

The approved asphalt rubber cement design profile should be available at the blending site and should contain the laboratory test results and the proportions of the components of the cement. The binder design profile that accompanies the binder material from the supplier is a guide that indicates the tested properties of the asphalt cement. The test data can provide potential warning of specification non-compliance and provide the opportunity for corrective measures to be taken.

	MINUTES OF REACTION					SPEC. LIMITS @ 45 MINUTES (CALTRANS 7/2002)
TEST	45	90	240	360	1,440	
VISCOSITY, CP HAAKE@ 190C	2400	2800	2800	2800	2100	1500 - 4000
RESILIENCE@ 25C (% REBOUND)	27	–	33	–	23	18 Minimum
R & B SOFTENING PT., C (ASTM D36)	59.0	59.5	59.5	60.0	58.5	52 - 74
CONE PEN @ 25C (ASTM D217)	39	–	46	–	50	25 – 70

Typical binder profile for field blended cements

A log of the production of the asphalt rubber cement should also be produced for each project, documenting the weight of each component, the reaction start time, the results of each viscosity test, which includes the time and the asphalt temperature, and the time when the batch of asphalt rubber cement was metered into the asphalt concrete plant. The log should also include any holdover information and/or reheat cycle information on the batch including the time heating was discontinued, the time reheating began, the corresponding asphalt rubber cement temperature, crumb rubber addition weight and time of addition, if applicable, and the results of any subsequent viscosity test results.

1.6.3 Sampling and Testing

Sampling and testing should be done for the asphalt cement periodically depending on the nature of the materials, the project size and the available resources. In addition, testing the asphalt rubber cement requirements and sampling should be conducted whenever there are changes to any material or in the material behaviour. Sampling can also be conducted during production and construction with limited interference to either process and with limited expense.

At least one set of viscosity tests is required to comply with the specifications for an asphalt rubber batch and holdover load. The results of every viscosity test, including the time of the test and the asphalt rubber cement temperature should be submitted to the contract administrator.

1.7 Terminal Blends

This wet process involves the CRM blending into the asphalt cement at the asphalt refinery. It can be ordered directly from the supplier and does not require any equipment modifications. It can also be tested according to the PGAC specifications as described earlier. This method does not require any additional agitation as the CRM is distributed evenly in the mix. This is possible due to the fact the CRM particles are finer in comparison to the wet high viscosity process. The particles break down through the normal circulation within the asphalt storage tank as opposed to requiring special mixing. These asphalt rubber cements may undergo significant modification changes. In any case, the minimum viscosity should be monitored to ensure the specifications are met [AI 2008].

The storage of terminal blended rubberized asphalts is similar to other blended asphalts. They are storage-stable binders, as long as the tire rubber is fully digested into the binder. No special equipment is required for shipment or paving with terminal blended asphalt. The material is delivered to the hot mix plant by truck, mixed and shipped to the job and no special equipment is required for paving or odour/fume control. The terminal blend mix is produced and compacted like regular hot mix asphalt. In some cases, the contractor will need a dedicated storage tank for the terminal blend asphalt cement.

1.7.1 Required Documentation

When using the wet process terminal blended RMA, quality control and assurance procedures must be followed to ensure the material and application is in accordance with the agency specifications. The terminal blend production log should be submitted as required documentation during the project. In addition, laboratory test results related to the specification including the chemical composition of the scrap tire rubber used as CRM should be documented. All documentation should be provided to the contract administrator when the materials are delivered. Samples of the components and the asphalt cement are typically tested by the owner to ensure specification compliance.

A log of the production of the terminal blend rubber cement should also be produced for each project, documenting the weight of each component, the reaction start time, the results of each viscosity test, including the time and the asphalt temperature, and the time when the batch of asphalt rubber cement was metered into the asphalt concrete plant.

1.8 Warm Mix Additives

Warm mix asphalt technologies were developed in Europe [FHWA 2008] in an effort to reduce both greenhouse gas emissions and energy requirements (and hence costs) by reducing the temperatures at which asphalt mixes are produced and placed. The direct benefit of WMA is largely the reduction in production temperatures, from 150 to 165°C for conventional HMA mixes to less than 120°C for WMA. This has the effect of reducing plant emissions and costs associated with emission control. In addition, there is a direct savings in energy costs to heat the asphalt mix [TAC 2012].

The three main WMA categories are: organic additives, chemical additives, and asphalt foaming systems. Organic additives are typically paraffin based organic compounds. Chemical additives are predominantly crystalline hydrated aluminum silicates, the most popular of which is synthetic zeolite. The asphalt foaming systems involve first pre-coating the aggregate with a softer binder, which allows for a lower mixing and compaction temperature, and then using a harder binder that is foamed to improve workability. Although the technology is relatively new, WMA asphalt mixes are considered to be acceptable for use provided they meet similar requirements to those of HMA. For more information on the warm mix additives and technologies used, please refer to the website of the Warm Mix Asphalt Technical Working Group (WMA TWG) at www.warmmixasphalt.com.

Warm mix technologies can be used with asphalt rubber mixes allowing for the mixes to be placed at night and in cooler climates. They also provide potential benefits through increased workability of asphalt rubber mixes, extending the paving season and allowing their use where asphalt rubber could not be used before. In addition, warm mix technologies can improve working conditions, reducing undesired asphalt rubber odour and blue smoke associated with conventional asphalt rubber placements and reducing fuel usage by reducing production temperatures by 20 to 45°C [Hicks et. al 2011, Cheng et. al 2011].

1.9 Overview of RMA Construction

RMA should be carefully mixed, transported and placed. The appropriate sampling and testing procedures should be done to ensure the correct degree of quality is met. Further details on the RAC construction procedures are provided in subsequent chapters.

1.9.1 Preparation for Paving

The paving surface must be prepared prior to the production of the RMA or spray application. Surface preparation includes removal and replacement of deteriorated pavement through cold milling or grinding for smoothness and/or to restore or adjust profile, crack filling and/or sealing. Patching is conducted using industry best practice and dense graded asphalt concrete. Cracks should not be overfilled since any excessive sealer/filler will cause bumps in the overlay that will be transferred to the RMA mat during compaction. Any pavement ruts should be filled as necessary. If a leveling course is required, a fine dense-graded asphalt concrete mix should be used. Immediately before the mixtures are delivered, the surface should be swept and the tack coat applied.

1.9.2 Mixing

Hot mix delivery is the same as conventional HMA delivery with additional care to temperatures. While any type of haul truck can be used to deliver conventional asphalt concrete materials, bottom dumps and windrows are not recommended for use when the ambient and pavement surface temperatures are cool. RMA should not cool below its minimum laydown temperature during transport to the job site and tarps can be used to reduce the cooling of the material.

1.9.3 Placement

The RMA temperatures in both the paver hopper and mat should be monitored throughout the paving operation. To achieve a high quality pavement, the paver should minimize starting and stopping and a high level of coordination of the mix delivery and placement should be met. A consistent paver speed is required to maintain a uniform head of material and to control the thickness of the pavement. The paver wings should be carefully dumped before the mix collected in the corners cools, though the wings should never be dumped in an empty hopper. Slat conveyors should not be allowed to run empty or close to empty.

1.9.4 Compaction

Adequate compaction is necessary to achieve the specified level of performance and durability of an asphalt pavement. Gap-graded RMA mixes require more compaction than conventional dense-graded asphalt concretes due to coarse aggregate structure and stiff asphalt rubber cements. Compaction is dependent on temperature and requires compactive effort. For gap-graded mixes, breakdown compaction is necessary and performed in vibratory mode, unlike open-graded mixes that do not have compaction requirements since they are usually used as surface courses with thin lifts. Open-graded mixes achieve compaction with only a few passes of a roller operating in the static mode.

Breakdown compaction of gap-graded rubberized asphalt should be conducted before the temperature of the mat is below 138°C. The mat temperature should be monitored during the placement and compaction processes so that adjustments to the rate of compaction can be made. An adequate number of breakdown rollers should also be used since breakdown rolling performed outside of the specified temperature range will result in poor quality pavement. Vibratory rolling should not be conducted below the minimum breakdown rolling temperature or after static rolling. Pneumatic rollers are not recommended because they stick to the rubberized asphalt mat.

1.9.5 Testing

To determine the degree of compaction needed to develop adequate in-place density of gap-graded RMA materials, test strips should be created. During test strip compaction, nuclear gauges should be testing the mat and the data should be later correlated with the core results in order for the nuclear density to provide accurate data for quality control.

1.10 Benefits and Other Considerations

The application of RMA has many reported benefits [Caltrans MTAG (2006), Caltrans AR guide (2003)]. The durability of the surface layer of the material should result in a longer service life. This durability is mainly due to its improved resistance to fatigue, reflection cracking, and aging resulting in a lower life cycle cost of the material. Inclusion of the rubberized asphalt may decrease the thickness of the RMA layer and reduce noise due to the inclusion of rubber in the material. There are also other environmental benefits to using RMA as rubber waste is being diverted from landfills to once again become a viable product.

1.10.1 Cost Considerations

When considering the cost of RMA over the pavement life, a standard life cycle cost analysis should be carried out. Most Canadian transportation agencies incorporate some form of economic analysis into their pavement design, preservation and rehabilitation design process based on a recent Canadian transportation agency survey [TAC 2012]. Life cycle cost analysis (LCCA) only refers to the financial cost associated with a project. LCCA evaluates competing alternatives by including not just initial construction costs, but also the expected cost to maintain the asset in a functional condition for its service life. This process is widely applied because it can evaluate differences between design options, such as pavement type and various feasible design cross sections [TAC 2012]. Local practices should be applied when conducting the LCCA on a specific RMA project. At this time, the performance information for RMA projects is not sufficient to perform cost analysis.

1.10.2 Environmental Benefits

The inclusion of rubber waste material reduces the number of rubber products in landfills and tire stockpiles. Consequently, the effective and engineered usage of RMA can provide many environmental benefits as the rubber waste material can be recycled into the HMA in either the wet or dry process as described earlier. RMA has also been shown to reduce tire/pavement noise levels which provide an ideal application to areas where excess noise pollution is a hazard, such as in residential neighbourhoods and near hospitals. The inclusion of rubber materials in HMA also has been shown to pose limited or no increased health or air quality risks [Sacramento 1999, Hicks 2011].

1.11 Summary

RMA can provide technical, economic and environmental benefits in Canada. When properly engineered, it can provide a long lasting pavement while also mitigating the number of tires that end up in landfills. RMA production and construction procedures have been successfully applied both nationally and internationally and this manual is directed at highlighting best practices.

2.0 Application and Usage Guide for Asphalt Rubber Cement

2.1 Introduction

The materials and their proportions that are included in the asphalt rubber cement are determined in accordance with the specifications of the specific project. The pavement structural design will dictate the total thickness required and the type of HMA or RMA that is used will be dictated by the traffic loading and environment. The materials including the asphalt cement PGAC and associated aggregate properties for the RMA will all meet the conventional HMA requirements. Some of the descriptions of materials in this chapter are repeated for ease of understanding.

2.2 Crumb Rubber Modifier (CRM)

CRM is composed of ground scrap tires, tread buffings, and other wastes or excess rubber products. There exist a number of processes and equipment used to produce the required range of CRM material to be used in asphalt paving materials. These products are produced in Ontario and can be obtained from the vendors shown in Chapter 1 of this manual.

2.3 Asphalt Cement

Design of paving mixtures and selection of the optimum proportions of their constituents require engineering and experience. For example, for low volume roads, a relatively higher percentage of asphalt cement is appropriate to ensure that pavement durability is provided. On a high volume road, with heavy truck traffic, permanent deformation distress would likely become a problem if relatively high asphalt cement contents were used. Thus, some compromise is necessary. Design criteria and the selection of appropriate asphalt cement are normally specified in consideration of traffic, climate and requirements necessary to mitigate the distress.

In Canada, asphalt cement and HMA design requires consideration of a number of distress types to which the pavement may be subjected in-service, including: low temperature cracking, permanent deformation (rutting, shoving, etc.), fatigue cracking, moisture sensitivity and stripping, aging of the asphalt/aggregate system and durability. Again, the usage of PGAC assists in ensuring long term performance in the field.

When using asphalt rubber cements, it is important that the binder be tested to ensure it meets all of the Superpave test procedures [TAC 2012]. The physical asphalt cement properties are measured on original (unaged) binder, on short term aged sample with the Rolling Thin Film Oven (AASHTO T240-10) and on long term aged samples in the Pressurized Aging Vessel (AASHTO R28-10). The Rolling Thin Film Oven simulates plant aging of binders during asphalt mix production, while the Pressurized Aging Vessel simulates in-situ aging of in-service asphalt mixes [TAC 2012]. In addition, the following tests listed below are also performed on the PGAC.

- Flash point tests (AASHTO T79-10) are used to determine the temperature at which asphalt binder fumes first may flash or spark.

- Rotational viscosity (AASHTO T316-10) measures the viscosity at high temperatures and is a measure that ensures the asphalt is fluid enough for pumping at the asphalt mix plant, as well as to provide design temperatures for mixing and compaction of asphalt mixes.

- Dynamic shear (AASHTO T315-10) is used to measure the flow properties of liquid asphalt binders at intermediate to high temperatures. The test is performed on original binder specimens and after conditioning in a Rolling Thin Film Oven and Pressurized Aging Vessel to ensure compliance with requirements that have been established to mitigate pavement rutting distress.

- Creep stiffness test (AASHTO T313-10) is performed on Pressurized Aging Vessel residue, and measures the flexural creep stiffness of binder specimens using a bending beam rheometer. The test is used to provide an indication of the low temperature stiffness and cracking potential of an asphalt binder.

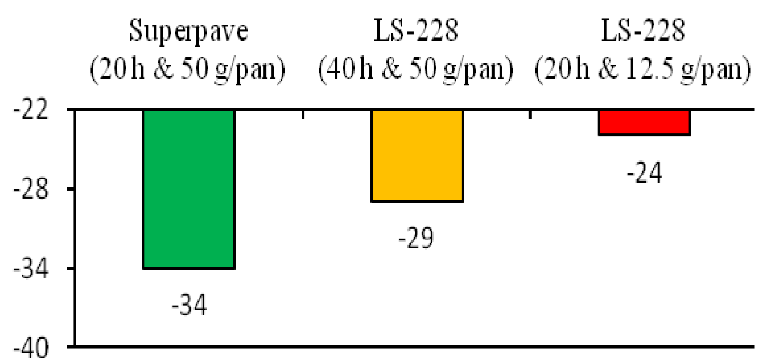
- Direct tension test (AASHTO T314-10) is used to measure the failure properties (stress and strain) of an asphalt binder at low temperatures.

Improved Asphalt Cement and Rubberized Asphalt Cement Grading

Over the past 15 years, asphalt binders have been specified and accepted in Ontario paving contracts based on their Superpave™ grades. Superpave was a product of the U.S. Strategic Highway Research Program (SHRP) that concluded in the early 1990s. It was completed in record time and hence contains certain assumptions and compromises that have produced a number of shortcomings. Research to address some of the main issues in Ontario has been completed and this has resulted in the recent publication, validation and implementation by the Ministry of Transportation of three standard laboratory test methods: LS-228, LS-299, and LS-308.

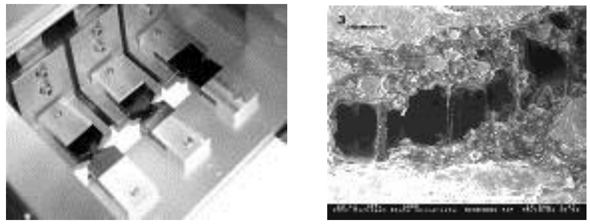
The *LS-228 Accelerated Aging of Asphalt Cement Using Modified Pressure Aging Vessel Protocols* standard assesses durability of a binder in terms of its resistance to oxidative aging in the Rolling Thin Film Oven (RTFO) followed by the Pressure Aging Vessel (PAV). Binders are aged according to standard Superpave protocols for 20 hours with 50 grams of asphalt binder in each PAV pan (film thickness of 3.2 mm). The low temperature grades are compared with those obtained after 20 hours of aging with 12.5 grams in each pan (film thickness of 0.8 mm), after 40 hours of aging with 50 grams in each pan, and in the presence of moisture. It has been shown that such simple changes allow for a more accurate determination of low temperature grades. While the regular 20 hours of aging in the PAV provides a single point measurement, doubling the time to 40 hours, reducing the film thickness, and/or adding moisture, can reveal if the grading properties are expected to persist in long-term service. Superior binders are found to deteriorate by less than half a grade (< 3°C) while inferior ones have been found to lose as much as one or two full grades (6-12°C). Figure 1 shows an image of a commercially available Prentex PAV. Figure 2 shows grade losses for a poor performing field-blended, rubberized asphalt cement sample from an Ontario paving trial (Xu et al., 2013).

Prentex Model 9300 Pressure Aging Vessel for Accelerated Laboratory Aging.

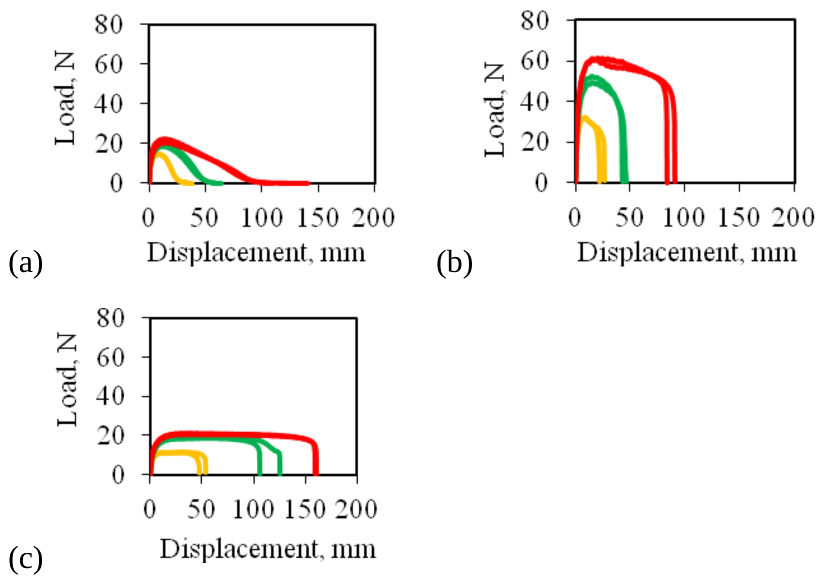


Deterioration of Low Temperature BBR Grades for Field Blended Rubberized Asphalt Cement Sample due to Modified PAV Aging According to LS-228 (Xu et al., 2013).
Note: A 10°C grade deficit at low temperatures usually has major negative implications for thermal cracking performance reducing the confidence that a road is not damaged in any given winter from the intended 98% to around 10%.

The *LS-299 Determining Asphalt Cement's Resistance to Ductile Failure Using Double-Edge-Notched Tension Test (DENT)* standard determines the strain tolerance of a binder in the ductile state. While Superpave only specifies low strain rheological properties, LS-299 sets a lower limit on the high strain tolerance in the ductile state, as determined by an approximate Critical Crack Tip Opening Displacement (CTOD). The CTOD indicates by how much a very thin fiber (fibril) of asphalt binder can stretch before it fails. This property has provided an improved correlation with fatigue cracking in mixtures and trial sections. The specification limits that were set for the CTOD are based on those obtained for good quality western Canadian asphalt cements, with the intention to prevent a deterioration of the ductile strain tolerance due to modification. Figure 3 provides images of the specimens with three different ligament lengths prior to testing and the fibrils between two aggregate particles that are modeled by the CTOD measurement. Figure 4 provides typical DENT test results for unmodified asphalt cement, a field-blended rubberized asphalt cement from an Ontario trial contract, and a hybrid polymer-crumb rubber modified binder. It should be noted that the CTOD values obtained vary by a large amount from a low of 4 mm for the field-blended material to a high of 28 mm for the hybrid formulation.



Double-Edge-Notched Tension Specimens with 5, 10 and 15 mm Ligaments Prior to Testing (left). and Fibrils Linking Two Large Aggregate Particles (after Rozeveld et al. 1997) (right). Note: (a) Water was removed to enhance image quality.

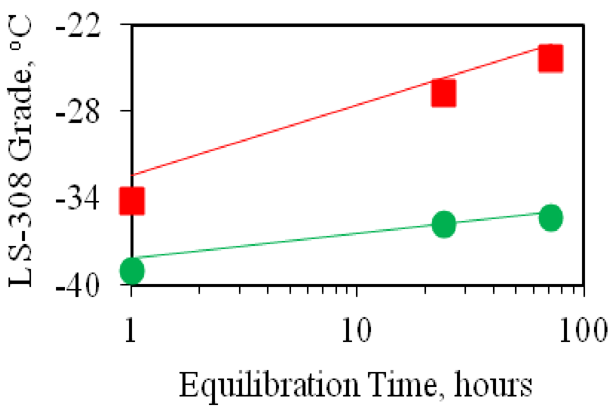


Duplicate Double-Edge-Notched Tension Test Results (Xu et al., 2013).
Note: (a) Straight Cold Lake Asphalt Roofing Flux (PG 51-34, CTOD = 13 mm); (b) Field Blended rubberized asphalt cement from Ontario Trial (PG 93-38, CTOD = 4 mm); and (c) Hybrid 2% SBS Polymer/18% Crumb Rubber Modified Material (PG 84-39, CTOD = 28 mm).

The *LS-308 Performance Grade of Physically Aged Asphalt Cement Using the Extended Bending Beam Rheometer (BBR)* standard provides a measure of durability in terms of a binder's resistance to gradual, reversible hardening at low temperatures. Binders are conditioned for the standard one hour prior to grading as well as 24 and 72 hours. It has been found that the grade losses in LS-308 are highly correlated with those found in LS-228, likely because the same colloidal instability issues are responsible for both hardening processes. The loss for superior binders is typically less than half a grade while for inferior materials it can be as high as one or two full grades. Figure 5 shows an image of the Canon Thermoelectric Bending Beam

Rheometer that is used for LS-308 grading. Figure 6 shows the losses in low temperature grade as a function of cold conditioning time for a superior binder made with Cold Lake asphalt cement (in green) and an inferior material from an Ontario pavement trial (in red).

Canon Thermoelectric Bending Beam Rheometer.



Low Temperature Grade Losses for Two Rubberized Asphalt Cements (Xu et al., 2013). Note: The poor performer (in red) loses 10°C over 72 h of conditioning at -18°C while the superior performer (in green) loses only a modest 3.6°C after conditioning at -24°C.

Employing these modified testing protocols can produce lower temperature limits that are warmer by one or two full grades (6-12°C), reducing the confidence that a pavement is not exposed to damage in any given winter from the intended 98% to less than 50% or even 10%. Hence, it allows user agencies to better pay for performance by preventing the use of substandard materials in a given climatic zone. The above three test methods have been extensively validated with Ontario pavement test sections and regular contracts and have consistently been able to explain from best-case to worst-case cracking performance differences in adjacent sections and regular contracts. Preliminary testing on rubberized asphalt cement (RAC) has shown that certain types of compositions are particularly sensitive to the effects of conditioning at low temperatures (Xu et al., TRB 2013). Hence, caution is warranted to assure that the RAC not only meets regular Superpave criteria but also the improved Ontario specifications as recently developed.

When using asphalt rubber binders, it is important that all the conventional test requirements be met for the given design.

2.4 Additives

Additives are materials that are included in the asphalt cement mixture to encourage interaction and the production of higher quality products. Possible additives used with CRM include: extender oils, high natural rubber (HNR), polymers (mainly in no agitation binders), and mineral admixtures which improve workability and compatibility of the mix. Some extender oils can improve RMA performance, others may have detrimental effects.

2.5 Rubberized Asphalt Applications

2.5.1 Hot Mix Asphalt (HMA) Applications

HMA includes a wide range of aggregate mix types, including gap-graded, open-graded, open-graded-high binder mixes, and dense-graded mixes. The gap- and open-graded mixes have been successfully placed using the wet process high viscosity rubber binder in surface courses while dense-graded mixes tend to use the wet process terminal blends or no agitation binders. These are the products currently used in Ontario.

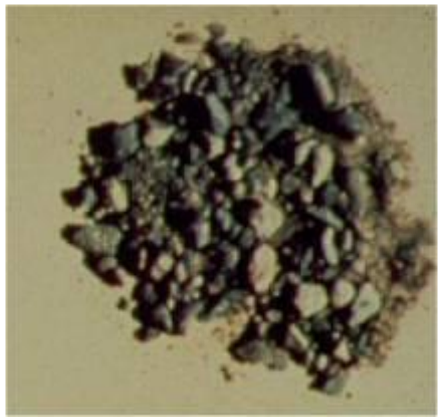
2.5.2 Rubberized Spray Applications (Seal Coats/Surface Treatment and Interlayers)

Asphalt rubber cement or terminal blends can be effectively incorporated into various typical Canadian seal coats, surface treatments and interlayers. Selection of the appropriate binder will depend largely on the application and local specifications should be followed in the design and construction of these pavements [TAC 2012]. These products have not yet been used in Ontario, but are being considered.

2.6 Asphalt Rubber Hot Mixes

2.6.1 Dense-Graded Asphalt Mixes

The dense-graded mix is a well-graded HMA mixture intended for usage in various layers of the pavement structure. It is designed to be impermeable and generally specified in accordance with the nominal maximum aggregate size [WSDOT 2012]. The aggregate gradation closely follows the FHWA's 0.45 power curve for maximum density. The most common HMA mix designs in Canada are dense-graded. Typical gradations are near the 0.45 power curve, but not right on it. Generally, a true maximum density gradation (exactly on the 0.45 power curve) would result in unacceptably low VMA. These mixes are further categorized as fine graded or coarse graded depending on the size and distribution of the aggregate contained in the mix. The fine graded mixes contain a higher percentage of fine aggregate while the coarse-graded mixes contain larger aggregate [WSDOT 2012]. Examples of dense-graded mixes would include SP 25, SP 29, SP 12.5 and SP 9.5 [Ontario MTO, 2011].



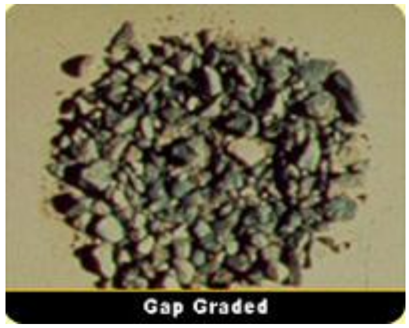
Dense graded rock

Dense-graded RMA can be effectively designed using the wet process terminal blend rubberized asphalt. However, usage of the dense-graded mixes with asphalt rubber is limited as the additional cost of the rubber has not always translated to improved field performance when a LCCA is conducted. This is related to the dense grade of aggregate whereby there are not enough voids available in the mix to allow the asphalt rubber cement to greatly impact the volumetric properties. However, if dense-graded RMA is suitable for the design, it is best used with the wet process terminal blend.

2.6.2 Gap-Graded Mixes

A gap-graded mix refers to a HMA where the aggregate gradation contains only a small percentage of aggregate particles in the mid-size range. This results in a gradation curve that is flat in the mid-size range [WSDOT 2012]. A good example of a Canadian gap- graded mix is a Stone Mastic Asphalt (SMA). SMA is a gap- graded asphalt mix that typically contains 100% crushed stone materials. The asphalt cement is often modified and in this case an asphalt rubber cement can be used in combination with some type of filler [TAC 2012]. The coarse stone skeleton is designed with a relatively thick asphalt/filler mastic to provide excellent durability while also providing increased resistance to permanent deformation through the stone-to-stone contact and increased fatigue resistance due to the thick mastic coating on the aggregate [Kennepohl, 1992]. A limitation to SMA is that the high SMA bituminous contents can lead to friction issues [TAC 2012].

HMA gap-graded mixes can be prone to segregation during placement. Gap-graded mixes provide adequate void space for the asphalt rubber binder to positively affect the material properties. It has been shown that many technical benefits can be achieved when used in conjunction with the wet process high viscosity asphalt rubber cements.

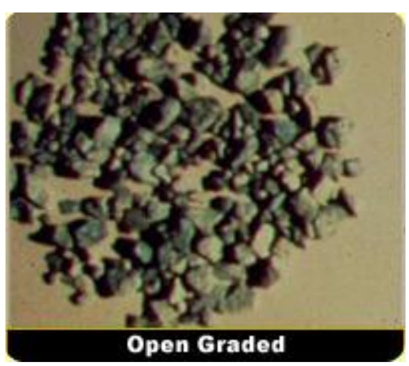


Gap graded rock

2.6.3 Open-Graded Course (OGC) Mixes

The open-graded course mix gradations contain only a small percentage of aggregate particles in a small range. This results in more air voids because there are not enough small particles to fill in the voids between the larger particles. The curve is near vertical in the mid-size range and flat and near-zero in the small-size range [WSDOT 2012]. Open graded courses have more void spaces than gap-graded mixes to allow for drainage through the pavement. Thus, they are permeable and allow for quick removal of surface water which reduces the potential of hydroplaning and water spray. In addition, the open texture acts to lower pavement/tire noise. OGC mixes are surface course mixes and are placed in conjunction with noise walls along freeways in heavily populated urban areas [TAC 2012].

OGC mixes can successfully be designed using an asphalt rubber cement to reduce splash and spray while also providing good surface friction. High binder OGC can also be designed with the same properties as OGC mixes; although, drainage can be limited while the durability of the pavement is improved.



Open graded rock

2.6.4 Warm Mix Asphalt Technology

Warm mix asphalt technologies allow asphalt producers to lower the mixing and placement temperatures of the asphalt pavement. The lower temperatures result in fuel consumption savings and decreased production of greenhouse gases. In addition, engineering benefits include better compaction on the road, the ability to haul paving mix for longer distances, and extension of the paving season by being able to pave at lower temperatures. Although the technology is relatively new, WMA mixes are considered to be acceptable for use provided they meet similar requirements to those of HMA [NAPA 2012].

Warm mix technologies have been used with asphalt rubber and terminal blend mixes allowing for the mixes to be placed at night and in cooler climates. They also provide potential benefits through increased workability of asphalt rubber mixes, extension of the paving season and allowing their use where these products could not be used before [Hicks 2011, Cheng et al. 2011].

2.7 Asphalt Rubber Spray Applications

There are a number of different asphalt rubber spray applications that are applied to pavements depending on the requirements of the project. A number of different spray application types are discussed in further detail below.

2.7.1 Chip Seal Construction Process

Chip seal spray application is a surface treatment that is greatly affected by construction operations and site conditions. Extreme care must be used when applying chip seals to maintain the appropriate level of quality needed for a project, especially in regards to the temperature of the project site, the aggregate type and pavement infrastructure.

The inclusion of asphalt rubber in chip seal material creates a thicker membrane. This practically means that the aggregate in the mix must be large enough to withstand the thick membrane while maintaining a uniform mix. The nozzle size for spraying should be sufficient to prevent clogging.

Construction of chip seals is a rapid process, usually performed at a production rate of 8 to 10 km per day. As mentioned above, temperature can drastically affect the quality of the final product, regardless of the type of binder. The use of clean or pre-coated aggregate chips is standard in all chip seal mixtures and they must be raised to the appropriate temperature when used in an asphalt rubber cement. The chips are to be included into the asphalt rubber membrane through rolling while the membrane is hot. The inclusion of chip seals in the asphalt rubber membrane at cooler temperatures (less than 15°C) may discourage the surface treatment to meet the quality requirements of the project.

Application rates for single-sized chip seals are most commonly designed in Canada using the Asphalt Institute method [AI 2009, TAC 2012]. Application rates for graded seals are generally based on empirical adaptations of the method used for single-sized chip seals [MnDOT 2006].

2.7.2 Chip Seal Equipment

Chip seal surface treatment involves utilizing a train of equipment. In California, a distributor truck with a fume catcher must be available to apply the asphalt rubber membrane via spray application. Warm mix asphalt rubber binders have also been used without the use of a fume catcher. A conventional chip spreader is then used to distribute the aggregate or chips into the membrane. To maintain continuous production, a haul truck replenishes the chip spreader and keeps the operation moving. Rubber tire rollers are then used to knead the aggregate into the membrane. For finishing, power brooms may be used which may be followed with a flush coat (or fog seal) applied using a distributor truck.

Photo of a rock spreader

2.7.3 Asphalt Rubber Spray Application

The rubberized binders must be applied uniformly using a distributor to maintain the required amount of asphalt rubber cement. Applications should begin and end on tar paper or roofing felt with the longitudinal joint on the centreline or edge of the driving lanes. Care should be given to the overlap area to ensure a good joint is achieved. Appropriate equipment adjustments are required, depending on the project environment and the site of application. Maintaining an ideal temperature when applying the binder is necessary as lower temperatures will cause the asphalt rubber binder to streak. Streaking can also occur if the binder is too viscous or if the spray bar is too low.

The rate of application is based on the existing pavement conditions and ranges from 2.5-3 l/m^2. Verification of the application rate should be determined in accordance with the haul distance, width and amount of asphalt rubber cement that is used during application. Dry, oxidized, raveled or brittle application surfaces will require higher binder applications.

Warm mix technologies can be easily added into the asphalt rubber cement. Although there is limited experience with these, no special considerations should be required when using a warm mix technology with an asphalt rubber or a terminal blend binder [Hicks 2011, Cheng et al. 2011].

2.7.4 Aggregate Application

The application of the aggregate is facilitated through the use of a chip spreader that follows the asphalt rubber distributor at a steady rate. The distributor is typically following 20-30 m behind the chip spreader. The binder must have a sufficient viscosity to allow the aggregate to become bonded. Due to the sensitive nature of aggregate application, the speeds and loads of the equipment must be carefully monitored to ensure the seal is properly set. A uniform distribution of the aggregate is necessary to limit areas of excess aggregate. In the case of excess aggregate, the particles must be redistributed to another roadway or removed from new pavement before it interferes with the embedment and adhesion properties. This is very important for preventing any future failures. In areas where aggregate cover is inadequate, additional aggregate should be immediately added before it sets. If the additional aggregate is added once the membrane sets, adhesion will not be achieved and an overall poor quality chip seal will be the end result. The degree of chip application must be monitored as an excess amount can have negative effects on the embedment and adhesion of the paving structure. If, after sweeping, there are a number of loose stones on the roadway edge, this may be an indicator of excess chip application, minimal asphalt rubber application or the lack of proper embedment and adhesion.

Rate of aggregate application is usually determined through laboratory testing procedures prior to construction. Alternatively, the aggregate could be laid out one-stone deep and weighed to determine the necessary weight per unit area. The rate should be in the range of about 15-24 kg/m^2. Embedment of the cover aggregate and individual chips should be checked to verify the adequateness of the rate of application.

2.7.5 Rolling Asphalt Rubber Chip Seals

Rolling asphalt rubber chip seals requires pneumatic-tired rollers due to the kneading action provided by the tires that encourages chip embedment to occur. The tires make contact with the aggregate instead of the membrane without removing portions of the applied surface. Skirts around the tires keep the heat in the process and help provide proper compaction. The aggregates are oriented and further embedded as the rollers operate over the surface at reduced speeds so as to not displace the aggregate.

2.7.6 Sweeping

Sweeping is conducted to remove any excess chips from the newly laid chip seal, minimizing flying rocks. It is best to sweep the newly placed surface within 30 minutes of applying the chip seal. Furthermore, during a cooler time of day, sweeping with a power broom is also desirable for achieving a good quality pavement.

Sweeping the chip seal

2.7.7 Flush Coat or Fog Seal

A flush coat involves the application of a fog seal over a newly constructed asphalt rubber chip seal, which is then followed by a sand cover. Fog seals aid in maintaining the quality of the chip seals by helping to retain the cover aggregate and providing a uniform appearance. A fog seal is applied at a rate of 0.2-0.45 l/m^2

Application of the flush coat

2.7.8. Sand Cover

Sand cover is often used to prevent vehicle tires from picking up and tracking the chip seal material. The sand cover layer is applied on top of the fog seal and spread at a steady rate of 1-2 kg/m^2.

2.7.9 Traffic Control

To maintain the quality of a newly constructed chip seal, the traffic speed must initially be kept below 40 km/h using flag persons, signage and/or a pilot car. The pilot car technique is most preferred, as it is better able to control the speed of the traffic that will provide pneumatic tire rolling and kneading of the pavement. Hot applied chip seals allow traffic to get back on the pavement sooner than for conventional emulsion chip seals.

Traffic control for a chip seal

2.8 Summary

As noted above, the material and construction procedures for asphalt rubber cement and its usage in HMA and chip seals/surface treatments are similar to those for conventional materials. The same engineering principles and material selection philosophies are followed when using rubber in asphalt pavement. The main difference with the asphalt rubber cement and RMA mix is that it contains CRM either in the asphalt cement or aggregate portion. There are a number of different RMA mixes that can be made depending on the gradation of the aggregate. The RMA mixes are designed and tested in the same way that the various conventional HMA are tested, including PG asphalt cement and other mix design tests.

3.0 Design and Specification Guide

3.1 Design Guides

References and resource guidelines on the application and maintenance of rubberized asphalt concrete have been published by the Rubber Pavements Association, Arizona DOT, and the State of California, where rubberized asphalt concrete (RAC) paving is widely used [Caltrans, 2008]. This chapter presents possible guides for use in Ontario

3.1.1 Publication Guide Resources

Most agencies in Canada have limited available information on the design and application of RMA. This document is intended to fill that need, even though most information in existing provincial design guides or the Transportation Association of Canada Pavement Asset Design and Management Guide [TAC 2012] is applicable to the design and specification of RMA pavement.

3.1.2 Where and Why Use Rubber Modified Asphalt?

RMA has the potential to provide many technical, economic and environmental benefits when designed appropriately for a given situation. It can be used as a replacement for conventional HMA. The higher binder content can improve durability [Hicks 2011] and RMA usage has been shown to resist fatigue cracking, bleeding, flushing, deformation and reflection cracking which are particular issues as the pavement gets older. Also, aggregate retention is improved providing a more uniform and potentially stronger material [AI 2008, Sacramento 1999].

3.1.3 Tests for Asphalt Rubber

There are a number of tests that can be conducted on field blended asphalt rubber binder to determine the properties of the material. A number of these tests are based on the ASTM and AASHTO testing methods and should be used for further reference. Special tests used for asphalt rubber binders have included the following:

- **Cone Penetration Test [AASHTO 2010 (Test T 49), ASTM 2006b].** A cone is used to create an impression in a binder sample and a penetrometer measures the impression to an accuracy of tenths of a millimetre. This test determines the consistency of the asphalt rubber cement with larger particles of crumb rubber and can be used under a range of temperatures to determine the effect of temperature of the cement.

Cone Penetration Test [AASHTO 2010 (Test T 49), ASTM 2006b]

- **Resilience [ASTM 2009].** The resilience of the asphalt rubber cement material is a measure of the degree of elasticity of the material. The test method can be found in ASTM D5329 [ASTM 2009a]. The elastic properties of the material are determined as a percentage of rebound.

Resilience [ASTM 2009].

- **Ring and Ball Softening Point [AASTO 2010 (Test T53), ASTM 2009b].** This test in accordance with ASTM D36 [ASTM 2009b] determines the tendency of the material to flow when the temperatures are raised. Using the ring and ball method, the stiffness of the material is determined for a number of temperatures.

Ring and Ball Softening Point [AASTO 2010 (Test T53), ASTM 2009b].

- **Field Viscosity [AASHTO 2010 (test T316), ASTM 2006a].** Using a field rotational viscometer, the fluid consistency of the asphalt rubber binder is assessed. This test is used to determine the pumpability of the asphalt rubber cement and to identify any components of the mix that may affect hot placement and compaction procedures.

Field Viscosity [AASHTO 2010 (test T316), ASTM 2006a].

3.1.4 Tests for Terminal Blends

Terminal blend asphalt cements are much like polymer modified asphalt binders and, as such, can be tested using the battery of tests used for performance graded asphalts. The MTO requires performance grade (PG) testing for all asphalt cements used in Ontario.

3.2 Behavior of Rubberized Asphalt Concrete (RAC) Hot Mixes

Hot mix asphalts that incorporate the wet process high viscosity asphalt rubber binders have low moduli when compared to their conventional dense-graded asphalt concrete counterparts. This is in part due to the higher binder contents used in these mixes. Rubberized modified asphalt mixes that include high viscosity binders exhibit elastic recovery which allows flexibility and resistance to permanent deformation. However, long term pavement performance is dependent on the amount of binder included in the mix.

When included in HMA, high viscosity asphalt rubber binders increase the binder content by creating a thicker consistency while also reducing the drain down of the asphalt cement. The increase in binder content has been responsible for improving the resistance to permanent deformation, fatigue and reflective cracking, aging and environmental damage and improved durability of asphalt rubber hot mixes. These benefits are best observed when there are sufficient voids in the aggregate to allow for dispersion of the CRM particles in the mix. Gap-graded or open-graded aggregate distributions are recommended in order to fully utilize the benefits of high viscosity RAC. Dense-graded aggregate distribution is not appropriate for use with high viscosity binders due to the lack of sufficient voids for the CRM dispersion.

Crack resistance of asphalt rubber

The wet process no agitation binders or terminal blends can also be included in RMA to achieve behaviour properties similar to conventional HMA. Because the viscosity of the terminal blend RMA is below the 1500 cPs level of the high viscosity binders, their potential to modify the behaviour of RMA is limited. A RMA mix can retain up to 0.5% more binder than conventional asphalt cement with a gap-graded or open-graded aggregate distribution. Densely graded aggregate can be incorporated with no agitation binders to gain performance levels similar to conventional dense-graded asphalt concrete. Hot mixes made with the wet process no agitation binder may be implemented for the environmental benefits. In short, they can achieve the same properties as the HMA while diverting rubber waste products from landfills.

3.2.1 Mix Properties

An asphalt rubber cement should be designed based on the design requirements of the pavement and the corresponding specifications. Consideration for the sources and grade of asphalt, asphalt modifier and crumb rubber modifier (CRM) materials should be included in the development of the design. Tests of the cement should also be conducted to determine whether the properties of the design meet the specifications. This is usually achieved by testing samples of the asphalt rubber cement at set intervals over a 24-hour interaction period.

Using the test data, a binder blend profile is created to evaluate the compatibility of the different materials in the design, to determine the stability of the blend after it has been created and what types of applications it is best suited for. Every project should document the binder blend profile to maintain quality control and assurance.

TEST	MINUTES OF REACTION					SPEC. LIMITS @ 45 MINUTES (CALTRANS 7/2002)
	45	90	240	360	1,440	
VISCOSITY, CP HAAKE@ 190C	2400	2800	2800	2800	2100	1500 - 4000
RESILIENCE@ 25C (% REBOUND)	27	–	33	–	23	18 Minimum
R & B SOFTENING PT., C (ASTM D36)	59.0	59.5	59.5	60.0	58.5	52 - 74
CONE PEN @ 25C (ASTM D217)	39	–	46	–	50	25 – 70

Binder profile

3.2.2 Factors Affecting Performance

Pavement performance is dependent on several factors. It is necessary to ensure that the pavement is properly designed to meet the required traffic and environmental loadings. This is discussed in more detail in the next section. It is also necessary that the mix design in terms of the materials, i.e. PGAC, aggregate type and gradations and the CRM meet all the design requirements. The plant should be able to incorporate the CRM so that the overall mix meets the standard HMA specifications. Finally, the mix should be hauled to the site and the mat should be placed in accordance with the temperature specifications and all as-built performance requirements should be met. Overall, the RMA should meet all the standard requirements for conventional HMA and no extraordinary operations or procedures should be required.

3.3 Structural Design

The structural design of a rubberized asphalt concrete (RMA) mix is dependent on the traffic loading, climate and functional classification of the road. For maintenance or preservation projects, a thin overlay should be sufficient to restore ride and surface friction, reduce noise, and improve the aesthetics of the pavement structure. The overlay design could either include gap-graded or open-graded aggregate and would be designed in accordance with provincial/municipal specifications. Gap-graded overlays should be compacted to a thickness ranging from 30 to 60mm for optimal use as a structural component of the pavement. Open-graded overlays are best utilized as a thin overlay for maintenance or preservation, but not for improving the structural integrity of the pavement.

For rehabilitation projects, gap-graded asphalt rubber hot mixes are ideal to provide resistance to reflective cracking. A gap-graded asphalt rubber hot mix is an alternative to the more commonly used dense-graded asphalt concrete and can require half the overlay thickness of the conventional mix (Caltrans MTAG). However, most states do not reduce the thickness; they just expect better performance. For rehabilitation projects where cracking is severe, alternate RMA mixes, including a rubberized stress absorbing membrane interlayer (SAMI) or an asphalt rubber aggregate membrane interlayer, can be applied beneath the overlay as a crack interruption layer. A layer of dense-graded asphalt concrete should be included directly beneath the gap-graded RMA overlay if more than 60mm of pavement is required to meet the thickness requirement.

For new construction projects, instead of using a conventional dense-graded asphalt concrete, a gap-graded asphalt concrete surface course could be substituted at an equal thickness. The gap-graded asphalt concrete could also be included as a structural mix. Open-graded RMA mixes cannot be included as a structural component of the pavement but can be included as a surface course over a dense-graded asphalt concrete or a gap-graded RAC. Using a RMA surface course for a new construction project instead of a conventional mix will provide a comfortable ride and an improved aesthetic. RMA thickness should be limited to about 60mm to minimize cost.

Based on recent Canadian research, gap-graded RMA is considered structurally equivalent to a dense-graded asphalt concrete [TAC 2012]. Gap-graded RMA has a slightly lower gravel factor than dense-graded asphalt concrete with a relatively low modulus of RMA materials. Gap-graded RMA is best utilized in the top 60mm of the pavement structure [TAC 2012]. In the USA, rubberized asphalt mixes have been shown to provide superior performance, both in the field [Shatnawi et. al.] and using accelerated performance testing (FHWA and Caltrans).

3.4 Selection of Mix Types

The type of mixture to be used in each layer of the pavement is specified by the designer. With high viscosity cements, a gap-graded mixture should be used for binder courses in the lower layer of the pavement structure while open-graded mixes should be used for surface courses. Either the high viscosity or terminal blend process mixes can be used in these RMA mixes. A dense-graded aggregate distribution is not suitable for high viscosity cements, though it is well suited for use with the terminal blend or no agitation cements.

Dry process mixes have been used with gap-graded aggregate distributions since this distribution provides adequate space for the CRM particles in the aggregate matrix to substitute 1-3% of the fine aggregate. Open-graded aggregate distribution has also been used in dry process mixes. The dry process does not modify the asphalt cement though there is some potential for interactions between the CRM and the asphalt cement during mixing, silo storage, hauling, placement and compaction. The dry process is not widely used anymore in RMA mixes.

Gap-graded mixes are most suitable for overlay applications on existing pavement and new construction for a wide range of traffic volumes and loadings. Gap-graded mixes can also be applied in high traffic volume areas where there is slow moving and stopped traffic. Parking areas and other areas where low speed braking and turning are prevalent are not suitable for gap-graded mixes as the surface is likely to be damaged more easily due to the low modulus of these mixes.

Open-graded mixes can also accommodate higher asphalt cement content. Open-graded mixes without the high asphalt cement content are able to free drain which reduces splash, spray and hydroplaning and increases driver visibility during wet conditions. The inclusion of the high cement content does not allow for the same degree of free draining effect; although, more drainage still occurs with this material when compared to other mixes. Open-graded mixes are also highly resistant to reflective cracking and fatigue due to the cement content. Open-graded mixes are best suited for nonstructural surfaces or surface courses to restore surface friction, improve drainage and reduce vehicular noise. Application of open-graded mixes is best used for free-flowing roadways, such as freeways, and can be placed in layers less than 25mm thick using 9.5mm aggregate. Open-graded mixes are not suitable for arterial streets, mill and fill sections, or parking areas due to the nature of traffic on these transportation structures.

3.5 RMA Mix Design

Mix designs for gap-graded RMA materials are usually developed using slight modifications of the current asphalt concrete mix design methods, similar to open-graded mixes. The high viscosity asphalt rubber cement that is initially developed for rubberized asphalt concrete mix design is the main difference in asphalt concrete mix design procedures.

There are two types of wet process cements used in Ontario and elsewhere: high viscosity and no agitation. Their difference in viscosity threshold is associated with the base asphalt cement and size of CRM resulting in different physical properties and long term performance. High viscosity and no agitation cements should never be used interchangeably as they are not considered equivalent.

The mix design procedure used in California is currently the Hveem method (Caltrans is switching to the Superpave mix design method in the near future) while Arizona uses the Marshall method. Ontario has been using the Superpave method as described in Appendix D. Examples of mix designs for both terminal and field blended RMA are provided.

3.5.1 Wet Process High Viscosity

To meet the quality requirements, high viscosity wet process asphalt rubber cement must meet all appropriate asphalt specifications on the project. Special consideration should be taken to ensure the interaction of the asphalt cement and the CRM is adequate depending on asphalt cement source and grade, rubber type and source, percentage and gradation of rubber and the interaction time and temperature. All of these parameters should be closely monitored throughout mixing and during the addition to the aggregate.

For an adequate binder design, testing should be carried out to develop a design profile for all of the specified properties which can be used later during the RMA production. This procedure is recommended by the Rubber Pavements Association and is used by the States of California and Arizona. The measured data from the samples tested should be taken over a 24 hour interaction period. The design profile should report the results at a period of 45 minutes and 4 hours after the initial interaction. The test results during a simulated overnight cool down at a temperature of 135°C for a period of 14 hours starting at 6 hours and 22 hours after the inclusion of the CRM should be measured to check stability. In addition, any other relevant test data in accordance with local practice should be measured.

After testing is completed on the asphalt rubber cement during the cool down period, the cement should be reheated and the viscosity should be measured. The design profile should also include a list of the material sources contained in the asphalt rubber cement as well their respective proportions and gradations. Any alterations to the proportions and/or material components would invalidate the design profile and a new one would need to be constructed.

Both the viscosity and resilience are expected to fluctuate as the asphalt and rubber components interact over time. The viscosity should be no less than the minimum of 1,500 cPs during the observed interaction period and there should be no drastic differences in readings. While there is no maximum of resilience values, a high resilience indicates a better performance.

3.5.2 Wet Process No Agitation (Terminal Blends)

Unlike high viscosity cements, no agitation cements are wet process CRM cements that do not need to be agitated to maintain a uniform distribution of the rubber particles in the hot asphalt cement. The ingredients of no agitation cements are often proprietary by the supplier. Despite this, the supplier should be able to supply and certify information on the amount of CRM and any other materials that are included in the rubberized asphalt cement. For no agitation cements, design profiles are not required or provided since the material is stable during storage. The quality and stability of a no agitation cement can only be verified through monitoring and testing conducted during the time of placement for specification compliance and for separation. The tests used for these cements are the same as for performance graded cements.

3.5.3 Rubber Mixes Using the Wet Process

If a wet process is used to manufacture the asphalt rubber cement, it is simply added into the asphalt plant similar to conventional asphalt cement. If it is a terminal blend, it should remain stable and no additional agitation is required as the conventional mixing in the asphalt tank is sufficient. If the asphalt rubber cement is high viscosity, it will require mixing at the plant prior to addition to the aggregate during the regular production process of HMA to create a RAC.

Gap-Graded RAC.

For gap-graded mixes, the CRM gradation and content in high viscosity cements slightly affect the volumetric properties of a gap-graded mix. The substitution of a different CRM gradation in the cement may be necessary to adjust the RMA mix volumetric to meet the requirements. If a gap-graded mix includes only a small amount of aggregate fines, an increase in the voids in the mineral aggregate occurs which does not create an adequate mix design. This has been observed in binders that include relatively coarse CRM thus causing the void structure to be altered by aggregate particles. To mitigate the situation, finer CRM particles should be used instead.

Standard mix design methods have been used to design gap-graded RMA mixes while modifying the method slightly to increase the mixing and compaction temperatures. The mixing temperature for the aggregate is about 140 to 165°C and when using a high viscosity binder ranging from 165 to 205°C. The field compaction temperature is then increased to approximately 140 to about 150°C.

No agitation binders can also be included in gap-graded mixes, exhibiting behaviour similar to polymer-modified asphalt cement during the mix design. The binder drain down requirement limits the amount of no agitation binder that can be included in the mix, allowing a lower amount of design binder contents than in a high viscosity binder with the same aggregate gradation.

Open-Graded RAC

For the open-graded RAC, the viscosity is determined to be 1.2 times the optimum PG asphalt content. The factor of 1.2 increases the PG asphalt content to accommodate for the amount of CRM included in the binder without increasing the amount of asphalt cement used and that provides free draining for the binder mix. In addition to determining the target high viscosity asphalt rubber binder content, the binder drainage should also be determined at the target binder content. To verify that the draindown is not excessive, binder drainage is evaluated at about 150°C.

No agitation binder can also be used in open-graded mixes and should be expected to behave similarly to polymer-modified asphalt cement during the mix design. The optimum binder content due to the inclusion of the no agitation binder will be limited by the drain down property of the binder, falling in a range between the optimum binder contents of a PG asphalt and an open graded RMA with a high viscosity binder.

Open-Graded RMA High Binder

Similar to the open-graded rubberized asphalt mix discussed in the previous section, the open-graded high binder mix uses a factor of 1.6 to account for the presence of the CRM in the binder. The binder mix should include a high viscosity binder content that ranges from 8.5-10% by weight of the dry aggregate. A no agitation binder is unlikely to be included in an open-graded high binder mix as it is difficult for the mix to hold enough of the binder to meet the requirements of an open-graded high binder RMA mix without the addition of fibres or fillers.

3.5.4 Dry Process Mixes

Dry process mixes can be designed using conventional procedures with slight modifications. In a dry process mix, the rubber is included with the dry heated aggregate and mixed thoroughly before the asphalt cement is added. The mixture is then compacted at a temperature between 143 and 150°C.

The CRM has some limited contact with the asphalt cement at various stages of the RMA process including during the asphalt concrete plant mixing, silo storage, hauling, placement and compaction, with the possibility of some interaction continuing after the completion of construction. This interaction may have some limiting effect on the pavement performance. If the dry process mix is designed using conventional methods, any effects of the prolonged interaction of the CRM and the asphalt cement can be minimized and the selection of appropriate target asphalt content can be adequately done. Without considering the long-term aging and absorption of the asphalt cement by the CRM when designing the mix, the target binder content may be underestimated resulting in the early raveling of the pavement. To ensure proper volumetric analysis, the appropriate adjustments should be made for the specific gravity of the CRM (1.15 ± 0.05), which is comparably lower than that of the aggregate specific gravity (range of 2.35-2.85). Again, these types of mixes are not widely used at this time.

3.6 Mix Design Submittals

Information on the rubberized asphalt pavement should be submitted by the contractor to verify that the specified materials have been included in the structure. All information should be submitted in accordance with provincial/municipal specifications. For example, the following information could be requested: aggregate gradation for the percent passing each sieve size for the aggregate blend, quality control tests for the coarse and fine aggregate and the aggregate blend, aggregate source, proportion of aggregate cold feed or hot bin used in the mix design, gradation of aggregate cold feed or hot bin used, rubberized asphalt cement grading, calculations for voids in mineral aggregate and all associated Material Safety Data Sheets (MSDS).

3.6.1 Crumb Rubber Modifier (CRM)

In terms of CRM, the following information would normally be required: supplier(s) and type of scrap tire and natural CRM used, gradation of each type of CRM material used from each supplier, scrap tire and natural CRM percentage by total mass of the asphalt-rubber blend from each supplier, laboratory tests results for the specified test parameters and Material Safety Data Sheets (MSDS).

3.6.2 Asphalt Rubber Cement

In terms of the asphalt rubber cement, the following information would generally be required: base asphalt PG binder grade, supplier, identification and test results demonstrating conformance, percentage of the combined blend of asphalt by total mass of asphalt-rubber binder, percentage of asphalt modifier by mass of asphalt-rubber binder, selected asphalt rubber content modified as appropriate for high viscosity binders, design profile, minimum interaction time and temperature and Material Safety Data Sheets (MSDS).

The design profile for the high viscosity cements provides all the relevant information on the asphalt cement design in order to ensure that the asphalt cement complies with the project specification. The design profile includes information on the compatibility of the components, and the quality and stability of the asphalt rubber cement properties. The viscosity and the resilience of the cement are the more important information as they are indicators of the performance of the asphalt cements. The profile also lists the results of the specification compliance tests conducted on samples of the cement during a 24-hour period and compares the results to the expected properties.

3.6.3 Anti-Strip Additives

If an anti-strip additive is used in the mix, the name of the product, manufacturer, manufacturer's designation and proposed rate, location, method of addition and the Material Safety Data Sheets (MSDS) is required.

3.7 Typical Specifications

The detailed specification for rubberized asphalt products is given in Appendix C. This section summarizes the important aspects of the specifications currently used.

The RMA mix designs are performed in accordance with both the CRM requirements and the respective Superpave mix type requirements. For the wet process-terminal blend, the mix is designed to incorporate RMA in place of PGAC. For the wet process-terminal blend Rubberized Asphalt Cement (RAC), it is produced by the PGAC supplier at their asphalt terminal. For the wet process-field blend, the mix is designed to incorporate RMA in place of PGAC. Wet process-field blend RMA is produced at the hot mix asphalt plant using a field blending plant. The Superpave 12.5FC 2 R-Gap Graded mix design and JMF are done according to the requirements specified in the MTO specifications. For mix design purposes, the RAC is produced in the laboratory according to the following procedure: heat up the base PGAC to 180^{o}C, add 18-20% CRM by weight of the PGAC while continuously blending the compound, and continue blending the RAC for 45 minutes at 180^{o}C.

The specifications describe the need for the contractor to submit a plan to ensure the CRM will be available and that it meets all the requirements. The basic information on the CRM supplier's name, address, CRM gradation, materials safety data sheet (MSDS), method and equipment used to mix CRM into mix need to be included. It also presacribes the CRM dosage, RAC reaction time, mixing temperatures, RAC storage conditions, and any need for agitation. Special attention is noted to prevent swelling of the briquettes during the mix design, ensure the CRM is homogeneously distributed in the RMA, that there is no pick-up during compaction of the RMA and information explaining how the CRM was ground (i.e. cryogenic or ambient ground or both). Finally, a letter from the CRM supplier indicating that the CRM they are supplying is produced in the province from scrapped tires should be provided.

Materials for the RMA should conform to the specifications and it is the Contractor's responsibility to identify a facility to produce the mixes in accordance with the supplier's instructions for the use of their materials. The Contractor is responsible for obtaining from the suppliers any and all information required for the proper preparation, handling, storage and use of their materials as well asobtaining materials, producing mixes, transportation, storage and use of all materials and ensuring the RMA is produced to prevent any deleterious effects to the finished product.

The CRM is processed from whole passenger vehicle tires. Use of uncured or devulcanized rubber will not be permitted. CRM will be ambient or cryogenic ground rubber, or both. The CRM must be produced in the province from tires scrapped in the province. The specifications also include requirements for gradntion, specific gravity and more. Additional testing being considered by the MTO on the crumb rubber is included in Appendix F.

Wet-terminal blend RAC is produced as a Type III Asphalt Rubber Cement according to ASTM D6114. CRM dosage by mass of wet-terminal blend RAC normally range from 10% to 15%. Wet-field blend RAC (after reaction) can be found in Table R4 of the specifications (see Appendix C). CRM dosage by mass of wet-field blend RAC is normally 18% to 20%.
When the RAC supplier specifies a CRM gradation with additional restrictions, the CRM must meet the RAC supplier's gradation requirements. The CRM material, PGAC and any anti-stripping additives required must be compatible to ensure a good dissolution and reaction time. If an anti-stripping agent is to be incorporated into the mix, the Contractor should contact and consult with each supplier to determine whether or not the proposed anti-stripping agent is compatible with the RMA or RAC or both.

The Contractor must contact OTS a minimum of 6 weeks prior to paving Superpave 12.5FC 2 R-Gap Graded to coordinate delivery and operation of the field blending plant. OTS contact information is provided in this special provision. Further, the Contractor must construct the trial section full width including shoulders. This is described in more detail in Appendix C.

For acceptance, all CRM must meet the gradation requirements specified in accordance with ASTM D5644. Acceptance of Rubber Modified Asphalt (RMA) and pay adjustment of the RMA containing RAC-terminal blend will be determined in accordance to the respective mix type HMA requirements specified elsewhere in the Contract Documents. Acceptance of the RAC wet-terminal blend will be determined according to the respective requirements for the PGAC grade specified and the RAC wet-terminal blend shall meet the Type III Asphalt Rubber Binder requirements of ASTM D6114. Acceptance of the TAC wet-field blend will be in accordance with the specification.

3.8 Summary

The design of rubberized asphalt concrete requires a number of tests to ensure compliance with the specified properties and degree of quality. The process can become quite complex due to the number of types of asphalt binders that could be implemented and the mix types that can be created. The design is ultimately determined based on the proposed use of the product and the desired properties. As with any project, all the required documentation in accordance with the local provincial or municipal specifications should be submitted to ensure the RMA will meet all of the quality standards.

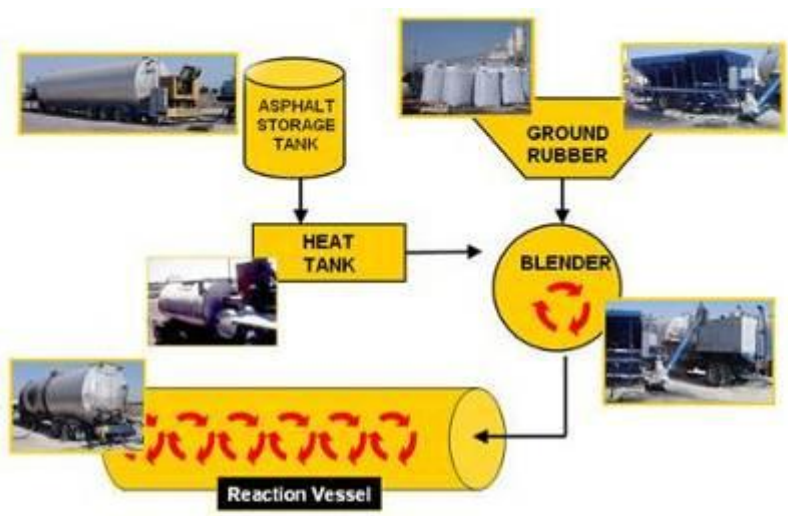
4.0 Production and Construction Considerations

As mentioned in the previous chapter, there are two main types of rubberized cement. The first is defined as wet process high viscosity (asphalt rubber) which is field blended, while the second is the wet process no agitation (terminal blend). The production and construction of both types of products are discussed in this chapter.

4.1 Wet Process High Viscosity (Asphalt –Rubber) Production

Production methods for wet process high viscosity asphalt rubber cements (minimum viscosity of 1,500 centipoises (cPs) or 1.5 Pascal-seconds) are essentially the same for both hot mix and spray applications. The primary difference is the coordination of asphalt-rubber and hot mix production to assure that enough asphalt-rubber cement is available to provide the desired HMA production rate. Cements for spray applications are typically produced close to the job site, not necessarily at a HMA plant, and their production must be coordinated with application operations.

The asphalt-rubber cement production process is relatively straightforward. The quality of the resulting asphalt-rubber cement 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 asphalt rubber between initial blending and use must be heated and insulated. Transfer lines may be wrapped with insulation. Asphalt rubber production equipment and storage tanks generally include retort heaters or heat exchangers to heat the asphalt cement and/or asphalt rubber cement.



Overview of the field blending process

The binder design profile submitted by the asphalt rubber cement supplier identifies and lists the respective components and their blend proportions. It presents results of specification compliance tests on laboratory samples of the subject cement taken over a 24-hour interaction period and indicates the expected pattern of the interaction properties. The design profile should be treated as a guide rather than as a specification, but major departures may indicate production issues that should be addressed immediately. The following table presents an example of a binder design profile and specification requirements.

Example of an AR Binder Design Profile

AR 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

Crumb rubber modifier (CRM) is typically packaged in one ton super sacks that should be clearly labeled and stored to prevent loss or damage. The CRM is fed into a weigh hopper for proportioning along with the asphalt cement and other additives such as extender oil, if used.

Super sacks of CRM

CRM bins

Equipment for component 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, if used, and CRM into the paving grade asphalt. The blending units thoroughly mix the CRM into the hot asphalt and the blend is pumped into a heated tank where the asphalt rubber interaction proceeds.

CRM blending unit

Augers are needed to agitate the high viscosity asphalt rubber inside the tanks 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 port where the auger control is inserted.

CRM reaction vessel

Hand held rotational viscometers (Haake, Rion, or equivalent) are used to monitor the rotational viscosity of the asphalt rubber interaction over time for quality control and assurance. Before any asphalt rubber cement can be used for hot mix production or spray application, compliance with the minimum viscosity requirement must be verified using an approved viscometer. As long as the viscosity is in compliance and the interaction has proceeded for at least 45 minutes, the asphalt rubber cement may be used.

Measuring viscosity of field blends using a viscometer

4.1.1 Holdover and Reheating

If an asphalt rubber material is not used within 4 hours after the 45-minute reaction period, most agencies require that heating be discontinued. Sometimes the asphalt rubber cement must be held overnight. The rate of cooling in an insulated tank varies, but reheating is required if the temperature drops below 177 to 191ºC. A reheat cycle is defined as any time that an asphalt rubber cement cools below its designated viscosity measurement temperature and is reheated.

Two reheat cycles are allowed, but the asphalt rubber cement must continue to meet requirements, including the minimum viscosity.

The asphalt and rubber 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 % more CRM by cement mass can be added to restore the viscosity to specified levels. The resulting asphalt rubber blend must be interacted at the designated temperature for 45 minutes and must meet the minimum viscosity requirement before it can be used. Most specifications have specific requirements for transferring holdover cement material between projects and Agencies. For Ontario's specifications, please refer to Appendix C.

4.1.2 Documentation

A Certificate of Compliance (COC) is required for every cement constituent as well as for the finished asphalt rubber cement. The COCs must include test results that show conformance of the materials to the respective special provisions, including chemical composition of the scrap tire as applicable. COCs for the component materials delivered to the site of the asphalt rubber cement blending operation should be provided to the engineer, inspector and/or project staff. Representatives of the owner typically sample the individual components and blended asphalt rubber materials at the blending site for testing and acceptance.

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

A log of Asphalt Rubber Cement Production should 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 the results of each viscosity test performed, including the time and asphalt rubber cement temperature and the time when the batch was metered into the AC plant. The production log should also include all holdovers and reheat cycle information including the time that heating was discontinued, the time that reheating began and corresponding asphalt rubber cement temperature, CRM addition weight and time if applicable, and subsequent viscosity test results. This is not yet required by the MTO.

4.1.3 Sampling and Testing Requirements

Frequency of sampling and testing may vary depending on the nature of the materials, project size, and available resources. Aside from minimum requirements, additional sampling is recommended whenever changes in any material or its behavior are observed. Sampling during production and construction is relatively easy and inexpensive, and it is rarely necessary to test every sample obtained. Suggested minimum requirements for quality control (QC) and quality assurance (QA) or acceptance sampling and testing are presented in the Table below.

Suggested Minimum Sampling and Testing Requirements

Minimum Sampling and Testing Requirements		
Material	**QC Sampling & Testing**	**QA Sampling & Testing**
CRM	Chemical composition each	Once per project for compliance
CRM	Gradation & physical properties each 10,000 pounds	Once per project for compliance
Paving Asphalt	Once per project for compliance	Once per project for compliance
Asphalt Modifier	Once per project for compliance	Once per project for compliance
Asphalt Rubber Cement	Viscosity every hour One gallon per batch and after each reheat cycle	Sample one gallon per batch and after each reheat cycle Test one gallon per day for compliance
RMA Mixture	Morning and afternoon daily Gradation, cement content For Gap-Graded mixes, measure Rice and lab compacted air voids	One sample daily Gradation, cement content For Gap-Graded mixes, measure Rice and lab compacted air voids
RMA Mixture Lifts ≥ 38mm thick	In-place compaction	Record pavement cores taken per day

For example, agencies such as Caltrans and Arizona DOT, require the Contractor (typically the asphalt rubber cement producer) to sample the asphalt rubber from the feed line into the AC plant and measure the viscosity at least every hour during AC production. At least one gallon of asphalt rubber cement should be wasted to assure that the sampling valve is clear, and the sample to be tested should be poured into a clean, dry one-gallon container that can be sealed and clearly labeled for possible additional laboratory testing after field viscosity measurements are completed.

Viscosity for the field blend is a go/no-go test

At least one viscosity test is required to establish compliance for each asphalt rubber batch and holdover load. The Engineer or Inspector may wish to be notified when the tests will be performed. Agencies such as Caltrans and Arizona DOT require that results of all viscosity tests performed, including the time and asphalt rubber cement temperature, be submitted to the Engineer on a daily basis. This is good practice for any project with high viscosity cement. MTO follows these practices as well.

Rotational viscosity is the go/no-go field test that governs use of the asphalt rubber cement. A 4.4 litre (1 gal) can is used to provide adequate clearance from the sides and bottom of the container, and should be 75-85% filled with the cement. The Caltrans Asphalt Rubber Usage Guide includes a description of the Caltrans field test method using the old style analog gauges, and suggested revisions [Caltrans, 2006]. Either method can be used with similar results, but neither addresses the new style digital readout gauges or how to control cement temperature during viscosity measurement. Test equipment, such as a hot plate, gas burner or stove, should be added for temperature control. An ASTM method is in development which is based on the proposed Caltrans laboratory procedure.

4.2 Terminal Blends

The wet process no agitation cements may be manufactured by different methods and are governed by different specifications than the high viscosity asphalt rubber cements described herein. No agitation cements are much like polymer modified asphalt and the resulting hot mixes are much more similar to conventional HMA. An example of the specification for the terminal blends are given in Appendix C. These products are provided by the binder supplier and generally come with a certificate of compliance certifying the material meets specifications.

4.3 Production of AR Hot Mixes

4.3.1 Mix production

Using AR cement has little effect on hot mix plant production operations for either batch or continuous AC plants, except that it may be necessary to increase the plant operating temperature in order to provide higher mixing and placement temperatures required for RMA mixtures.

Typical plant operation in Ontario

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

Blending unit in Ontario

The asphalt rubber cement provider provides special heavy duty pumps to transfer the asphalt cement. A two or three way valve can be installed in the asphalt feed line that allows the plant to switch between using asphalt rubber or regular asphalt cement. For drum plants, the asphalt rubber producer is required to use a flow meter that interlocks the cement feed with the aggregate feed.

Photo of field blended asphalt rubber

RMA production rates may be reduced somewhat from HMA production due to higher cement content and the lower rubber cement production rate. However, planning and coordination between the asphalt rubber cement producer and the AC plant operator can be used to minimize impacts on RMA production. The cement supplier can, in many cases, arrange to use more or larger storage and interaction tanks and schedule materials deliveries and asphalt rubber blending operations to expedite production of asphalt rubber cement and mix.

4.3.2 Inspection and Troubleshooting of the RMA Mixture

The primary change to the Plant Inspector's normal duties is the addition of monitoring the asphalt rubber production and viscosity results and sampling the asphalt rubber cement and its components. As mentioned earlier, an Asphalt Rubber Cement Production Log and Testing Log should contain the pertinent information, and should be available for inspection. The Inspector should obtain at least one 4.4 litre (1 gal) sample from each batch of asphalt rubber cement produced for the project to test for compliance with specification limits, and additional samples if any changes in appearance or behavior are observed.

The normal activities related to plant inspection for AC 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 RMA characteristics;

- Verifying that the correct mixture is being produced according to the design and in compliance with specifications, etc.

Sampling the aggregate

Sampling the asphalt rubber

Sampling the mix

4.3.3 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 at the typical mixing and compaction temperatures. Temperature is critical to:

- Asphalt rubber cement manufacture
- RMA hot mix production
- RMA delivery
- RMA placement
- RMA compaction

It is important to closely monitor temperature of the materials during all phases of asphalt rubber cement and mixture production and construction. The Inspector should have appropriate equipment for checking the temperature of asphalt rubber cement 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.

Checking the mix temperature

Temperature measuring devices

Both the plant and field inspectors should visually inspect the RMA in the haul truck bed for signs of any problems with the mix and check mix temperature. RMA temperature should be measured with a thermometer that has a probe at least 150mm (6 in) long, by sticking the full depth of the probe into the mix. Surface readings are not an accurate indicator. If only a heat gun is available, it will be necessary to measure the temperature of the RMA as it is flows out of the plant discharge chute into the haul truck.

Whenever any type of RMA mixture problem is suspected, the Inspector should obtain samples immediately and have them tested immediately for gradation and asphalt rubber cement content. In some cases, it may be necessary to check the voids of the compacted hot mix specimens.

The Inspector should enter a full description of the problem observed and subsequent activities in the daily project log, and immediately report these observations to the Engineer. Test results should be relayed to the Engineer 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 RMA appear segregated even if it is not. Identify the affected truckloads and corresponding placement areas, take samples and test gradation and cement content to verify. It is also recommended that, if possible, samples of RMA 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**: The mix is too hot.

- **White smoke**: Steam, not smoke, which indicates too much moisture in the mix. This means that the aggregate was not dried enough prior to mixing with asphalt rubber cement. This may cause the RMA mix to become tender and may contribute to compaction problems.

- **Dull, flat appearance**: Indicates low asphalt rubber cement content and/or excessive fines (minus 0.075 mm (No. 200) sieve size). Localized areas of dullness may indicate insufficient mixing of the asphalt rubber cement and aggregates, or mix segregation. Take samples and test for gradation and cement content.

- **Slumped and shiny**: High asphalt rubber cement 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 cement draindown and take and test samples for asphalt rubber cement content and gradation.

4.3.4 Safety Considerations

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

4.4 Hot Mix (RMA) Paving Equipment

Conventional equipment is used to place and compact RMA materials. The field inspector should confirm that the necessary paving and compaction equipment is on site before any asphalt rubber hot mix is shipped from the AC plant.

4.4.1 Haul Trucks

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

Haul truck receiving mix in Ontario

4.4.2 Material Transfer Vehicle (MTV)

Use of this type of equipment is optional. MTVs (also called shuttle buggies) have been described as “surge bins on wheels” and are most often used when smoothness, segregation (particle size or temperature) or mixture delivery rate are concerns.

MTV used on project in Ontario

4.3 Pavers

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

Typical paving operation in Ontario

4.4.4 Rollers

Rubber tired rollers are not appropriate for compacting RMA mixes because of excessive pick up of the mixture by the tires. Rollers for RMA 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 or other surfactant to the watering system.

Rolling operation

RAC-G mixtures are likely to require more compaction effort than DGAC due to the relatively coarse nature of the aggregate skeleton. Minimum recommended roller weight is 8 tonnes; pup rollers cannot provide sufficient compaction. The types of rollers include:

- Breakdown roller with vibratory capability: It is strongly recommended that two breakdown rollers be used to keep up with the paver, especially if paving width exceeds 3.7m.
- 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 shall be required if only one breakdown roller is available.

4.5 Final Preparation for Paving

Surface preparation must be completed prior to RMA production or spray application. This includes customary items such as removal and replacement of failed pavement and pothole repair (patching), milling or grinding for smoothness and/or to restore or adjust profile, crack filling and/or sealing.

4.5.1 Patching

Patching should be performed using standard good practice and DGAC. Do not overfill cracks, as excess sealer/filler will cause bumps in the overlay and may migrate up through the RMA mat during compaction and to create "fat spots." Fill ruts as necessary. If a leveling course is required, use a fine DGAC mix. Immediately prior to mixture delivery, the surface should be swept and tack coat applied.

4.5.2 Tack Coat

A tack coat should be uniformly applied 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 an asphalt rubber interlayer will be placed prior to overlaying, and is not usually recommended when RMA will be placed directly on a new pavement. The types of tack coats used include:

- Paving Grade Asphalt Cement: Unmodified paving grade asphalt is preferred as the tack for RMA mixes. Asphalt tack must be hot enough 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.

- Emulsified Asphalt: Recommended application rate is 0.23 to 0.45 l/m^2 (0.05 to 0.1 gal/yd^2) 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 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 and delamination. Cold or damp site conditions and lack of sun slow evaporation and may delay paving operations.

4.6 Hot Mix Delivery

The same good practices recommended for conventional hot mix delivery should be applied to RMA materials, along with special attention to temperature. Any type of conventional AC 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 RMA does not cool below the minimum laydown temperature of 138 to 149ºC, depending on owner agency and temperature at paving site during transport. Tarps are needed to maintain acceptable mixture shipment temperatures ranging from 143 to 163ºC..

Hot mix delivery

4.6.1 Coordinating Mix Delivery and Placement

Coordination and balance of cement and mix production with mix delivery, placement, and compaction operations are essential to achieving a smooth finished pavement with a pleasing appearance, which are the two factors that motorists reportedly consider the most important indicators of pavement quality.

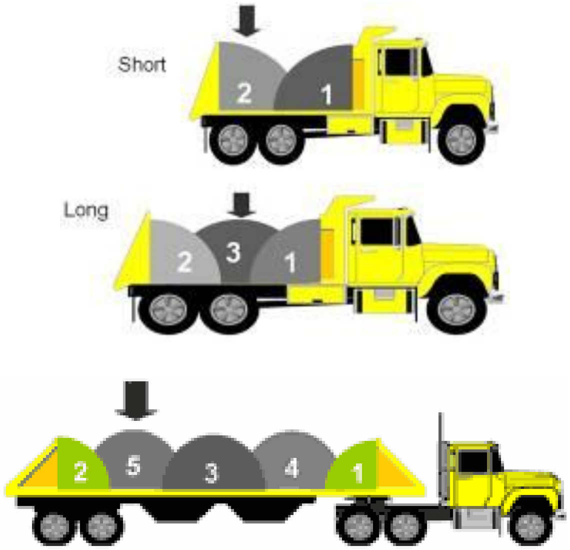
The paver should never have to stop due to lack of material. If it stops on the new mat, the result will be either a bump or depression that cannot be removed by rolling. If it pulls off the mat, it may be necessary to construct a transverse joint. A long line of haul trucks waiting to access the paver 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.

4.6.2 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 cement. Soapy water (dish or laundry soap) is recommended; it is effective and cheap. Diluted silicone emulsions may also be used.

4.6.3 Loading Haul Trucks

One of the most common causes of particle size segregation is improper loading of haul trucks. To avoid segregation of the RMA material, trucks should be loaded as shown in the illustrations below:



Recommended truck loading process

4.6.4 Unloading Hot Mix into a Paver Hopper

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. 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.

4.6.5. Unloading Hot Mix into a Material Transfer Vehicle

MTVs also have a front hopper to receive the mix and eliminate the problem of bumping the paver. The same method of discharge should be used to "flood" the MTV hopper as a paver hopper.

4.6.6 Load Tickets

Load tickets should be collected when the mix is discharged from the haul truck to document quantities delivered and used. 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.

4.7 Hot Mix Placement

Placement of asphalt rubber materials or any HMA materials requires good paving practices. Temperature is critical for proper placement of all HMA materials. Asphalt rubber cements 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 mixtures. How much shorter depends on a number of variables that are discussed in the section on compaction.

As for conventional dense-graded mixes, 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 conditions improve. Otherwise, expect significant problems in achieving adequate compaction of hot mixes. Weather conditions may change during the paving operation. If necessary, paving should be stopped until conditions improve.

Caltrans specifications for RAC-G specify minimum atmospheric and pavement surface temperatures of 13ºC and rising for mixture placement. Other agencies such as Ontario allow a slightly lower ambient temperature of 10ºC and rising for placement, but require that breakdown compaction start before the mat temperature drops below 143ºC. Placement at minimum ambient temperatures is not recommended because time available for compaction is very limited and leaves no margin for circumstance or error, resulting in inadequate compaction. When feasible, it is recommended that the minimum ambient temperature requirement for placement be increased to 18ºC. Because of the importance of temperature in achieving adequate RMA compaction, operating in the mid to upper end of specified temperature ranges is strongly recommended.

4.7.1 Paver Operations

Paver operations for RMA 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 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.

Stress the importance of coordination

4.7.2 Raking and Handwork

Asphalt rubber mixtures are not particularly amenable to raking or handwork. The relatively coarse RAC-G aggregate gradation and stiffer cement make handwork a problem and may affect the appearance of joints. Luting the joints segregates the mix and interferes with joint compaction. Handwork and raking of RMA should be minimized, but, if necessary, should be performed immediately before the mix cools. The higher asphalt rubber cement content of RAC-O-HB makes raking and handwork a little easier, but it should still be kept to a minimum. **Do not broadcast the mix: it is no longer considered to be good practice.**

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. RMA placed by hand may not provide a pleasing appearance even if the workmanship is excellent and the best practice is applied.

4.7.3 Joints

HMA joints are typically defined as longitudinal or transverse, cold or hot. Longitudinal joints are most likely to be cold joints. 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 RMA mixes.

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 the 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 about 25 to 38 mm (1 to 1.5 in). The screed should be set above the elevation of the cold side by approximately 6.4 mm (1/4 in) for each 25 mm (1 in) of compacted pavement thickness being placed. Roll from the hot side of the longitudinal joint, not the cold side, to make a tight joint.

Compacted thickness of RMA is generally between about 25 mm (1 in) and 64mm (2.5 in), which typically yields height differences between adjacent paver passes of about 08 to 17 mm (.3 to .65 in). Since lack of fines makes it difficult to feather the coarse-graded RAC-G mixtures, some raking may be unavoidable, but should be kept to the minimum necessary. Extra material should be raked onto the hot side, not the cold.

If the mix is placed by hand rather than machine, the height difference for compaction should be increased to 9.5mm (3/8 in) for each 25mm (1 in). The height difference may vary among mixes, so experience and engineering judgment should be used as appropriate.

Transverse joints may be hot or cold. Hot joints should be treated the same as conventional DGAC, but the RMA 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, but this is usually not practical and rarely done. Transverse joints are generally rolled longitudinally.

4.8 Hot Mix Compaction

Compaction is essential to the performance and durability of any asphalt pavement including asphalt rubber mixtures. The best materials, mix designs, and placement techniques cannot compensate for adverse effects that result from poor compaction during construction.

Typical paving operation showing compactor near the paver.

The coarse aggregate structure and stiff asphalt rubber cements in RAC-G mixes often require more compaction effort than conventional DGAC. 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.

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 25 to 30 mm (1 to 1.2 in) thick. Compaction is achieved with a few passes by rollers operating in the static mode.

4.8.1. Temperature Requirements

According to Caltrans specifications for RAC-G, if the atmospheric and pavement surface temperatures are less than 18ºC then breakdown compaction must be completed before the mat temperature drops below 127ºC. For site temperatures with temperatures of 18ºC and greater, breakdown compaction must be completed before the mat temperature drops below 121ºC. Regardless of the specification used, it is strongly recommended that breakdown compaction of RAC- G should be completed before the temperature of the RMA mat drops below 138ºC.

It is also recommended that mat temperature be closely monitored during placement and compaction, and that adjustments 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. In addition, vibratory rolling below the minimum breakdown rolling temperature should not be allowed, nor should vibratory rolling after static (finish) rolling.

4.8.2 Factors That Affect RMA 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 50 mm (2 in) 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 asphalt rubber mixtures, it is important for the breakdown roller to follow immediately behind the paver to achieve 95% of the required compaction during the vibratory breakdown while the mix is still hot. The number of vibratory coverages required may vary depending on the mix and site conditions during placement. The anticipated roller coverages may need to be adjusted based on mix and site temperatures 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 RMA mixes.

4.8.3 Test Strips and Rolling Patterns

Test strips for RAC-G materials are recommended when feasible to indicate what level of compaction effort is needed to achieve adequate in-place density. However, if California Test 113 is used for RAC-G, the temperature ranges for the test must be modified. During test strip compaction, both contractor and agency representatives should correlate their respective nuclear gauge(s) on the test strip according to the MTO specifications. Gauge data should then be correlated with core results in order for nuclear density to provide accurate data for quality control during paving.

4.8.4 Opening New Pavement to Traffic

RMA mixes are relatively cement-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 RMA pavement at a rate of about 1 to 2 kg/m^2 (2 to 4 lbs/yd^2) to act as a blotter. Sand shall be free from clay or organic material. Excess sand shall be removed from the pavement surface by sweeping. Any approved spreader with uniform distribution capabilities to provide a sand blotter for opening the RMA surface to traffic.

4.9 Examples of Good Paving Practices

Examples of good paving practices may be found in the "Hot-Mix Asphalt Paving 2000 Handbook," The Asphalt Institute Manual MS-22 "Principles of Construction of Hot-Mix Asphalt Pavements," The National Highway Institute course on Hot-Mix Asphalt Construction, the Caltrans Construction Manual, and various industry publications among other sources. Some of the fundamental guidelines are summarized below:

- 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 cement drain-off.
- Coordinate mix production, delivery, placement, and paving operations to provide a smooth uninterrupted flow of material to the paver. MTVs may be used to minimize effects of variations in delivery.
- 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 specified for these operations.

4.10 Asphalt Rubber Spray Applications

The cements used for asphalt rubber chip seals and interlayers are generally the same as those used to make RMA mixes, using the equipment previously described. Chip seals are also called Stress Absorbing Membranes (SAMs) or Asphalt Rubber and Aggregate Membrane (ARAM) and may be used on the surface or as crack resistant interlayers under a conventional hot mix or RMA overlay. The primary difference in construction is that a flush coat is not applied to the surface of an interlayer prior to overlaying it.

4.10.1 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 the aggregate chips must be large enough so as not to be "swallowed" by the membrane. Appropriate sizing of distributor nozzles minimizes the tendency to clog due to the presence of discrete rubber particles. Chip seal construction moves relatively rapidly. A reasonable production rate is about 8-11 lane km (5-7 lane miles) per day.

Temperature is critical to successful chip seal construction whether the cement is conventional paving grade asphalt or high viscosity asphalt rubber. Clean or precoated chips are also critical and, for use with asphalt rubber cements, are required to be hot (127 to 163ºC). Embedment and adhesion of the chips must be accomplished by rolling while the asphalt rubber membrane is still hot. Specifications used in California indicate that the higher temperature of the asphalt rubber cement and the use of hot precoated chips allow placement of asphalt rubber chip seal at cooler temperatures, even at night, than do emulsion cements. However, is not advisable to place chip seals when ambient or pavement temperature is less than 16ºC; such cool conditions leave little margin for variability in materials, application or site temperature conditions.

Recently, warm mix additives have been used with chip seals in California. The temperature can be lowered as much as 16°C, which greatly reduces the emissions and the odour.

4.10.2 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
- For surface treatments, distributor truck to apply a flush coat (typically diluted emulsion)

4.10.3 Asphalt Rubber Spray Application

The distributor must be properly adjusted and operated to apply the proper amount of asphalt rubber cement 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 cement is too cold, when its viscosity is too high, or the spray bar is too low. The person who monitors the application for uniformity and nozzle shall be protected from fumes by a pollution hood over the spray bar. Application rate typically ranges from about 2.5 to 2.9 l/m2 (.55 to .65 gal/yd2). The rate should be based on the condition of the existing pavement surface: dry, oxidized, raveled or brittle surfaces require higher cement applications.

Asphalt spray application. Note the smoke

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.

4.10.4 Aggregate Application

Aggregate application rates can be determined in the laboratory prior to the start of construction. The easiest method 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. Typical application rates range from about 15 to24 kg/m2 (28 to 40 lbs/yd2) with the exact rate to be determined by the Engineer. To verify if application rates for cement and chips are appropriate, also check the embedment of the cover aggregate. Individual chips should be embedded to a depth of about 50-70% after seating in the lab or by rollers and traffic in the field.

Spreading the chips

Excess chip application interferes with embedment and adhesion. Bidding chips on a square metre basis rather than by the ton helps minimize over-application of cover aggregate. 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 cement cooled before embedment and adhesion were achieved. Excess asphalt rubber application can literally submerge or swallow the chips, and result in flushing/bleeding.

The chip spreader should follow within 20 to 30m of the asphalt rubber distributor and must keep up. The asphalt rubber cement must be fluid so the rock will be embedded by the displacement of the asphalt. A chip seal train consisting of cement distributor truck, chip spreader, and roller is shown below.

Trucks should back into the spreader box and should not cross over any exposed asphalt rubber membrane. This is illustrated in the photo below; 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. However, 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% 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.

4.10.5 Rolling Asphalt Rubber Chip Seals

Pneumatic-tired 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. Unlike RMA mixes, the tires are in contact with the cover aggregate rather than the asphalt rubber cement, so excessive pickup is rarely a problem. Skirts around the tires can help maintain elevated tire temperature to aid compaction. 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 about 6.4 to 9.7 km/h (4 to 6 mph) so that the rock is set in the cement, 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.

Rolling the chips

4.10.6 Sweeping

Sweeping (brooming) removes surplus aggregate from the surface of the new chip seal to minimize flying rocks. Sweeping can usually be started within 30 minutes after chip application. It is desirable to sweep during the cool period of the day using a rotary power broom. The photo below 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.

4.10.7 Flush Coat or Fog Seal

The flush coat consists of an application of fog seal over the new asphalt rubber chip seal followed by a sand cover. 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 about .23 to .45 l/m2(0.05 to 0.1 gal/yd2), or as determined by the Engineer.

4.10.8 Sand Cover

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, i.e., free of clay fines or organic material. It is spread in a single application of about 1 to 2.2 kg/m^2 (2 to 4 lbs/yd^2), or at a rate determined by the Engineer.

4.10.9 Traffic Control

Some form of traffic control is required to keep the initial traffic speed on the new chip seal below about 40 km/h (25mph). 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.

4.11 Emissions

4.11.1 Air Quality

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

4.11.2 FHWA/USEPA Studies

In June 1993, the FHWA and the US Environmental Protection Administration (EPA) issued a report on the "Study of The Use of Recycled Paving Material - Report to Congress" which described an analysis of the results of seven studies to compare the relative threats/risks to human health and the environment from conventional asphalt paving and CRM asphalt paving. The report discussed some of the variables that influenced the health and environmental comparisons. Conclusions indicated that the data evaluated contained no obvious trends to indicate a significant increase or decrease in emissions attributed to the use of CRM. The FHWA/USEPA report recommended further study of this issue. Subsequent studies have been conducted but have not provided sufficient evidence to change the original conclusions (references).

4.11.3 AC Plant Emissions Tests

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

In 2001, Caltrans investigated emissions at two AC plants in the San Francisco Bay area. The Bay Area study was the result of severe blue smoke problems that occurred at a plant in November 2000, which were attributed to use of CRM rather than a lack of modern emissions controls. A partnership among the Bay Area Air Quality Management District (BA AQMD), Caltrans, and paving industry organizations developed a plan to test AC plants producing RMA during summer 2001. The scope of the testing program included the following:

- Cal ARB Method 429 - Polyaromatic Hydrocarbons (PAH)
- Cal ARB Modified Method 5 – Determination of Particulate (BTEX)
- Test during production of Conventional AC and RMA in triplicate at two hot plants
- Testing during normal production runs

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

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

4.11.4 Worker Health and Safety

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

4.11.5 National Institute for Occupational Safety and Health (NIOSH)

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

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

4.11.6 Industry Studies in California

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

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

4.11.7 Worker Exposure

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

4.11.8 Water Quality

Water quality is another area of concern regarding the use of CRM. Southwestern Laboratories tested leachate from stockpiles of reclaimed CRM pavement milled from IH10 in San Antonio, Texas, to evaluate the potential for contamination of surface runoff and groundwater.

Simulated precipitation leachates were prepared to represent the cumulative effects of acid rainwater leaching and were analyzed for the presence of trace metals, volatile organic compounds (VOCs) and semivolatile organic compounds. The only compound of interest that was present at a level above the analytical detection limit was mercury, but levels detected were below EPA limits (Crockford et al, 1995). The report concluded that levels of detectable leachates were too low to be environmentally significant or dangerous.

4.12 Summary

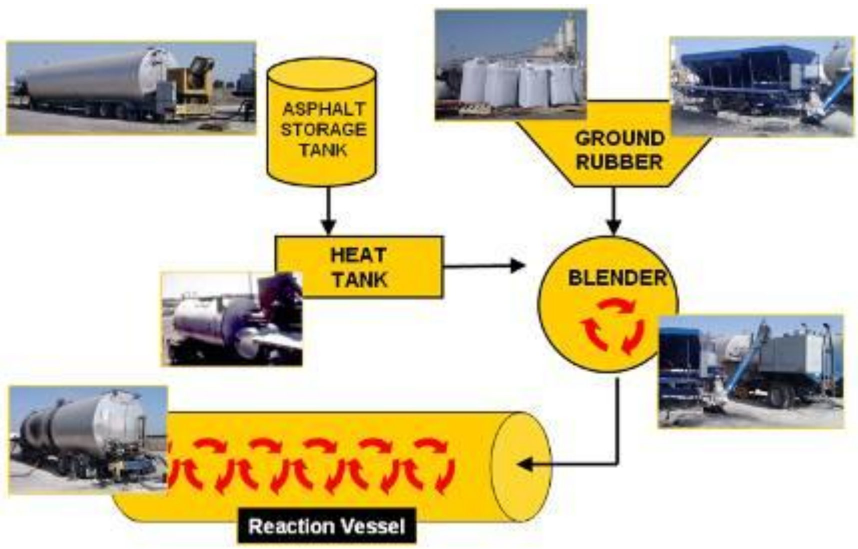
This chapter presents a summary of the production and construction practices for the wet processes used in Ontario and other places for comparison. The rubberized asphalt cements have been produced for some time and pilot projects have been constructed for several years in Canada.

5.0 Inspection Guide for Rubberized Asphalt Operations

5.1 Introduction

Inspection is a very important part of producing a successful project. This inspection mission is to verify that the final field product is in conformance with the plans and specifications.

As a construction inspector, you are the vital link between the designer and the final field product. Your knowledge of the material and equipment used to manufacture and place Rubberized Asphalt Concrete (RAC) coupled with your expertise in the proper construction techniques needed to ensure a high-quality, long-lasting roadway surface will determine the performance of the final product.



Remember, the contract documents (plans, specifications, etc.) provide minimum requirements. Any deviations below these minimum requirements will reduce the useful life of the pavement and add additional unplanned maintenance costs.

5.1.1 Purpose

This chapter provides an overview of the basic information about RMA mix design, manufacture, pavement surface preparation and construction techniques. The goal of the chapter is to give you brief, yet substantial, information in a checklist format rather than providing full descriptions of how to perform each function.

While the information presented in this chapter is geared toward the construction of HMA, the same principles apply to the construction of conventional asphalt concrete pavements. For more detailed information, we recommend the following publications:

- **Principles of Construction of Hot-Mix Asphalt Pavements**, Asphalt Institute, Manual Series No. 22

- **Hot-Mix Paving Handbook 2000**, AASHTO, FAA, FHWA, NAPA, U.S.A.C.E., APWA and NACE. Available through National Asphalt Pavement Association

- **National Highway Institute** (NHI) Hot Mix Asphalt Construction Course – FHWA

- **Transportation Association of Canada**, Pavement Asset Design and Management Guide 2012, Available through Transportation Association of Canada

5.1.2 Advantages of RMA

Ontario generates nearly 15 million scrap tires annually. Benefits identified with recycled tires in RMA by other agencies include:

- Ensures long-lasting, durable pavement that resists reflective cracking.
- Saves money. By using its superior resistance to reflective cracking, a RMA resurfacing project can save as much as $20,000 per lane mile over AC by placing a thinner section (50 mm (2 in) RMA vs. 102 mm (4 in) AC).
- Provides a highly skid-resistant surface, reduces tire noise by 50 to 80%, and resists rutting and shoving.
- Uses over 2,000 tires per lane mile in a 50 mm (2 in) thick resurfacing project, making RMA environmentally friendly.
- Provides excellent color contrast for striping and marking.

To date, the benefits of using RMA in Canada and particularly in Ontario have not been as promising. The Ministry needs to identify and clearly document the benefits in Ontario.

5.2 Inspection of RMA Production

As an inspector, one needs to understand how RMA is produced. As discussed in the preceding chapters of this manual, RMA is made by blending crumb rubber from scrap tires, asphalt cement, and properly graded, sound aggregates in specified proportions in a central mixing plant. Other additives such as high natural rubber and extender oil may be included as appropriate. The processes for producing RMA are summarized below for the sake of convenience.

5.2.1 Wet Process High Viscosity (Asphalt Rubber)

Blending of the crumb rubber is generally done by the "wet process" in which the crumb rubber is blended and interacted with the hot asphalt cement prior to adding the asphalt rubber cement to the aggregates.

Currently, the "wet process" is the major process used in states like California and Arizona. It is also one of the primary processes being evaluated by the Province of Ontario. Two different types of cements may be made by the wet process: high viscosity (meets ASTM definition of asphalt rubber including minimum viscosity of 1,500 cPs, or 1.5 Pascal seconds) and no agitation, which is often referred to as terminal blend, and has viscosity <1,500 cPs. Viscosity is the discriminator for appropriate use. The information herein applies to high viscosity asphalt rubber materials.

5.2.2 Wet Process no agitation (Terminal Blends)

This process, which has been used in the USA since 1995, digests the crumb rubber into the asphalt cement at the refinery so that no agitation is required. A number of refineries in Arizona, California, Nevada and Texas are now producing similar products, such as PG 76-22TR+, PG 64-28TR, PG 70-22TR, MAC-15TR and MAC-TR10. An advantage of these products is that they can be applied at much lower temperature in comparison to high-viscosity wet process, without the need for specialized equipment. Now produced at CRM contents greater than 15% in California, they have a variety of applications in dense- and open/porous-graded pavements. Also, the product is homogeneous with high solubility. This also allows it to be emulsified for slurry seal applications.

5.2.3 Dry Process

The "dry process" mixes the rubber particles with the aggregate prior to the addition of the asphalt. This process is not used by many agencies. Caltrans has special provisions for RUMAC, a generic dry process mix made with gap-graded aggregates, but rarely uses this type of CRM modification. Recently constructed test sections are being monitored to evaluate potential for wider use.

5.3 Composition of RMA, Mix Designs and Certification

5.3.1 Aggregates

In Ontario, two gradations are used in RMA mixes. Gap-graded is used when the field blended process is employed while a dense-graded aggregate is used when the terminal blends are employed. Aggregate properties for RMA must meet either the requirements of Superpave 12.5 FC 2 or Superpave 9.5.

5.3.2 Rubberized Asphalt Cements

CRM added to the RMA shall meet the gradation requirements specified in Table R3 of Appendix C and determined according to ASTM D5644. Wet-terminal blend RMA is produced as a Type III Asphalt Rubber Cement according to ASTM D6114. CR dosage by mass of wet-terminal blend RMA shall be 10% to 15%. Wet-field blend RMA (after reaction) shall meet the requirements found in Table R4. CR dosage by mass of wet-field blend RMA shall be 18 to 20%. For the production of the RAC, parameters such as CR gradation, mixing method and equipment, dosage, reaction time, mixing temperature, storage conditions and need for agitation, blending location (project site vs. asphalt supplier's terminal) shall be determined by the Contractor.

When the RMA supplier specifies a CR gradation with additional restrictions, the CR shall also meet the RMA supplier's gradation requirements. The CR material, PGAC and any anti-stripping additives required shall be compatible to ensure a good dissolution and reaction time. RMA produced shall be a homogenous mixture of CR and asphalt cement.

5.3.3 Mix Design and Certifications

A mix design is provided by the Contractor and reviewed by the Agency. The Contractor certifies that the mix provided corresponds to the submitted mix design. A mix design should include:

- Combined aggregate gradation
- Cement content
- CRM content (scrap tire and high natural)
- CRM gradation (scrap tire and high natural)
- Maximum density – Rice
- Air voids at laboratory density
- Voids in mineral aggregate (VMA)

The mix design process currently used in Ontario is summarized in Appendix D. It makes use of the Superpave mix design process

5.4 Equipment

A typical asphalt plant consists of the following:

- Aggregate storage bins
- A weighing device to measure specific amounts from each bin onto a cold feed belt or into a pug mill
- A heated storage tank for the asphalt cement
- A drum dryer to dry and heat the aggregates
- A mixing drum or pug mill to mix the aggregate with the asphalt cement
- A storage silo to temporarily store the asphalt concrete
- A weighing device to drop the AC into the trucks fordelivery to the job
- A RMA plant adds equipment to blend the crumb rubber with the asphalt cement (wet process) or aggregates (dry process)

Overview of a typical plant operation

RMA is placed with a conventional, mechanical, self-propelled paver designed specifically to distribute a layer of RMA (or any AC paving mix) to a predetermined thickness.

Compaction is done with self-propelled, vibrating steel wheel rollers. Rubber tired rollers are not permitted due to potential for pick up. Vibratory mode is used for the break down coverages, and static mode for intermediate and finish rolling.

5.5 Surface Preparation

The existing pavement to be resurfaced shall be clean with all cracks over 6 mm (1/4 in) filled (do not overfill) and all badly deteriorated sections removed and replaced. Longitudinal and transverse joins shall be milled. An approved tack coat (preferably paving grade asphalt) shall be applied evenly at the specified rate over the entire surface to be paved.

5.6 Inspection at the Plant

Inspection at the plant should take place at various locations. This section provides checklists for items to be checked.

5.6.1 Plant Inspection Is Critical to Success of Every RMA Project

Problems observed at the plant can be corrected immediately to ensure that the material delivered to the site conforms to the specifications. Important items to watch for at the plant:

- Verify that the scales have been certified for accuracy.
- Check aggregate bins for properly sized material in each bin.
- Check aggregates off of the cold feed belt for proper gradation.
- Monitor the proportioning devices to verify that the proper amount of crumb rubber is added to the asphalt cement and to ensure that the proper amount of asphalt rubber cement is added to the aggregates.
- Check the viscosity of the asphalt rubber cement to make sure that it meets requirements and that the crumb rubber is thoroughly blended and interacted with the asphalt cement.
- Take samples of the crumb rubber, aggregates, asphalt cement, asphalt rubber cement, and RMA mix for possible laboratory testing. Test as needed.
- Check the temperature of the RMA in the trucks.

- Haul trucks should be covered (tarped) to maintain RMA mix temperature.

- Maintain an accurate log of test samples, aggregate gradations, CRM quantities, viscosity measurements and corresponding temperatures of the asphalt rubber cement.

5.7 Inspection at the Site

At the construction site, you have the opportunity to help ensure that the materials and the lay down procedures are consistent with those that will result in a high-quality product. By working with the Contractor's foreman, you help resolve potential problems and correct irregularities.

It is extremely important, however, to remember that you should not direct the work; that is the Contractor's responsibility.

5.7.1 Prior to Paving

For overlays, check existing pavement condition and the following:

- Are cracks over 6mm (1/4 in) filled? Is application of sealant too heavy?
- Are the badly deteriorated areas repaired?
- Are the joints milled?
- Is the surface clean?
- Has the tack coat been properly applied?

In addition, one needs to check the following:

- Ambient temperature and the temperature of the pavement to be resurfaced. Specifications require minimum air and pavement temperatures of 13 ºC and rising. At minimum temperatures, little time is available for compaction.

- Ensure that the paver and the rollers are the proper type and that they are in good working order.

- Verify that the specified numbers of rollers are on the job and that there is a trained operator available for each.

Remember, compaction is the key to long-lasting pavement and compaction depends on the temperature of the mat.

There must be a sufficient number of breakdown rollers to cover the width of each paver pass immediately behind the paver. In California, the Greenbook requires higher temperatures for mix delivery and compaction than Caltrans specifies. Breakdown compaction should start before mix temperature drops below 143ºC (Greenbook) or 138ºC (Caltrans). To meet compaction requirements, it is typically necessary to achieve at least 95% of the required compaction during breakdown rolling, before the mat temperature drops below 127ºC.

It is necessary to verify that the method of delivery of the RMA is appropriate for the job and weather conditions (end dumps vs. bottom dumps). When weather is marginally cool, windrows are not recommended.

5.7.2 During Paving

The following items need to be checked during the paving operations:

- Collect load tickets on a regular basis and calculate the yield to ensure that the proper thickness is being placed.
- Physically verify mat thickness at spot locations.
- Verify that the paver is operating at a speed that is consistent with the delivery of the mix. Pavers should not have to wait between loads of mix and loads of mix should not have to wait to unload.
- Verify that the screed height is not being adjusted unnecessarily
- Are the trucks carefully backing up to the paver?
- Is the paver pushing the trucks?
- Does the rate of loading the RMA into the hopper result in a full hopper without spilling over the sides?
- Is the roller drive wheel forward?
- Are the roller’s wheels kept wet to avoid picking up the RMA mix and are the scraper pads effective?
- Is the roller operator reversing directions on existing or newly cooled pavement?
- Is the roller operator rolling the joints properly and rolling the mat from the low side toward the high side?

Visually inspect the RMA as the trucks dump it into the hopper by checking the following:

- Is the RMA mixture smoking? (too hot)
- Is the RMA mixture stiff? (too cool)
- Is the RMA mixture shiny or slumped? (Excessive cement - maybe. RAC mixes may look rich even at correct asphalt rubber content, so sample and test.)
- Is the RMA mixture segregated? (Improper mixing or handling – maybe. Gap- and open-graded mixes can look segregated due to limited fines, so sample and test aggregate gradation and cement content.)
- Verify that the breakdown roller(s) follow immediately behind the paver and that the breakdown rolling is completed before the mat reaches 127ºC.

5.7.3 After Paving

The following items need to be checked after paving is complete:

- Check the compacted pavement surface for roller marks, scuffing, irregularities, smoothness, etc.
- Verify relative compaction by nuclear gauge or lab testing of pavement cores.
- Check the longitudinal and transverse joints for evenness, texture, and ride.
- Keep an accurate record of the tons placed and the area that was paved. Note any rejected loads or unusual occurrences.

5.8 Summary

RMA is a proven product that will stretch your agency's roadway maintenance funds and help reduce the stockpiles of scrap tires in California. When used in appropriate situations and constructed properly, RMA will produce a safe, high-quality, durable, quiet road that is more cost effective than conventional asphalt concrete. However, quality construction is a must!

As the eyes and ears of the agency you represent, you are charged with a great responsibility. Each project has been designed in accordance with accepted criteria using specifications that are, in reality, minimum requirements for the quality of the materials and the workmanship. Your job is to verify that the final field product conforms to the plans and specifications. It is an important job. It deserves your full attention.

6.0 Summary of Key Points

This final chapter presents a summary of the key points raised in this manual. As stated in the manual, the Ministry of Transportation of Ontario has been placing projects throughout the province using difference rubberized asphalt processes. They have made use of asphalt rubber similar to that used in California and Arizona in gap-graded mixes. This product contains at least 18 % crumb rubber modifiers and requires a special field blending unit to react the rubber. The terminal blends, which often contain less crumb rubber contents and are blended at the refinery, is also used in Ontario primarily in dense graded mixes. These are products similar to those used in the United States.

The manual contains important information on the following:

- Application and use. In Chapter 2, the manual discusses the types of applications and when and where they should or could be used.

- Design and specification guide. In Chapter 3, the manual discusses how the products should be designed and specified including the cements and the mixes. Structural design consideration are mentioned but not included in detail.

- Production and construction. Chapter 4 presents information on the production of the cements as well as construction of both hot mix and spray applications.

- Inspection. Chapter 5 presents checklists on things to look for during inspection. You get what you inspect so it is important to make sure inspectors are collecting the correct information.

Ontario has placed a number of pilot projects in recent years. If the guides suggested in this manual are followed, one can expect that the performance of the rubberized asphalt placed will performed well.

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8.0 Appendices

Appendix A. Glossary

A.1 Types of Rubberized Asphalt

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." The Ontario 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).

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.

Semi Dry Process - The semi-dry/semi-wet or moist process lies somewhere between the wet and dry processes. Very fine rubber crumbs are added to the mixer just prior to the addition of asphalt cement. A longer mixing time is required than for normal HMA to allow for some reaction between the crumb rubber and AC, resulting in partially modified asphalt cement.

Rubberized asphalt - asphalt cement modified with CRM that may include less than 15 % CRM by mass and thus may not comply with the ASTM definition of asphalt rubber . In the past, terminal blends (wet process, no agitation CRM-modified asphalt binders including Modified Binder (MB) materials) have typically fallen in this category. In California, the terminal blend suppliers now provide products that are greater than the 15 % CRM that has traditionally been used.

Terminal blend – See Wet Process- No Agitation or Rubberized asphalt

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.

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. One advantage is these products can be applied at much lower temperature without the need for specialized equipment.

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%.

A.2 Types of Rubber

Crumb rubber modifier (CRM) – general term for scrap tire rubber that is reduced in size for use as a 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:

Ground crumb rubber modifier – irregularly shaped, torn scrap rubber particles with a large surface area, generally produced by a cracker mill.

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

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

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

Tread peel – pieces of scrap tire tread rubber that are also a byproduct 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.

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.

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

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.

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

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.

A.3 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.

A.4 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 mm) 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 mm) sieve size.

A.5 Mix Types

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

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

- **Gap-graded** – aggregate that is not continuously graded for all size fractions, but is typically missing or low on some of the finer size fractions (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.

- **Open-graded** – aggregate gradation that is intended to be free draining and consists mostly of 2 or 3 nominal sizes of aggregate particles with few fines and 0 to 4% by mass passing the 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.

- **Warm mix asphalt rubber mixes**. Warm mix additives have been used in California with open- and gap-graded asphalt rubber mixes and terminal blends to extend the construction season, improve cool weather compaction and extend the haul distance.

RUMAC – This is a generic type of dry process RMA mixture that has taken the place of proprietary dry process systems such as PlusRide. This type of product is still used in some states, like Alaska.

A.5 Other Mix Ingredients

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.

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.

A.6 Reactions between Rubber and Asphalt

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.

Reaction – commonly used term for the interaction between asphalt cement and crumb rubber modifier when blended together at elevated temperatures (see Interaction).

A.7 Interlayers

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-in. (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.

A.8 Aggregates for Asphalt Concrete

General description. Most aggregates can be used in rubberized asphalt concrete mixes or chip seals. They include the following:

Classification of Rock
- Sedimentary
- Igneous
- Metamorphic

Aggregate Sources
- Natural aggregates - gravel, sand
- Processed aggregates - crushed aggregate
- Synthetic aggregates - blast furnace slag

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.

Important aggregate properties. Some of the important properties are given below:

Maximum Particle Size and Gradation
- Specified for each asphalt concrete paving mix
- Coarse aggregate - retained on the No. 4 sieve
- Fine aggregate - passes the No. 4 sieve
- Mineral filler/dust - passes the No. 200 sieve

Specific Gravity
- Aggregates of low specific gravity cover a larger volume per ton and, therefore, require a higher percentage of asphalt cement.
- Aggregates of high specific gravity cover a lower volume per ton and, therefore, require a lower percentage of asphalt cement.

Cleanliness
- Free of unsuitable material
- Toughness
- Abrasion resistant

Particle Shape
- Crushed particles interlock to provide strength.
- Fine, rounded particles provide workability but act as ball bearings in the mix so content should be limited. Many agencies limit such materials to a maximum of 15% of the total aggregate to minimize adverse effects on aggregate interlock and VMA.

Surface Texture
- Asphalt tends to strip from smooth surfaces.

Absorptive Capacity

- Ability to absorb asphalt influences the total amount of asphalt required. High absorption increases binder content.

Affinity to Asphalt

- Ability of the aggregate to bond with the asphalt binder
- This affects moisture sensitivity.

A.9 Asphalt

Asphalts are materials that consist of black cementitious material made up largely of hydrocarbons and are a visco-elastic plastic material - brittle and hard when cold; soft and viscous when hot. Classes of asphalts include:

- Asphalt cement (paving grade asphalt)
- Liquid asphalt (mixed with cutbacks) - not used in RAC
- Emulsified asphalt (mixed with water) - not used in RAC

Important physical properties include:

- Durability
- Adhesion
- Temperature susceptibility - CRM modification reduces temperature susceptibility
- Aging and hardening
- 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 RMA mixtures.

A.10 Asphalt Binder Tests

The following tests are used for asphalt rubber binders, but not for testing Performance Graded (PG) asphalt:

- **Viscosity** - ability to flow, consistency - temperature dependent
- **Penetration** - hardness value, also measure of consistency at single temperature
- **Flashpoint** - temperature at which a sample "flashes" i.e. bursts into flame
- **Thin Film Test/Rolling Thin Film Test** - aging methods
- **Ductility** – discrete CRM particles affect test results, typically exhibits early

fracture.

- **Specific Gravity** – used in volumetric mix design calculations, and for metering during mix production

A.11 Mix Design Methods

Mix design methods used for rubberized asphalt mixes are to determine the optimum binder content. The methods used have included:

Marshall Mix Design Method

- Hot mix asphalt paving mixes, one-inch maximum size aggregate (for 4-inch molds)
- Determines optimum asphalt cement content for a particular blend of aggregates.
- Principal features are: 1) a density/void analysis and 2) a Marshall stability/ flow test.

HVEEM Mix Design Method (used in California)

- Hot mix paving, one-inch maximum size aggregate
- Principal features are:
- Centrifuge Kerosene Equivalent
- Hveem Stability test
- Swell test (permeability)
- Air voids
- Bleeding/flushing.

Superpave Mix Design Method (used in Ontario) –See Appendix D

A.12 Mix Design Characteristics

Mix design of asphalt and rubberized asphalt paving mixes is a tradeoff between high binder content to enhance long term durability and performance, and sufficient in-place void space to avoid rutting, instability, flushing and bleeding.

- Air voids provide spaces for the movement of the asphalt cement or asphalt rubber binder within the compacted mix.
- High air voids indicate relatively low density and increased permeability of the compacted mix. The maximum design target is 6% air voids, for special high volume and/or hot climate conditions.
- Low density typically results in raveling and/or stripping, increased susceptibility to aging, fatigue, and environmental damage, and related reduced service life.
- Low air voids indicate relatively high density and increased tendency for asphalt flushing, and mixture rutting and shoving. The minimum design target is 3% air voids.
- High density also enhances resistance to fatigue and environmental damage, long term performance and durability, as long as in-place air voids are sufficient to prevent bleeding or instability.

Voids in Mineral Aggregate (VMA)

- Total voids excluding those permeable to water and asphalt. VMA is a function of aggregate gradation, particle shape and texture.
- Proper VMA provides sufficient space for binder, which results in durable asphalt film thickness.

Design Asphalt Content

- Depends on aggregate gradation (particularly VMA), ability to absorb asphalt, and compaction type and effort. Hveem and Marshall Methods will yield different results for the same mixture.
- Mineral filler greatly affects design asphalt binder content. Too much filler fills the voids, reduces VMA, and has high demand for binder which results in a dry mix. Too little filler results in a wet mix. However very little filler is used in RMA mixes due to limitations on percentage passing the No. 200 sieve size.

A.13 Mix Design Properties

Important mix design properties include:

Stability

- Ability to resist shoving and rutting, i.e. permanent deformation.
- Dependent on internal friction of the aggregates (interlock) and the cohesion of the asphalt binder to the aggregate surface.
- Angular aggregate particles with a rough surface texture result in pavements with high stability.

Durability

- Ability to resist changes in the asphalt (polymerization and oxidation), aggregate disintegration, and stripping of the asphalt film
- Durability can be enhanced by increasing the asphalt binder, and achieving proper compaction

Impermeability

- Related to the air void content and the characteristics of the voids (whether they are interconnected, the size of voids, and whether the voids are at the surface). The size of the voids is related to the sizes of the aggregate particles; large stone mixes have larger individual voids.

Workability

- Workability describes the ease with which the mix can be placed and compacted.
- Harsh mixes (coarse aggregates, few fines) tend to have low workability - RAC-G mixes are not amenable to handwork
- Tender mixes (too much sand or rounded aggregate particles) tend to shove during rolling.

- Temperature of the mix greatly affects workability.

Flexibility

- Ability to adjust to gradual changes in the subgrade or unequal stresses in overlays across cracks without cracking.
- Open- or gap-graded mixes have more flexibility than dense-graded mixes because of higher asphalt rubber binder content and, therefore, are used when resistance to reflective cracking is desired.

Fatigue Resistance

- Ability to resist repeated bending and deflection under wheel loads
- Low air void content and high asphalt content increase fatigue resistance.
- High viscosity asphalt-rubber binders have been shown to be highly resistant to fatigue cracking

Skid Resistance

- Measures the ability of the asphalt surface to resist skidding or slipping of vehicle tires.
- Rough pavement has higher skid resistance than smooth or flushed pavements.

A.12 Typical Asphalt Paving Failures (include typical photos)

Typical pavement failures in Canada include:

Weathered or Dry Surface

- Insufficient binder content during mix production
- Loss of binder due to stripping or raveling, overheating, or absorptive aggregates

Pot Holes

- Structural failure due to lack of base and/or subgrade support
- Insufficient pavement thickness or segregated mix
- Water infiltration is generally an important contributing factor.

Alligator (Fatigue) Cracking

- Structural failure due to lack of base and/or subgrade support
- Insufficient pavement thickness, aged binder, or water saturation

Bleeding and Instability

- Excessive binder content, heavy tack coat
- Excessive aggregate fines, rounded aggregates, low air void content

Raveling

- Lean (low binder content) or overheated mix
- Low density/under compacted

Slippage failures

- High shear stresses
- Lack of bond with underlying layer due to improper tack coating or inadequate cleaning of existing surface

Stripping

- Loss of binder, most often due to moisture damage or aggregate surface characteristics
- Leads to raveling, potholes or others types of distress

Surface Erosion

- Water running or standing on pavement for long periods of time
- Soft aggregates

Reflective Cracking

- Reflective cracks from existing pavement - difficult to prevent
- Resistance to reflective cracking is one of the primary performance benefits of asphalt-rubber hot mixes

Longitudinal Cracking

- Longitudinal cracking usually manifests along paving joints
- If located in the wheel paths, it is a precursor to alligator cracking

Thermal Cracking

- Transverse cracks due to low temperatures or to thermal fatigue
- Occur at regular frequencies

Appendix B. Summary of International Survey

Introduction

Stockpiles of waste tires, especially illegally dumped, have caused significant damage to the public health, safety, and environment. Tire piles are not only aesthetically disagreeable but, if mismanaged, they pose a fire hazard. Tire fires are characterized by incomplete combustion resulting in thick clouds of toxic black smoke and the liberation of toxic oils. The potential benefit of using rubber modified asphalt is great because the use of tire rubber in asphalt mixes can increase the engineering properties and this application could consume a lot of waste tires. To determine the potential benefits, the OTS and MTO wanted to identify the performance of rubberized asphalt products used in cold regions for the following applications:

- Hot mix asphalt with and without a Stress Absorbing Membrane Interlayer (SAMI layer);
- Rubberized asphalt with warm mix additives; and
- Rubberized asphalt chip seals or surface treatments.

A survey of users throughout the world on the use of rubberized asphalt in a variety of applications was conducted. The focus was to identify the performance of rubberized asphalt products in cold regions similar to those found in Ontario, Canada. **The detailed full survey report can be obtained from Ontario Tire Stewardship (OTS)**.

Objectives

The objective of the survey was to identify the extent of use of rubberized asphalt, the performance of rubberized asphalt used especially in cold regions, and to develop a summary report based on the survey. The survey report will further help with the effective application of crumb tire rubber in Ontario and aid with the development of related specifications.

Survey Process

An online survey was conducted on the use of rubberized asphalt in a variety of applications. The focus was to identify the performance of rubberized asphalt products in cold regions similar to those found in Ontario. The link of the survey was emailed to various users in the fall of 2011 in the following regions of the world:

- United States
- Canada (Alberta, British Columbia, Yukon, and Ontario)
- Scandinavia (Sweden, Denmark, and Finland)
- China

A total of 40 responses to the survey were returned from the above regions indicating widespread use of rubber in asphalt pavements. Based on the survey responses, there is wide interest in using ground tire rubber in asphalt pavements.

Summary of Survey Responses

Type of Rubber Modified Pavements

As shown in Figure 1, rubberized asphalt has been used worldwide. A total of 20 agencies replied that they use rubber in hot mix. Eight said that they use rubber in chip seals, and six said that they use rubber in interlayers. It has been used in the cold regions of the United States, Sweden, Finland, Denmark, Canada, and China.

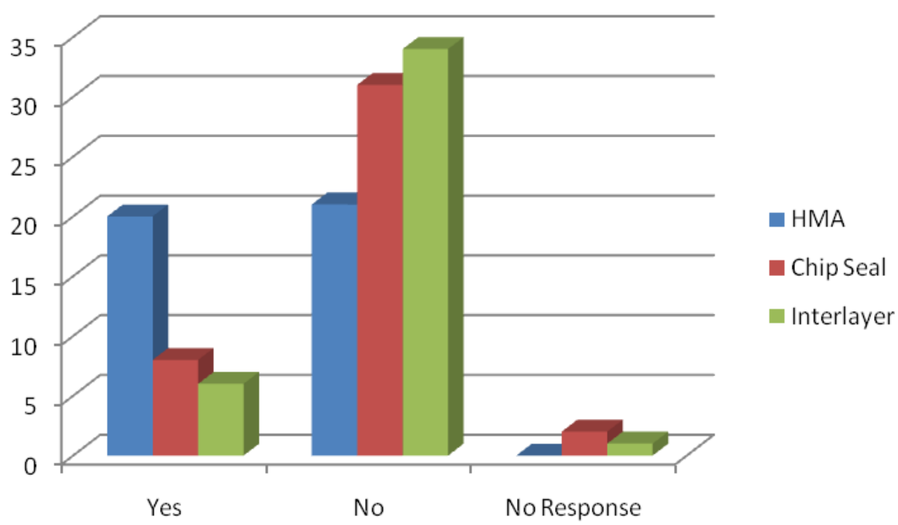

Figure 1. Status of Agencies Using Tire Rubber in Asphalt Pavements

Types of Binder Used

Out of the 40 survey responses, sixteen indicated they utilized asphalt rubber binders, thirteen used terminal blend rubberized binders, and two indicated they used other types of rubberized binders. The other types included using the dry process which means that CRM was used as part of the aggregate and the crumb rubber modifier is about 10% of the binder content.

Frequencies of Using Rubber Modified Pavements

There were eight agencies which said that they routinely use asphalt rubber or terminal blends in their pavements, which means that they know how to effectively utilize the rubberized asphalt in their pavements. Eleven agencies said they rarely use it and six indicated other. The answers for the other category included: (1) one test section, (2) research only, (3) experimental AR chip seal, (4) past trial projects, (5) used on experimental bases, (6) 3 test cases, and (7) when needed.

Benefits of Using Rubber Modified Pavement

Based on the survey responses, there are many benefits of using rubber modified pavement. The responses are summarized in Table 1.

Table 1. Benefits of Using Rubber Modified Binder

Agencies	Benefits of using rubber modified binder
Alaska DOT & PF	Resists studded tire wear. Adds additional friction for winter driving.
Arizona DOT	Increases durability. Increases resistance to oxidative aging. Increases resistance to reflective cracking. Quiet and smooth. Recycling of tires which would otherwise end up in landfills.
City of Calgary, Alberta	Reduces reflective cracking. Improves resistance to rutting. Decreases traffic noise levels (Initial, but not maintained after 1 year service). Allows reduction in paving thickness.
Danish Road institute, Denmark	Tire recycling, cracking resistance is better on some projects. Can use effectively in areas with cobble pits. Less thickness required (60% of conventional AC thickness is designed using asphalt rubber.
Delaware DOT	Competition for polymer modified rubbers to keep costs lower.
Florida DOT	Improves cracking resistance for dense-graded mixes. Reduces raveling of open-graded friction courses. Some improvement in rutting resistance by stiffening the binder. Research conducted by the University of Florida documents some of the benefits.
Georgia DOT	Can provide reduced project costs while maintaining quality and at the same time provides a productive outlet for end-of-life tires.

Jiangsu Transportation Research Institute, China	Good durability and sliding stability. Decreases noise pollution. Uses a waste resource.
Nevada DOT	Viscosity is very high, adhesion property is very good
New Jersey DOT	Use asphalt rubber in Open-Graded Friction Courses. We have seen benefits with the longevity of the OGFC along with the wet weather accident and noise reduction seen with the use of OGFC.
Ohio DOT	Good elasticity and flexibility.
Oklahoma DOT	Better performance than virgin binder.
Ontario Ministry of Transportation	Resistance to reflection cracking.
Pennsylvania DOT	2007 AR experimental seal coat project appeared to provide good performance with minimal stone loss. AR or terminal blend in HMA is best suited for gap-graded or OGFC mixtures. Penn DOT does not use OGFCs due to past use which resulted in aggregate anti-skid material clogging up the openings resulting in water retention and freezing causing more winter icing conditions and resulting in higher rock salt application rates. Our use of gap-graded HMA mixtures is mainly for SMA mixtures, but lack of AR blenders or terminal blend limits its application in gap-graded SMA. However, we have incorporated CRM in SMA in a dry process as a mastic stabilizing agent on two SMA projects since 2009 which have performed well to date.
Rhode Island DOT	Better performance.
Saskatchewan Ministry of Highways and Infrastructure	Use of asphalt rubber would replace the addition of polymers in mixes, therefore resulting in potential cost savings.

Sito Oy, Finland	It's more flexible than ordinary asphalts and it is used to avoid reflective cracking between concrete and asphalt pavements.
South Carolina DOT	Recently started to use some terminally blended PG 76-22 on some trial projects as an alternate modifier to SBS modified PG 76-22. We have done some limited SAMI projects over old deteriorating concrete pavements.
Svevia, Sweden	Mitigates reflection cracking. Improves adhesion of bitumen to aggregates. Increases softening point of binder. Increases fatigue life.

Challenges and Limitations of Using Rubber Modified Pavement

Due to various reasons including experience, equipment, materials, and construction issues, some agencies expressed the following challenges (or limitations) of using rubber modified pavement shown in Table 2.

Table 2. Limitations of Using Rubber Modified Binder

Agencies	Limitations on using rubber modified binder
Alabama DOT	Current market prices for CRM are higher than SBS in Alabama. Another limitation is keeping the liquid asphalt tank agitated when asphalt rubber is used.
Alaska DOT/PF	Cost is high so use only on high volume roads that rut quickly. Note that the "Dry Process" is used.
Arizona DOT	Limited paving window due to temperature constraints. Some mixes can be more difficult to compact and require more effort on the part of the contractor. Construction inspectors must have high degree of training and experience in order to be assured all specifications are met.
Chang'an University, Shanxi Province	High temperature for producing asphalt rubber. More energy should be used for producing asphalt rubber. More greenhouse gas will be produced.

	High temperature performance of CRM is not better than SBS modified asphalt mixture.
City of Calgary, Alberta	Higher production costs. Does not appear to maintain long-term noise reduction qualities. Does not appear to stop all reflective cracking.
Delaware DOT	Costs Unknown long-term performance.
Georgia DOT	Crumb rubber modified asphalt (rubber at 10% of liquid AC) is allowed in Superpave mix, as an alternate to polymer modified asphalt, at Contractor's discretion. It is not allowed for SMA and OGFC.
Ministry of Highways and Infrastructure-Saskatchewan	Compaction can be difficult; some area may not have suitable aggregates. Only 2 contractors in province. Limitations on available period in year due to weather restrictions.
Nebraska DOT	Cost Consistency Availability
Nevada DOT	Issues with moisture sensitivity have been encountered in the past.
Nova Scotia TIR	Department tried one pilot project, but we were un-successful and the project was cancelled.
Ohio DOT	Cost based on trials in 2009.
Oklahoma DOT	More expensive Fewer sources
Ontario Ministry of Transportation	Inexperience of hot mix industry with rubberized asphalt concrete. Shortage of quality CRM meeting specifications.
Pennsylvania DOT	Limited AR blending companies for onsite or project specific blending of AR and limited terminal blend companies to provide terminal blend. Mobilization of AR blenders results in higher costs which limits their use due to current tight funding situation. We have tried AR and CRM (dry process) in several dense-graded HMA projects in the past several decades as experimental projects

	with mixed results. Some performed fairly well or equal to the dense-graded HMA control section, but some did not have equal performance with the HMA control section. Higher CRM percentages in these dense-graded HMA projects resulted in poorer performance too.
Rhode Island IDOT	Binder performance grading is more challenging.
Utah DOT	Difficult to pave in cold weather.
Washington DOT	Increased cost for the same or reduced performance.

Rubber Modified Asphalt Mix Type

Rubberized asphalt has been used in different types of mixes including dense-, gap- , and open-graded. Due to high viscosity and relatively large rubber particle size used in the asphalt rubber wet process, California and Arizona use asphalt rubber mostly in gap- and open-graded designs. Because of the finer rubber used in terminal blends, these modified asphalts have been used in dense- and open-graded mixes in Arizona, California, and Florida. Figure 2 shows the number of agencies using different types of asphalt rubber mix designs. Rubber has been used in other types of mixes as well. Sweden and Denmark have used tire rubber in stone matrix asphalt (SMA) mix. This is referred to as stone mastic asphalt in Ontario.

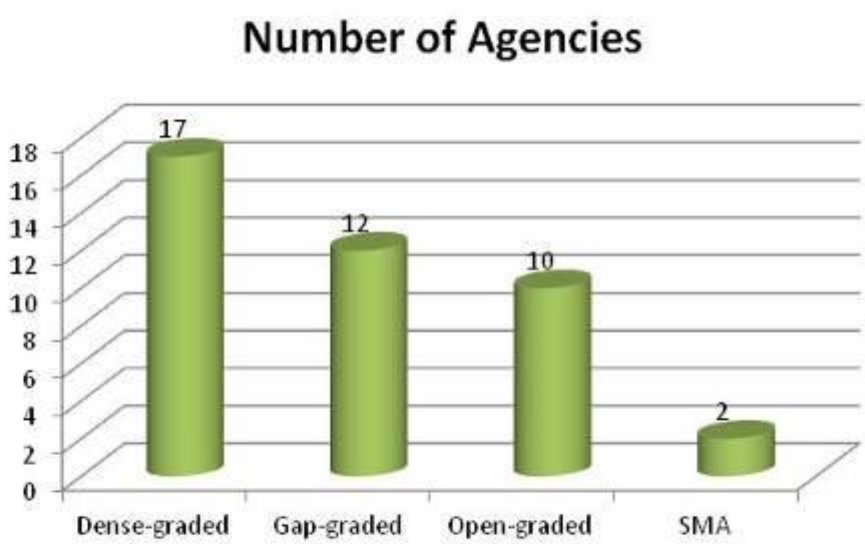

Figure 2. Number of Agencies Using Different Types of Rubberized Asphalt Pavement

Rubber Modified Asphalt Cement Content by Total Weight of Mix

Binder content is a very important parameter related to the durability and performance of rubberized asphalt pavement. Responses from various agencies showed that they have different binder contents for different types of rubber modified asphalt pavements including dense-, gap-, and open-graded, as well as SMA mixtures. Typically, the range in binder contents for dense-graded is from 5 to 6.5% by weight of total mix. The gap- and open-graded rubberized asphalt have higher binder contents than dense-graded mixes. The typical values for gap-graded and open- graded are between 7-9%.

Mix Design Methodology

Surveyed agencies use different mix design procedures. Based on the survey results shown in Figure 3, the Marshall mix design is the most widely used method by the agencies surveyed. Superpave mix design is being looked at but not fully developed. MTO is currently using the Superpave mix design approach.

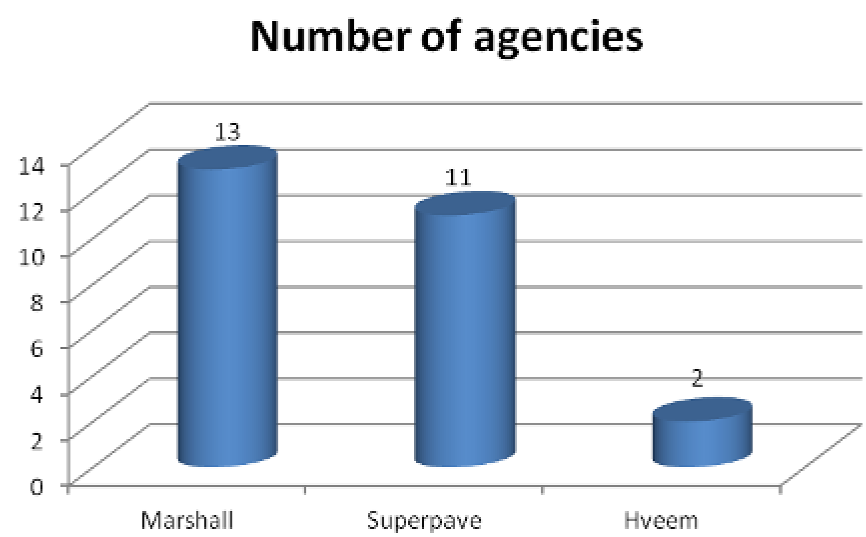

Figure 3. Number of Agencies Using Different Mix Design Techniques

Allowing Reduced Pavement Thickness

A total of 26 agencies responded to this question, of which 5 agencies including California allow reduced thickness. Figure 4 shows the percent of agencies which allow reduced thickness when using rubberized asphalt as an overlay. As can be seen, most agencies do not allow reduced thickness for rubberized asphalt pavement design. However, experiences from different agencies have shown benefits such as longer life and less maintenance of rubber modified pavement when they are applied effectively.

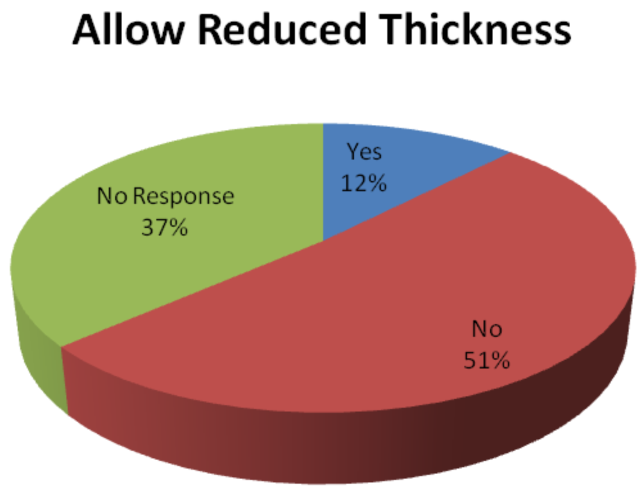

Figure 4. Agencies That Allow Reduced Thickness

Expected Lives of Chip Seals or Interlayers

Although AR chip seals have been used since the 1960s, the major cold region users of this treatment are concentrated in the United States and China. Some agencies provided expected lives for their asphalt rubber chip seal projects shown in Table 3. However, the actual treatment life depends on many factors including existing pavement structure and condition, traffic, and environmental situations. Most of the longer lives for AR chip seals or interlayers come with higher binder contents.

Table 3. Expected Life of Chip Seals or Interlayers

Agencies	Expected life, years
Arizona DOT	5 to 10
California DOT	5 to 10
Delaware DOT	5
Florida DOT	15
Jiangsu Transportation Research Institute, China	10
Kansas DOT	5
Nevada DOT	5

Oklahoma DOT	10
Pennsylvania DOT	5
Rhode Island DOT	10
South Carolina DOT	5 to 7
Tennessee DOT	5

Recycling Asphalt Rubber Products

Table 4 summarizes the responses on recycling asphalt rubber products. Some agencies have successfully recycled rubberized asphalt pavement or seal coats. Currently, the performance and emissions of the recycled rubber products are not any worse than recycling other types of pavement as long as the percentage of RAP from rubber products is kept low, such as less than 15 %.

Table 4. Agencies' Experiences with Recycling Asphalt Rubber Products

Arizona DOT	Gap-graded ARAC is milled and used as RAP.
California DOT	Caltrans allows using rubberized asphalt pavement as RAP for up to 15% into new hot mix asphalt. Caltrans conducted a study in 2005, which showed that rubberized asphalt concrete could be recycled by hot plant recycling, full depth reclamation, and CIR. Since rubberized asphalt concrete can be recycled into dense graded asphalt concrete, there is no need to mix existing rubber into new rubberized asphalt concrete because it will not increase rubber usage (Caltrans 2005).
Florida DOT	We use lower percentages of rubber in our mixes (5% in dense-graded mixes; 12% in open-graded mixes) so it hasn't been a problem, so far.
Kentucky DOT	One job in 1993.
New Jersey DOT	Recycled a Plus Ride pavement back in the 1990s - a TRB report was published at the time. Look for a report by Eileen Connolly and Robert Baker. Basically, there were no problems recycling 10% in a surface course.

Ontario Ministry of Transportation	Just once in 1991 on Hwy 2 in Thamesville, Ontario. We managed to re-use rubberized RAP in the new HMA. However emissions were slightly elevated compared to the regular HMA.

Using Warm Mix Additives with Asphalt Rubber Products

Warm mix technology can reduce the mixing and construction temperatures of rubber modified asphalt pavement, which can significantly reduce the emissions. Warm mix technologies can also lower the viscosity of asphalt rubber binder, which can extend the construction season, increase opportunities for cool temperature paving, and overcome long haul distances. Some agencies shown in Table 5 replied that they have tried the warm mix technology with rubberized asphalt pavements.

Table 5. Warm Mix Technologies Used by Agencies on Rubber Products

Agencies	Warm Mix Technologies
Alaska DOT/PF	Evotherm additive, Contractor did not place mix as required so data is unavailable.
California DOT	Advera, Evotherm, Sasobit are allowed. Aztec Double Barrel Green, Engineering additives, and several others are still in testing stage. No problems with the use.
Chang'an University, China	Sasobit and Evotherm warm mix additives have been used.
Danish Road Institute, Denmark	The way we have tried crumb rubber in Denmark recently is through the Road+ concept (Crumb rubber + Vestanamer).
Florida DOT	Several - mainly Aztec Double Barrel Green foaming process.
New Jersey DOT	Have used a PG 64-22 modified with Evotherm to blend the rubber into. We were able to then keep the temperature below 300° F (149°C) and significantly reduced fumes.
Rhode Island DOT	Sasobit, Sonnewarmix

Svevia, Sweden	Cement and Wetfix

Conclusions and Recommendations

Based on the results from the survey of cold regions in the world, the following conclusions and recommendations from this study appear warranted.

Conclusions

Based on the 40 responses from different countries, mostly from parts of the United States and Canada, there is wide interest in using rubber in asphalt pavements. The following are the major conclusions from the survey:

- There are 15 agencies utilizing asphalt rubber binder, 13 using terminal blend rubber, and some agencies using asphalt rubber chip seals or as interlayers. This means that rubber product has been utilized in many parts of the world.
- Based on the responses from agencies, the following are the benefits of using rubber modified binders:

    a. Improved performance;
    b. Competition with more expensive polymer modified binders;
    c. Improved elasticity;
    d. Improved durability and reduced aging;
    e. Quiet and smooth pavements;
    f. Improved crack resistance;
    g. Increased fatigue life;
    h. Possible reduction in paving thickness;
    i. Reduced wet weather accident rates with open-graded mixes; and
    j. Energy and environmental savings associated with recycling and reuse of waste tires.

- There are barriers with using rubber products in asphalt pavement, such as the following:

    a. Inexperience of hot mix industry;
    b. Shortage of quality CRM;
    c. Binder performance grading of asphalt rubber;
    d. Compaction issues;
    e. Weather restrictions;
    f. Cost, equipment, availability;
    g. High temperatures for production and construction;
    h. Limited paving window; and
    i. Need for an established Superpave mix design procedure.

- Asphalt rubber can be used effectively in gap- and open-graded mixes. Asphalt binder contents in gap- and open-graded are normally higher than for dense-graded mixes. Terminal blends can be used in dense- or open-graded mixes. The binder contents used by various agencies are summarized in the report.

- The mix design procedures for using rubberized products vary. The most commonly used are Marshall, Superpave, and Hveem in descending order.
- The pavement design methods include AASHTO, Mechanistic Empirical methods, and local empirical designs. The AASHTO method is the most widely used
- Some agencies allow reduced thickness based on their experiences; however, most do not. They expect improved performance compared with conventional mixes.
- High binder content AR chip seal and interlayer are more durable and effective for resisting reflective cracking.
- Expected life of asphalt rubber chip seal varies based on locations. The range is wide from 5 to 15 years.
- Rubberized asphalt pavement can be recycled. However, more studies are needed if RAP content is high.
- Warm mix technology can be a big helper to reduce the limitations of using rubber product in pavements. Some agencies including Caltrans have successfully utilized several warm mix technologies.

Recommendations

The following recommendations are made based on rubber asphalt online survey results:

- There are many different specifications on rubberized asphalt products. A more detailed study on specifications should be conducted. A summary report on the specifications used by various regions should help develop a more suitable specification for Ontario.
- Research documentation was provided by some of the surveyed agencies. It would be helpful to synthesize the research results over the past to provide better guidance for agencies that are interested in increasing rubber usage.

Appendix C. MTO Rubber Specifications

SUPERPAVE 12.5FC 2 R - Item No.

SUPERPAVE 9.5 R-GAP GRADED - Item No.

Special Provision

Rubber Modified Hot Mix Asphalt

313.01 SCOPE

Subsection 313.01 of OPSS 313 is amended by the addition of the following:

This Special Provision covers the additional requirements for the construction of trial sections that include the use of rubber material processed in Ontario from Ontario tire waste. The trial sections shall incorporate rubber in the HMA using the wet process.

313.05 MATERIALS

313.05.01 Hot Mix Asphalt

Subsection 313.05.01 of OPSS 313 is deleted and replaced with the following:

The Materials used in the production of HMA shall be according to OPSS 1151, with the following amendments:

The HMA types, lift and location of the control and trial sections are provided in Table R1.

1151.02 REFERENCES

Section 1151.02 of OPSS 1151 is amended by addition of the following:

American Society for Testing and Materials (ASTM) Standards

ASTM D5644	Test Methods for Rubber Compounding Materials - Determination of Particle Size Distribution of Recycled Vulcanizate Particle Rubber
ASTM D6114	Standard Specification for Asphalt-Rubber Binder
ASTM D217	Standard Test Methods for Cone Penetration of Lubricating Grease
ASTM D5329	Standard Test Methods for Sealants and Fillers, Hot-Applied, for Joints and Cracks in Asphaltic and Portland Cement Concrete Pavements
ASTM D36	Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus)
ASTM D297	Standard Test Methods for Rubber Products-Chemical Analysis

State of California Laboratory Procedure

LP-11	Rotational Viscosity Measurement of Asphalt Rubber Binder

1151.03 DEFINITIONS

Section 1151.03 of OPSS 1151 is amended by addition of the following:

Ambient Ground: scrap tire rubber processed or ground at or above 20°C (68°F) to provide irregularly shaped, torn particles with relatively large surface areas.

Crumb Rubber (CR): scrap tire rubber that is reduced in size for use in asphalt paving materials such as hot mix asphalt or asphalt cement or both.

Cryogenic Ground: scrap tire rubber processed or ground at temperatures low enough that the rubber shatters.

Rubberized Asphalt Cement (RAC): asphalt-rubber binder; which is PGAC modified with crumb rubber through the wet process.

Rubber Modified Asphalt (RMA): hot mix asphalt that contains crumb rubber added as an aggregate, as RMA or as both. May also refer to CR added with the asphalt cement to the aggregates during mix production of the HMA.

Superpave 12.5FC 2 R: means RMA that meets the requirements of Superpave 12.5FC 2 and contains RMA that is produced using wet process-terminal blend.

Superpave 9.5 R-Gap Graded: means RMA with gap-graded aggregates having 9.5 mm (0.4in.) nominal maximum size and contains RMA produced using the wet process-field blend. Requirements for Superpave 9.5 R-Gap Graded are specified in this special provision.

Transition Area: the length of the section within which the change from one section to the next shall be fully accomplished.

1151.04 DESIGN AND SUBMISSION REQUIREMENTS

1151.04.01 Design Requirements

Subsection 1151.04.01 of OPSS 1151 is amended by the addition of the following:

1151.04.01.07 Rubber Modified Asphalt

The RMA mix designs shall be according to the respective Superpave mix type specified in addition to including CR using the process specified in Table R1 and according to the following:

a) Wet Process-Terminal Blend

The mix shall be designed to incorporate RMA in place of PGAC. Wet process-terminal blend RMA shall be produced by the PGAC supplier at their asphalt terminal.

b) Wet Process-Field Blend

The mix shall be designed to incorporate RMA in place of PGAC. Wet process-field blend RMA shall be produced at the hot mix asphalt plant using a field blending plant.

The Superpave 9.5 R-Gap Graded mix design and JMF shall be according to the requirements specified in Table R2, Table 3 of OPSS 1151, and LS-309. For mix design purposes, the RMA shall be produced in the laboratory according to the following procedure:

- Heat up the base PGAC to 180°C (356°F). Add 18-20% CR by weight of the PGAC while continuously blending the compound.
- Continue blending the RMA for 45 minutes at 180°C (356°F).

1151.04.02 Submission Requirements

Subsection 1151.04.02 of OPSS 1151 is amended by the addition of the following:

The Contractor shall submit a plan and schedule to the Contract Administrator within two weeks of contract award describing how the Contractor will meet all the requirements of this non-standard special provision for review and approval including the following information in writing:

a) Special actions to be taken to assure that the CR will be available meeting the requirements of the Contract Documents, including that the CR processor selected by the Contractor or asphalt cement supplier or both can provide the material required for the Contract, and how the Contractor will assure that the CR processor selected has sufficient time to produce the quantity of CR required.

b) Information such as CR supplier's name, address, CR gradation, materials safety data sheet (MSDS), method and equipment used to mix CR into mix, CR dosage, RMA reaction time, mixing temperature, RMA storage conditions and any need for agitation, RMA blending location (hot mix asphalt plant vs. asphalt supplier's terminal) shall be provided.

c) Special actions to be taken to prevent swelling of the briquettes during the mix design.

d) Special actions to be taken to assure that the CR will be homogeneously distributed in the RMA.

e) Special actions to be taken to prevent pick-up during compaction of the RMA.

f) Product information on CR including information on how it was ground, whether cryogenic or ambient or both, shall be submitted with the mix design.

g) A letter from the CR supplier indicating that the CR they are supplying is produced in Ontario from tires scrapped in Ontario.

No RMA shall be placed on any trial section until the Contract Administrator acknowledges receipt of the plan and schedule in writing. Separate mix designs shall be submitted for each RMA type and for the control mix.

1151.05 MATERIALS

Section 1151.05 of OPSS 1151 is amended by addition of the following:

1151.05.06 Rubber Modified Asphalt and Rubberized Asphalt Cement

1151.05.06.01 General

Materials for the RMA shall conform to OPSS 313 except as amended by this special provision. It is the Contractor's responsibility to identify a facility to produce the mixes in accordance with the supplier's instructions for the use of their materials. The Contractor is responsible for obtaining from the suppliers any and all information required for the proper preparation, handling, storage and use of their materials.

The Contractor shall be solely responsible for obtaining materials, producing mixes, transportation, storage and use of all materials. The Contractor shall assure that the RMA is produced to prevent any deleterious effects to the finished product. The Contractor shall be responsible for ensuring cross contamination does not occur between the sections.

The Contractor shall contact Ontario Tire Stewardship (OTS), at either of the contact information below, who will facilitate the sourcing of the field blending plant, needed for producing Superpave 9.5 R-Gap Graded. The field blending plant shall only be sourced through OTS. The Contractor shall be responsible for the cost of supplying and operating the field blending plant. The Contractor shall allocate sufficient space at the hot mix asphalt plant to house the field blending plant. An area of about 30 m x 20 m would be sufficient for the field blending plant. The Contractor shall provide points of contact for supply lines from and to the field blending plant. The Contractor shall cooperate with the operator of the field blending plant and harmonize the operation of the field blending plant with the hot mix asphalt plant in order to produce the RMA mix meeting the requirements of the Contract Documents. The Contractor shall be responsible to supply and feed the CR into the field blending plant.

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1151.05.06.02 Crumb Rubber

The CR shall be processed from whole passenger vehicle tires. Heavy equipment tires shall not be used. Use of uncured or devulcanized rubber will not be permitted. CR shall be in the form of ambient or cryogenic ground rubber, or both. The CR shall be produced in Ontario from tires scrapped in Ontario. CR shall not contain more than 0.01% of wire and 0.05% fabric by weight. CR shall be free of other contaminants. The CR shall be dry and free-flowing and not produce foaming when blended with the PGAC. The CR shall have a specific gravity in the range of 1.1 to 1.2, as determined according to ASTM D 297.

The CR shall meet the gradation requirements specified in Table R3 determined according to ASTM D5644. No particles shall exceed a length of 5 mm as measured on any axis.

The Contractor shall contact Ontario Tire Stewardship (OTS), at the above contact information, who will facilitate the sourcing of the CR.

1151.05.06.03 Aggregates

Aggregate properties for RMA shall meet the requirements of Superpave 12.5FC 2 specified elsewhere in the Contract Documents. Coarse and fine aggregate properties for Superpave 9.5 R-Gap Graded shall meet the requirements of Superpave 12.5FC 2 specified elsewhere in the Contract Documents.

1151.05.06.04 Rubberized Asphalt Cement

CR added to the RMA shall meet the gradation requirements specified in Table R3 determined according to ASTM D5644. Wet-terminal blend RMA shall be produced as a Type III Asphalt Rubber Binder according to ASTM D6114. CR dosage by mass of wet-terminal blend RMA shall be 10% to 15%. Wet-field blend RMA (after reaction) shall meet the requirements found in Table R4. CR dosage by mass of wet-field blend RMA shall be 18% to 20%. For the production of the RAC, parameters such as CR gradation, mixing method and equipment, dosage, reaction time, mixing temperature, storage conditions and need for agitation, blending location (project site vs. asphalt supplier's terminal) shall be determined by the Contractor.

When the RMA supplier specifies a CR gradation with additional restrictions, the CR shall also meet the RMA supplier's gradation requirements. The CR material, PGAC and any antistripping additives required shall be compatible to ensure a good dissolution and reaction time. RMA produced shall be a homogenous mixture of CR and asphalt cement.

In case of terminal blend, the following asphalt cement suppliers have indicated their ability to supply the RAC:

a) Bitumar; b) Coco; c) McAsphalt; d) Shell

1151.07 PRODUCTION

1151.07.01 Anti-Stripping Additives

Subsection 1151.07.01 of OPSS 1151 is amended by addition of the following:

When an anti-stripping agent is to be incorporated into the mix, the Contractor shall contact and consult with each supplier to determine whether or not the proposed anti-stripping agent is compatible with the RMA or RMA or both. In those cases where a supplier deems that the anti-stripping agent is incompatible, that anti-stripping agent shall not be used and the Contractor shall select and employ another anti-stripping agent that the suppliers indicate is compatible with the mix and RAC.

1151.07.03 Field Blending Plant

The Contractor shall contact OTS a minimum of 6 weeks prior to paving Superpave 9.5 R-Gap Graded to coordinate delivery and operation of the field blending plant. OTS contact information is provided earlier in this special provision.

313.07 CONSTRUCTION

313.07.06.01 Operational Constraints

Clause 313.07.06.01 of OPSS 313 is amended by addition of the following:

The Contractor shall provide a minimum of 7 Days notice in writing to the Contract Administrator and to the Ministry’s Regional Head of Quality Assurance Section before paving any trial section.

313.07.06.02 Paving

Clause 313.07.06.02 of OPSS 313 is amended by addition of the following:

The Contractor shall construct the control section and trial sections as indicated in Table R1, full width including shoulders. Transition areas shall be less than 50 m in length at the start of the trial and control sections. The Contractor shall adjust the paving and compaction operations to eliminate roller pick-up and provide a smooth surface without tearing, cracking, or shoving.

313.07.15 Sampling

Subsection 313.07.15 of OPSS 313 is amended by the addition of the following clause:

313.07.15.06 Rubber Modified Asphalt

Samples shall not be taken from the transition areas. In addition to other samples specified in the Contract Documents, the Contractor shall procure RMA samples of a minimum quantity specified in Table R5 for each of the control and trial sections.

Sample labeling shall include: highway number, highway direction, lane number, contract number, section (trial or control), mix type, corresponding Lot/Sublot numbers, station, date sampled. The Contractor shall deliver the samples specified in Table R5 to the address below:

c/o Seyed Tabib

Bituminous Section, MERO

Shipping and Receiving

Room 15, Building C

1201 Wilson Ave,

Toronto, ON M3M 1J8

Section 313.07 of OPSS 313 is amended by the addition of the following subsection:

313.07.19 Identification of RMA Paving Limits

The Contractor shall provide to the Contract Administrator, no later than 7 Days after completion of RMA paving, an as built sketch identifying the stations as well as the GPS data for the RMA paving limits. The GPS data shall be geo-referenced and NAD83 geographic coordinates (latitude, longitude) shall be used. Geographic coordinates (latitude, longitude) shall be provided within metre-level accuracy.

313.08 QUALITY ASSURANCE

313.08.01.02.01 Lot Size

Clause 313.08.01.02.01 of OPSS 313 is amended by the addition of the following:

Each mix type for the trial section shall be considered as a single lot with a minimum of three sublots.

313.08.01.02.03 Basis of Acceptance

Clause 313.0.8.01.02.03 of OPSS 313 is amended by the addition of the following:

a) Acceptance of Crumb Rubber

   i. All CR shall meet the gradation requirements specified in Table R3 determined according to ASTM D5644.

b) Acceptance of Rubber Modified Asphalt (RMA)

i. Acceptance and pay adjustment of the RMA containing RAC-terminal blend shall be determined accordance to the respective mix type HMA requirements specified elsewhere in the Contract Documents.

ii. Acceptance and pay adjustment of the Superpave 9.5 R-Gap Graded shall be according to requirements for Superpave 9.5 specified elsewhere in the Contract Documents with the exception of VMA and coarse and fine aggregate physical properties. VMA will not be considered an acceptance criterion for Superpave 9.5 R-Gap Graded. Coarse and fine aggregate physical properties for Superpave 9.5 R-Gap Graded shall be according to requirements for Superpave 12.5FC 2 specified elsewhere in the Contract Documents. Aggregate gradation for Superpave 9.5 R-Gap Graded shall be according to Table R2.

iii. RMA containing RAC wet-terminal blend will be rejectable if there are clumps of CR in the RMA visible to the naked eye.

c) Acceptance of Rubberized Asphalt Cement (RAC)

i. Acceptance of the RAC wet-terminal blend shall be determined according to the respective requirements for the PGAC grade specified according to OPSS 1101. Additionally, to be acceptable the RAC wet-terminal blend shall meet the Type III Asphalt Rubber Binder requirements of ASTM D6114.

ii. Acceptance of the RAC wet-field blend shall be according to Table R4.

313.08.01.02.04.01 General

Clause 313.08.01.02.04.01 of OPSS 313 is amended by the addition of the following:

The Owner will use LS-292 for determination of the asphalt cement content for the RMA, therefore, the referee laboratory shall also follow LS-292 (ignition oven).

313.09 MEASUREMENT FOR PAYMENT

313.09.01.01

Clause 313.09.01.01 of OPSS 313 is amended by the addition of the following item:

Superpave 9.5 R-Gap Graded

313.10 BASIS OF PAYMENT

313.10.01.01

Clause 313.10.01.01 of OPSS 313 is amended by the addition of the following item:

Superpave 9.5 R-Gap Graded - Item

313.10.01.02.02.04 Payment Factor for Voids

Clause 313.10.01.02.02.04 of OPSS 313 is deleted in its entirety and replaced with the following:

For RMA mixes, as long as the lot mean air voids are between 2.5 and 5.5%, the payment factor for voids, PF_{VOIDS}, shall be equal to either:

a) PF_{GAC}, if the PF_{GAC} is less than 1.0; or,

b) 1.0, if the PF_{GAC} is equal to or greater than 1.0.

Otherwise, if the lot mean air voids are outside the 2.55.5% range, the PF_{VOIDS} shall be considered to be 0.5.

313.10.01.02.02.06 Payment Factor for Combined Mix Properties and Compaction

Clause 313.10.01.02.02.06 of OPSS 313 is amended by the addition of the following:

For RMA mixes, as long as the lot mean compaction is between 90.5 and 98.0 %, the payment factor for compaction, PF_C, shall be equal to either:

a) PF_M, if the PF_M is less than 1.0; or,

b) 1.0, if the PF_M is equal to or greater than 1.0.

Otherwise, if the lot mean compaction is outside the 90.5-98.0 % range, the PF_C shall be considered to be 0.65.

Table R1

Trial Sections

Trial Section	Pavement Course	Location (Stations)	Mix Type
Wet Process-Field Blend	Surface	14+500 to 17+500	Superpave 9.5 R-Gap Graded
Wet Process-Terminal Blend	Surface	11+500 to 14+500	Superpave 12.5FC 2 R
Control Section	Surface	Remainder of the contract to the west of Wet Process-Terminal Blend Section	Superpave 12.5FC 2

Table R2

Superpave 9.5 R-Gap Graded Properties

Hot Mix Asphalt Type	Percentage Passing by Dry Mass of Aggregates — Sieve Size, mm						Traffic Category	Base PGAC Grade	% Air Voids	% VMA min.	AC_{BID} (%)
	12.5	9.5	4.75	2.36	1.18	0.075					
Superpave 9.5 R-Gap Graded	100	90-100	28-42	15-25	5-15	2-7	C	58-28	4	18	7.0

Table R3

Gradation Requirements for Crumb Rubber

Process	Sieve	Percent Passing Sieve by Mass
Wet-Terminal Blend (see Note 1)	2.36 mm	100
Wet-Field Blend	2.36 mm	100
	2.00 mm	98 – 100
	1.18 mm	45 – 75
	600 µm	2 – 20
	300 µm	0 – 6
	150 µm	0 – 2

Notes:

1. The RAC supplier shall select a gradation suitable for producing a Type III Asphalt Rubber Binder according to ASTM D6114 and this non-standard special provision in addition to meeting the minimum requirements of OPSS 1101 for the PGAC grade specified elsewhere in the Contract Documents.

Table R4

Requirements for Field Blend RAC (after reaction)

Test Parameter	Test Method	Specification Limit
Field Viscosity @ 191°C (375°F), centipoises (see Note 1)	California Laboratory Procedure LP-11	1500 – 4000
Cone Penetration @ 25°C, 0.1 mm	ASTM D 217	25 – 70
Resilient @ 25°C, % Rebound	ASTM D 5329	18 minimum
Field Softening Point, °C	ASTM D 36	52 – 74

Notes:

1. The operator of the field blending plant usually has a field viscometer. This test shall be carried out at least once per production day and the results observed and recorded by the Contract Administrator.

Table R5

Additional Sample Requirements

Trial Section	RAC or PGAC (litres)	Crumb Rubber (kg)	RMA or HMA (kg)
Wet Process-Field Blend	4	5	50
Wet Process-Terminal Blend	4	5	50
Control	4	N/A	50

Appendix D. Laboratory Mix Design for Rubber Modified Asphalt

Background

Currently, the MTO allows the terminal blend and field blend process in their specifications. At this time, the semi wet and dry processes are not being used.

In the terminal blend process, the crumb rubber is blended at the terminal to meet ASTM D 6114, Type 3. MTO, however uses from 10-15 % crumb rubber by weight of the asphalt cement. The rubber gradation passes the 2.36 sieve as shown in the specifications. Asphalt suppliers have indicated that they use an ultrafine rubber with particles smaller than 0.6 mm (passing the 30 sieve) for their terminal blend products

For the field blended asphalt rubber, the crumb rubber is blend on site using 18-20 % crumb rubber by weight of the asphalt cement. The asphalt cement is heated to 180-190°C (356-375°F) and crumb rubber is added. The rubber is digested for 45 minutes to 1 hour prior to its use.

The expected impacts of the added rubber are as follows:

- The binder content for the mixture should increase, particularly for the gap-graded mixes.
- The crumb rubber provides bulk to the asphalt cement.
- Range of binder content increase is about 10-20%.

Laboratory Mix Design Considerations

When completing a mix design for rubberized asphalt concrete, the aggregate selection process remains unchanged from standard mix design procedures. Aggregates need to be blended in the right proportions to meet the gradation specifications. The rubber particles act like aggregate, particularly in the field blended binders and may be in part responsible for any swelling of the mix.

For the terminal blends, the rubberized asphalt cement is pre-blended and ready to be mixed with the aggregate. The rubber has been digested at the terminal: however, lab samples will require stirring while hot to uniformly distribute the crumb rubber. Generally, the aggregate is dense-graded according to the specifications.

For the field blended process, the asphalt cement is heated to 180°C (356°F) and 18-20 % crumb rubber is added by weight of the AC. The mixture is blended continuously for 45 minutes and used immediately. The product is normally used with a gap-graded aggregate.

The modified asphalt cements are similar to polymer modified asphalt cement. Standard temperature viscosity guidelines do not apply. Typical mixing and compacting temperatures are as follows:

- Terminal blends: follow manufacturers recommendations
- Field blends
    - Rubberized asphalt cement (RAC) – 163 to 182°C (325 to 360°F)
    - Aggregate - 143 to 164° C (290 to 327°F)
    - Compaction temperature -143 to 149°C (290 to 300°F)

Briquette swell needs to be addressed in mix design. After compaction, there is a potential for swell, particularly in the field blends RAC. Swelling results in a loss of density and can vary with the different processes. In the Superpave mix design process, each lab needs to check for swell. In the past, labs in Ontario have used a weight to control the swell. It needs to be placed immediately after compaction as swelling can occur on release of the load by the Gyratory compactor. The following steps have been used to control the swell;

- Leave the sample under load in the Gyratory compactor for 15 minutes. This allows the sample to cool as well.
- Place a 15 kg weight on the sample after it has been removed from the compactor
- Do not extrude the sample until the sample reaches a temperature of 35°C (95°F).

Mix designs with crumb rubber are still new in Ontario. This process will likely evolve as more projects are placed. The following section provides some detailed designs for projects constructed in 2011.

Detailed Mix Designs

The remainder of the Appendix provides an example of detailed SuperPave mix design for a terminal blend and a field blend rubberized modified asphalt mix.

Example of Terminal Blend Mix Designs

DBA ENGINEERING LTD.

DHILLON BURLEIGH & ASSOCIATES
Consulting Engineers

401 Hanlan Road
Vaughan, Ontario L4L 3T1
Tel: (905) 851-0090
Toll Free: 1-800-819-8833
Fax: (905) 851-0091

TERMINAL BLEND

SUPERPAVE MIX DESIGN REPORT

Mix Number:	2081	**Project No.:**	**Date Sampled:**	10-Sep-11
Contract:			**Date Completed:**	05-Oct-11
Location:			**Date Revised:**	
			Mix Type:	SP 9.5 R-Gap Grad
Item Number:			**Traffic Category:**	D
Contractor:			**Asphalt Cement Type:**	64 28 PMA
Client:			**Asph. Cement Supplier:**	
Plant Location:			**Mixing Temperature:**	180 °C
			Compaction Temperature:	142 °C

Test Data Certified By:

P.S. Dhillon, P.Eng.,

JOB MIX FORMULA GRADATION PERCENT PASSING															
%AC / Sieves	% AC	50	37.5	25	19	16	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.08
JMF	7.8	100.0	100.0	100.0	100.0	100.0	100.0	95.5	37.5	22.9	15.0	10.9	7.6	6.2	5.8
	Percent	**Aggregate Gradation**													
CA 1	64	100.0	100.0	100.0	100.0	100.0	100.0	93.0	5.2	0.8	0.6	0.6	0.5	0.4	0.4
CA 2															
CA 3															
FA 1	13	100.0	100.0	100.0	100.0	100.0	100.0	100.0	97.1	71.6	46.7	32.9	22.5	16.3	13.3
FA 2	10	100.0	100.0	100.0	100.0	100.0	100.0	100.0	66.0	10.8	2.6	1.9	1.4	1.2	1.2
FA 3	13	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	91.7	59.3	37.4	20.4	9.7	5.3
FA 4															
RAP 1															
RAP 2															

	Selected	Specification	
BRD (Gmb)	2.446		
MRD(Gmm)	2.551		
% Air Voids (Va)	4.0	4	
% VMA	22.1	18	
% VFA	81.7		
D/P	0.8	0.9	1.6
% Gmm @ ini	87.5	89	
% Gmm @ des	96	96	
% Gmm @ max	97.8	98	

2.922

% RAP	0.0
% AC From RAP	0.0
Virgin AC	7.8

Nini	8
Ndes	100
Nmax	160

Dust Returned: 3.0

TSR	84.2	Spec. Min 80
Additive Supplier	N/A	
Additive Type	N/A	
% Additive	0.0	

Briquette Wt.	4029
Recomp Temp	142
Water Absorp	0.3

	Aggregate Name	Aggregate Source	Aggregate Inventory #
CA 1	9.5 stone		
CA 2			
CA 3			
FA 1	Unwashed Screenings		
FA 2	1/4" Chip		
FA 3	DFC Fines		
FA 4			
RAP 1			
RAP 2			

Coarse Specific Gravity
2.903
Coarse Absorption
0.39
Fine Specific Gravity
2.687
Fine Absorption
0.47
Combined Specific Gravity
2.897

1 The pass 4.75mm portion of the blend gradation has been adjusted for fines returned to mix
2 Core lock was used for BRD
3 Gradation is based on Process control and sample results.
4 BRD's were cooled with weights on top.

Professional Engineers Ontario   CCIL   Canadian Council Testing Laboratory   ISO 9001

ENGINEERING RESEARCH DEVELOPMENT

Example of Field Blend Mix Designs

DBA ENGINEERING LTD.

DHILLON BURLEIGH & ASSOCIATES
Consulting Engineers

401 Hanlan Road
Vaughan, Ontario L4L 3T1
Tel: (905) 851-0090
Toll Free: 1-800-819-8833
Fax: (905) 851-0091

FIELD BLEND

SUPERPAVE MIX DESIGN REPORT

Mix Number: 1945	**Project No.:**		**Date Sampled:**	17-May-11
Contract:			**Date Completed:**	29-Aug-11
Location:				
			Mix Type:	12.5 Rubber
Item Number:			**Traffic Category:**	B
Contractor:			**Asphalt Cement Type:**	58-34 PMA
Client:			**Asph. Cement Supplier:**	
Plant Location:			**Mixing Temperature:**	160 °C
			Compaction Temperature:	145 °C

Test Data Certified By:
P.S. Dhillon, P.Eng.,

JOB MIX FORMULA GRADATION PERCENT PASSING															
%AC / Sieves	% AC	50	37.5	25	19	16	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.08
JMF	7.2	100.0	100.0	100.0	100.0	100.0	97.5	93.9	33.5	17.4	15.0	13.4	10.7	7.7	5.4
	Percent	**Aggregate Gradation**													
CA 1	**43**	100.0	100.0	100.0	100.0	100.0	94.1	62.7	7.4	3.9	3.6	3.3	2.8	2.1	1.2
CA 2	**40**	100.0	100.0	100.0	100.0	100.0	100.0	99.9	39.3	7.9	6.7	5.8	4.6	3.3	2.3
CA 3															
FA 1	17	100.0	100.0	100.0	100.0	100.0	100.0	100.0	85.8	74.1	61.3	51.9	37.7	22.8	11.5
FA 2															
FA 3															
FA 4															
RAP 1															
RAP 2															

	Selected	Specification	
BRD (Gmb)	2.395		
MRD(Gmm)	2.495		
% Air Voids (Va)	4.0	4	
% VMA	19.9	18	
% VFA	79.9		
D/P	0.8	0.6	1.2
% Gmm @ ini	86	90.5	
% Gmm @ des	96	96	
% Gmm @ max		98	

2.8103

TSR	80.5 Spec. Min 80
Additive Supplier	
Additive Type	
% Additive	1.0

% RAP	0.0	Nini	7
% AC From RAP	0.0	Ndes	75
Virgin AC	7.2	Nmax	115

Dust Returned	2.0
Briquette Wt.	4823
Recomp Temp	145
Water Absorp.	0.0

	Aggregate Name	Aggregate Source	Aggregate Inventory #
CA 1	HL-1 Stone		
CA 2	Chip		
CA 3			
FA 1	Unwashed Screenings		
FA 2			
FA 3			
FA 4			
RAP 1			
RAP 2			

Coarse Specific Gravity
2.774
Coarse Absorption
0.54
Fine Specific Gravity
2.780
Fine Absorption
0.21
Combined Specific Gravity
2.776

1 The pass 4.75mm portion of the blend gradation has been adjusted for fines returned to mix.
2 Core lock was used for BRD's
3 Gradation is based on Process control and sample results
4 BRD's were cooled with weights on top.

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ENGINEERING RESEARCH DEVELOPMENT

Appendix E. Summary of 2011 RMA projects

Introduction

In 2011, the MTO led several pilot projects to evaluate the feasibility of construction of both field and terminal blend rubberized asphalt. The projects constructed, as well as some of the preliminary observations, are summarized in this appendix. This was a cooperative effort with the OTS which assisted with the supply of the rubber, the blending equipment, and funding for the projects. The full report on these projects which includes project data, photos and more can be obtained from the OTS.

Projects Constructed

Table 1 summarizes the 6 projects planned for construction during the 2011 season. Mohamed Hegazi of OTS and Seyed Tabib of MTO provided input on the completed projects. As can be seen in Table 1, only 3 of the projects were completed as planned using the rubberized asphalt. They others were either paved using a conventional hot mix or delayed until 2012. It should be noted that all of the projects completed as planned were accomplished by one contractor.

Table 1. 2011 project summaries

TABLE 1 2011 PROJECT SUMMARIES

Highway	Mix type	Lane (km) Placed	Tonnage Placed	Date Completed	Comments
Highway 3	Field blend SP 9.5 R Gap-Graded	0	0	Rubber section has been cancelled	Problems with rubber gradation and mix design.
Highway 60	Field blend SP 12.5 R Dense-Graded	0	0	Rubber section has been cancelled	Problems with the mix design and blending equipment.
Highway 7	Field blend SP 9.5 R	6	3600	Completed	Night paving. Barrel

	Gap-Graded			in October 2011	stuck
	Terminal Blend SP 12.5 FC2 R Dense-Graded	5.6	3100		
	Hot Mix Asphalt SP 12.5 FC2 Dense-Graded	2.8	4800		
Highway 35	Field Blend SP 12.5FC1 R Gap-Graded	6	4400	Completed in October 2011	
	Hot Mix Asphalt SP 12.5 FC1 Dense-Graded	13.5	11200		
Highway 115	Field Blend SP 12.5 FC2 R Gap-Graded	6	4100	Completed in October 2011	
	Hot Mix Asphalt SP 12.5 FC2 Dense-Graded	3	3900		
Highway 24	Field blend SP 9.5 R Gap-Graded	0	0	Rubber section has been cancelled	Problems with mix design and blending equipment.
Highway 60	Terminal blend SP 12.5 R Dense-Graded	4	2600	Completed in June 2011	
	Hot Mix Asphalt SP 12.5 Dense-Graded	17.6	12400		
Highway 35	Terminal blend SP 12.5 R Dense-Graded	0	0	Delayed until 2012.	Project carried over to 2012.

R = Rubber Modified Asphalt Mix

Highway 3 project

Some of the issues associated with this project included:

- Initial rubber samples did not meet gradation requirements.
- On July 26, 2011, OTS received an email regarding a second sample which did not meet gradation requirements.

- The contractor had difficulties obtaining a mix design and had many delays due to difficulty with rubber sample gradations, etc.
- On August 11, 2011, Fath Industries (supplier of the blending unit) did a site visit at the contractor's plant to view connections and perform required modifications.
- On September 1, 2011, DBA Engineering was contracted to develop a mix design since the contractor had difficulty obtaining one.

In November 2011, the contractor informed OTS that the contract has been deferred until the next year.

Highway 60

Some of the issues associated with this project included the following:

- DBA Engineering was contracted to develop a mix design for the project, but it took longer than expected to deliver to the mix design to the contractor.
- Swelling in the mix design was discovered and was corrected by slightly changing the gradation of the crumb rubber to the finer side of the specifications.
- Once the blending equipment was set up, a faulty part was discovered which caused the equipment to not produce any asphalt rubber. Fath Industries tried to take care of the issue as soon as possible, but the contractor was instructed to continue with conventional hot mix while the part was held up in customs.

As a result, the project ended up to be placed using conventional mix.

Highway 7

This project was placed in 2011 and had few issues including:

- The contractor had questions on the mix design that were answered by Anne Stonex (AMEC) and Mark Belshe (Rubber Pavements Association).
- There was a lot of rubber wasted due to clumping while it was stored outdoors; therefore, more rubber was required to be shipped during production.

Paving took place at night without significant problems. The contractor obtained samples for the OTS and the University of Waterloo. A 300 kg of sample per mix was required (one conventional mix, one terminal blend rubber mix, one field blend rubber mix). The paving operations went smoothly, but the rubberized mix was reported to be harder to work with. The blending unit was able to keep up with the production quantity requirements of the contractor's plant.

Highway 35

This project was constructed by the same contractor who constructed the Highway 7 project. Some of the issues on the project included:

- During the paving, the contractor had requested extra bags of rubber to be delivered in short notice and OTS in cooperation with CRM, Inc. were able to deliver the rubber.
- Any others

Paving took place in October 2011. A summary of the observations are as follows:

- Weather caused few delays in the paving of this highway section.
- The contractor collected samples for OTS and the University of Waterloo. A 300 kg of sample per mix was required (one conventional mix, one field blend rubber mix).
- Paving operation was smooth.
- It was noted that multiple parties that had conducted site visits liked the look and feel of the rubber asphalt.
- The paving operators did not like the material as it was "too hard to work with."
- The blending unit was able to keep up with the production quantity requirements of the contractor's plant.

Highway 115

The contractor who paved Highway 7 and 35 also paved this project. The paving took place in October 2011. The one issue encountered on this project was that the contractor required extra bags of rubber to be delivered in short notice, which OTS and CRM, Inc. were able to do.

The paving operation went smoothly with a few minor problems:

- Weather caused a few delays in the paving of this highway section.
- The contractor collected samples for OTS and the University of Waterloo. A 300 kg sample per mix was required (one conventional mix, one field blend rubber mix).
- Paving operation was smooth.
- It was noted that multiple parties that had conducted site visits liked the look and feel of the rubber asphalt.
- The paving operators did not like the material as it was "too hard to work with."
- The blending unit was able to keep up with the production quantity requirements of the contactors plant.

Highway 24

This project was scheduled as a rubberized asphalt project. The contractor requested a mix design from one of the Ontario labs in September 2011. Because of the late start, the contractor asked the MTO to switch the job to a conventional mix. Some of the issues which led to the delays were as follows:

- During the initial phases, there was difficulty obtaining the right gradation of crumb rubber to send to the contractor.
- Modifications to the asphalt plant to accommodate for the blending unit were an issue for the contractor.

Summary of Observations

Only 3 of the 6 projects were completed as planned. These projects went smoothly, even though contractor personnel reported the mix to be more difficult to work with. The initial reports show that the pavements look good. Only time will tell how well they will perform.

Preliminary Conclusions

It is too early to determine how these projects will perform over the long run. Testing planned by the University of Waterloo and Queens University will help with the prediction of the long term performance. These tests are not available at this point in time. The tests are expected to be completed by the end of 201`2.

Appendix F. Crumb Rubber Sample Examination Performed by the MTO

By

Carole Anne MacDonald and Seyed Tabib

January 12, 2012

This appendix describes the type of analysis performed on a sample of Crumb Rubber Modifier (CRM) that was examined in the Microscopy Laboratory of the Materials Engineering & Research Office, MTO. The CRM sample was supplied by Ontario Tire Stewardship (OTS) for use on 2011 MTO Rubber Modified Asphalt (RMA) contracts. It is understood that the CRM sample has been subjected to two stages of grinding: 1) an initial cryogenic grind, and 2) a secondary ambient grind. Keeping this in mind it was attempted to distinguish the different types of grinding during the examination.

Material As Received

The material was initially examined in an as received condition to identify the basic nature of the material and any obvious contaminants such as fibers, metals, plastics, etc. No steel or other metals were observed. No plastics or cellulose fibers were observed.

Initial observations indicate the material consists mainly of black cryogenic (Photo 4) and ambient ground (Photos 4 and 5) rubber with particle sizes generally less than 2.36 mm. White rubber (Photo 6), synthetic fibers (Photos 7 to 13), and mineral grains were also observed. Synthetic fibers and mineral grains occur mainly as individual particles and individual fibers within the sample, but may also occur adhered to or partially or wholly embedded within the rubber particles (Photos 9, 10 and 13). Clusters or bunches of synthetic fibers were also observed and presumably occurred from the action of rolling or vibration on a mesh screen during fractionation of the material. The same “bunching” was observed during sieving of the material for this examination (Photo 8). Table 1 lists the materials found in this sample and their identifying properties.

Table 1. Materials present in the crumb rubber sample provided.

Material	Size Range	Morphology	Colour	Optical Properties	Description
Black cryogenic ground rubber	<75µm – 2 mm	Particle; cubical	Black	Opaque	Generally smooth reflective surfaces, conchoidal to plumose fracture surfaces
Black ambient ground rubber	<75µm – 5 mm	Particle, cubical with irregular to elongate shapes common	Black	Opaque	Rough, dull surfaces, high surface area to volume ratio as compared with cryogenic ground. Often has a “ragged” appearance.
White rubber (cryogenic and ambient ground)	0.1 mm - 4 mm	Particle, cryogenic and/or ambient ground	White	Opaque	Surfaces of cryogenic particles tend to appear rougher and less reflective as compared with cryogenic ground black rubber
Black synthetic fibre	up to 3 cm long, <1/5 mm diameter	Straight, not flexible; round in cross section	Black	Opaque	Melts under flame Only one fibre of this nature was observed (Photo 12)
Type 1 fibre Transparent to translucent synthetic fibres	1 to 8 mm long, <5 - 15 µm diameter	Flexible fibres Occurs as single fibres and wound composite strands Straight to wavy or crimped	Colourless to white, rare blue to red	Transparent to translucent; Anisotropic Parallel to undulose extinction index of refraction > n=1.515 3 – 4^{th} order birefringence (up to 0.20); +ve elongation	Chopped fibres; Melts in flame, does not burn Fibres often appear wavy or crimped Consistent with the published optical data for the Aramid-Polyamide-Polyester types of synthetic fibres. Most closely matches **polyester** or **Aramid**[1]
Type 2 fibre Yellow to brown synthetic fibres	Up to 7 mm long, up to 0.2 mm wide	Composite strands - numerous fibres clustered together to make a single fibre, individual strands are <5 µm wide Straight	Yellow to orange brown	Translucent Anisotropic Parallel extinction index of refraction > n=1.515 ~1^{st} to 2^{nd} order birefringence +ve elongation	Chopped fibres; Coating or colouring on outer surface of fibres makes birefringence difficult to estimate Melts in flame, does not burn Consistent with the published optical data for the Aramid-Polyamide-Polyester types of synthetic fibers[1]
Silicate	0.25 mm to	Particle, cubical	Colourless,	Transparent to	Conchoidal fracture surfaces

mineral **(Quartz)**	<75µm	subangular to subrounded	white to light orangey yellow	translucent Glassy lustre Anisotropic Light grey to white birefringence	locally Locally higher birefringence (yellow – orange to first order blue where particle is thicker) Abundant
Carbonate mineral **(Calcite)**	0.25 mm to <75µm	Particle, cubical rhombohedral shape in grain mount	Colourless, white to light orangey yellow	Transparent to translucent Anisotropic 3^{rd} to 4^{th} order birefringence	Characteristic calcite twins observed Reacts with HCl (aq) Abundant
Silicate Mineral **(Plagioclase)**	Pass 75 µm	Particle, subangular	Colourless to white	Transparent to translucent Anisotropic Light grey to white birefringence	Characteristic albite twinning observed Very minor component
Silicate Mineral **(Hornblend)**	Pass 75 µm	Particle, subangular	Green	Transparent to translucent; Anisotropic; Pleochroic	Cleavage Very minor component

Gradation

A 300g sample was sieved to obtain the particle size distribution (Table 2).

Table 2. Grain size distribution of the crumb rubber sample

Sieve (mm)	Cumulative % Retained	% Retained	% Passing
2.36	0.00	0.00	100
1.18	7.5	7.5	92.5
0.60	46.8	39.3	53.2
0.30	81.2	34.4	18.8
0.150	96.8	15.6	3.2

0.075	99.8	3.0	0.2

Point Count

A modified version of Test Method LS-616 (Procedure for the Petrographic Analysis of Fine Aggregate) was used to further examine the crumb rubber. Five glass slides were prepared with each containing a random assortment of particles from each size fraction (P=Passing, R=Retained): P2.36mm/R1.18 mm, P1.18mm/R600µm, P600 µm/R300 µm, P300 µm/R150 µm and P150 µm/R75 µm (Photos 17 to 21).

Point counts were completed on each slide using an automatic point counter set at 2 mm intervals. A target count of 400 particles was completed for each size fraction. Note that the pass 75 µm fraction is not examined by point counting under the stereomicroscope as the grain size is typically too small to make this practical or feasible.

The material was separated into seven categories:

1) cryogenic ground black rubber. Cryogenic ground crumb rubbers are characterized by particles that tend towards cubical in shape with smooth, shiny reflective surfaces (Photos 4 and 6). Fracture surfaces of cryogenically ground particles can best be described as conchoidal in nature and may also locally exhibit a plumose-like pattern. Irregularly shaped or elongated cryogenically ground particles may locally occur especially where fibers still adhere to the rubber (Photo 13).

2) ambient ground black rubber. Ambient ground crumb rubber particles tend towards less cubical with more elongated and irregular morphologies (Photos 4, 5 and 13). Ambient ground crumb rubber samples also may appear torn or ripped apart and have rough, less reflective surfaces. Ambient ground particles will generally have a higher surface area to volume ratio as compared with the cryogenically ground particles.

3) "mixed" ground black rubber (Photo 5). Where a particle displayed characteristics of both types of grinds or a clear distinction between ambient or cryogenically ground could not be determined the particle was classified as "mixed" (Photo 5).

4) white rubber (cryogenic or ambient ground),

5) transparent to translucent synthetic fiber (Type 1). Flexible; transparent to translucent; colorless to white and yellow-white; that are generally <5 µm in diameter and typically 1 to 8 mm long (Photos 7 to 10). Fiber type 1 typically occurs as individual fibers but was also observed in composite strands (Photos 7, and 13) or clusters (Photo 8). Individually, type 1 fibers may appear as straight, wavy or crimped. Under the petrographic microscope, the fiber type 1 is anisotropic with high relief, a refractive index >1.515 and 3rd to 4th order birefringence under cross polarized light (Photos 9 and 10).

6) brown to yellow synthetic fiber (Type 2). Shorter; straight; opaque to translucent fibers that typically appeared yellow to brown under the stereomicroscope (Photo 7). Type 2 fibers were only observed as composite strands. Under the petrographic microscope a surface coating on these particles lends a somewhat “dirty” appearance (Photos 9 and 10). Individual strands of a single type 2 composite fiber are typically narrower (<5 µm) as compared with fiber type 1 (Photos 9 and 10). First to second order birefringence is estimated for the individual strands.

7) mineral grains. Mineral grains were noted in both the initial observation as well as in the point count. Grain size is generally less than 0.2 mm, with most being <75 µm. Mineralogy of the particles is dominantly quartz with lesser calcite (Photos 14 to 16). Hornblende and plagioclase were also found to be present but does not constitute the major portion of the mineral component of the sample. Different types of minerals were not distinguished during the point count (Table 3) as they were found to be mainly quartz. The results of the examination are included in Table 3.

Summary

Following are the findings of this analysis:

- The sample as provided was found to consist mostly of cryogenic ground black rubber (~65.7%) with lesser amounts of ambient ground black rubber (15.4%).
- Black rubber particles with characteristics of both methods of grinding (mixed) were also observed (~13.9%).
- White rubber also displayed the same cryogenic, ambient and “mixed” character as the black rubber particles. Subdivision of the white rubber particles into same categories as the black rubber was not attempted as it overall comprised only 1.5% of the total sample (Table 3).

- Two main types of synthetic fibers were observed. Both fiber types have optical properties consistent with the Aramid-Polyamide-Polyester types of synthetic fibers[1]. Combined, these fibers comprise approximately 3.5% of the total sample (Table 3).
- The mineral component of this sample was heavily concentrated in the passing 150 µm portion (Table 3) and consisted mostly of quartz with minor calcite, hornblende and plagioclase.
- No steel or other metals were observed.

Recommendations

It is recommended that the rubber producers in Ontario submit a similar Materials Quality Report for their CRM products that includes some test results pertaining to the quality of the crumb rubber. MTO is looking at making such report a requirement for any CRM supply that is to be used in production of RMA in Ontario.

References

1. Petraco, N. and Kubic, T. 2004. Colour Atlas and Manual of Microscopy for Criminalists, Chemists, and Conservators. CRC Press, 313p.

Table 3. Detailed analysis of crumb rubber sample by point counting.

ANALYST:_______________	**SIEVE SIZE**												
	4.75 -2.36 mm		**2.36 - 1.18 mm**		**1.18 – 600 µm**		**600 – 300 µm**		**300 – 150 µm**		**150 – 75 µm**		**WEIGHTED AVERAGE**
MATERIAL TYPES	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**	
Black Cryogenic Ground Rubber	**Not Sufficient Material in This Fraction**		279	**69.75**	257	**64.25**	270	**67.5**	265	**66.25**	203	**50.75**	**65.66**
Black Ambient Ground Rubber			43	**10.75**	67	**16.75**	63	**15.75**	55	**13.75**	58	**14.5**	**15.42**
Mixed Ground Rubber			65	**16.25**	58	**14.5**	44	**11**	61	**15.25**	101	**25.25**	**13.89**
White Rubber (Cryogenic and/or Ambient Ground)			6	**1.5**	7	**1.75**	5	**1.25**	5	**1.25**	8	**2**	**1.49**
Type 1 Synthetic Fiber (translucent to transparent, colourless, white, yellow-white)			7	**1.75**	10	**2.5**	16	**4**	14	**3.5**	17	**4.25**	**3.17**
Type 2 Synthetic Fiber (translucent, yellow to brown)			0	**0**	2	**0.5**	2	**0.5**	0	**0**	1	**0.25**	**0.38**
Mineral Grains (mainly quartz)			0	**0**	0	**0**	0	**0**	0	**0**	12	**3**	**0.10**
TOTAL			400	100	400	100	400	100	400	100	400	100	
GRADATION: percent retained on individual sieve	**0%**		**7.5%**		**39.3%**		**34.4%**		**15.6%**		**RET. 3.0%** **PASS**. 0.2%		

Photo 1. A Rubber modified asphalt test section

Photo 2. A RMA test section

Photo 3. Close up photo of RMA test section with gap gradation

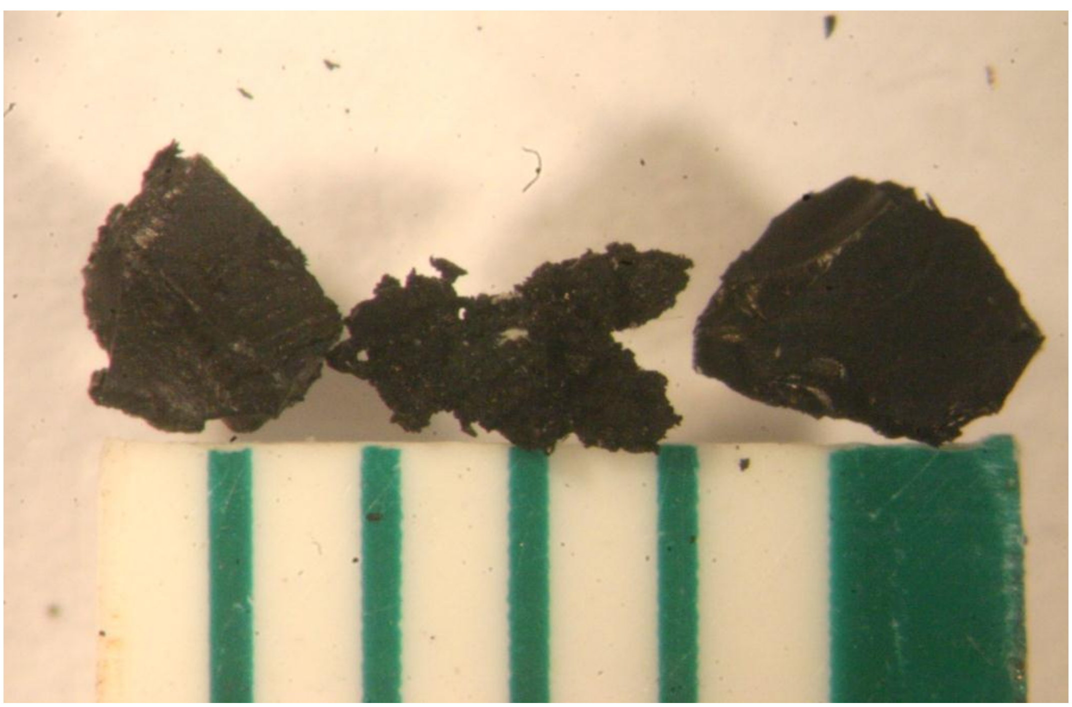

Photo 4. Taken under the stereomicroscope showing one particle of ambient ground black rubber between two particles of cryogenically ground rubber. Scale bar at bottom of photo is in millimeters. Particles were taken from the pass 2.36 mm/retained 1.18 mm fraction

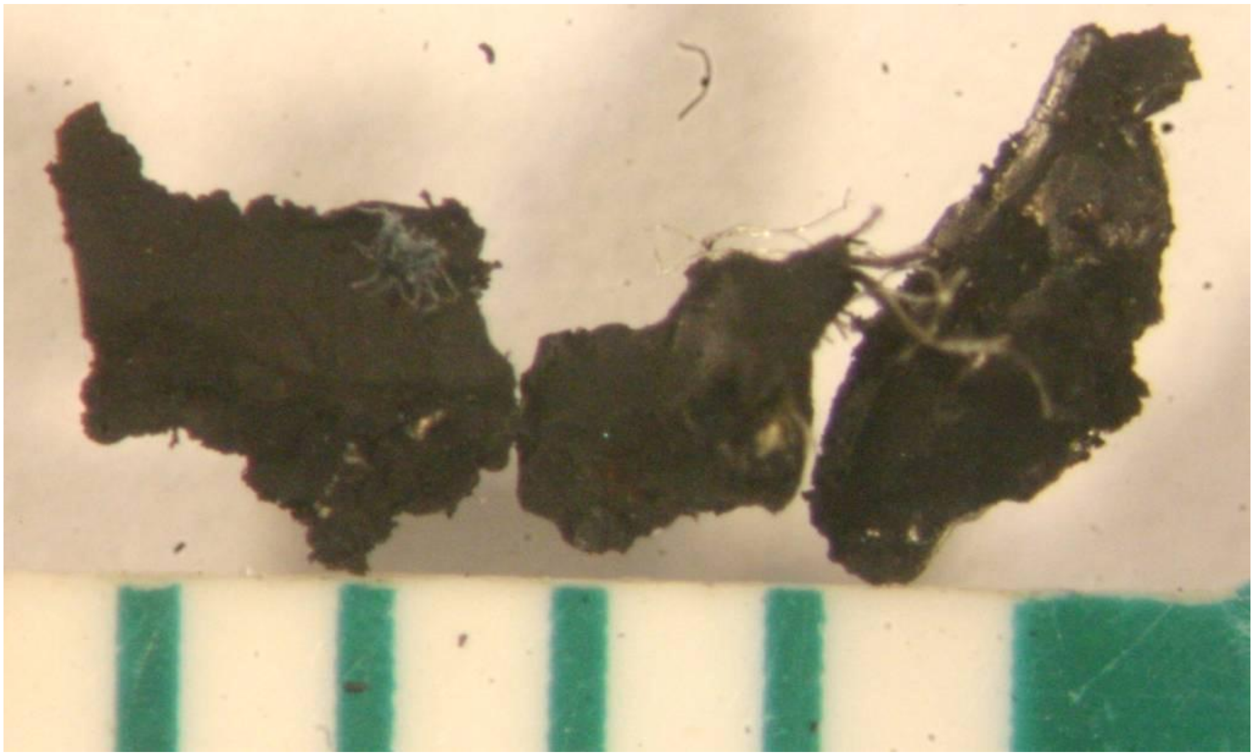

Photo 5. Examples of particles with attributes of both the ambient and cryogenic grinding methods. Particles shown tend towards cubical with some smooth and conchoidally fractured surfaces, but also display some ragged rough edges characteristic of ambient ground. Particles are from the pass 2.36 mm/retained 1.18 mm fraction. Scale bar at bottom of photo is in millimeters

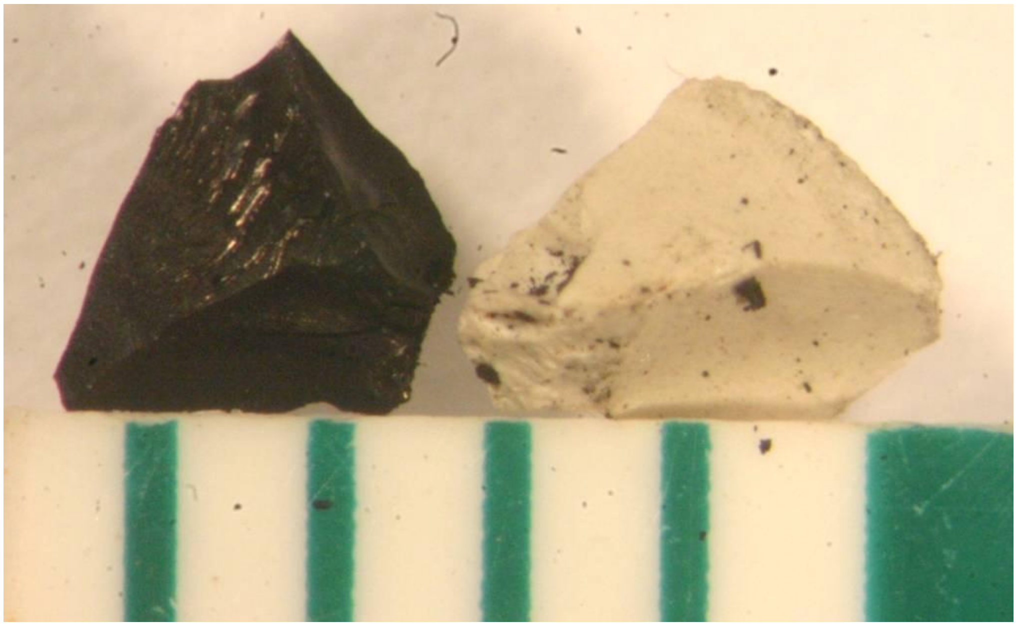

Photo 6. Cryogenic black and white rubber particles. Note the cubical shape and smooth, locally reflective surfaces with conchoidal fractures and plumose-like texture. Note that the surface luster of the white rubber particle appears somewhat dull in comparison to the black rubber particle. Scale bar at bottom of photo is in millimeters. Particles were taken from the pass 2.36 mm/retained 1.18 mm fraction

Photo 7. Example of the two main types of synthetic fibres found in the sample. Material on the left is a cryogenically ground black rubber particle with a composite strand of white to colourless synthetic fibres partially imbedded. Yellow to yellow brown synthetic fibre (also composite/made up of multiple fibres) shown on the right. Taken from the pass 4.75 mm/retained 2.36 mm fraction. Scale bar is in millimetres.

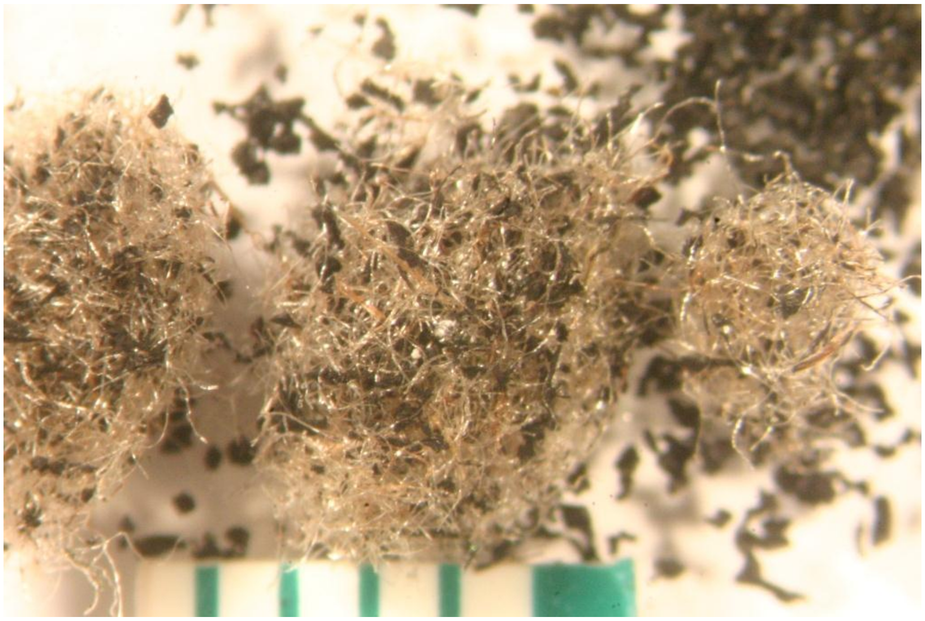

Photo 8. Material taken from the passing 300 µm/retained 150 µm fraction of the crumb rubber to illustrate the bunching or clustering of the synthetic fibres during sieving of the material. Scale bar at bottom of photo is in millimetres.

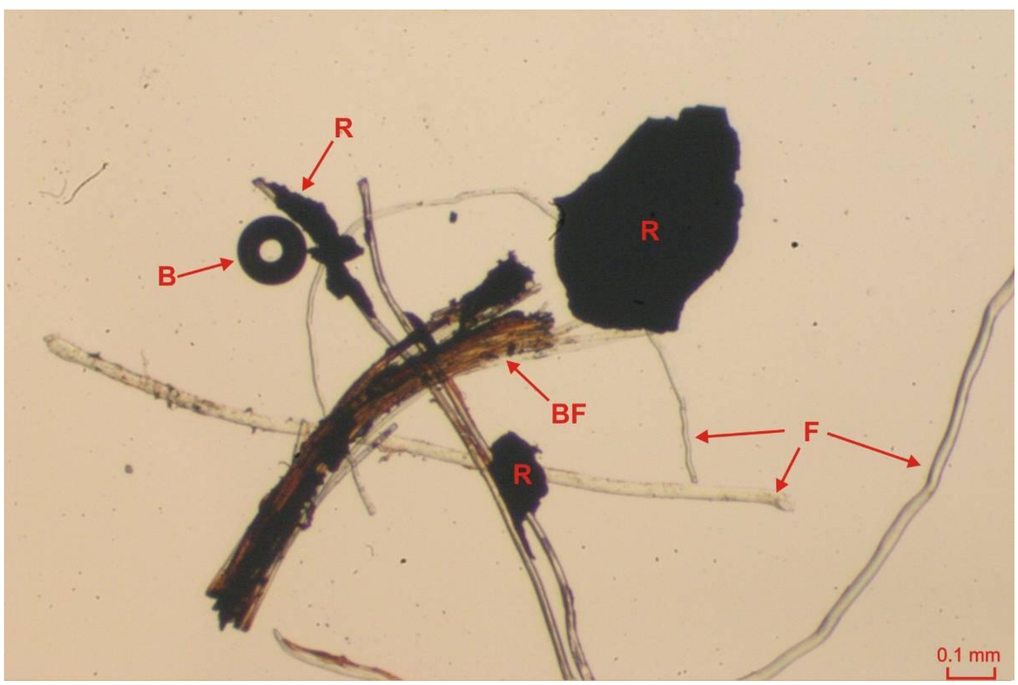

Photo 9. Fibres picked from cluster shown on the right side of photo 13 as viewed under the petrographic microscope in plane polarized light. Fibres are mounted on a glass slide in 1.5150 refractive index fluid. Note the individual rubber particle (R) in the upper central part of photo as well as other accumulations of rubber (R) adhered to the fibres. Colourless synthetic fibres (F) and chopped brown synthetic (BF) are also shown in this

photo. B denotes an air bubble trapped in the refractive index oil. Scale bar at lower right is 0.1 mm or 100 µm long for scale.

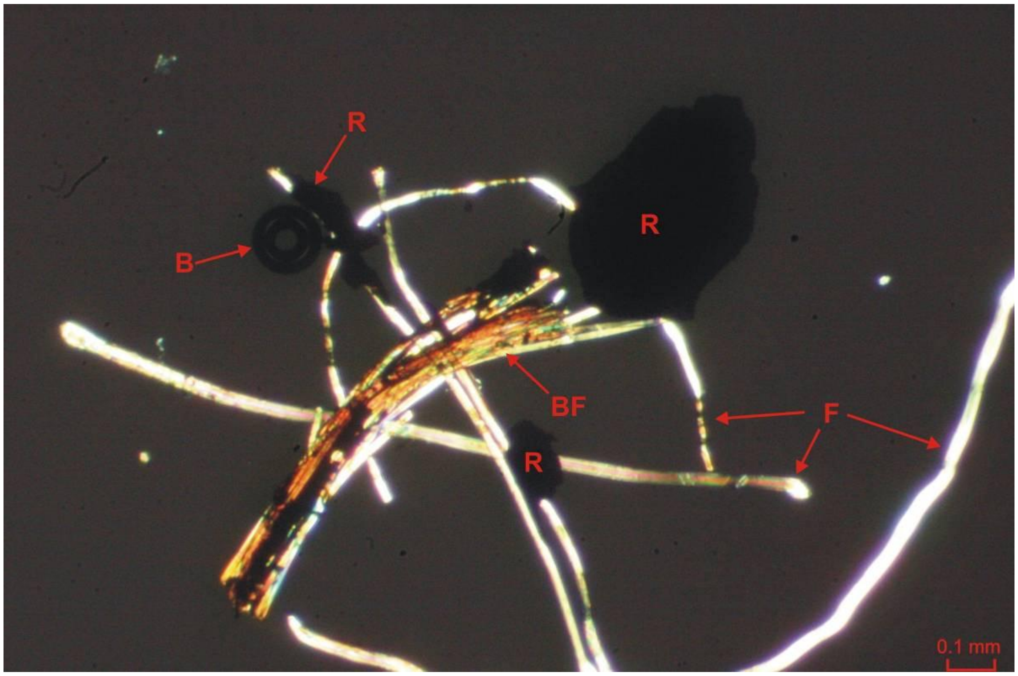

Photo 10. Same view as previous except in cross polarized light. Note the high birefringence of both types of synthetic fibres. The brown fibre birefringence is masked to some degree by the strong colouration due to a combination of a coating and/or the opaque rubber adhering to the fibre surface.

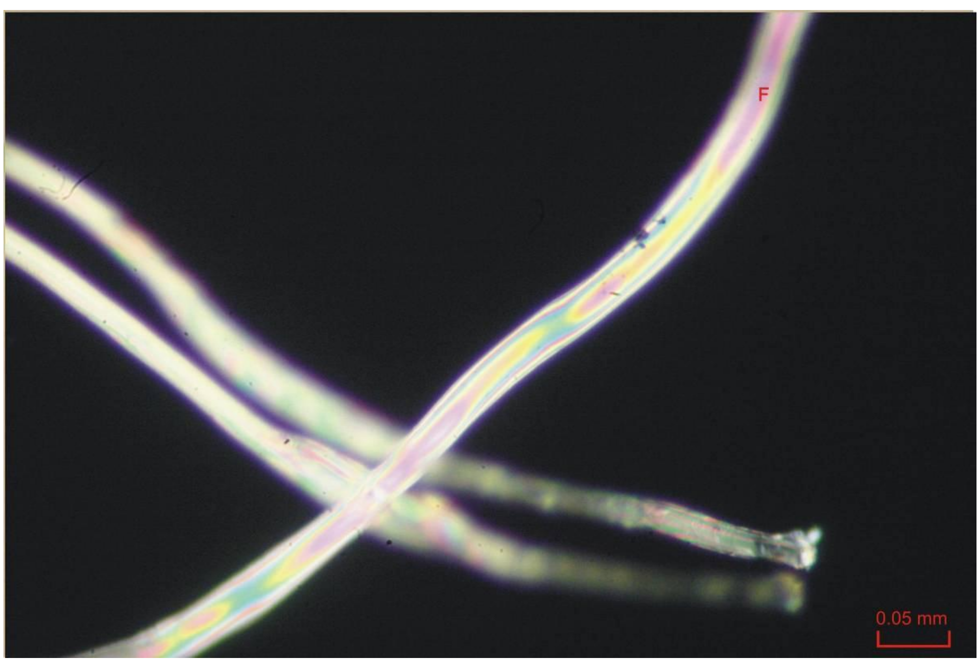

Photo 11. Increased magnification view of colourless transparent fibres (F) from previous photo showing the high second to fourth order birefringence. Scale bar at lower right is 0.05 mm or 50 µm long for scale.

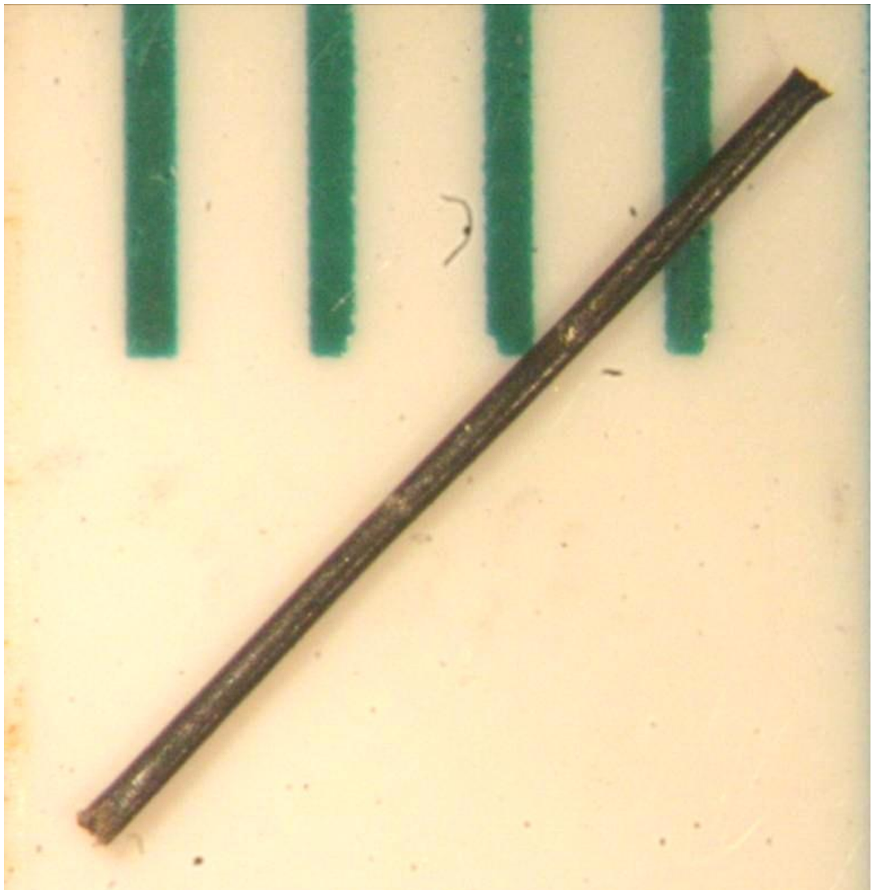

Photo 12. Single fiber found in the pass 4.75 mm/retained 2.36 mm fraction of its kind. Black, opaque, relatively non-flexible fiber.

Photo 13. Left to right: ambient ground rubber particle, ambient ground particle with colourless synthetic fibers adhered to and/or embedded in the particle (middle), and cryogenic grind particle with the same type of synthetic fibers partially embedded in the particle (right). Photo was taken under the stereomicroscope. Scale bar at bottom of photo is in millimeters. Material was taken from the pass 2.36 mm/retained 1.18 mm fraction.

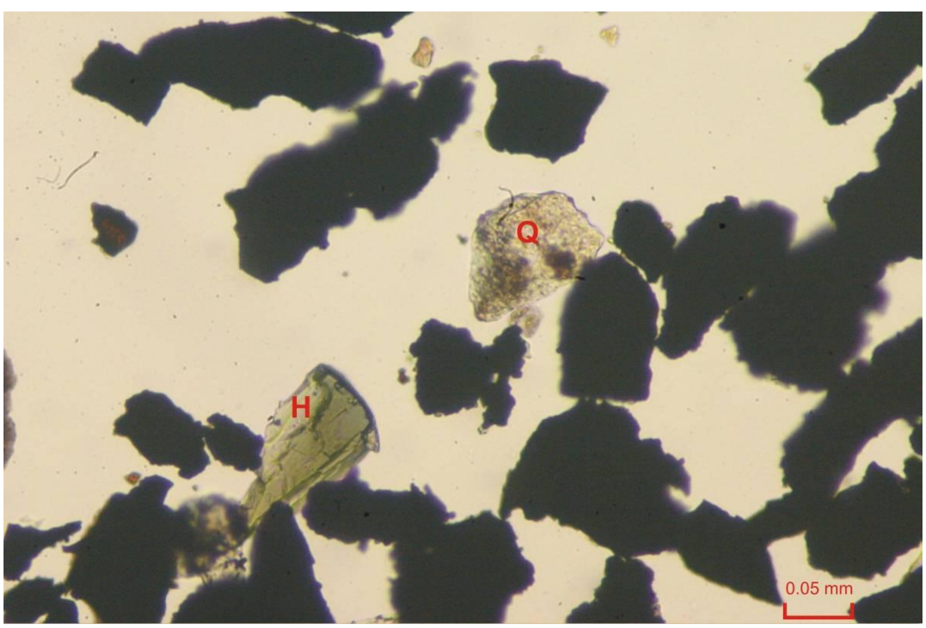

Photo 14. Material from the pass 75 µm fraction mounted on a glass slide in 1.5150 refractive index fluid as viewed under the petrographic microscope in plane polarized light (PPL). Mineral grains of quartz (Q) and

hornblende (H) are identified. Opaque (black) particles are rubber. Scale bar at lower right is 0.05 mm or 50 µm long for scale.

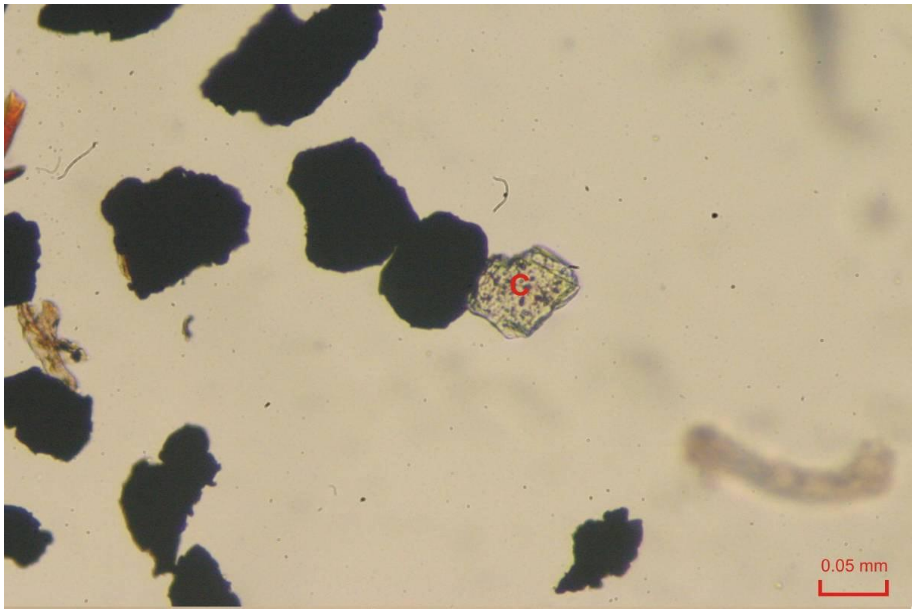

Photo 15. Material from the pass 75 µm fraction mounted on a glass slide in 1.5150 refractive index fluid as viewed under the petrographic microscope in plane polarized light (PPL). A mineral grain of calcite (C) is identified. Note the characteristic rhombohedral shape of calcite. Rhombohedral cleavage (PPL/XPL) and characteristic high birefringence (XPL) were also observed. Opaque (black) particles are rubber. Scale bar at lower right is 0.05 mm or 50 µm long for scale.

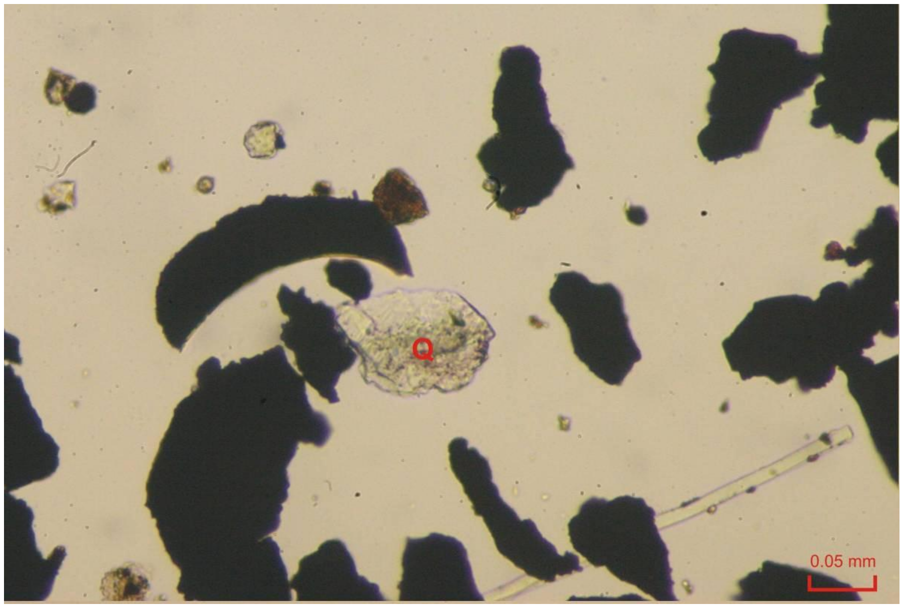

Photo 16. Material from the pass 75 µm fraction mounted on a glass slide in 1.5150 refractive index fluid as viewed under the petrographic microscope in plane polarized light (PPL). A mineral grain of quartz (Q) is identified near centre of photo. Also note the presence of other (smaller) mineral grains toward the upper left part of photo which is mostly quartz. Also note the presence of a synthetic (type 1) fiber toward the lower right part of photo as well as the presence of numerous opaque (black) rubber particles. Scale bar at lower right is 0.05 mm or 50 µm long for scale.

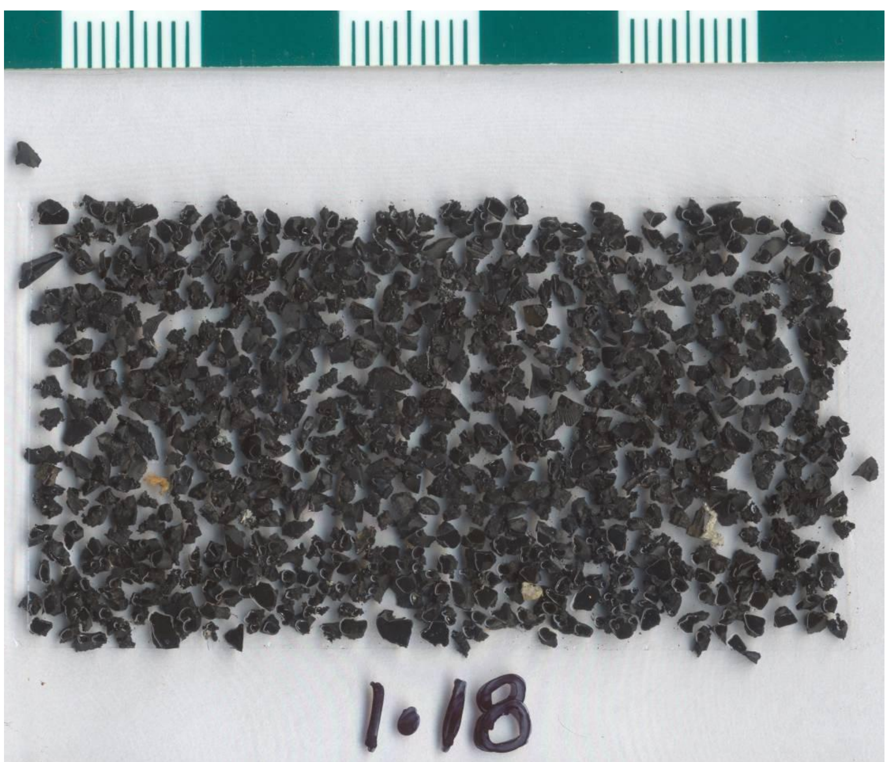

Photo 17. Glass slide prepared of material from the pass 2.36 mm/retained 1.18 mm portion of the crumb rubber sample for point counting.

Photo 18. Glass slide prepared of material from the pass 1.18 mm/retained 600µm portion of the crumb rubber sample for point counting.

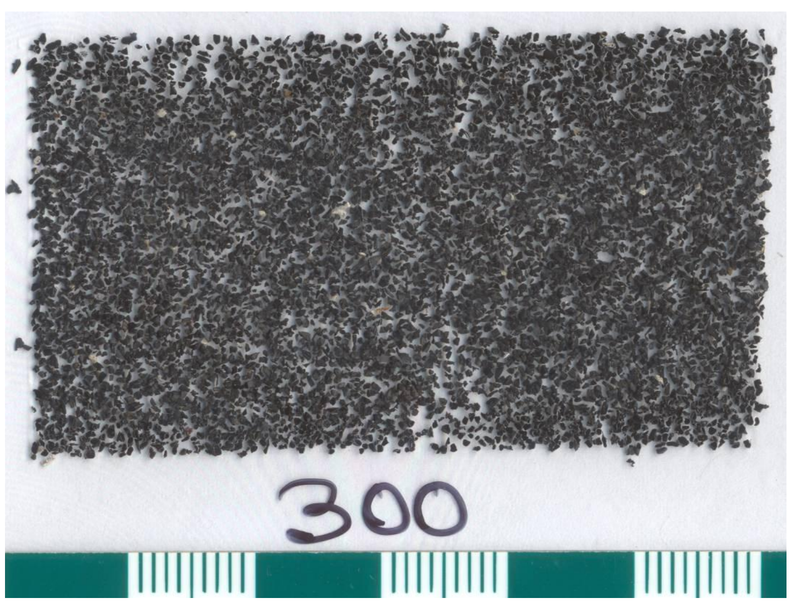

Photo 19. Glass slide prepared of material from the pass 600µm/retained 300 µm portion of the crumb rubber sample for point counting.

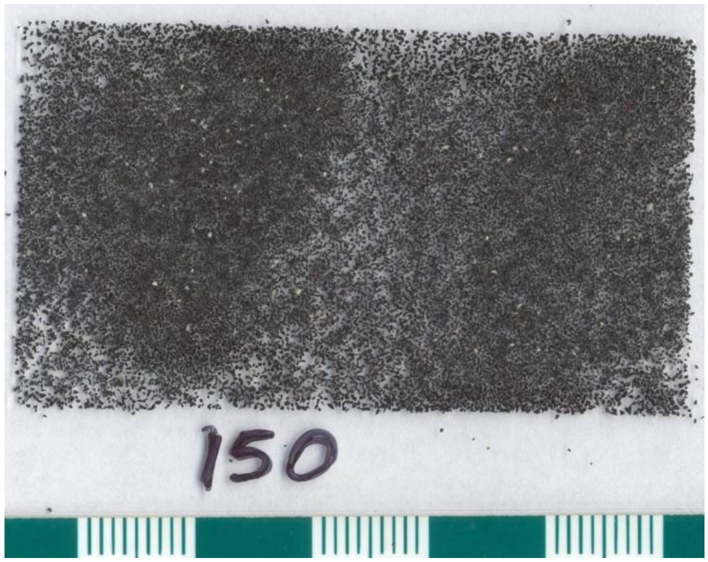

Photo 20. Glass slide prepared of material from the pass 300µm/retained 150 µm portion of the crumb rubber sample for point counting.

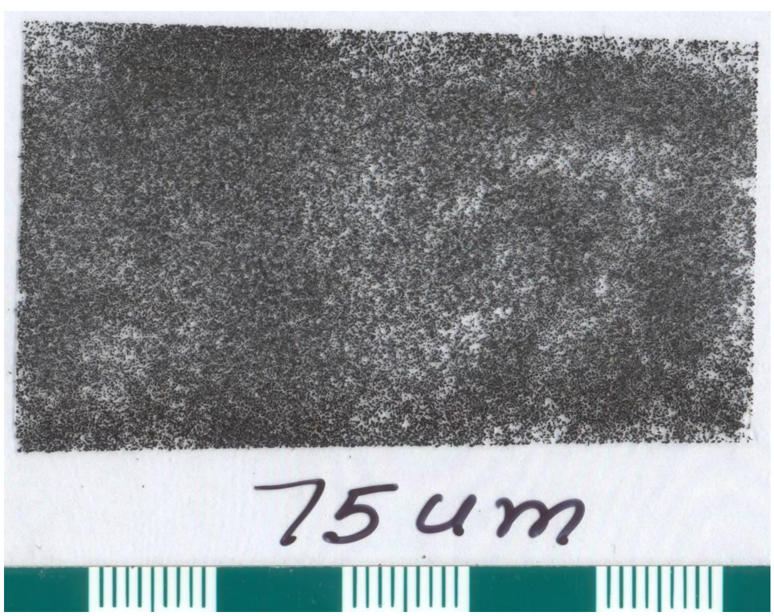

Photo 21. Glass slide prepared of material from the pass 150 µm/retained 75 µm portion of the crumb rubber sample for point counting.