# Asphalt-Rubber Standard Practice Guide

Prepared for the Rubber Pavements Association

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# Preface

This Guide provides basic information about the design and use of asphalt-rubber. The information in this guide represents the Rubber Pavements Association (RPA) suggested best practices for the making of asphalt-rubber, and the use of asphalt-rubber as a seal coat material or in hot mix asphalt and other related uses. By the use of this guide, the RPA does not in any way warrant the performance of asphalt-rubber, but rather provides advice and suggestions that should be helpful in producing a quality product to meet the needs of the designer or user of the product.

Asphalt-rubber is a mixture of hot asphalt binder and crumb rubber manufactured from scrap or waste tires. Asphalt-rubber contains visible particles of scrap tire rubber. This guide focuses on asphalt-rubber as defined by the American Society of Testing and Materials (ASTM) D-8. The ASTM D-8 defines asphalt-rubber as "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". This ASTM standard definition was developed in the early 1990's soon after the patents ended for asphalt-rubber. Asphalt-rubber as described in this guide is a product in the public domain. Asphalt rubber is a sustainable product because of its many environmental benefits and excellent engineering performance.

This guide also contains a historical collection of research studies by individuals, numerous companies and many government agencies, that helped to develop this very unique asphalt binder. This collective effort spans a period from approximately 1965 to the present, where asphalt-rubber application grew and expanded from seal coats to asphalt binders used for hot mix asphalt paving and warm mix asphalt.

The authors cannot list all the people that have contributed to this guide, but certainly the late Charles McDonald should be singled out for his vision to create such a unique asphalt binder. His early work in Phoenix, Arizona, to research, develop and patent asphalt-rubber primarily as a seal coat material initiated all the work that followed. McDonald was helped by Gene Morris who, at that time, was the research director for the Arizona Department of Transportation. Morris advanced McDonald's early work by sponsoring research studies and test projects in the state of Arizona. These two individuals were two of the early pioneers and champions of asphalt-rubber and deserve much credit for all that followed.

Since that early work in the 1960's and 1970's, much additional research and development continued and was sponsored by the City of Phoenix, Arizona Department of Transportation, California Department of Transportation, Florida Department of Transportation, Texas Department of Transportation, and the Federal Highway Administration. The University of Arizona, Arizona State University and University of California at Berkeley also contributed to the early research on asphalt-rubber. Private companies including Sahuaro Asphalt and Petroleum (no longer in business), Arizona Refining Company (no longer in business), International Surfacing Inc. (now International Surfacing Systems) and Crafco also contributed to the early development of asphalt-rubber as a binder and seal coat material. Later FNF Construction Inc., Cox Paving and Granite Construction contributed to the development of the use of asphalt-rubber binder in hot asphalt mixes. These agencies, universities and businesses

collectively sponsored considerable research, technical and practical developments that is included in this guide. Much of this early work was reported on in workshops and summary reports including: the 1980 Scottsdale Workshop [First, 1980], the 1989, Kansas City Seminar [National, 1989], the 1993 FHWA Crumb Rubber Modifier Workshop [Crumb, 1993] and the 1996 FHWA Summary of Practice [Hicks, 1996].

Later on, several very successful international conferences on asphalt-rubber were held, where research studies were reported on by authors from countries around the world. These international conferences included the first conference in Tempe, Arizona in 1998 (no published report), followed by AR2000 held in Portugal [AR2000, 2000], AR2003 held in Brazil [AR2003, 2003], AR2006 held in Palm Springs, California [AR2006, 2006] and AR2009 held in Nanjing, China [AR2009, 2009]. These international conferences have also been a source of background material for this guide.

In addition, the RPA has an extensive library of research reports on asphalt-rubber. Many of these reports can be found on line at http://www.rubberpavements.org/library.html. Also, the RPA has numerous videos that describe the manufacturing, testing and construction of asphalt-rubber. Many of these videos can be obtained from the RPA. The RPA website also contains links to many other useful support libraries on asphalt-rubber. Few of the links include: the Arizona Department of Transportation, the California Department of Transportation, the Florida Department of Transportation, the Texas Department of Transportation, the Federal Highway Administration and the California Integrated Waste Management Board, now California Department of Resources Recycling and Recovery (CalRecycle).

# Acknowledgment

The authors thank the Rubber Pavements Association (RPA) for the opportunity to prepare this first edition of an asphalt-rubber standard practice guide. In particular, Doug Carlson, the previous Executive Director, Mark Belshe, the current Executive Director, Dr. Barry Takallou, past President of the RPA and Jeff Smith current president of RPA for their support and many helpful comments and input. Also, we thank the numerous authors of asphalt-rubber papers and research projects that contributed to this guide. The list is too long to thank each contributor individually, but they are all named in the numerous references cited throughout the guide. Also, thanks to Arizona State University which has consistently supported cutting edge research of asphalt rubber in various engineering applications for the purpose of creating a better sustainable society. Thanks also to Dr. Jorge Sousa for his great efforts in putting together four international conferences on asphalt-rubber. These four conferences [AR2000 in Portugal, AR2003 in Brazil, AR2006 in the United States and AR2009 in China] provided a wealth of information and technical papers that contributed to this guide.

# Disclaimer and Copyright Notice

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# Asphalt-Rubber and "the 5 Ws"

**W**ho – The RPA is an international non-profit organization that promotes the beneficial use of asphalt-rubber. RPA members represent contractors, scrap tire recyclers, equipment suppliers, engineers, government agencies, academe, environmentalists and other interested persons.

**W**hat – Asphalt-rubber is a binder used in various types of flexible pavement construction including surface treatments and hot mixes. According to the ASTM definition (ASTM D8, Vol. 4.03, "Road and Paving Materials" of the Annual Book of ASTM Standards 2001) asphalt-rubber is "a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles". In addition asphalt-rubber physical properties fall within the ranges listed in ASTM D 6114, "Standard Specification for Asphalt-rubber Binder," [ASTM D 6114, 2009]. Recycled tire rubber or scrap tire crumb rubber is used for the reclaimed tire rubber portion of asphalt-rubber binder. The asphalt-rubber is formulated and reacted at elevated temperatures and under high agitation to promote the physical interaction of the asphalt cement and scrap tire crumb rubber constituents, and to keep the scrap tire crumb rubber particles suspended in the blend. Asphalt-rubber is typically used as either a Type 1 or Type 2 formulation. For purposes of this guide both Type 1 and 2 are considered as equal. Asphalt-rubber is a combination of scrap tires and asphalt used as an asphalt binder. It is a material defined and specified by ASTM, as well as various state agencies and large city communities. It can be used as a seal coat or as a hot mix binder. Asphalt-rubber contains visible particles of scrap tire rubber.

**W**hen – asphalt-rubber was developed in the late 1960's and has been used in above mentioned states since that early development. It has gone from a seal coat type material to a hot mix or warm mix asphalt binder and can be used with modern paving equipment.

**W**hy – asphalt-rubber was initially developed as a maintenance seal coat material to hold older cracked pavements together until an overlay or reconstruction could be accomplished. Over the years asphalt-rubber has been shown to reduce the degree and severity of cracking while being applied in thin applications. Also, it reduces maintenance and provides a smooth riding, good skid resistant and quiet surface. It has also been demonstrated to be environmentally beneficial in terms of reducing energy and $CO_2$ emissions. In addition to this it is a good sustainable engineering use of waste tires, thus reducing or eliminating the potential negative liabilities of scrap tire piles, such as burning and the breeding ground of life threatening insects, namely mosquitoes and undesirable vermin. Given asphalt-rubber many overall benefits there is every reason to know why it should be considered as a pavement surfacing material.

**W**here – asphalt-rubber is successfully used in many parts of the world, however, the greatest and most continuous use has been primarily in Arizona, California, Texas and Florida. Admittedly, these are in warmer climate areas of the United States; however, both Arizona and especially California have colder climate areas and have had good success with the use of asphalt-rubber in such colder climates.

# Frequently Asked Questions (FAQs)

**What is asphalt-rubber?** - Asphalt-rubber as described in this manual of practice is a mixture of hot asphalt (bitumen) with ground tire rubber from waste tires as defined in ASTM D-8, [ASTM D8, 2009], where 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". In addition to this asphalt-rubber conforms to the specification requirements of ASTM Standard D 6114, [ASTM D 6114, 2009]. Asphalt-rubber contains visible particles of scrap tire rubber, Illustration 1.


**Illustration 1** – *Asphalt-rubber with rubber particles compared to other forms of asphalt binder*

**How is asphalt-rubber different from typical unmodified asphalt?** – Asphalt-rubber is a form of modified asphalt. The major difference from unmodified asphalt is that asphalt-rubber contains a minimum 15 percent ground scrap tire rubber. The scrap tire rubber imparts resilience to the asphalt-rubber (AR) binder. The addition of the ground scrap tire rubber means that a greater amount of AR can be applied in a seal coat. Typical unmodified asphalt binder seal coats use an asphalt emulsion and the resultant asphalt residue left on the pavement before the chips are applied is approximately 0.20 gal/sq. yd. (0.9 liters/square meter). An AR application rate for a seal coat is in the range of 0.55 gal/sq. yd. (2.5 liters/square meter) to 0.75 gal/sq. yd. (3.4 liters/square meter). This greater degree of binder application improves the crack resistance

capability of the seal coat and reduces the rate of aging of the asphalt-rubber binder compared to a typical seal coat binder.

AR is also used in gap graded or open graded hot mixes. AR gap graded hot mixes contain from 7 to 9 percent of binder by weight of the mix whereas dense mixes with unmodified asphalt contain typically 4.5 to 5.5 percent asphalt by weight of mix. Open graded asphalt mixes generally contain typically 6 percent asphalt by weight of mix, whereas AR open graded mixes contain 9 to 10 percent binder by weight of mix. The greater degree of AR binder in the mixes affords a greater film thickness which imparts greater cracking resistance and slower aging of the binder. The base asphalt for the AR is generally one to two grades less viscous then the routine unmodified asphalt used in a dense graded hot mix in the same climatic zone. Also, since the AR contains the rubber it improves the fatigue cracking resistance. The AR mixes are generally placed in less thickness. AR gap graded mixes are generally placed in the range of 1 to 2 inches (25 to 50 mm) in thickness and the open graded 0.5 to 1.0 inch (12.5 to 25 mm) in thickness.

**How easy is it to make?** – Asphalt-rubber is typically made either at the project paving site or near to it as practical. However, with proper care and planning asphalt-rubber can be transported up to several hundred miles from a blending operation to a paving project via a specially equipped transport (nurse) truck equipped with heating and agitation. Some special equipment is needed to make the asphalt-rubber binder, keep the asphalt-rubber heated and agitated; and pump the asphalt-rubber into the hot plant, or to spray apply it as a seal coat material. This equipment is referred to as blender or spray applied equipment and is available from various venders. Spray applied equipment has been manufactured since the late 1970's and many units are still in use. Blending equipment has been manufactured since the mid 1990's and many units are still in operation. Presently, all equipment is computerized and has been successfully used in the USA as well as many other countries including but not limited to Portugal, Spain, Italy, Brazil, Russia and China. Generally speaking asphalt-rubber is relatively easy to make with the proper equipment and training.

**How much does asphalt-rubber cost?** – Costs of any material moves up and down over time. Just before the asphalt-rubber patents ended in approximately 1994 asphalt-rubber cost about twice as much as normal asphalt. Since then the cost have come down and the most recent cost comparisons at the time of this printing indicate that asphalt-rubber cost about 10-20 percent more than regular asphalt. However, many asphalt-rubber paving materials are placed thinner than regular asphalt pavements and last longer than regular asphalt. Oftentimes when the final design is completed asphalt-rubber pavements may actually cost slightly less than other pavement surfaces.

**Why don't more agencies use asphalt-rubber?** – Asphalt-rubber needs a ready supply of scrap tire crumb rubber and in some places supply, or at least, an economical supply source is not readily available. In addition as stated above some special blending or spray application equipment is needed to manufacture asphalt-rubber. This equipment like all equipment is a capital expense and contractors need some assurance that there will be enough future asphalt-rubber projects to warrant making such a capital investment. Some equipment suppliers have been able to rent or lease the equipment which helps to mitigate this obstacle to asphalt-rubber use. Adoption of any new technology or product takes time, even in the case of Arizona and California routine use of asphalt-rubber took several decades to accomplish.

# Chapter 1 – Brief History

Asphalt-rubber is a mixture of hot asphalt and crumb rubber derived from waste or scrap tires. It is used extensively in the highway paving industry, particularly in the states of Arizona, California, Texas and Florida. It is a material that can be used to seal cracks and joints, be applied as a chip seal coat and added to hot mineral aggregate to make a unique asphalt paving material. The American Society of Testing and Materials (ASTM) defines asphalt-rubber as "a blend of asphalt cement, reclaimed tire rubber and certain additives, in which the rubber component is at least 15% by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles," [ASTM, 2009] This definition was developed in the late 1990's, however the story of how asphalt-rubber was originally invented, patented, how it has been and how it is presently used, how it is made, and its benefits which have increased with time, that story begins in the 1960's. The initial development of asphalt-rubber started in the mid 1960's when Charles McDonald, then City of Phoenix Materials Engineer, began searching for a method of maintaining pavements that were in a failed pavement condition as a result of primarily cracking [Morris, 1993]. McDonald's early efforts resulted in the development of small, prefabricated asphalt-rubber patches that he called "Band-Aids", Figure 1. Others had investigated the use of rubber in asphalt as noted in a Federal Highway Administration (FHWA) report in 1971, [Rostler, 1971]. As noted in this report most of the reviewed studies involved the incorporation of unvulcanized natural rubber or latex rubber in asphalt. Some research did involve the testing of vulcanized rubber in asphalt but results were somewhat inconclusive.

The early experiments that McDonald attempted were unique in that fairly high percentages of vulcanized crumb rubber were mixed with hot asphalt. McDonald's early experiments used the product of asphalt and a fairly high amount of rubber in the form of premade patches. These patches were generally 24 in. x 24 in. (0.6 m x 0.6 m) and consisted of asphalt-rubber placed on paraffin coated paper with 3/8 in. (9.5mm) chips embedded.

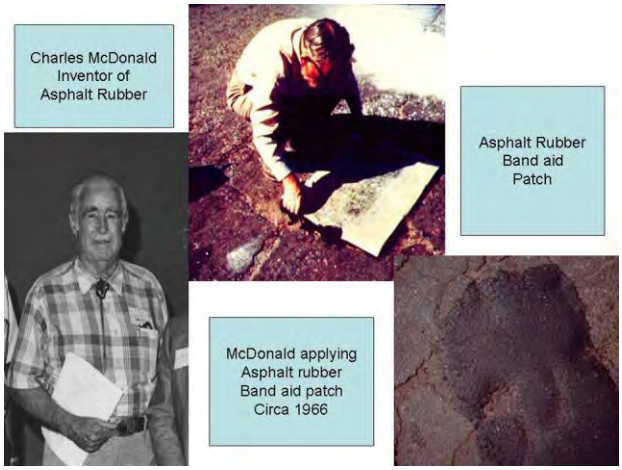



**Figure 1 -** *Charles McDonald Asphalt-rubber Band-aid*

Recognizing that fatigue cracking generally occurred in larger areas rather that small patches couldn't handle, the concept was extended to full pavement sections by spreading the asphalt-

rubber with slurry seal equipment, Figure 2, followed by aggregate application with standard chip spreaders [McDonald, 1981]. This process had two distinct construction problems. First, in order to achieve the desired reaction of the asphalt and crumb rubber in the limited time available in the slurry equipment, it was necessary to employ asphalt temperatures of 450°F (232°C) and higher. Second, the thickness of the membrane varied directly with the irregularity of the pavement surface. This resulted in excessive materials in areas such as wheel ruts and insufficient membrane thickness in between.

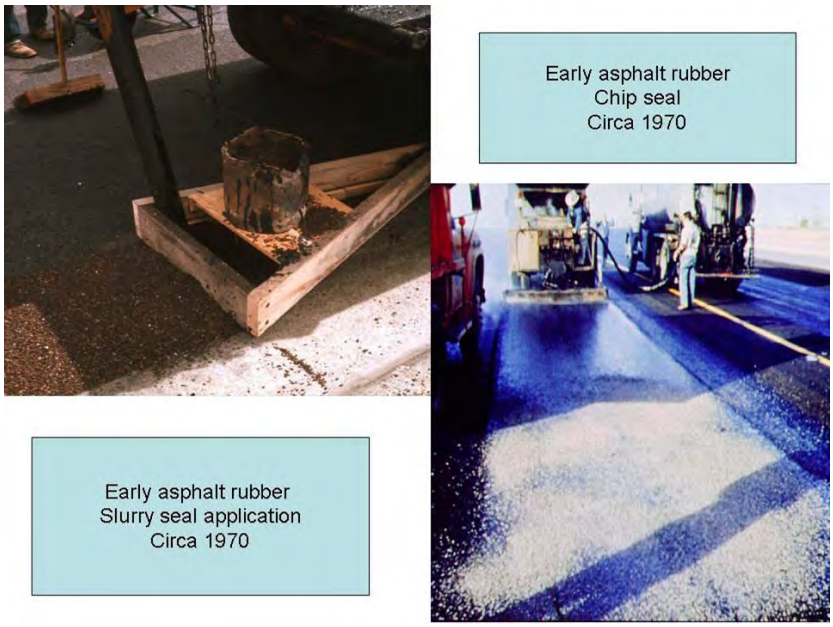



**Figure 2 -** *Asphalt-rubber applied as a slurry seal*

Although these early experiments with asphalt-rubber involved much trial and error they ultimately led to the present day asphalt-rubber binder and its many uses. The following Chapters present a guide to the manufacture and use of asphalt-rubber.

# Chapter 2 – Components of Asphalt-Rubber

## Asphalt

Asphalt-rubber is composed of asphalt (bitumen) and vulcanized rubber derived and recycled from scrap tires. Asphalt is the binder that is used for pavement seal coating and paving. Almost all of the asphalt binders produced in the United States of America (USA) and the World today is obtained by the processing of crude oil [Hobson, 1975], [Ekholm, 2002]. Many refineries in the USA and other parts of the World are located near water transport or are supplied by pipelines from the crude field or marine terminals. Figure 3 shows a listing of many of the sources of asphalt-bearing crude oils.

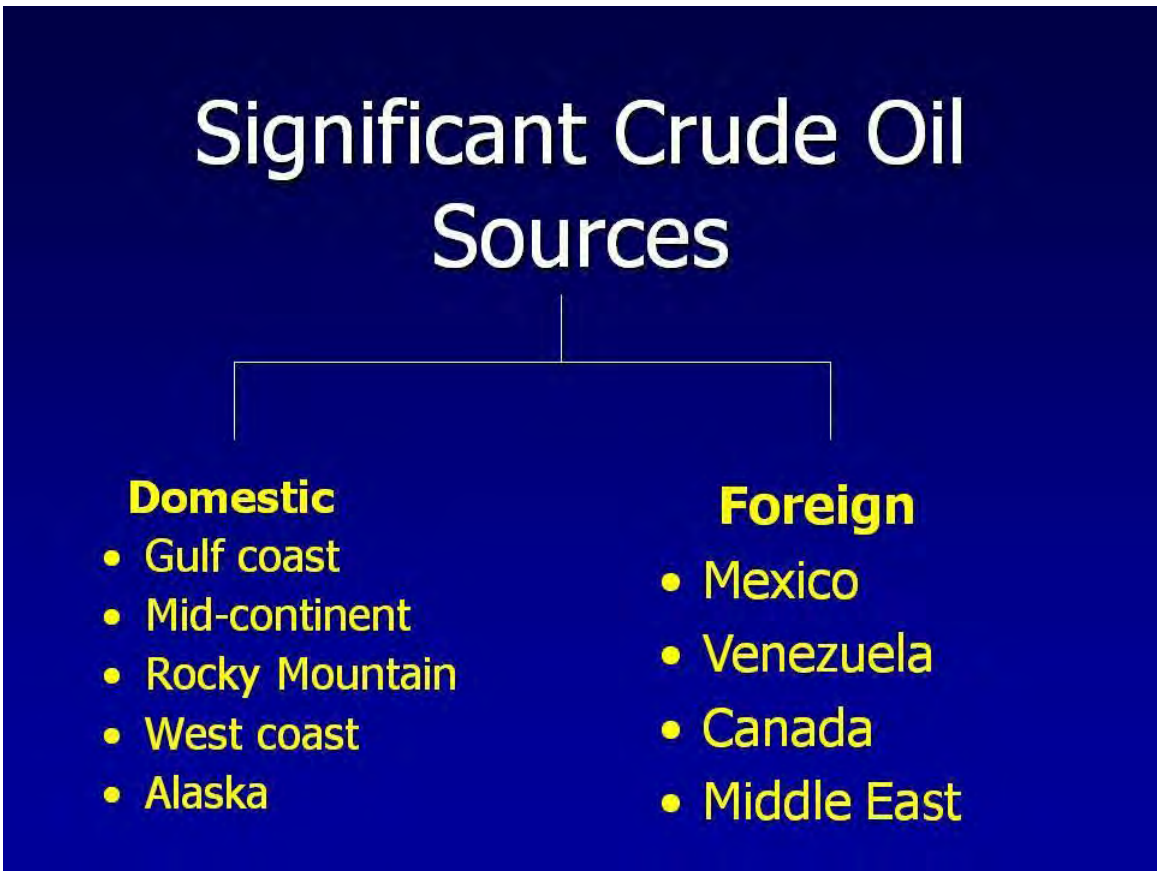



**Figure 3 -** *Sources of Asphalt*

The first step in the processing of all crude petroleum is the straight reduction by distillation. The distillation principle is based on the concept that various crude fractions which have different boiling point temperature ranges. Because asphalt binder is made up of the highest temperature boiling fractions, it becomes the residuum from the refinery tower. The crude oil is introduced into a distillation tower where the lightest components vaporize, rise to the top, cool, condense, and are drawn off for further processing. The bottom fraction from this unit is called

vacuum processed, steam refined asphalt binder. The grade of asphalt binder is controlled by the amount of heavy gas oil removed. Figure 4 is a typical refinery installation.

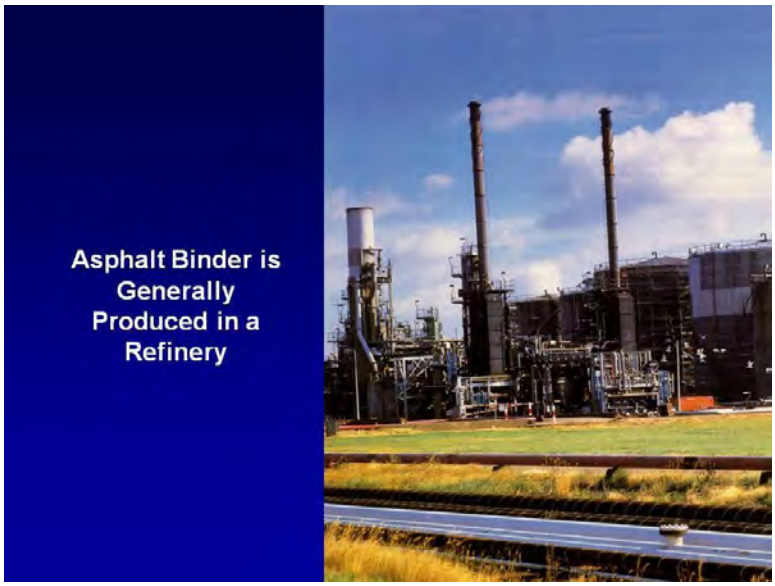



**Figure 4 -** *Typical Petroleum Refinery*

Vacuum residuum is subjected to solvent de-asphalting to extract additional amounts of high boiling point temperature fractions for applications such as lube manufacture. A high temperature softening point, hard asphalt binder is obtained by this process. This hard asphalt binder can be used as a blending component for producing paving grade asphalt binders. The resultant asphalt binder contains asphaltenes, resins and oils. The asphaltenes are of a solid like nature, resins which are of glue like nature and the oils are of a lubricating nature. All three components are blended to produce an asphalt binder. To this asphalt binder other additives or modifiers or fillers may be added to make a particular type or grade of asphalt material. Considerably more information about the nature of petroleum asphalt can be obtained from the Asphalt Institute [Asphalt, 1989]. Typically the oil component of petroleum asphalt is the component that interacts with crumb rubber derived from scrap tires and causes the swelling of the scrap crumb rubber particles.

## Rubber

Rubber has become over time a rather generic term. It is used to describe anything that is of a rubber-like nature. Originally rubber referred to natural rubber derived from plants like the rubber tree. However, now rubber refers to a whole family of synthetic rubbers, including chloroprene rubber, neoprene and styrene butadiene rubber to name a few. Generally anything that has bounce, stretch, elongation and memory (meaning it returns to its original shape after the force of deformation is removed) is referred to as rubber or rubber-like. For purposes of this guide the focus is on the vulcanized rubber used in tires. Tire rubber is a solid or dense rubber. The solid rubber used in tires is basically of a recipe type of material. The recipe ingredients are mixed by machines called internal mixers and/or mills. Once the formula of ingredients is thoroughly mixed, small amounts of special ingredients is added. These additives are known

collectively as curatives, these generally include accelerators, activators, and sulfur. These ingredients are typically very chemically active. They are the ingredients in a rubber formula that cause the rubber to become vulcanized (cross-linked). Vulcanization is an irreversible chemical process which transforms the chewing gum like rubber into a product with tensile, elongation, and memory similar to a rubber band. This amazing transformation from one physical state to another is what makes vulcanized rubber different from plastic [Rubber, 1973]. Plastics are typically thought of as thermal plastic materials. That is as plastics get hot soften and when they get cold they harden much like asphalt cement. Rubber, however, over a much higher and lower temperature range maintains its original room temperature properties such as elongation, memory, tensile and hardness. The many rubber properties and components are ultimately formed into tires to meet the needs of the traveling public.

## Tires, Scrap Tires and Crumb Rubber

*Tires*

Millions of new tires are produced annually around the world to meet the needs of vehicle owners. In the US it is estimated that one scrap tire is produced annually for each person, which is approximately 300 million tires. New tires are manufactured worldwide by several tire companies as shown in Figure 5, [Peralta, 2009].

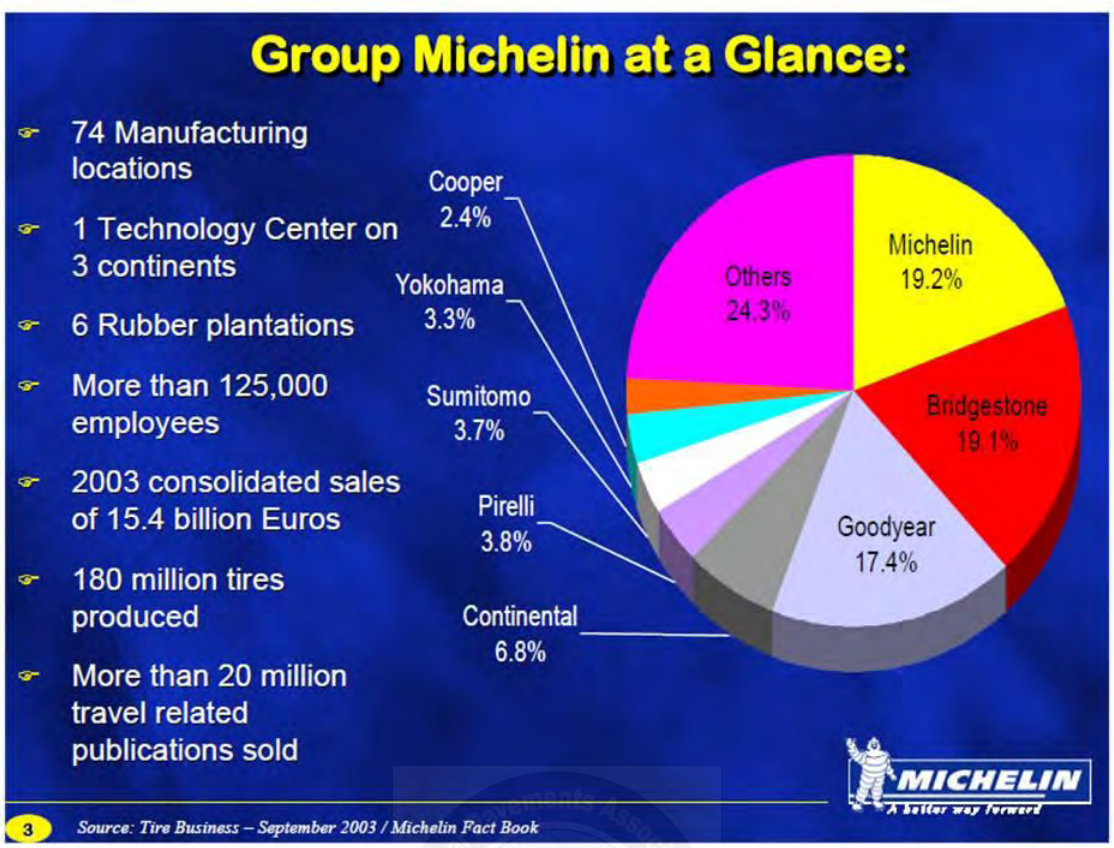



**Figure 5 -** *Tire Production, Tire Business-September 2003 / Michelin Fact Book (Michelin, 2003)*

Judging from the *Tire Business* statistics the worldwide tire market is upwards of 900 million tires produced annually. Tires are composed of many layers as shown in Figure 6. Furthermore tires contain many different types of material.

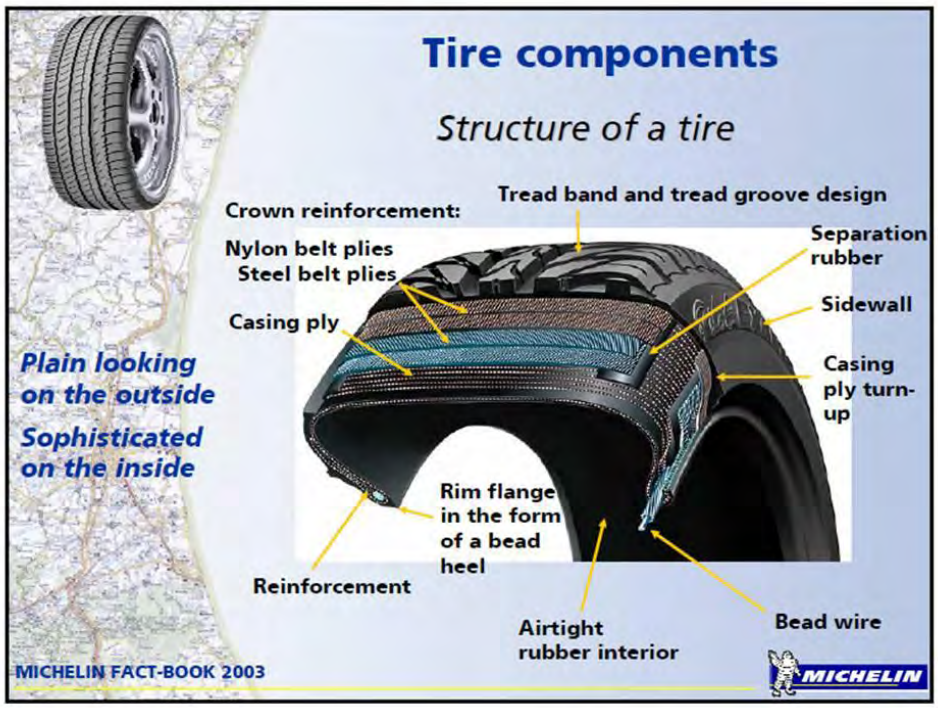



**Figure 6 -** *Tire Components, Michelin Fact-Book 2003, (Michelin, 2003)*

The most important component of a tire is the elastomer (natural and synthetic rubber). The second most important component of a tire is carbon black. Carbon black is mainly used to enhance rigidity in tire treads (to improve traction, control abrasion and reduce aquaplaning) and to add flexibility and reduce heat buildup in sidewalls [Shulman, 2000]. The proportion of natural and synthetic rubber varies according to the size and use of the tire. The generally accepted rule of thumb is that the larger the tire and the more rugged its intended use, the greater will be the ratio of natural to synthetic rubber [Rahman, 2004]. In general, truck tire rubber contains larger percentages of natural rubber compared to that from car tires (Artamendi, 2006). The third largest component is steel, mainly high grade steel. This provides rigidity, and strength as well as flexibility to the casing. The most common traditional textiles used in rubber are nylon, rayon and polyester. In recent years, a range of new textiles, primarily aramid, which is an ultra-light weight material, have been substituted for more traditional materials, primarily in the more expensive tires [Rahman, 2004].

*Scrap tires and Crumb Rubber*

As the millions of new passenger tires wear out they become available for reprocessing into crumb rubber which ultimately can be used in asphalt-rubber. The passenger tires are composed of in total about 70 % rubber. The rubber is composed of synthetic rubber (27%), natural rubber (15%) and carbon black (28%). Other components include 15 % steel and 16 % fabric, Figure 7.

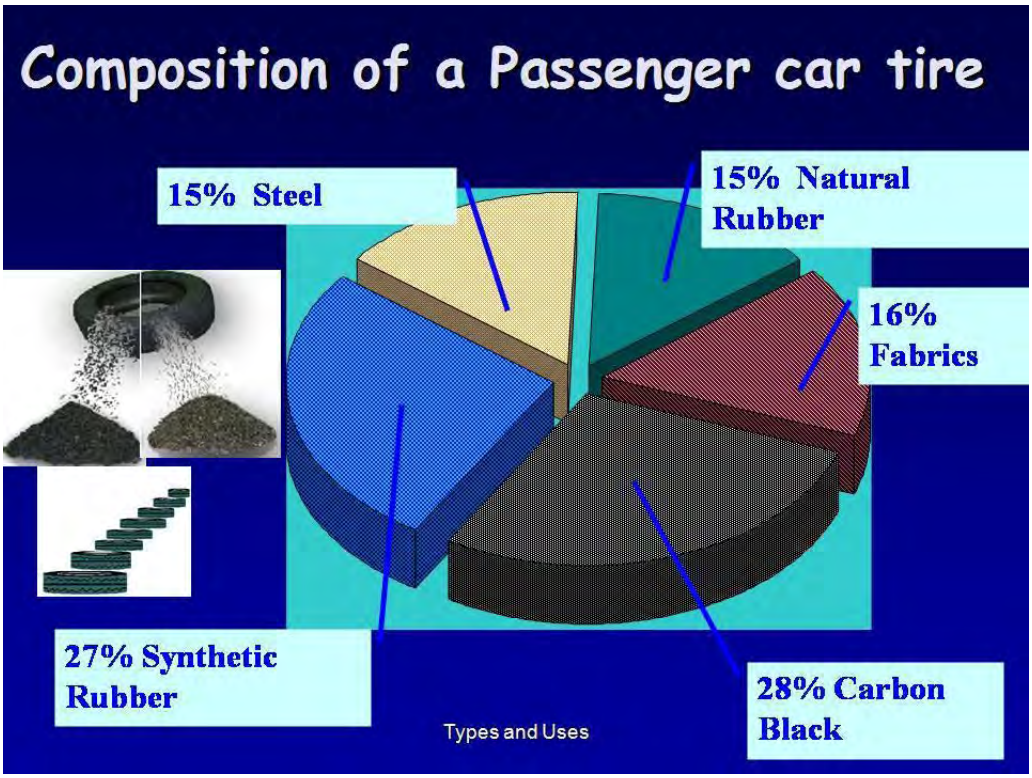



**Figure 7 -** *Composition of Passenger Tires*

To create crumb rubber the scrap tires are commutated, by shredding and grinding or cryogenic reduction in size. Crumb rubber used in asphalt-rubber asphalt normally has 100 percent of the particles finer than No. 4 (4.75 mm) sieve. The majority of the particle sizes range within No. 20 (1.2 mm) to No. 40 (0.42 mm). Some crumb rubber particles may be as fine as No. 200 (0.075 mm). The specific gravity of the crumb rubber varies from 1.10 to 1.20 (depending on the type of production) and the product must be free from any fabric, wire and/or other contaminants [Rahman, 2004]. The initial step in the production of crumb rubber is shredding the scrap tires. Scrap tire rubber is delivered to rubber processing plants either as whole tires, cut tires (treads or sidewalls), or shredded tires.

The shredded tires are further reduced in size and the steel belting and fiber reinforcing are separated and removed. Crumb rubber is produced by one of three processes. The granulator process produces cubical, uniformly shaped particles ranging in size from 3/8 in. (9.5 mm) down to No. 40 (0.42 mm) sieve, which is called granulated crumb rubber.

The crackermill process, which is the most commonly used, produces irregularly shaped torn particles sized from No. 4 (4.75 mm) sieve to No. 40 (0.42 mm) sieve.

The micro-mill process produces a very fine ground crumb rubber, usually ranging from No. 40 (0.42 mm) sieve down to as small as No. 200 (0.075 mm) sieve [Epps, 1994]. In practice there are two methods of producing crumb rubber ambient and cryogenic.

*Ambient Grinding*

Ambient grinding can be classified in two ways: granulation and crackermill. Typically, the material enters the crackermill or granulator at "ambient" or room temperature. The temperatures rise significantly during the grinding process due to the friction generated as the material is being "torn apart". The granulator reduces the rubber size by means of a cutting and shearing action. A screen within the machine controls product size. Screens can be changed according to end product size.

Rubber particles produced in these methods normally have a cut surface shape and are rough in texture, with similar dimensions on the cut edges. Crackermills are low speed machines and the rubber is usually passed through two to three mills to achieve various particle size reductions and further liberate the steel and fiber components. The crumb rubber produced in the crackermill process is typically long and narrow in shape and has high surface area [Rahman, 2004].

The schematic in Figure 8 is an example of a typical ambient scrap tire recycling plant. The process is called ambient, because all size reduction steps take place at or near ambient air temperatures, i.e. no cooling is applied to make the rubber brittle [Reschner, 2006].

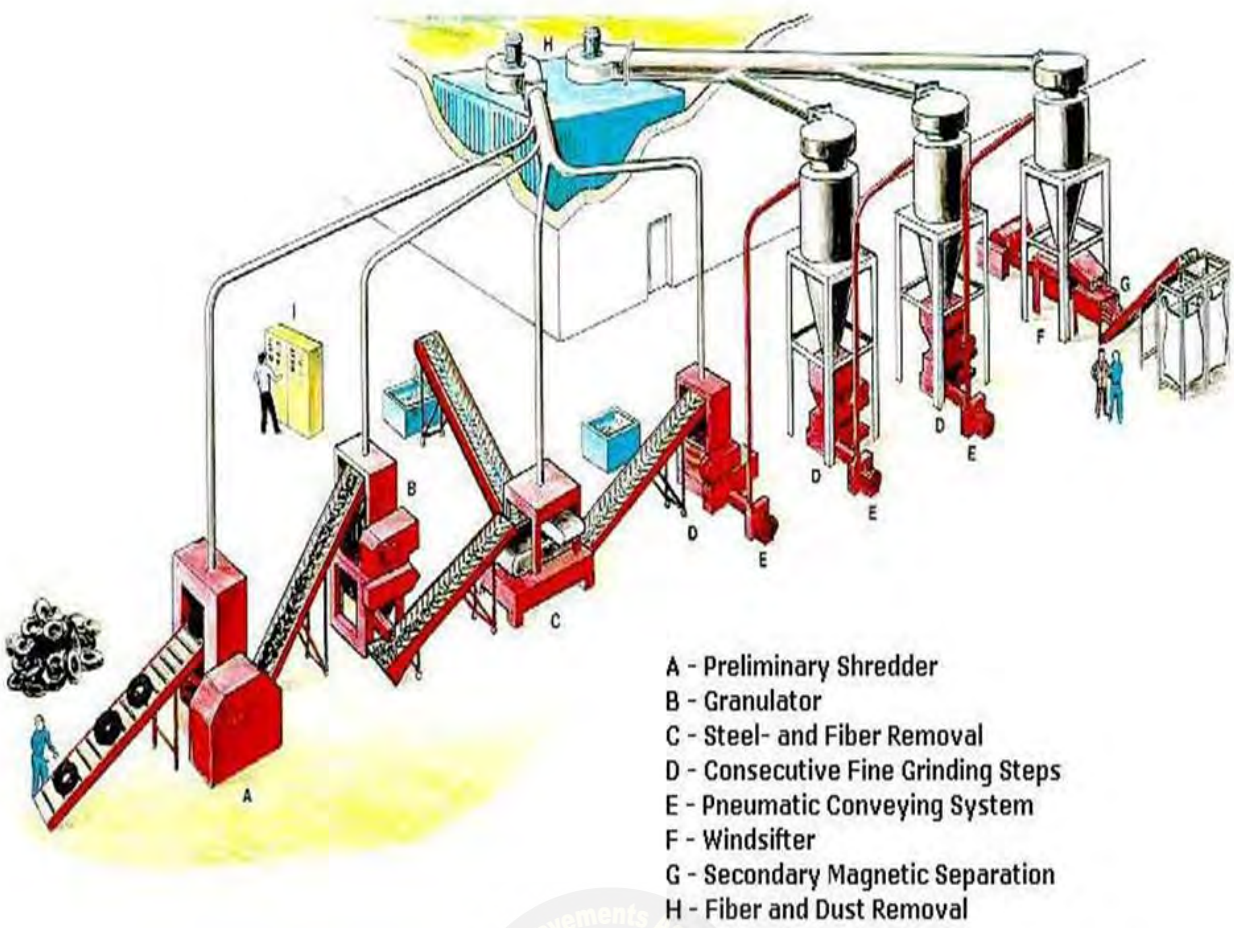



**Figure 8 -** *Schematic of an ambient scrap tire processing plant (Reschner, 2006)*

In this plant layout, the tires are first processed into chips of 2 in. (50 mm) in size in a preliminary shredder (A). The tire chips then enter a granulator (B). In this processing step the chips are reduced to a size smaller than 3/8 in. (9.5 mm), while liberating most of the steel and fiber from the rubber granules. After exiting the granulator, steel is removed magnetically and the fiber fraction is removed by a combination of shaking screens and wind sifters (C) [Reschner, 2006]. While there is some demand for 3/8 in. (9.5 mm) rubber granules, most applications call for finer mesh material, mostly in the range of No. 10 (2.5 mm) to No. 30 (0.85 mm) mesh. For this reason, most ambient grinding plants have a number of consecutive grinding steps (D). The machines most commonly used for fine grinding in ambient plants are [Reschner, 2006]:

- Secondary granulators;
- High speed rotary mills;
- Extruders or screw presses;
- Cracker mills.

Ambient grinding can be operated safely and economically if the bulk of the rubber output needs to be relatively coarse material, i.e., down to approximately No. 20 mesh (1.2 mm) material [Reschner, 2006].

A related form of scrap tire grinder is the powderizer [Granutech, 2011]. It appears that the powderizer produces a rubber particle that is similar cryogenic particle. The high output powderizer is coupled to a 50HP electric motor and supported on a cast-steel base. The powderizer feed should be wire-free -¼" tire chips. The chips must be fed into the powderizer via a controlled feed device (i.e., auger). Depending on screen selection, the feed rate could be as high as 30 pounds per minute, or as low as 12 pounds per minute. Output sizes range from 5/32 to 30 mesh, Figure 9.

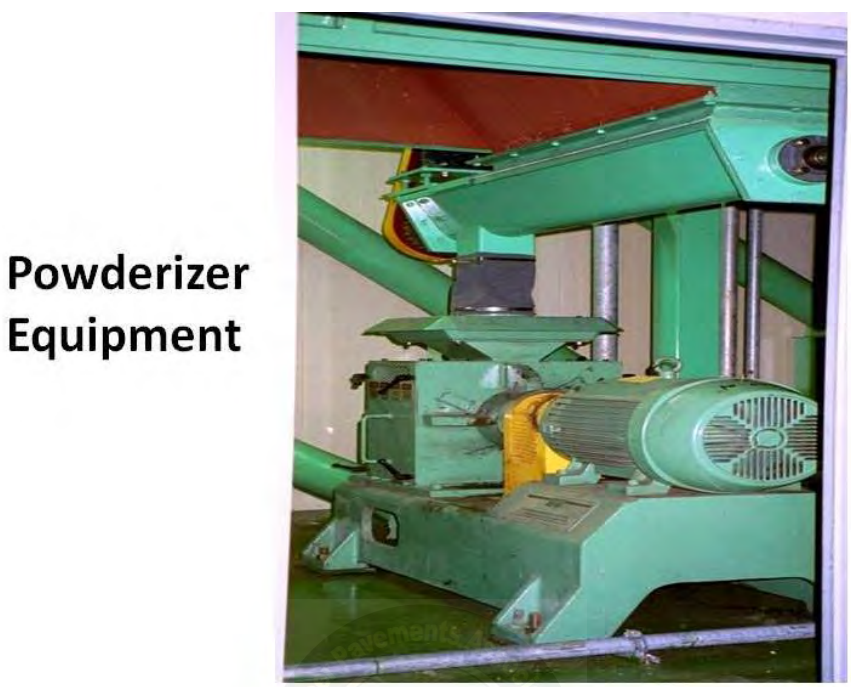



**Figure 9 -** *Powderizer equipment (Granutech, 2011)*

*Cryogenic Tire Grinding*

This process is called "cryogenic" because whole tires or tire chips are cooled down to a temperature of below -112ºF (-80ºC). Below this "glass transition temperature" rubber becomes nearly as brittle as glass and size reduction can be accomplished by crushing and breaking [Reschner, 2006]. The use of cryogenic temperatures can be applied at any stage of size reduction of scrap tire. Typically, the size of the feed material is a nominal 2 in. (50 mm) chip or smaller. The material is cooled in a tunnel-style chamber or immersed in a "bath" of liquid nitrogen to reduce the temperature of the rubber or tire chip. The cooled rubber is ground in an impact type reduction unit, usually a hammer mill. This process reduces the rubber to particles ranging from ¼ in. (6 mm) to less than No.30 (0.85 mm) sieve. Steel from the scrap tire is normally separated out of the product by using magnets. The fiber is removed by aspiration and screening. The resulting material appears shiny, clean, with fractured surfaces and low steel and fiber content due to the clean breaks between fiber, steel and rubber [Rahman, 2004]. This type of size reduction requires less energy and fewer pieces of machinery when compared to ambient size reduction. Another advantage of the cryogenic process is that steel and fiber liberation is much easier, leading to a cleaner end product. The drawback, of course, is the cost for liquid nitrogen [Reschner, 2006].

The crumb rubber industrial process takes place in three stages [Recipneu, 2006]:
1. Shredding raw material;
2. Cryogenic processing;
3. Bagging and storage.

Shredding raw material consists of fragmenting light and heavy tires into small, homogeneously cut pieces – the "chips" [Recipneu, 2006)].

Cryogenic processing performs the complete and individualized separation of rubber, steel and textiles without noticeable waste or losses in material, Figure 10. This is a continuous, automatically controlled process which takes place under an inert nitrogen atmosphere [Recipneu, 2006].

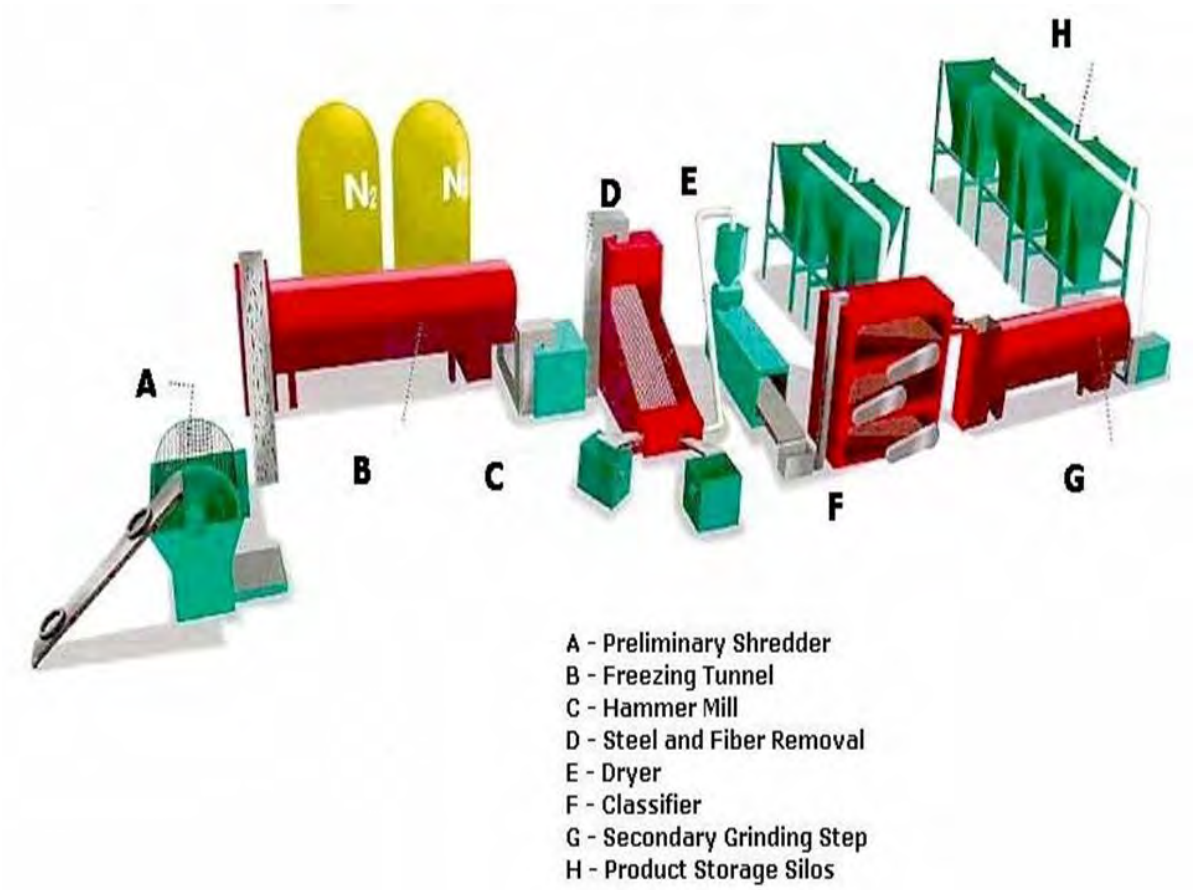



**Figure 10 -** *Schematic of a cryogenic scrap tire processing plant (Reschner, 2006)*

In the cryogenic cooling the 2 in. (50 mm) tire chips are dropped into a long continuously operating freezing tunnel (B), and are cooled down by the action of liquid nitrogen at around -321ºF (-196ºC), resulting in a cold exchange between the chips at room temperature and the liquid nitrogen. When the chips are cooled to a temperature of -112ºF (-80ºC), the glass transition point is reached for all the rubber polymers of the tire, and then the "rubber" behaves like glass [Recipneu, 2006]. The tire chips are then dropped into a high RPM hammer mill (C). In the hammer mill, the chips are shattered into a wide range of particle sizes, while, at the same time, liberating fiber and steel. Because the rubber granules may still be very cold upon exiting the hammer mill, the material is dried (E) before classification into different, well defined particle sizes (F) [Reschner, 2006]. The separation, drying, sorting and purifying of the various materials follows the next steps and lead to the completion of the process [Recipneu, 2006]:

- Separation of textiles using a shaker screen and different suction profiles;
- Magnetic separation of steel;
- Drying the granulated rubber;
- Sieving the rubber into different standard sizes;
- Elimination of dust and steel contaminations.

From the cryogenic line, the granulate that is obtained moves on to various silos, where it is put into big-bags over palettes, made of synthetic raffia fiber, which can carry up to 1.2 tons. The

packaged product is then stored until delivery [Recipneu, 2006]. Generally speaking, cryogenic scrap tire processing is more economical if clean, fine mesh rubber powder is required [Reschner, 2006]. In the cryogenic-grinding process the equipment cost is less, operating costs are lower, productivity is increased, and the product has better flow characteristics than ambient ground rubber [Adhikari, 2000]. The cryogenic technology allows the efficient production of rubber powders and very small rubber granules, with negligible steel or textile contaminations, and minimizes the wastes obtained in the recycling operation. The cryogenic products obtained maintain the molecular structures of the initial rubber polymers, which are not degraded in this process by side reactions of oxidation, devulcanization, or scission/reduction of molecular weights [Recipneu, 2006]. Crumb rubber used in asphalt-rubber normally has 100 percent of the particles finer than No. 4 (4.75 mm) sieve. The specific gravity of crumb rubber is approximately 1.15, and the product must be free of fabric, wire, or other contaminants [Chesner, 1998].

Crumb rubber properties have been reported to affect conventional binder properties [Oliver, 1981]. Natural rubber tends to be superior to synthetic rubber for elastic properties and that synthetic rubber is more stable than natural rubber with regard to the interaction conditions of time and temperature. Earlier studies reported that truck tires are considered rich in natural rubber, while passenger tires are rich in synthetic rubber. Recent studies and reports show the difference between truck tire rubber and passenger tires has been reduced [Jensen, 2006].

Whether by ambient or cryogenic means the crumb rubber process can be summarized as a series of interrelated steps wherein the whole scrap tire is reduced in size to crumb rubber suitable for use in the production of asphalt-rubber, Figure 11.


**Figure 11 -** *From whole tires to crumb rubber suitable for asphalt-rubber*

By using the ingredients of asphalt, scrap tire crumb rubber and other components or additives if specified asphalt-rubber can be produced.

# Chapter 3 – Design and Manufacture

Asphalt-rubber is made by blending and reacting hot asphalt with crumb rubber and other components or additives if specified. The asphalt is paving grade asphalt and it is heated to about 375°F (190°C). Crumb rubber at ambient temperature is added to the hot asphalt and thoroughly mixed. Other specified components or additives may also be included with the blended asphalt and rubber. Examples of such specified components and additives may include natural rubber, extender oil and anti-strip. During the heating and mixing of the asphalt and the rubber the rubber particles swell as shown in Figure 12 which changes the resultant mixture to a gel like material.

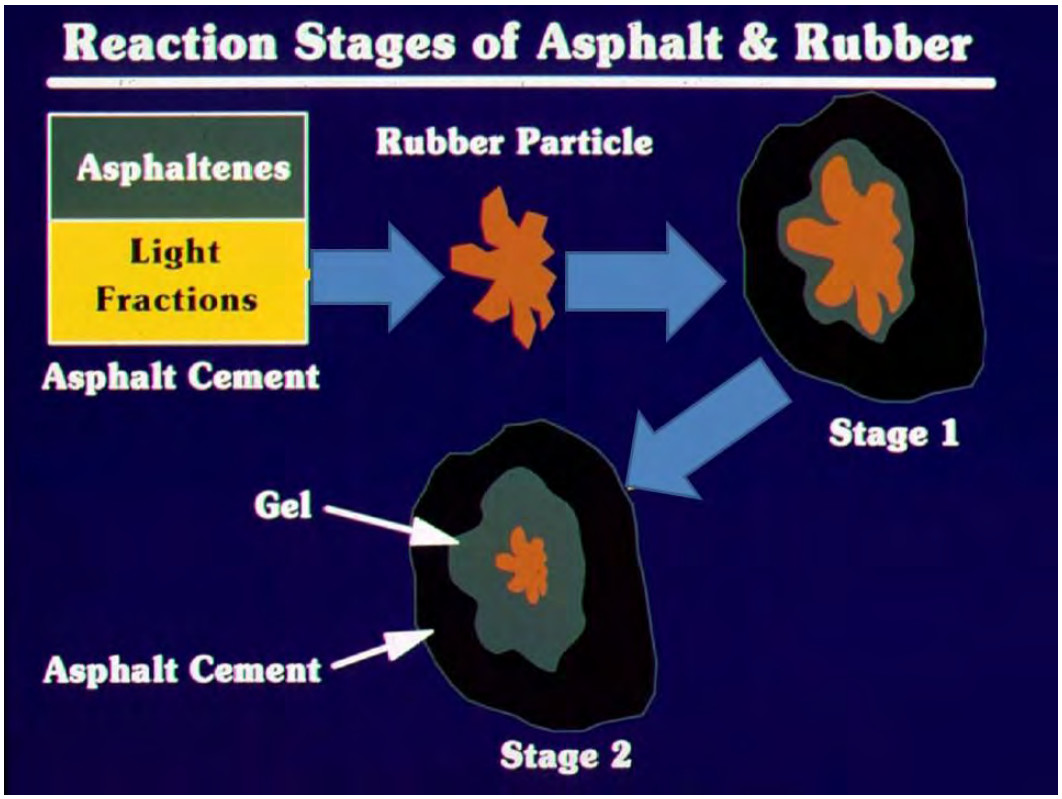



**Figure 12 -** *Asphalt-rubber reaction/blending process*

The resultant asphalt-rubber is pumped into a holding tank where the asphalt-rubber is kept to a temperature of at least 350°F (177°C) for a period of 45 to 60 minutes. Components of the asphalt-rubber blending process shown in Figure 13 include the hopper for crumb rubber (ground tire rubber), asphalt storage tank, heat tank that brings asphalt up to a high temperature, high shear blender mixing chamber and finally reaction vessel where asphalt and crumb rubber interact (swell). Reaction vessel has continuous agitation mixing.

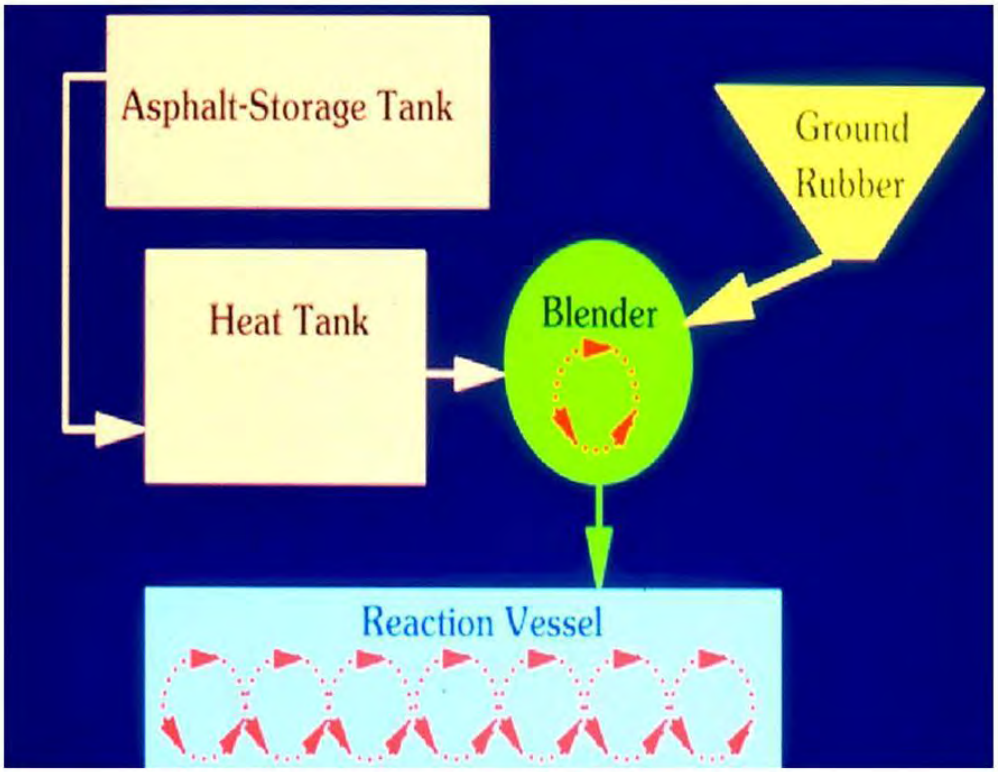



**Figure 13 -** *Asphalt-rubber reaction/blending process*

## Asphalt-rubber binder design

Before asphalt-rubber binder can be manufactured a binder design profile is developed by a laboratory experienced in such binder design. The asphalt is selected to correspond to an appropriate grade for a given climatic region, such as hot, mild and cold. Table 1 represents grades of asphalt selected by various agencies for their associated climatic conditions. Likewise Table 2 shows the gradation of crumb rubber selected and specified by various agencies for Type 1 or Type 2 High Natural rubber to be used in their respective asphalt-rubber binder.

A design profile is typically developed to evaluate the compatibility between materials used, component interaction and to check for stability of blend over time. Four laboratory tests are conducted on the asphalt-rubber prepared in the laboratory to check for compliance with respective agency specifications. Table 3 is an example of the asphalt-rubber binder specifications that will be tested for during binder profile development testing. Table 4 is an example of an asphalt-rubber binder design profile.

**Table 1 -** *Asphalt selected and specified by grade for use in asphalt-rubber by agencies*

| Agency | ADOT[1] | ADOT[1] | ADOT[1] | ASTM | Caltrans | FDOT[4] | TxDOT[1] | TxDOT[1] | TxDOT[1] |
|---|---|---|---|---|---|---|---|---|---|
| Binder Type | 1 | 2 | 3 | 1 | 2 | ARB 12 | I | II | III |
| CRM Type: scrap Tire (ST)<br>High Narual (HN) | ST<br>-- | ST<br>-- | ST<br>-- | ST | 75±2% ST<br>25±2% HN | ST<br>-- | ST<br>-- | ST<br>-- | ST<br>-- |
| Minimum CRM by total weight of binder, % | | | | | | | 15 | 15 | 15 |
| Minimum CRM by weight of asphalt cement, % | 20 | 20 | 20 | 15 | 18 | 12 | | | |
| Base Asphalt Cement Grade | PG 64-16 | PG 58-22 | PG 52-28 | Not Specified[2] | AR-4000 | PG 64-22 | PG 58-28<br>PG 64-22 | PG 58-28<br>PG 64-22 | PG 58-28<br>PG 64-22 |
| Asphalt Modifier (extender oil) by weight of asphalt cement, % | Not Allowed | Not Allowed | Not Allowed | May be allowed but not specified | 2.5-6.0 | Allowed but not used | Allowed but not used | Allowed but not used | Allowed but not used |
| Minimum Interaction Temperature | 163°C 325°F | 163°C 325°F | 163°C 325°F | 177°C 350°F | 190°C 375°F | 150°C 300°F | -- | -- | -- |
| Maximum Interaction Temperature | 190°C 375°F | 190°C 375°F | 190°C 375°F | 190°C 375°F | 218°C/425°F<br>226oC/440oF | 175°C 350°F | -- | -- | -- |
| Minimum Interaction Time | 60 minutes | 60 minutes | 60 minutes | User Defined | 45 minutes | 15 minutes | -- | -- | -- |

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

[2] ASTM directs the user to select binders based on climate

[3] Caltrans dual units specifications are presented in this table.

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

**Table 2 -** *Gradation of crumb rubber selected and specified by various agencies*

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

**Table 3 -** *Example of typical asphalt-rubber binder specifications*

| Binder Designation<br>Climate Zone | | CRA 1<br>Hot | CRA 2<br>Mild | CRA 3<br>Cold |
|---|---|---|---|---|
| Grade of base asphalt cement PG recommended; Pen suggested<br>Grade | | PG 64-16<br>Pen 60/70 | PG 58-22<br>Pen 85/110 | PG 52-28<br>Pen 120/200 |
| Rotational Viscosity; 350° F (177°C) Spindle 3, 20 RPM, Pa·s, [cp] ASTMD2196 | | 1.5-4.0<br>[1500-5000] | 1.5-4.0<br>[1500-5000] | 1.5-4.0<br>[1500-5000] |
| Penetration; 77 F (4°C), 200 g, 60 sec. (ASTM D 5) | Min | 10 | 15 | 25 |
| Softening Point; (AASHTO T-53 or ASTM D 36) °C or F | Min | 57<br>[135] | 54<br>[130] | 52<br>[125] |
| Resilience 77 F (25°C) ASTM D 5329<br>%, min. | Min | 30 | 25 | 15 |

**Table 4 -** *Example of an asphalt-rubber laboratory profile design*

| Test Performed | Minutes of Reaction | | | | | Specified Limits |
|---|---|---|---|---|---|---|
| | 60 | 90 | 240 | 360 | 1440 | |
| Viscosity, Haake at 177°C, Pa-s<br>Centipoise cP | 2.7<br>2700 | 2.8<br>2800 | 2.8<br>2800 | 2.8<br>2800 | 2.0<br>2000 | 1.5-4.0<br>1500-4000 |
| Resilience at 25°C, % Rebound (ASTM D3407) | 34 | | 36 | | 32 | 30 Minimum |
| Ring & Ball Softening Point, °F (ASTM D36) | 150.0 | 150.5 | 152.5 | 154.5 | 145.0 | 135 Minimum |
| Needle Penetration at 4°C, 200g, 60 sec., 1/10mm (ASTM D5) | 22 | | 24 | | 26 | 10 Minimum |

The four tests that are conducted during the design profile testing include [ASTM, 2009]:

- Apparent viscosity measured by the Brookfield viscometer ASTM D2196 or handheld rotational viscometer (Haake, Rion or other suitable device), [ASTM D2196, 2009]
- Resilience ASTM D5329, [ASTM D5329, 2009]
- Softening Point ASTM D36, AASHTO T 53, [ASTM D36, 2009] [AASHTO T 53, 2009]
- Penetration ASTM D 5, AASHTO T 49, [ASTM D 5, 2009] [AASHTO T 49, 2009]

Each test is generally described as follows:

## Apparent Viscosity

Measured by a rotational viscometer and presented in centipoise (cP) or Pascal Seconds (Pa-s).

- *Brookfield Viscometer, Figure 14*
- *Haake or Rion or other suitable handheld Viscotester, Figure 15*

Rotational viscometer used to monitor fluid consistency of asphalt-rubber binder to ensure pump-ability, and to identify binder changes which might affect hot mix placement, compaction or performance. If the Brookfield is the required method for acceptance, then the handheld viscometer should be calibrated and correlated to the Brookfield measurement for field use.

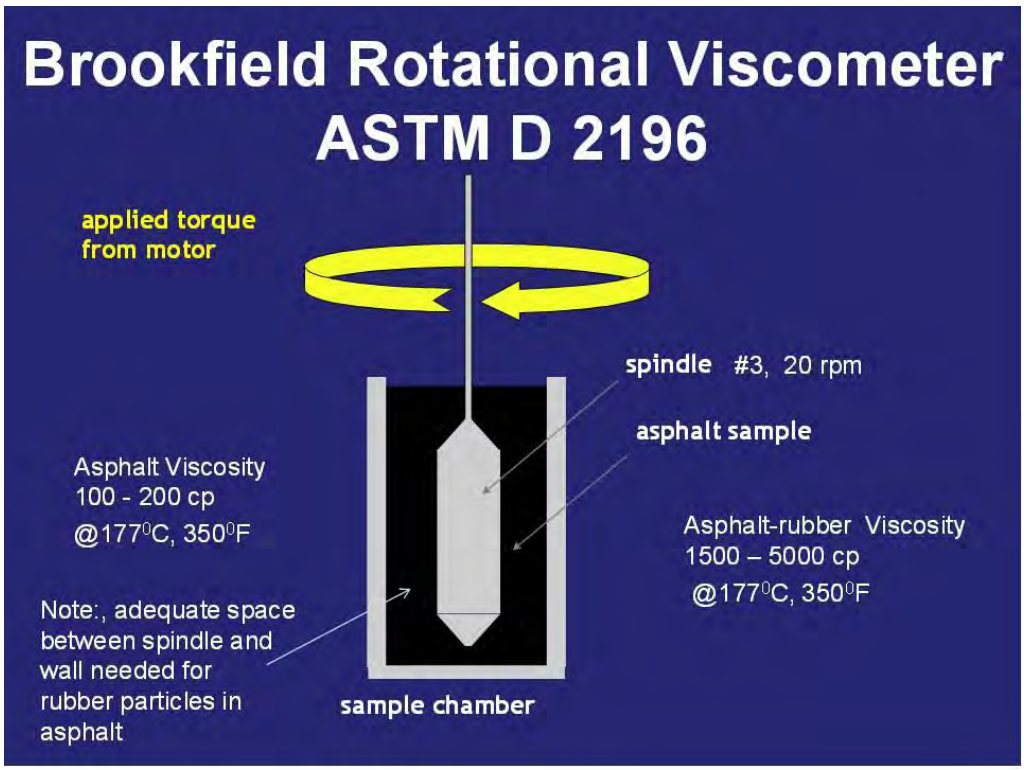



**Figure 14 -** *Brookfield Rotational Viscometer*

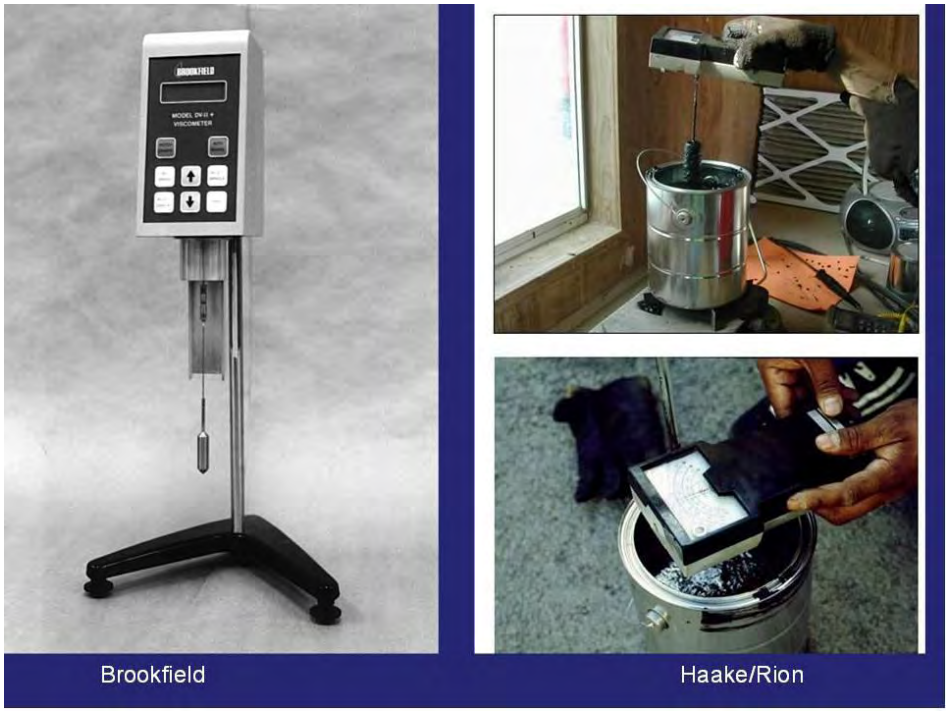



**Figure 15** – *Brookfield Rotational Viscometer and Haake/Rion Handheld Viscometer*

As more rubber is added to the asphalt the apparent viscosity increases in the manner shown in Figure 16.

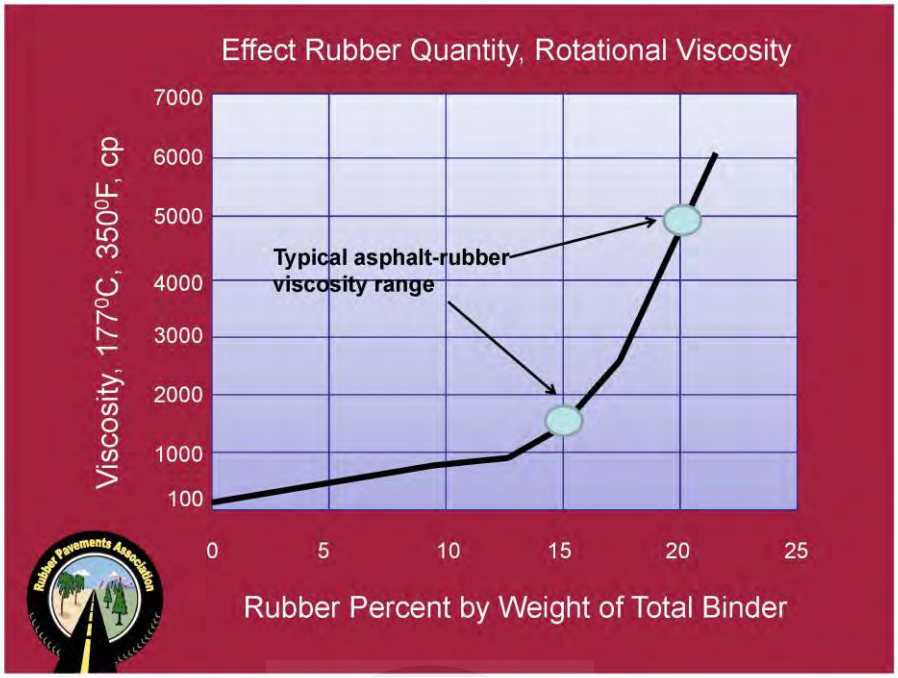



**Figure 16 -** *Example of apparent viscosity increase with scrap tire rubber content [Chehovits, 1989]*

## Resilience

Resilience, ASTM D5329, is a measure of the elastic properties of the asphalt-rubber binder. Resilience is expressed as a percentage of rebound for the binder. Resilience is one of the most important properties of AR binders and is considered a primary indicator of performance, Figure 17. Figure 18 shows how resilience increases with scrap rubber content.


**Figure 17 -** *Example of resilience test*

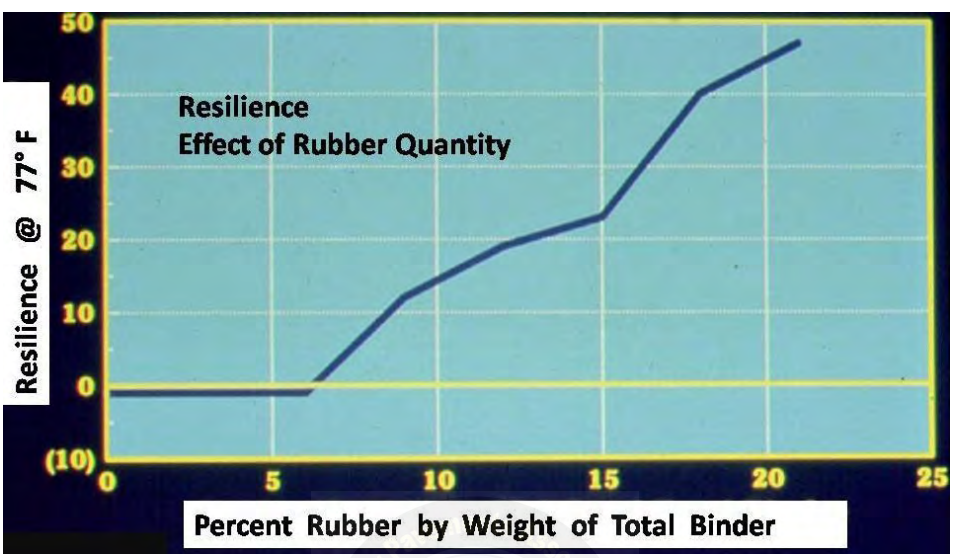



**Figure 18 -** *Example of resilience test [Chehovits, 1989]*

## Softening Point and Penetration

For the Softening Point Ring and Ball test method (ASTM D36, AASHTO T 53) the results are recorded in °F or °C, which is an indicator of the material stiffness and extent of modification and shows the tendency of the material to flow at elevated temperatures. For the Penetration test method (ASTM D 5, AASHTO T 49), the measurement is by a penetrometer and test results recorded in tenths of a millimeter units (dmm). Asphalt-rubber binder consistency can be evaluated at low, moderate, and high temperatures. Penetration is usually tested at the standard temperature of 39.2°F (4°C) and 77.0°F (25°C). Cone penetration is typically used with asphalt-rubber binder with larger particle size crumb rubber 10 mesh (2.5 mm) and larger. Figure 19 shows an example of the softening point and penetration test equipment.

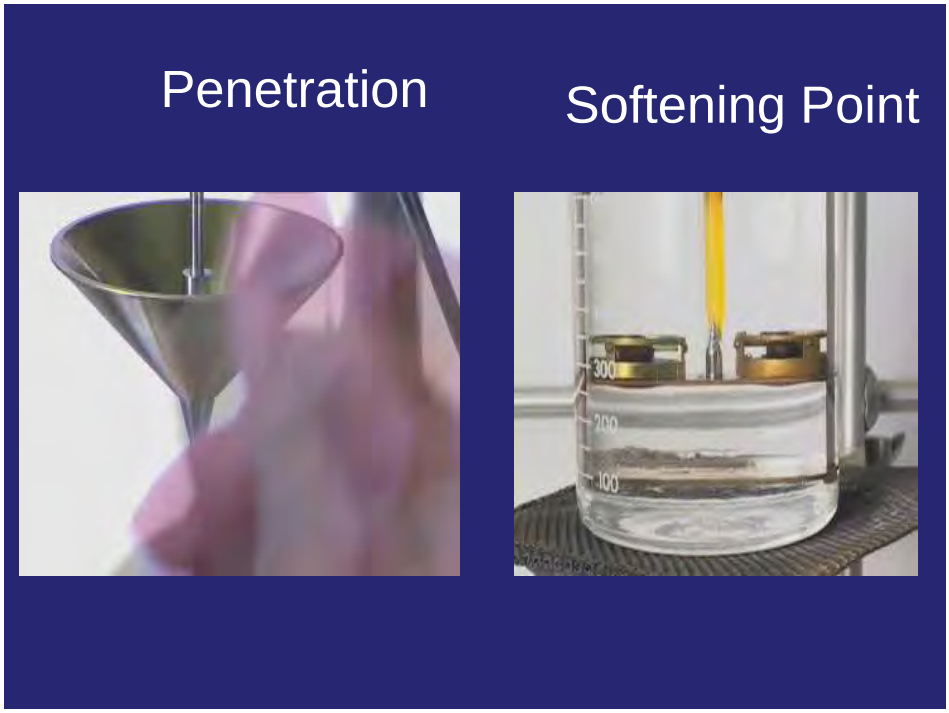



**Figure 19 -** *Softening Point and Penetration test*

Typically 20 percent scrap tire crumb rubber that meets an example gradation as shown in Table 5 and Figure 20 is added to the hot base asphalt heated to a temperature of about 190°C (375°F). Other rubber gradations may be specified. Table 2 as previously shown provides several examples of scrap tire crumb rubber specified gradations. After reaction the AR mixture is kept at a temperature of about 175°C (350°F) until it is introduced into the mixing plant. Figure 21 and 22 show examples of two different types of portable asphalt-rubber blenders. Samples of the rubber, base asphalt, and AR mixture are taken and tested accordingly.

**Table 5 -** *Example Scrap Tire Crumb Rubber Gradation*

| Sieve | Mesh | Percent Passing |
|---|---|---|
| | | |
| 2 mm, #10 | 9/10 | 100 |
| 1.18 mm, #16 | 14 | 65-100 |
| 600 um, #30 | 30 | 20-100 |
| 300 um, #50 | 48 | 0-45 |
| 75 um, #200 | 200 | 0-5 |


**Figure 20 -** *Typical Crumb rubber used in asphalt-rubber*

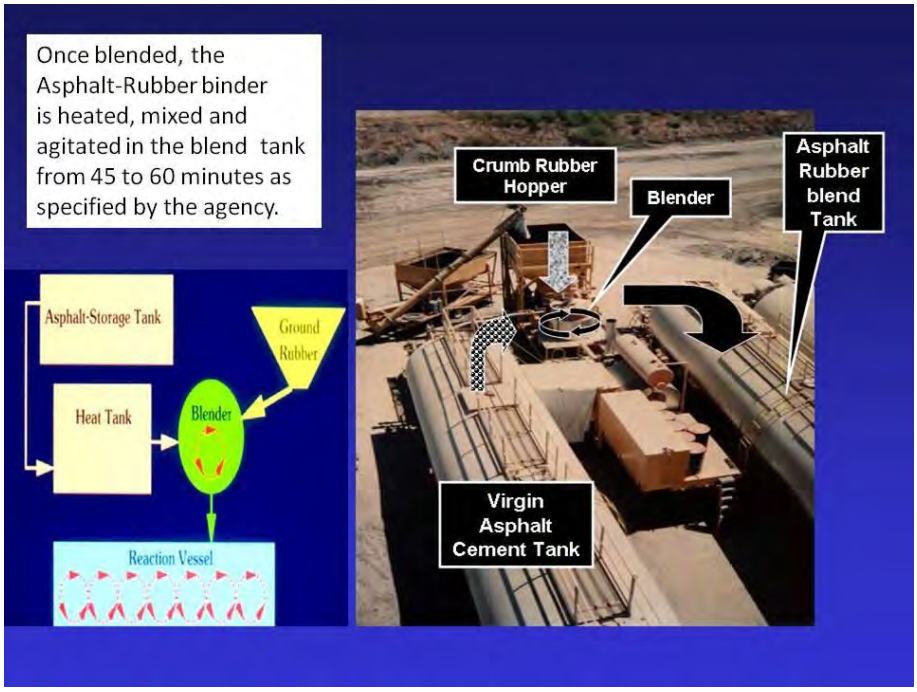



**Figure 21 -** *Asphalt-rubber blender equipment and reaction process*

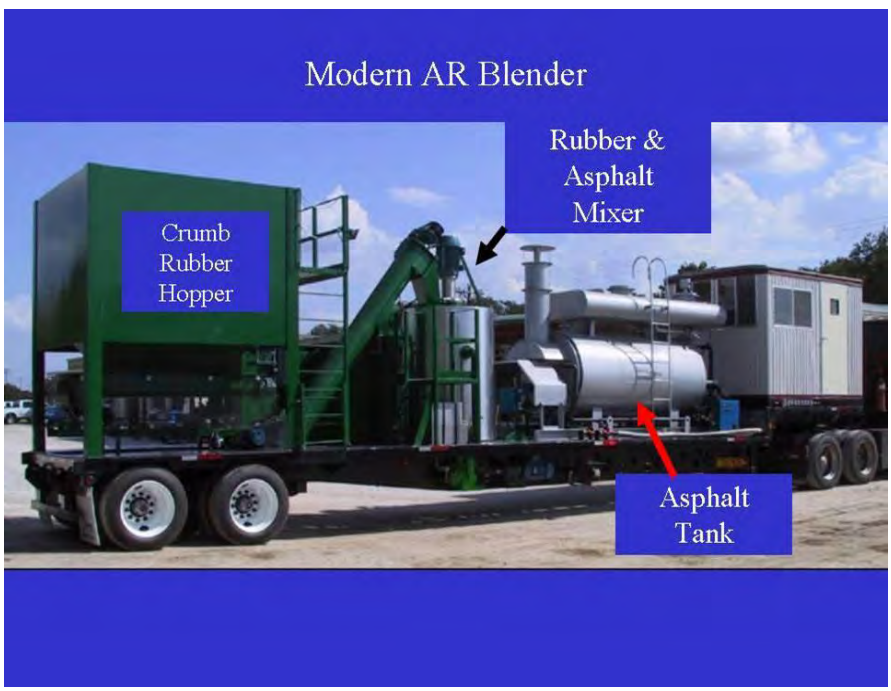



**Figure 22 -** *Self contained mobile small asphalt-rubber blender*

The cumulative effect of heating and mixing of the asphalt-rubber is to develop an asphalt binder that has elastic properties as measured by the resilience test and a higher viscosity at high temperature. The imparted elastic properties create a greater degree of strain tolerance. It was noted that the asphalt-rubber binder can accept up to five times more strain compared to

unmodified asphalt [Green, 1977]. This allows a greater film thickness of asphalt-rubber to be applied to hot aggregate in a hot mix as shown in Figure 23. The greater film thickness also contributes to less aging of the asphalt-rubber binder [Way, 1976].

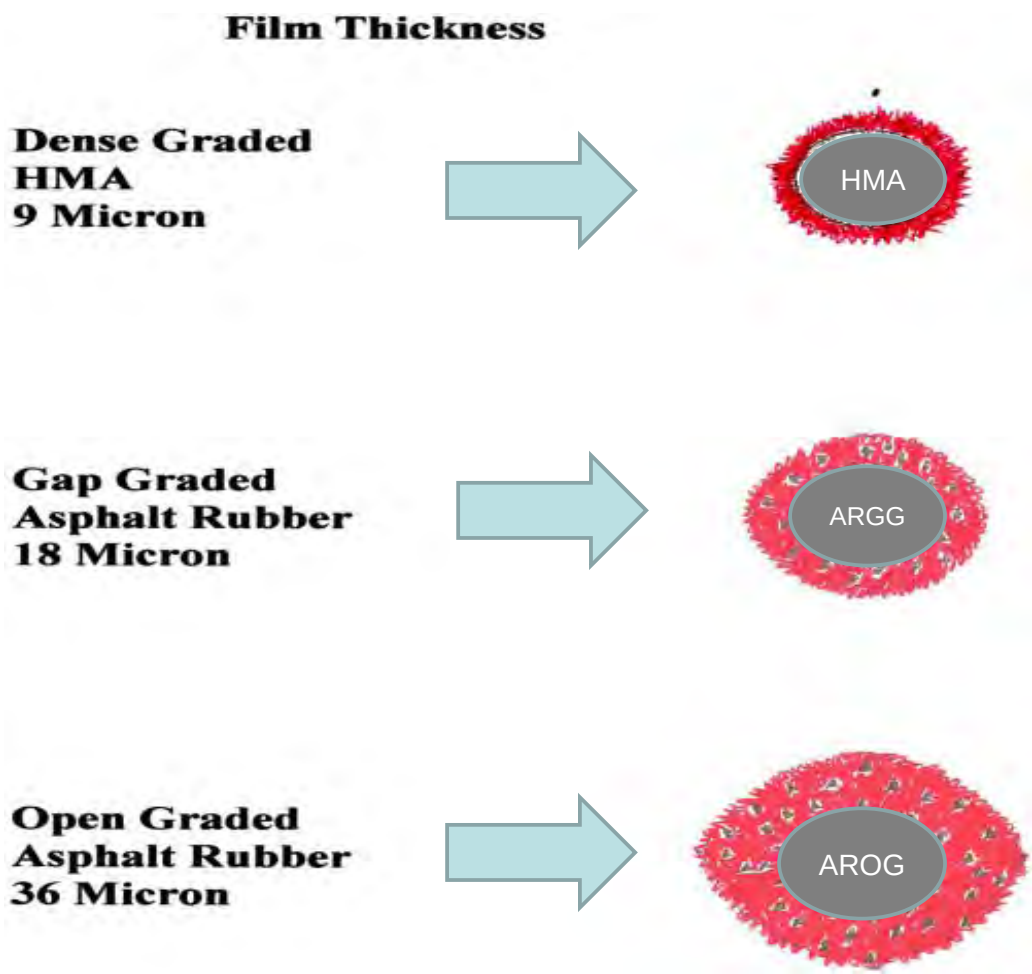



**Figure 23 -** *AR film thickness for various hot mixes*

## Asphalt and Asphalt Rubber Binder Characterization

Witczak et al. (maybe the MW initials of the author GD EDITS) experience with the application of conventional binder consistency tests to modified asphalt cements had shown that they can be rational and can be used as a general guide [Witczak, 1995]. Most refined asphalt cements, exhibit a linear relationship when plotted on a log-log viscosity (centipoise) versus log temperature (in degree Rankine: R = F + 459.7 F) scale [ASTM, D2493]. The approach uses only viscosity units (centipoise) to define the viscosity-temperature relationship. Figure 24 shows a comparison of a stiff conventional binder (PG 76-16) versus four different AR binders with crumb rubber at RTFO conditions. From this Figure it can be seen that the AR binders have the better viscosity-temperature susceptibility indicated by higher viscosities at high temperature, and lower (or unchanged) viscosities at lower temperatures.

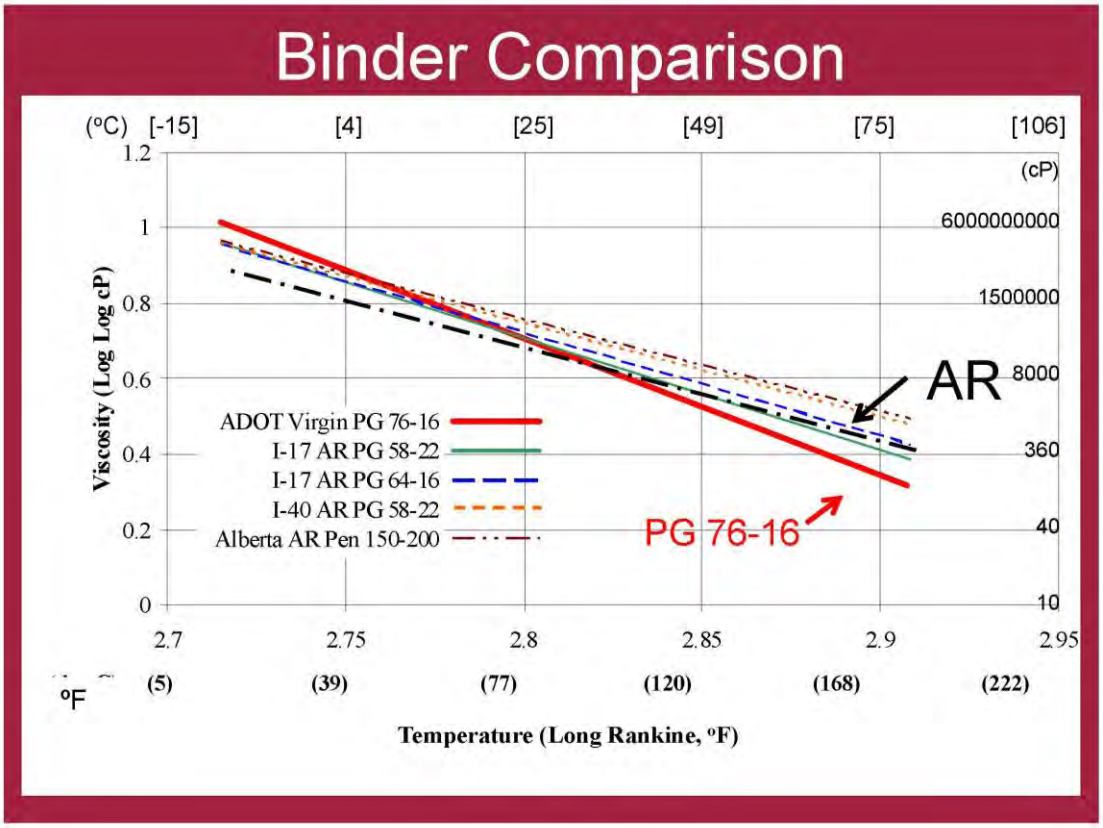



**Figure 24 -** *Viscosity-Temperature Susceptibility Comparison of Conventional and Crumb Rubber Modified Binders*

# Chapter 4 – Chip Seal Applications

In 1971, technology had developed to the point that standard asphalt distributor trucks were employed to apply a uniform thickness of binder to the pavement, Figure 25. Although problems with distribution and segregation of materials were encountered on the early projects, these were recognized as primarily equipment limitations. Within the next few years equipment was developed with pumping, metering and agitation capabilities needed to handle the highly viscous asphalt-rubber materials.

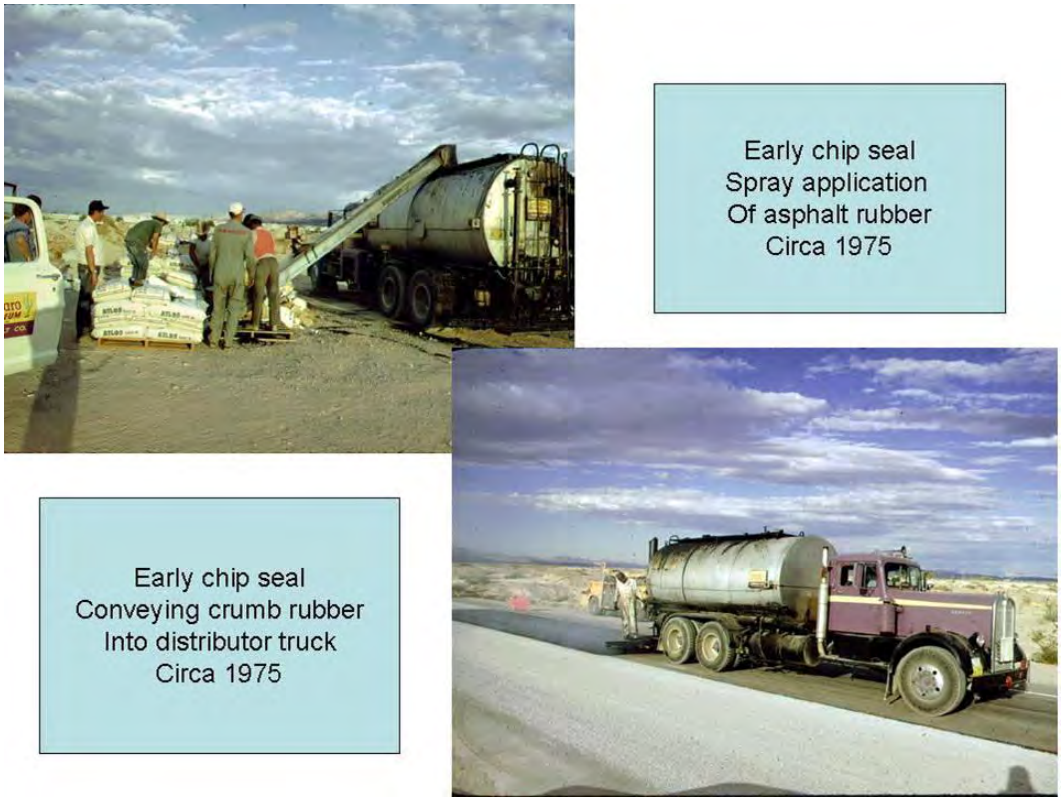



**Figure 25 -** *Crumb rubber chip seal*

Following the development of suitable equipment to spray apply asphalt-rubber Charles McDonald and his colleagues in the development of this material and others were granted various asphalt-rubber related patents in the 1970's. This group of patents was in general described as the McDonald Process or Wet Process for making asphalt-rubber (AR). It should be noted that AR patents generally ended in the early 1990's. As noted earlier the Arizona Department of Transportation (ADOT) monitored the development of AR and placed a band aid type maintenance application of AR in 1964. In 1968, experience from trial and error and the burning of a couple of distributor boot trucks lead to improvements in mixing to a satisfactory degree that AR could be safely and consistently placed with a distributor truck by using a diluent (kerosene). From 1968 - 1972, ADOT placed AR on six projects that were slated for reconstruction. The cracking on these projects was generally typical of a failed pavement needing at least a six inch overlay or complete reconstruction, Figure 26.

**Figure 26 -** *Asphalt-rubber chip seal applied to badly cracked pavement, circa 1972*

For these seal coat type application projects a boot truck distributor was used to apply the AR. In these early applications the ground tire rubber was introduced into the top of the boot truck and mixed by rocking the truck forward and backward. Even with this rather primitive early technology it was possible to construct the first full scale ADOT field experiment in 1972 using AR as a seal coat or Stress Absorbing Membrane (SAM), as well as an interlayer under a hot mix asphalt (HMA) surfacing. The interlayer application is typically referred to as a Stress Absorbing Membrane Interlayer (SAMI), Figure 27 and 28. Both the SAM and SAMI applications showed great promise in reducing reflective cracking [Way, 1979].

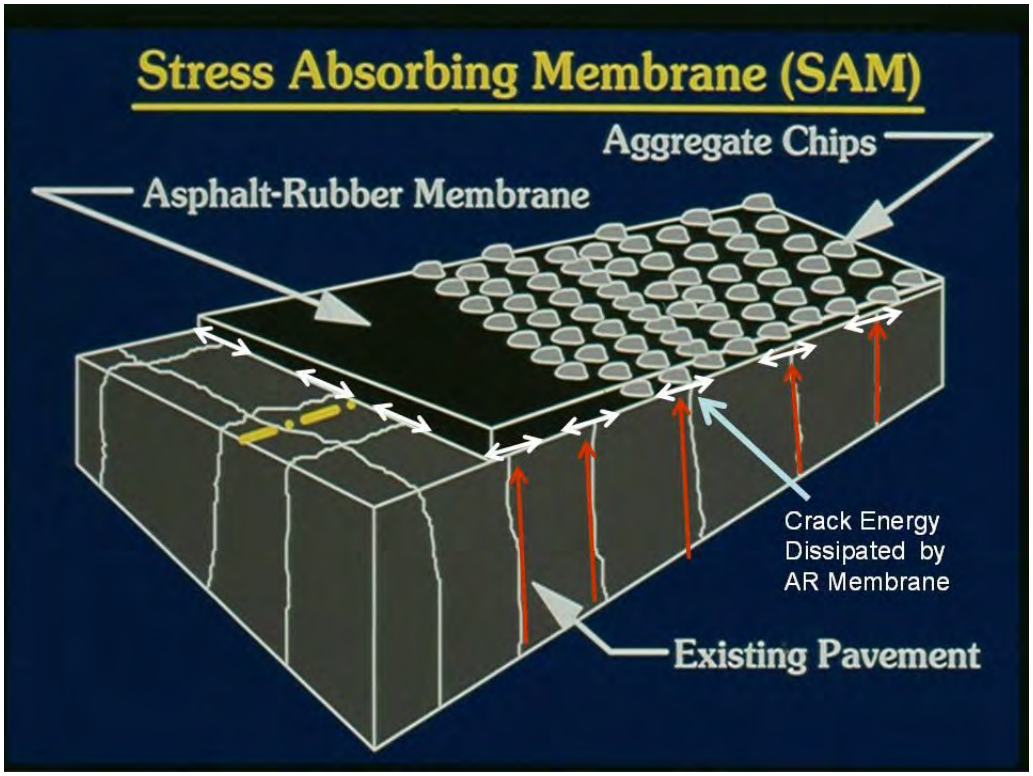



**Figure 27 -** *Asphalt-rubber Stress Absorbing Membrane (SAM)*

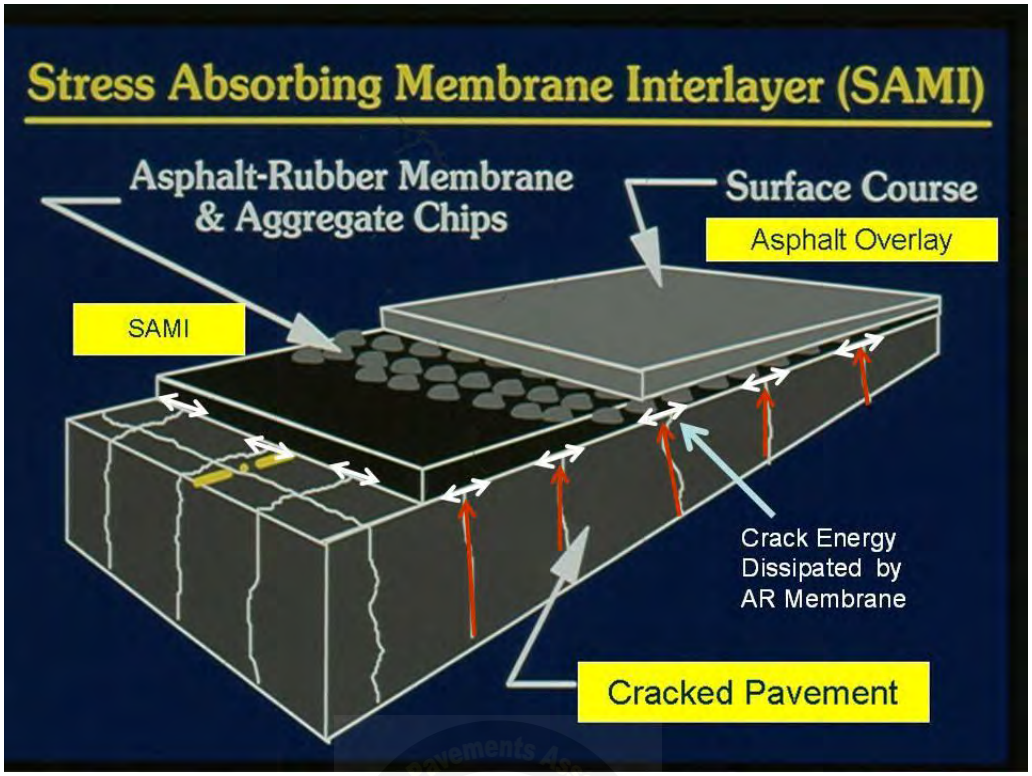



**Figure 28 -** *Asphalt-rubber Stress Absorbing Membrane Interlayer (SAMI)*

From 1974 until 1989, approximately 660 miles (1,100 km) of state highways were built using a SAM or SAMI application of AR. In addition to this, ADOT and the Federal Highway Administration (FHWA) sponsored numerous research studies, thus greatly increasing the state-of-the-knowledge concerning AR.

The chip seal application rate of AR binder can range from 0.50 – 0.70 gallons/ square yard (2.4-3.4 liters/square meter) depending upon many factors such as chip seal size, embedment, pavement porosity and traffic. The application rate of stone chips can vary from 20-30 pounds/square yard (11.0-16 kg per square meter). Oftentimes it is recommended that the aggregate be pre-coated with 0.5-1.0 percent asphalt. The FHWA recommended an AR SAM binder and aggregate design procedure which is shown in Appendix B, [Heitzman, 1992]. The SAM design procedure is further elaborated on in ASTM D 7564 [ASTM D 7564, 2009].

In addition to reducing reflective cracking, it was noted early on that AR is a waterproofing membrane. Several projects were built to control subgrade moisture in order to control expansive (swelling) clays or to reduce structural pavement sections. This application proved to be very successful [Forstie, 1979]. In 1989 ADOT documented in a research report the history, development, and performance of asphalt-rubber at ADOT [Scofield, 1989]. In that report the following conclusion is stated, "asphalt-rubber has successfully been used as an encapsulating membrane to control pavement distortion due to expansive soils and to reduce reflection cracking in overlays on both rigid and flexible pavements. During the twenty years of asphalt-rubber use, ADOT has evolved from using slurry applied asphalt-rubber chip seals to utilizing reacted asphalt-rubber as a binder in open and gap graded asphalt concrete." The report noted that AR could be used as a binder for HMA. Concurrent with this conclusion, it became evident that AR as a binder could provide a HMA mixes suitable for addressing cracked pavements.

# Chapter 5 – Hot Mix Asphalt Use and Design

In 1985 ADOT began experimenting with two asphalt-rubber mixes an asphalt-rubber open graded friction course (ARFC) and a gap graded asphalt-rubber asphaltic concrete (ARAC). ADOT had experienced cracking problems with its conventional dense graded mixes and raveling of its conventional open graded mixes, Figure 29 and 30.

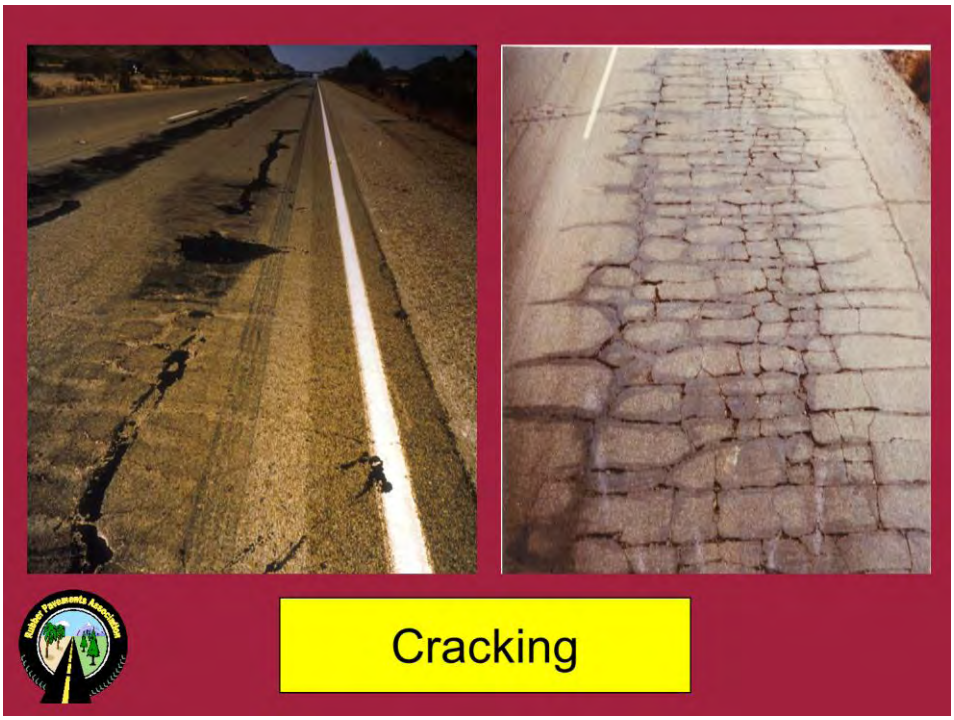



**Figure 29 -** *Cracked highway*


**Figure 30 -** *Raveled pavement*

Given the good results with AR as a chip seal coat material, ADOT thought that hot mix asphalt with AR binder could reduce cracking and resist raveling. In addition an AR mix needed to resist rutting, Figure 31.


**Figure 31 -** *Rutted pavement*

To fully utilize AR properties it was realized that the AR binder would provide greater film thickness due to the rubber particles in the AR. Thus the aggregate gradation was adjusted to have a high amount of voids in the mineral aggregate (VMA). The gap graded mix (ARAC) was developed by the City of Phoenix in Arizona in the early 1980's for use as a thin overlay 1 in. (25 mm) on city streets. ADOT later adopted the City of Phoenix gap gradation and Figure 32 shows the ARAC gradation and selected mix properties compared to a typical Marshall dense graded HMA. As can be seen the ARAC mix has a much higher VMA than a normal dense graded HMA mix and much higher binder content. Table 6 shows more detailed ARAC mix properties. Appendix C is an overview of the ARAC mix design. Appendix D shows a much more detailed ARAC volumetric Marshall mix design procedure. Appendix E shows an example of a Marshall mix design report and asphalt rubber binder design.

**Table 6 -** *ARAC Mix Design Properties*

| Sieve Size | | Average % Pass/%Retained |
|---|---|---|
| Metric | US Customary | |
| 25 mm | 1 inch | 100/0 |
| 19 mm | 3/4 inch | 100/0 |
| 12.5 mm | 1/2 inch | 88/12 |
| 9.5 mm | 3/8 inch | 73/15 |
| 6.4 mm | 1/4 inch | 53/20 |
| 4.75 mm | #4 | 35/18 |
| 2.36 mm | #8 | 20/15 |
| 2 mm | #10 | 19/ |
| 1.18 mm | #16 | 15/5 |
| 0.6 mm | #30 | 10/5 |
| 0.4 mm | #40 | 7/4 |
| 0.3 mm | #50 | 6/2 |
| 0.15 mm | #100 | 4/2 |
| 75 micron | #200 | 2 |

| HMA Properties | |
|---|---|
| Asphalt Content by Wt. of Mix | 7.30% |
| Bulk Specific Gravity | 2.271 |
| Theoretical Max. Specific Gravity | 2.396 |

| Volumetrics | |
|---|---|
| VMA | 20% |
| Air Voids | 5.20% |
| Volume of Asphalt | 14.80% |
| Volume of Aggregate | 80.00% |

| Aggregate Properties | Average |
|---|---|
| Sand Equivalent | 85 |
| Water Absorption | 1.60% |
| Asphalt Absorption | 0.50% |
| Oven Dry Specific Gravity | 2.642 |

| Strength Properties | Average |
|---|---|
| Marshall Stability | 9.9 kN; 2195 lb |
| Marshall Flow | 3.25 mm; 13 |

| Immersion Compression | Average |
|---|---|
| Dry Strength | No Test |
| Wet Strength | No Test |
| Wet Strength w/ Cement | No Test |

| Miscellaneous | Average |
|---|---|
| Film Thickness | 27 microns |

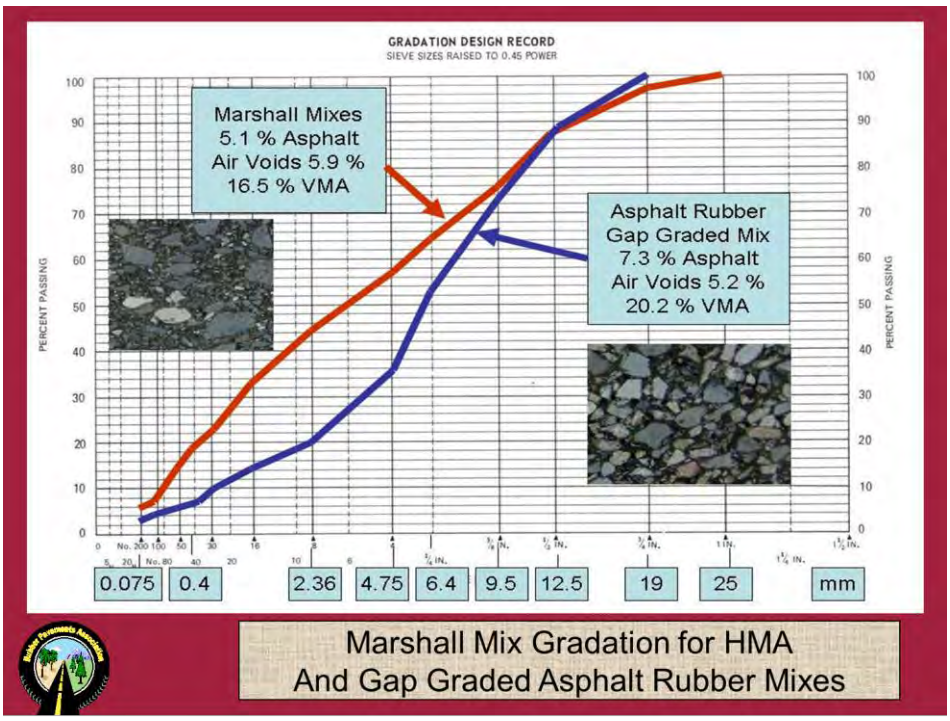



**Figure 32 -** *Marshall Mix HMA and ARAC gradations*

In addition to the AR gap graded mix the ADOT developed an open graded AR mix and began to use it in the late 1980's. The ADOT began to use Open Graded Friction Courses (OGFC) with conventional asphalt as early as 1954 [Morris, 1973]. The primary reason for using this mix was to provide a surface with good skid resistance, good ride and appearance. However, open graded mixes with unmodified asphalt oftentimes would crack and ravel prematurely. Nevertheless, open graded mixes with unmodified asphalt binder were used by the ADOT from 1950's into the late 1980's. Starting in 1988 ADOT constructed its first AR open graded friction mix (ARFC) as a 1 in. (25 mm) overlay on top of an older concrete pavement Interstate 19 just south of Tucson, Figure 33. This ARFC mix contained 10.0 percent asphalt-rubber by weight of the mix as the binder was placed on top of a plain jointed concrete pavement. Since 1988, no cracks reflected through until 1996, when only a few transverse cracks appeared over the concrete joints. In 2004 District Maintenance reviewed this project and concluded that as before no maintenance was needed and amazingly for the sixteen year period no maintenance was performed on this section, Figure 34.

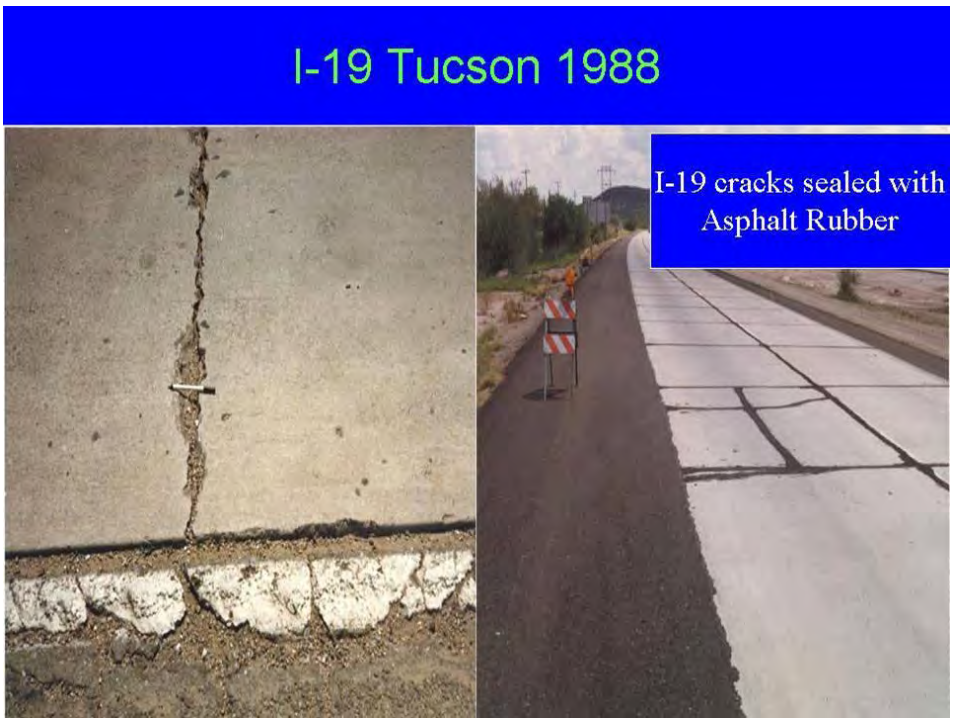



**Figure 33 -** *I-19 Concrete pavement before ARFC overlay*


**Figure 34 -** *ARFC overlay on I-19 after 16 years of service*

From 1988 to the present ADOT has constructed thousands of lane kilometers (lane miles) of ARFC final wearing surfaces. Figure 35 shows the ARFC gradation and selected mix properties compared to a typical open graded HMA. As can be seen the ARFC mix has about the same VMA but much higher binder content. Table 7 shows more detailed ARFC mix properties. Appendix F is an overview of the ARFC mix design. Appendix G is an ARFC mix design report. A more detailed mix design procedure can be found in ASTM Standard D 7064 Standard Practice for Open-Graded Friction Course (OGFC) Mix Design [ASTM7064, 2009].

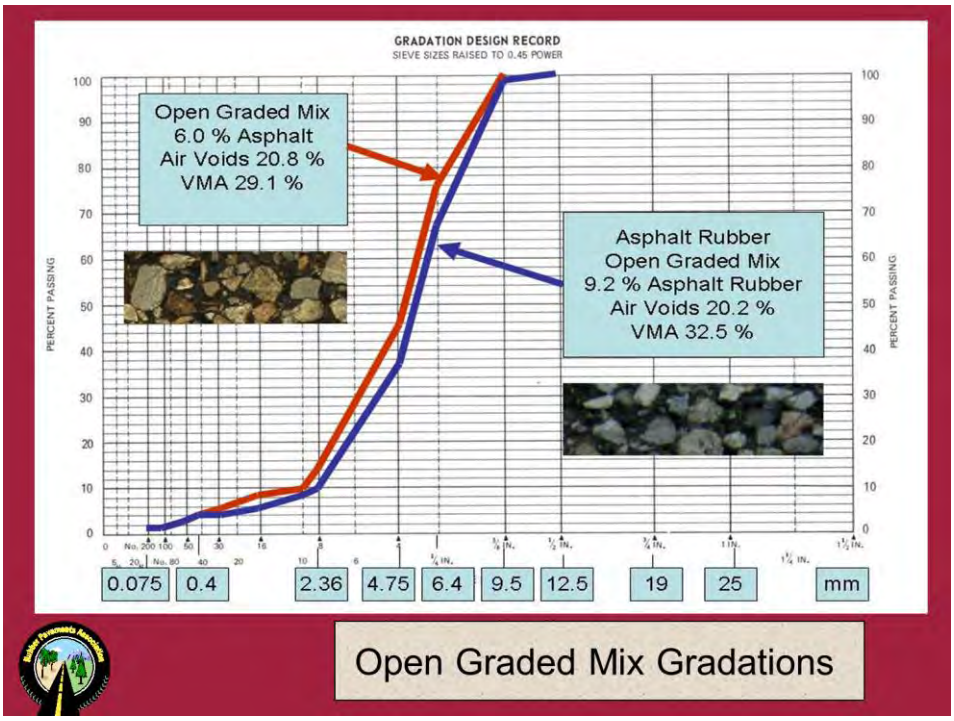



**Figure 35 -** *Open Graded Mix and ARFC gradations*

**Table 7 -** *ARFC mix properties*

| Sieve Size | | Average % Passing/Retained |
|---|---|---|
| Metric | US Customary | |
| 25 mm | 1 inch | 100 |
| 19 mm | 3/4 inch | 100 |
| 12.5 mm | 1/2 inch | 99 |
| 9.5 mm | 3/8 inch | 99 |
| 6.4 mm | 1/4 inch | 68/32 |
| 4.75 mm | #4 | 37/31 |
| 2.36 mm | #8 | 19/18 |
| 2 mm | #10 | 10/9 |
| 1.18 mm | #16 | 6/4 |
| 0.6 mm | #30 | 4 |
| 0.4 mm | #40 | 4/2 |
| 0.3 mm | #50 | 3/1 |
| 0.15 mm | #100 | 2/1 |
| 75 micron | #200 | 2 |

| Aggregate Properties | Average |
|---|---|
| Sand Equivalent | 85 |
| Water Absorption | 1.50% |
| Asphalt Absorption | 0.60% |
| Oven Dry Specific Gravity | 2.642 |

| Strength Properties | Average |
|---|---|
| Marshall Stability | No Test |
| Marshall Flow | No Test |

| Immersion Compression | Average |
|---|---|
| Dry Strength | No Test |
| Wet Strength | No Test |
| Wet Strength w/ Cement | No Test |

| HMA Properties | |
|---|---|
| Asphalt Content by Wt. of Mix | 9.20% |
| Bulk Specific Gravity | 1.981 |
| Theoretical Max. Specific Gravity | 2.456 |

| Volumetrics | |
|---|---|
| VMA | 33% |
| Air Voids | 20.20% |
| Volume of Asphalt | 23.80% |
| Volume of Aggregate | 56.00% |

| Miscellaneous | Average |
|---|---|
| Film Thickness | 65 microns |

# Chapter 6 – Thickness Design and Structural Analysis

AR Chip Seals are generally used for maintenance or preservation and thus thickness design is not an issue. ARFC's are typically placed as the final wearing course on major highways with no stop and go intersections or turnout driveways. They are placed on either flexible asphalt or rigid concrete pavements. When placed on top of flexible asphalt pavements they are typically placed 0.5 inch (12.5 mm) thick. When placed on top of rigid concrete pavements they are typically placed 1.0 inch (25 mm) thick.

Caltrans developed a thickness design procedure for ARAC (RAC-GG) based upon deflection testing research and test section performance [Caltrans, 1992]. Additional research conducted with the heavy vehicle simulator further confirmed the overlay thickness reduction due to the use of an ARAC type mix [Shatnawi, 2000]. This Caltrans thickness design method typically indicates that ARAC mixes can be placed at approximately half the thickness of a design graded HMA overlay. Table 8 shows a Caltrans example of the relative thickness tradeoffs between ARAC (RAC Type G) and HMA (DGAC) mixes. In addition Caltrans also considers the influence of reflective cracking in overlay thickness as shown in Table 9.

**Table 8 -** *Structural Equivalencies for RAC Type G, Thickness (ft)*

| DGAC | RAC Type G | RAC Type G on SAMI-R |
|---|---|---|
| 0.15 | 0.10 | - |
| 0.20 | 0.10 | - |
| 0.25 | 0.15 | 0.10 |
| 0.30 | 0.15 | 0.10 |
| 0.35 | 0.20 | 0.15 |
| 0.40 | 0.20 | 0.15 |
| 0.45 | 0.15 (1) | 0.20 |
| 0.50 | 0.15 (2) | 0.20 |
| 0.55 | 0.20 (1) | 0.15 (3) (5) |
| 0.60 | 0.20 (2) | 0.15 (4) (5) |

NOTES:

(1) Place 0.15 ft (45 mm) of new DGAC then place the RAC Type G. (See Note 5.)
(2) Place 0.20 ft (60 mm) of new DGAC then place the RAC Type G. (See Note 5.)
(3) Place 0.15 ft (45 mm) of new DGAC; a SAMI-R; then 0.15 ft (45 mm) of RAC Type G.
(4) Place 0.20 ft (60 mm) of new DGAC; a SAMI-R; then 0.15 ft (45 mm) of RAC Type G.
(5) If the existing surface is open graded asphalt concrete, it has to be milled off prior to placing the new DGAC. Therefore, a new calculation should be completed to determine the correct thickness to be placed after the reduction of the structural section by the milling procedure.

**Table 9** - *Reflection Crack Retardation Equivalencies, Thickness (ft)*

| DGAC | RAC Type G | RAC Type G on SAMI-R |
|---|---|---|
| 0.15 | 0.10 | - |
| 0.20 | 0.10 | - |
| 0.25 | 0.15 | - |
| 0.30 | 0.15 | - |
| 0.35 [(a)] | 0.15 or 0.20 [(b)] | 0.10 [(c)] |

NOTES:

(a) A DGAC thickness of 0.35 ft (105 mm) is usually the maximum thickness recommended by Caltrans for reflection crack retardation on AC pavements.

(b) Use 0.15 ft (45 mm) only if the crack width is <1/8 inch (3 mm). Use 0.20 ft (60 mm) if the crack width is = 1/8 inch (3 mm) or if the underlying material is a CTB, LCB, or PCC.

(c) Use 0.10 ft (30 mm) if the crack width is = 1/8 inch (3 mm) and the underlying base is an untreated material. Use 0.15 ft (45 mm) if the crack width is = 1/8 inch (3 mm) and the underlying base is a CTB, LCB, or PCC. Do not use a SAMI-R if the crack width is <1/8 inch (3 mm).

Sousa also developed an AR overlay method to reduce reflective cracking based upon pavement deflection and finite element analysis [Sousa, 2003]. The method relied upon Falling Weight Deflection data, the pavement cracking condition, traffic loading and environmental climate. The resultant computational methodology is compiled into an Excel spreadsheet. An example calculation is shown in Figure 36. Typically the procedure developed by Sousa also showed an approximate one half thickness relationship.

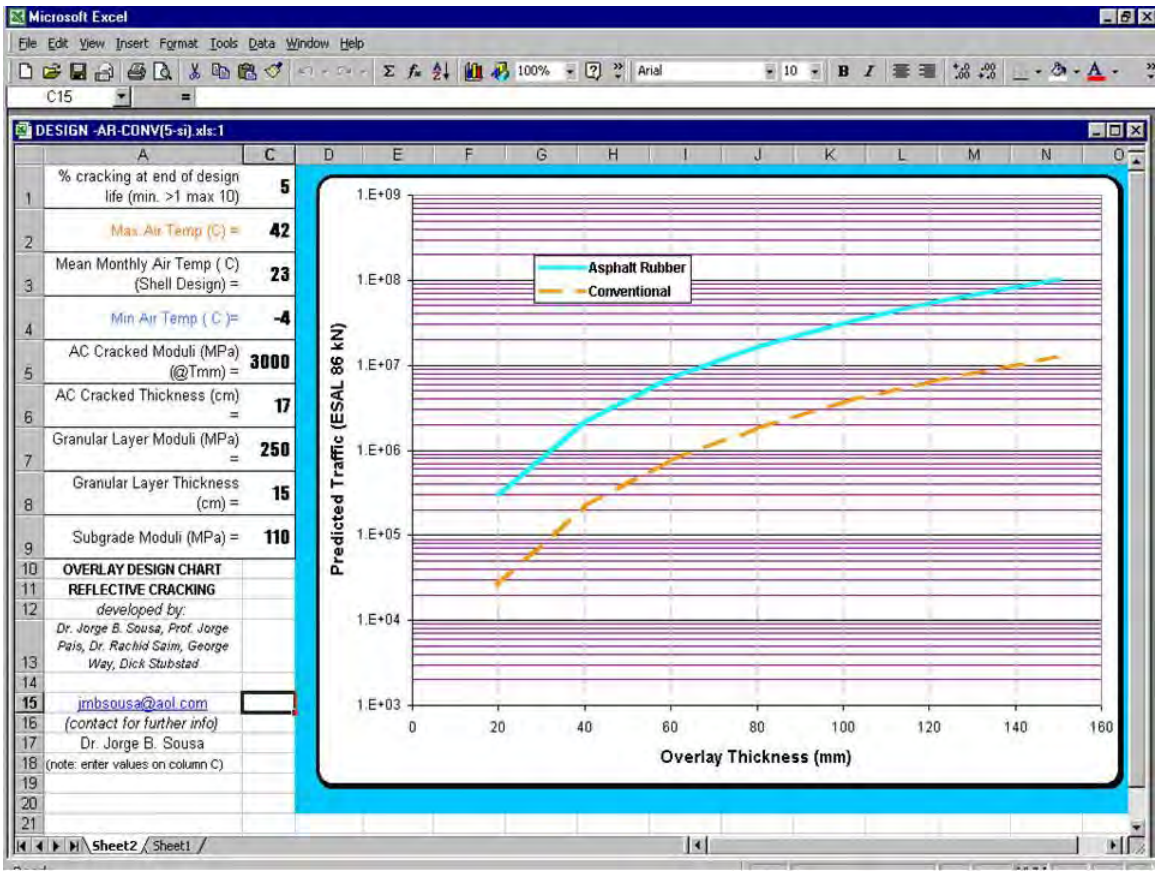



**Figure 36** – *Reflective Cracking Overlay Thickness Design with and without asphalt-rubber*

## Mechanistic- Empirical Pavement Design Guide (MEPDG)

Example MEPDG pavement designs and analysis have been conducted at Arizona State University (ASU) with asphalt-rubber binder and asphalt-rubber gap graded and open graded mixes. Kaloush et al and staff at ASU have conducted numerous studies involving the inclusion of asphalt-rubber binder and mixes into the MEPDG [Kaloush, 2003], [Kaloush, 2004], [Zborowski, 2006], [Way, 2009], [Rodezno, 2009] and [Zborowski, 2009]. The MEPDG was developed in a manner reflecting the use of dense graded mixes and typical PG graded asphalts, thus additional research was needed to determine how to include AR binder and mixes into the MEPDG. It is beyond the scope of this practice guide to review this large body of work, however, portions of this large body of pavement design and analysis research deserves some mention, albeit readers are encouraged to review the reports for more detailed information concerning the use of AR binder and AR mixes in the MEPDG program. The following is a summary of some of the reported findings concerning asphalt-rubber properties obtained for input into the MEDPG program:

## Binder Properties

From the binder test results and the A VTS parameters obtained, it is concluded that all the AR binders had improved viscosity-temperature susceptibility. The crumb rubber modification generally bumps up the Performance Grade for the binder by at least one level, both at high and lower temperature ranges, Figure 37. For example Table 10 is derived from a paper presented in South

Africa (Kaloush, 2011). As the paper showed how the A VTS values for unmodified asphalt PG grades PG 58-22 and PG 64-16 changed after blending with scrap tire rubber to make AR. the A VTS values become equivalent to PG 70-40 and PG 76-34 as indicated in the MEPDG cross over table for levels 2 and 3. This method allows a means to use AR binder in the MEPDG until such time as a test is developed to determine the DSR PG grade according to SHRP.

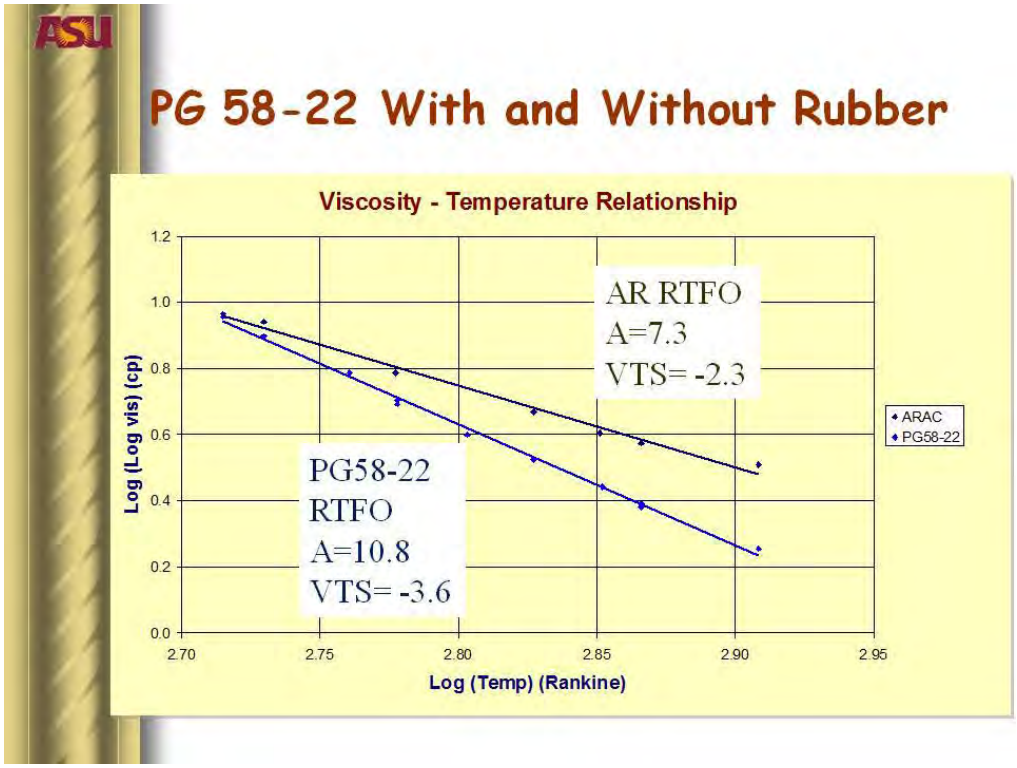



**Figure 37** – *MEPDG Binder A, VTS Properties for Asphalt and Asphalt-Rubber*

**Table 10** – *Equivalent AR PG grades by using the A VTS values*

| Binder Type | Original | Original | RTFO | RTFO |
|---|---|---|---|---|
| | A | VTS | A | VTS |
| **PG 58-22 base asphalt** | **11.164** | **-3.764** | **11.076** | **-3.722** |
| **PG 58-22 after rubber added (AR)** | **8.3595** | **-2.726** | **8.0475** | **-2.598** |
| **AR binder equivalent A VTS like a PG 70-40** | **8.129** | **-2.648** | **8.129** | **-2.648** |
| | | | | |
| **PG 64-16 base asphalt** | **11.163** | **-3.755** | **11.116** | **-3.728** |
| **PG 64-16 after rubber added (AR)** | **8.39** | **-2.738** | **8.543** | **-2.781** |
| **AR binder equivalent A VTS like a PG 76-34** | **8.532** | **-2.785** | **8.532** | **-2.785** |

## Dynamic Modulus

From the analysis of the test results of unconfined Dynamic Modulus tests, it is observed that conventional mixes have higher moduli than ARAC and ARFC mixes. The ARAC mixes also have higher moduli than the ARFC mixes.

From the confined Dynamic Modulus test results, especially at higher temperatures 100 and 130 °F (40 and 55 °C), the ARAC mixes test results show equal or better moduli values than the conventional mixes.

The effect of confinement on moduli values is more pronounced for asphalt rubber mixtures compared to the conventional ones Figures 38-40.

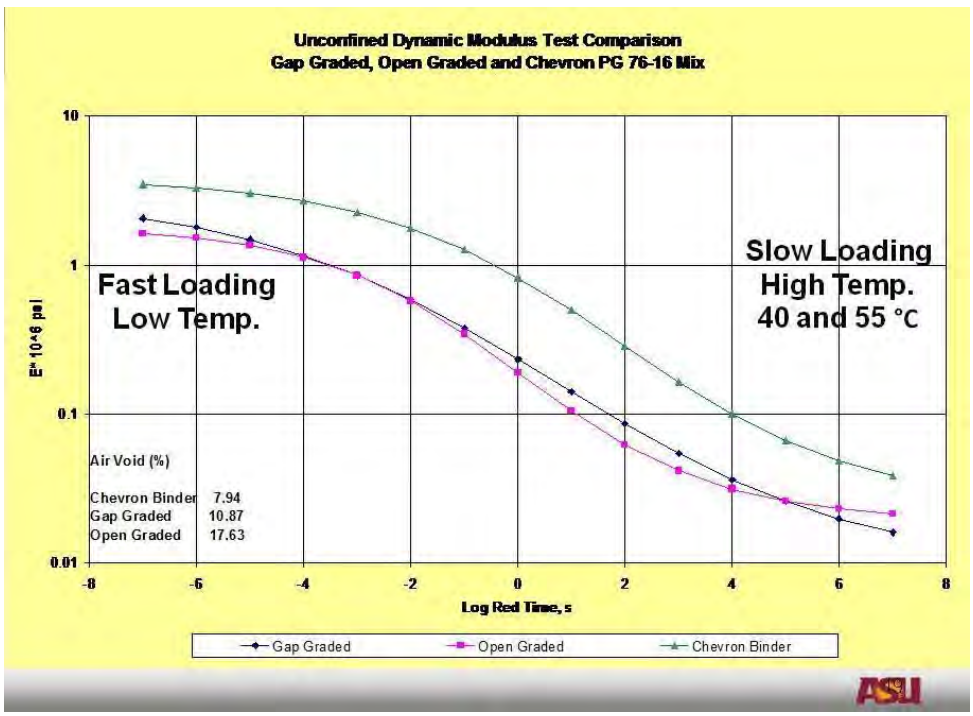



**Figure 38** – *Unconfined Dynamic Modulus with and without asphalt-rubber*

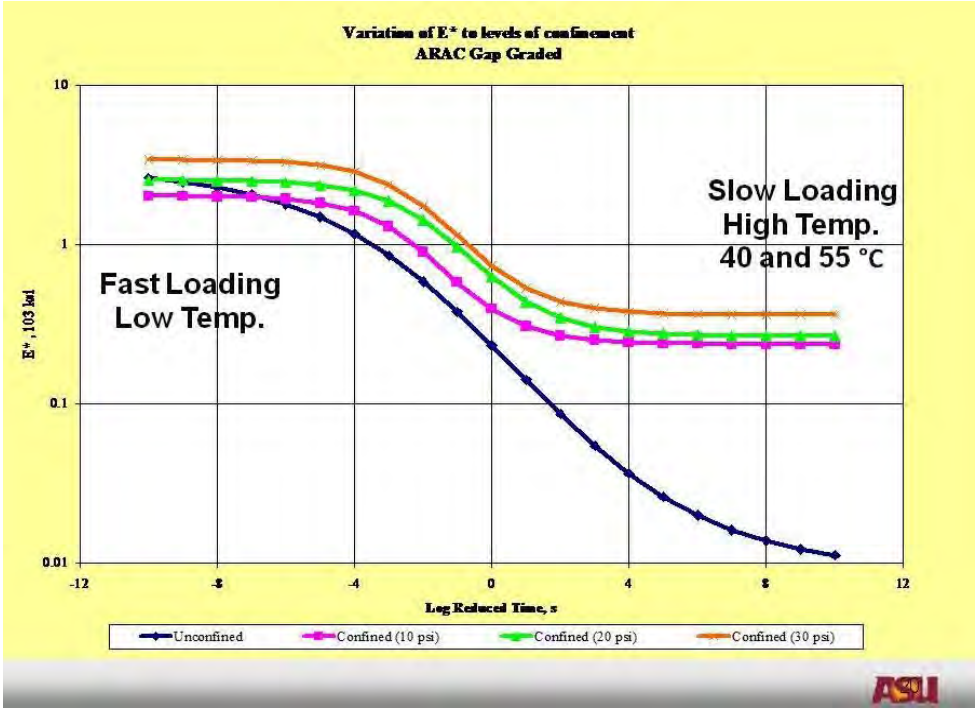



**Figure 39** – *Unconfined and Confined Dynamic Modulus Gap Graded Asphalt-Rubber*

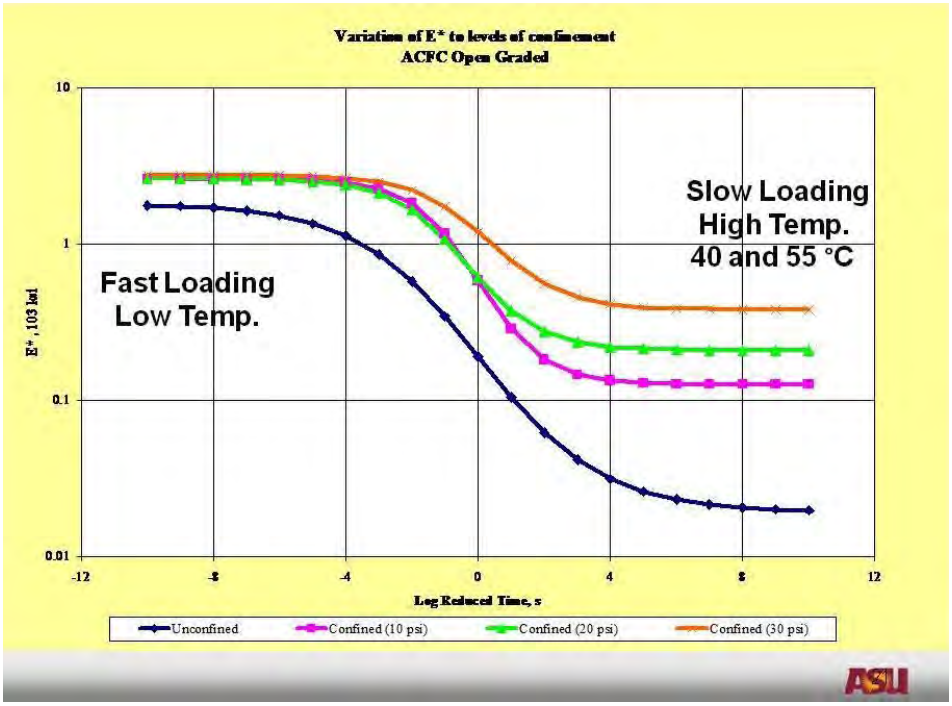



**Figure 40** – *Unconfined and Confined Dynamic Modulus Open Graded Asphalt-Rubber*

Additional MEPDG related research conducted by ASU also demonstrates asphalt rubber mixes improved mechanical structural properties such as fracture energy area under the curve and rate of crack propagation, Figure 41 and 42.

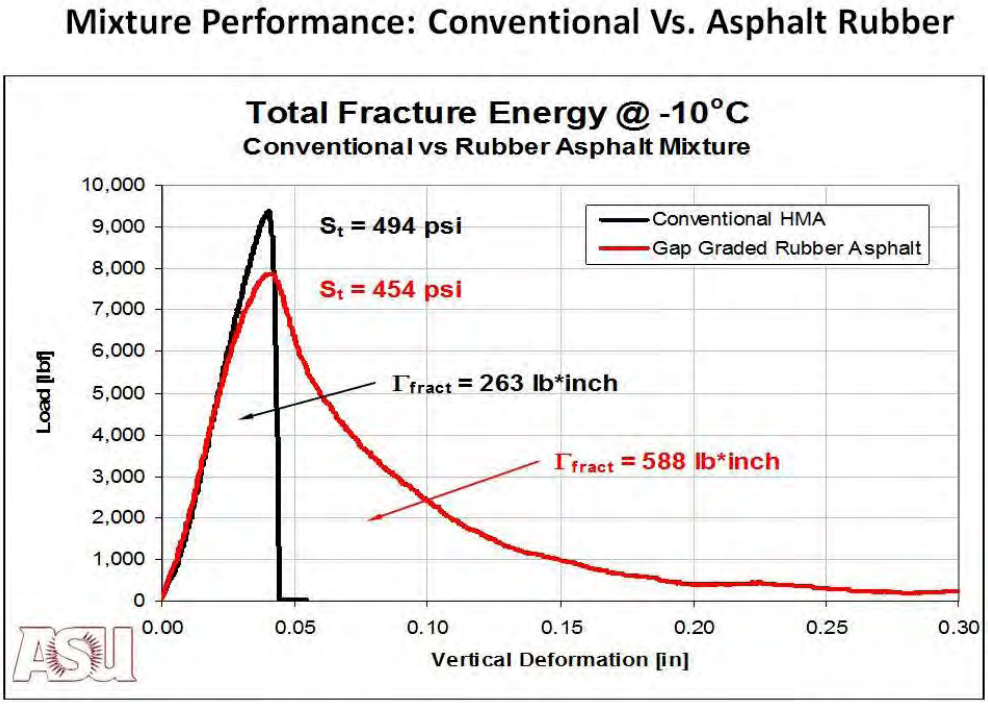



**Figure 41** – *Fracture Energy Conventional and Gap Graded Asphalt-Rubber*

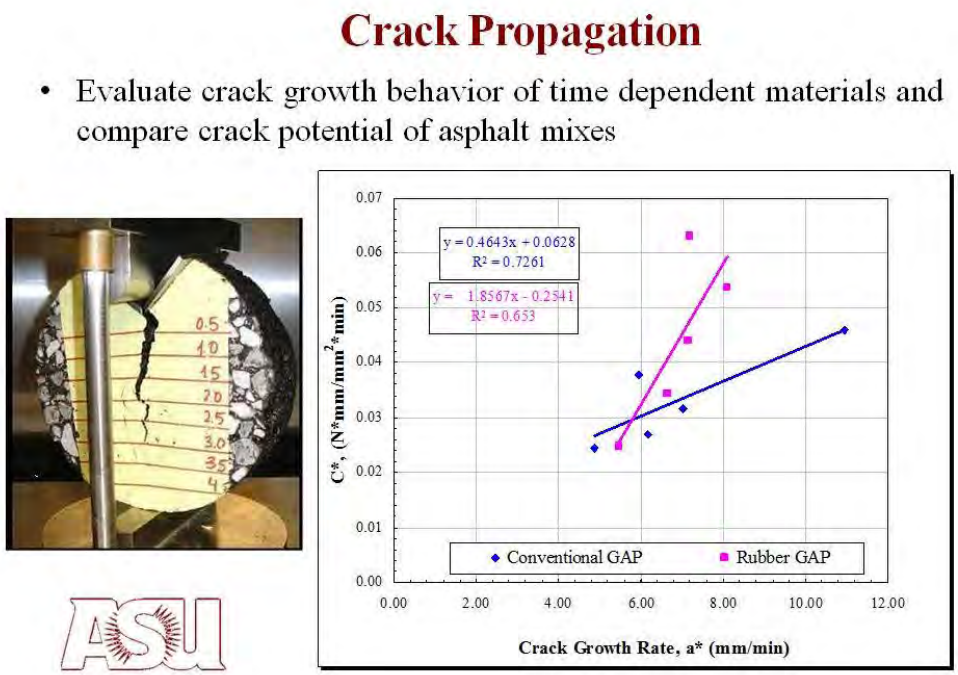



**Figure 42** – *Crack Propagation Gap Graded with and without Asphalt-Rubber*

# Chapter 7 – Construction

The construction of an AR pavement involves mixing the crumb rubber with the hot asphalt as required by specification. A super sack of bagged ground tire rubber is added to the hot base asphalt via a weigh hopper at a metered rate of typically 20 percent by weight of the asphalt cement, Figures 43 and 44. After high speed mixing the resultant batch of reacted asphalt-rubber is heated to a temperature of from 325°F to 375°F (160°C to 190°C) and agitated mixing continues in a blend tank for 45 minutes to one hour, Figures 45 and 46.

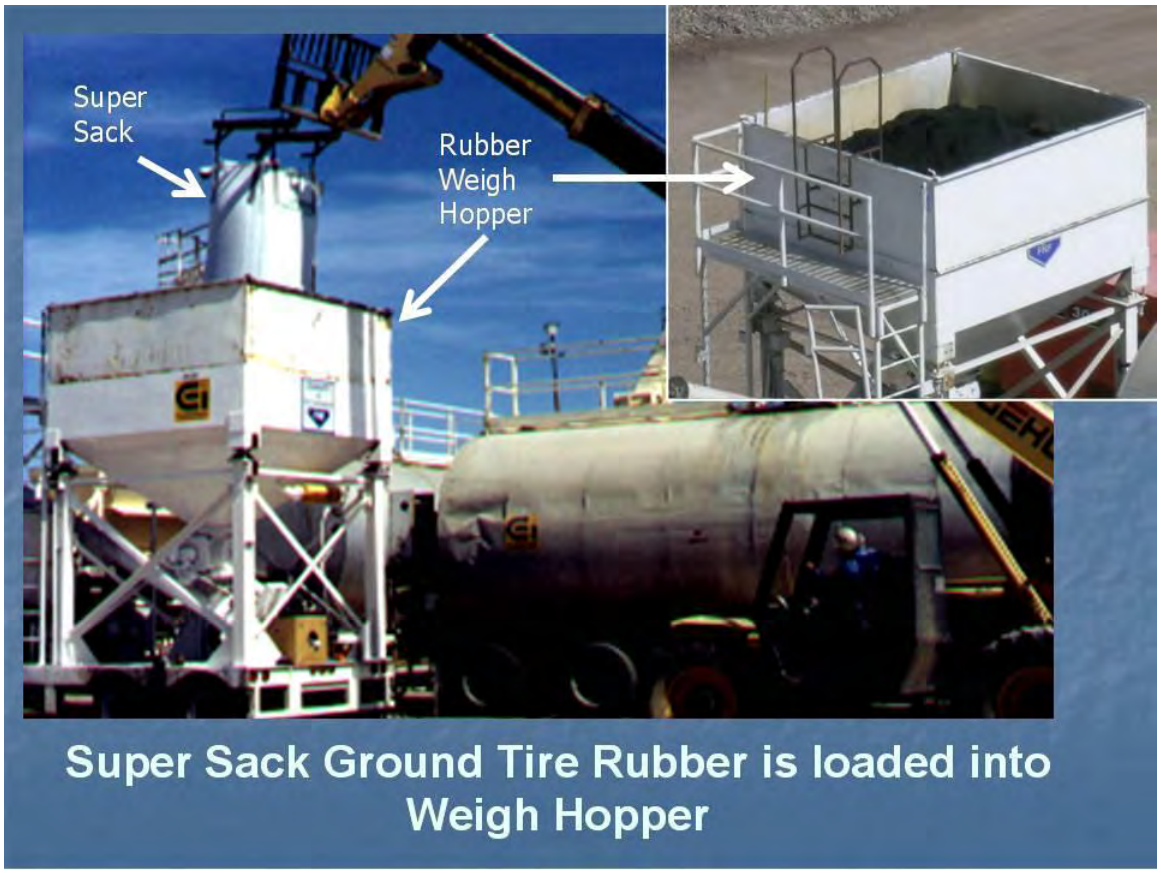



**Figure 43** – *Loading Ground Tire Rubber into Weigh Hopper*

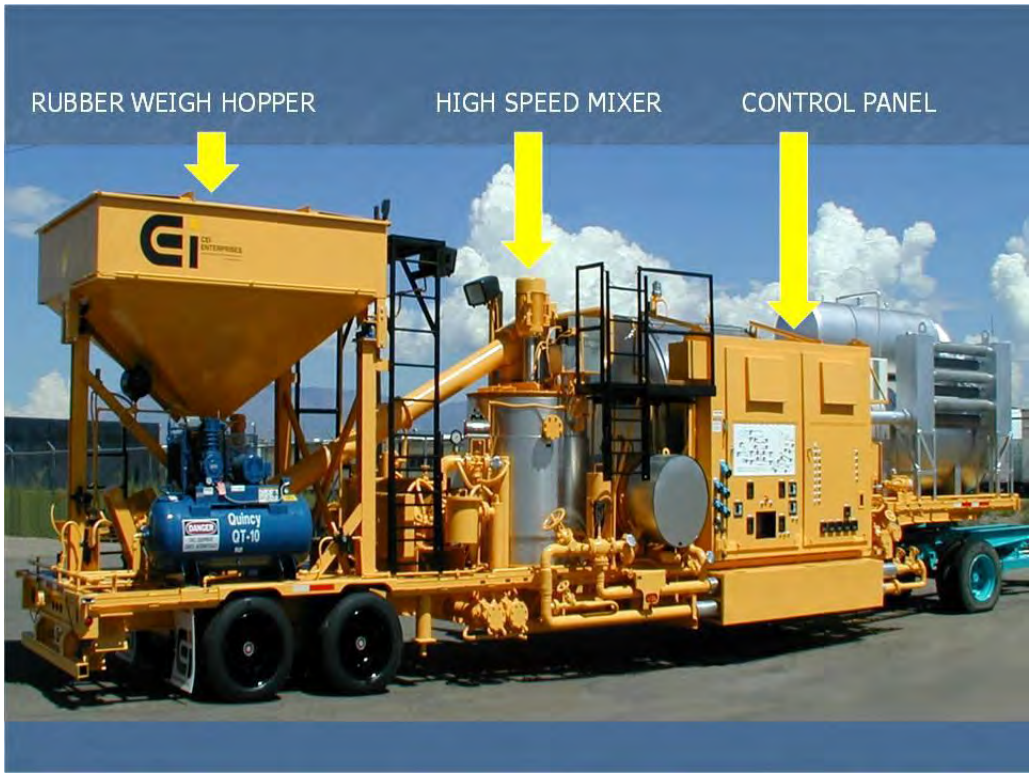



**Figure 44** – *Example Ground Tire Rubber and Asphalt Blender Unit*

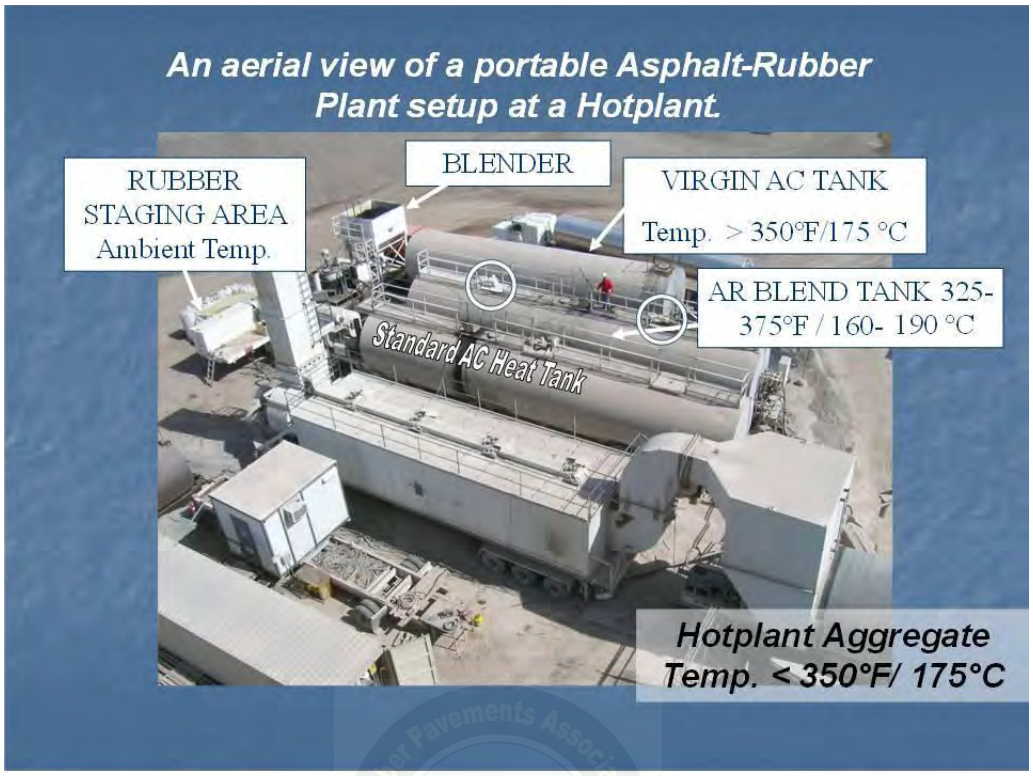



**Figure 45** – *Example Asphalt Blender Unit Setup*

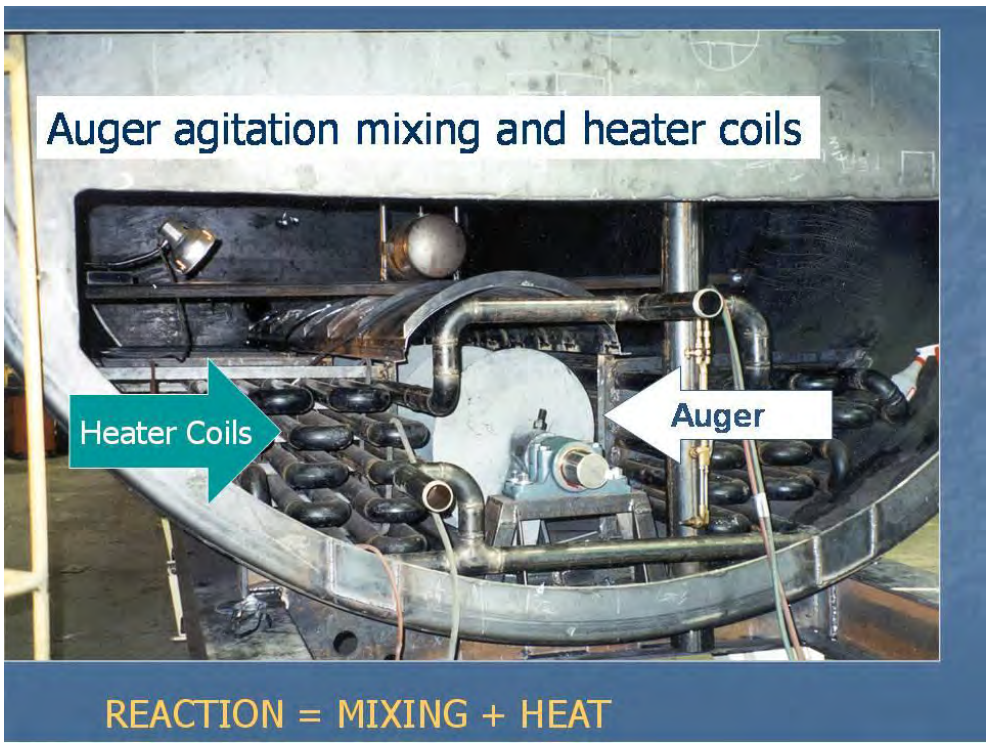



**Figure 46** – *Example Blend Tank with Heat and Agitation*

After a high speed mixing the AR binder is kept at a temperature of about 350°F (175°C) in the blend tank until it is introduced into the mixing plant. AR is a rather unique liquid and thus some additional special pumping and flow measuring equipment is usually employed. Pumping and metering the proper amount of volume (weight) of such a high viscosity material as AR is somewhat difficult. Currently many equipment users are employing a novel pump with special heat tracing, relief valve and helical gear [Hill, 2011]; and a special mass flow meter [Motion, 2011], Figure 47 and 48. Samples of the rubber, base asphalt, and AR mixture are taken and tested accordingly as noted in Chapter 3. The AR hot mix, which typically has one percent lime added, is placed with a conventional laydown machine and immediately rolled with a steel wheel roller, Figure 49 and 50. Only steel wheel rollers are used and rubber tire rollers should not be used. Lime water is used on rare occasions (high temperatures) to reduce pickup from tires. Generally one bag of lime is added to a water truck and sprayed on the pavement.

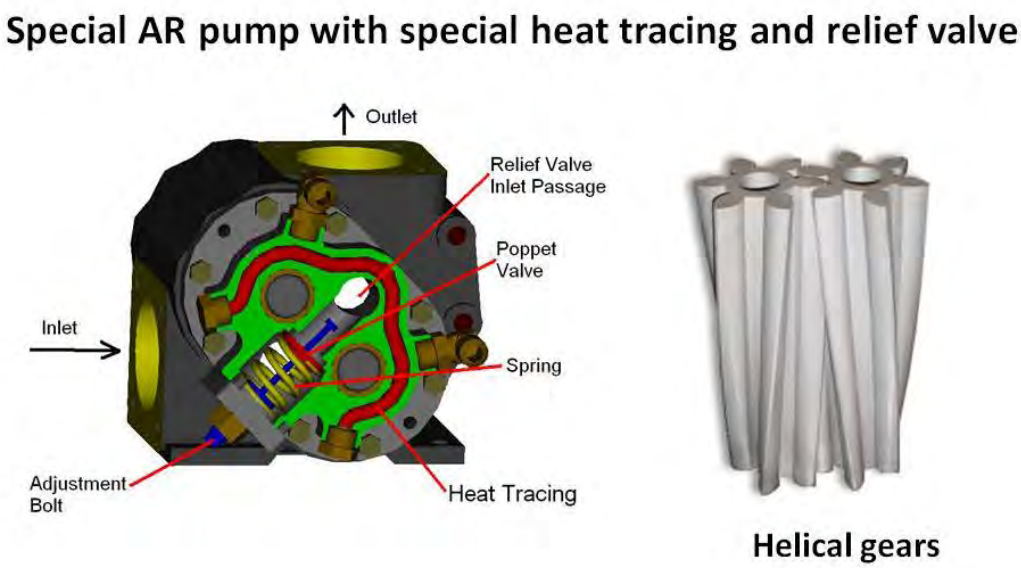



**Figure 47** – *Unique AR Helical Pump*

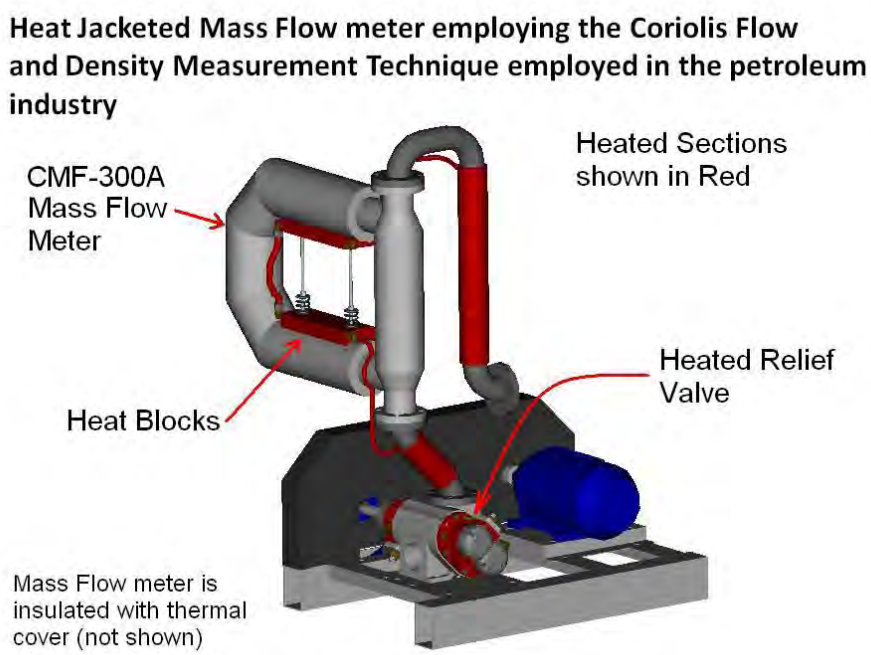



**Figure 48** – *Mass Flow Meter [Motion, 2011]*


**Figure 49** – *Example ARAC Paving with Conventional Equipment*

**Figure 50** – *Example ARFC Construction on Top of Concrete*

ARFC is generally used as the final wearing surface for both concrete and HMA pavements. For concrete pavements the joints are cleaned and resealed with AR. Spalled areas are cleaned and filled with HMA to level the surface. A one inch (25 mm) ARFC is placed to improve the smoothness, reduce reflective cracking, improve skid resistance, and reduce noise, Figure 51.

**Figure 51** – *One inch* (*25 mm) ARFC on top of concrete pavement*

If the concrete is in poor condition and the roadway geometrics allow, a leveling and strengthening course of ARAC is placed 2 inches (50 mm) thick before the ARFC is placed. For HMA pavements a standard deflection based design is conducted to correct structural deficiencies. The ARFC is used as the final wearing surface. It is placed 0.5 in. (12.5 mm) thick and is used to improve smoothness, reduce cracking, provide adequate skid resistance, and reduce noise. On some badly cracked pavements a gap-graded ARAC, generally 1.5 inches (37.5 mm) to 2 inches (50 mm) thick, is placed to address cracking, Figure 52. ASTM 6932 provides a guide for the construction of ARFC.

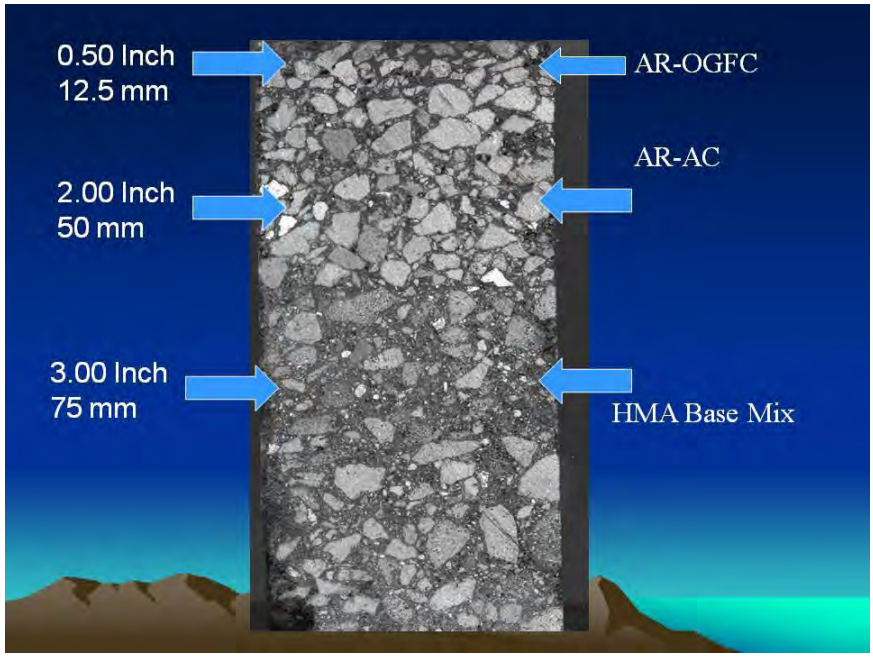



**Figure 52** – *Cross section of a pavement core with all three layers of mix*

## Asphalt-rubber Warm Mix

Warm Mix Asphalt (WMA) is a very recent technology that allows a reduction in the traditional asphalt mix production and paving temperatures. In general there are four different WMA categories; organic additives for the reduction in asphalt viscosity, chemical additives for the reduction in asphalt viscosity, chemical foaming processes and foaming caused by water injection. Presently, in the US there are over 20 proprietary WMA products/processes being marketed. WMA has become popular because of numerous benefits including: savings in energy, expanded paving season, longer haul distances, improved workability at lower temperatures and less emissions (fumes/odors), Figure 53. Many states have begun to use WMA primarily for dense graded mixes. Both California and Texas have used WMA for gap graded AR mixes. California has also tried WMA with open graded asphalt-rubber mixes. The use of AR-WMA is very new so it is not possible to be able to recommend a standard AR-WMA technology at this time. What is known is that AR-WMA can provide the listed benefits. As an example, Figure 54 shows the results of a California special study of gap graded AR-WMA [Van Kirk, 2009]. The gap graded AR-WMA was mixed in either a double barrel green system, a multi nozzle device that creates a foamed AR asphalt binder, or an Evotherm, MeadWestvaco, emulsion process. Figure 54 shows that plant mix temperature reductions were 35 – 55°F (20 – 30°C) with a gap graded AR-WMA. Results from a comprehensive 2010 study of AR-WMA conducted in California [Hicks, 2010] suggested the following conclusions:

- Warm mix technologies can be used with asphalt rubber mixes. They allow the mixes to be placed at night and in cooler climates.

- Warm mix technologies can increase the workability of asphalt rubber mixes. It extends the paving season and allows its use where asphalt rubber could not be used before.

- Warm mix technologies can improve workers' working conditions. It reduces undesired asphalt rubber odor and blue smoke coming with regular asphalt rubber job.

- Warm mix technologies can reduce fuel usage because it reduces the production temperatures by 30 to 80 °F. It has energy saving benefits for asphalt rubber mixes.

- Warm mix technologies can reduce emission at both production and paving procedures. The carbon footprint and greenhouse gas conditions can be improved.

- To date, the initial performance of warm mixes asphalt rubber placed in California is good.


**Figure 53** – *Emission comparison HMA and WMA*

## RHMA Prod/Place/Comp

| | Plant Mix Temp | Mix Behind Paver | Comp. Temp. |
|---|---|---|---|
| RHMA | 325 F | 290 F/310 F | 300 F/275 F |
| Astec WRHMA | 270 F/290 F | 250 F/270 F | 270 F/230 F |
| Astec/Evo WRHMA | 270 F | 240 F/250 F | 260 F/220 F |

**Figure 54** – *AR-WMA (RHMA) temperature reduction*

# Chapter 8 – Cost and Benefits

Cost comparisons would indicate that the AR binder alone is more expensive than unmodified asphalt binder. The higher cost needs to be considered in light of actual usage.

On the I-19 project, only a 1 in. (25 mm) ARFC was placed at a cost of about $2.05 per square yard ($2.45 per square meter). The comparable repair strategy is to grind the concrete, which costs about $4.20 per square yard ($5.00 dollars per square meter), thus the AR mix was actually less expensive to construct. The ARFC continued to provide a smooth riding, virtually crack free, good skid resistant, quiet and virtually maintenance free surface for a period as long as sixteen years as previously shown in Figures 32 and 33.

One of the best examples of the beneficial cost effectiveness of asphalt-rubber is a major national concrete pavement rehabilitation project conducted as part of the Strategic Highway Research Program, in Flagstaff, Arizona on Interstate 40, Figure 55, 56 and 57 [Way, 2000] . An $18 million dollar savings was demonstrated by the use of an AR overlay atop the cracked concrete pavement compared to alternative pavement designs. In addition the construction was completed in three months which compared to a comparable paving operation of up two years.

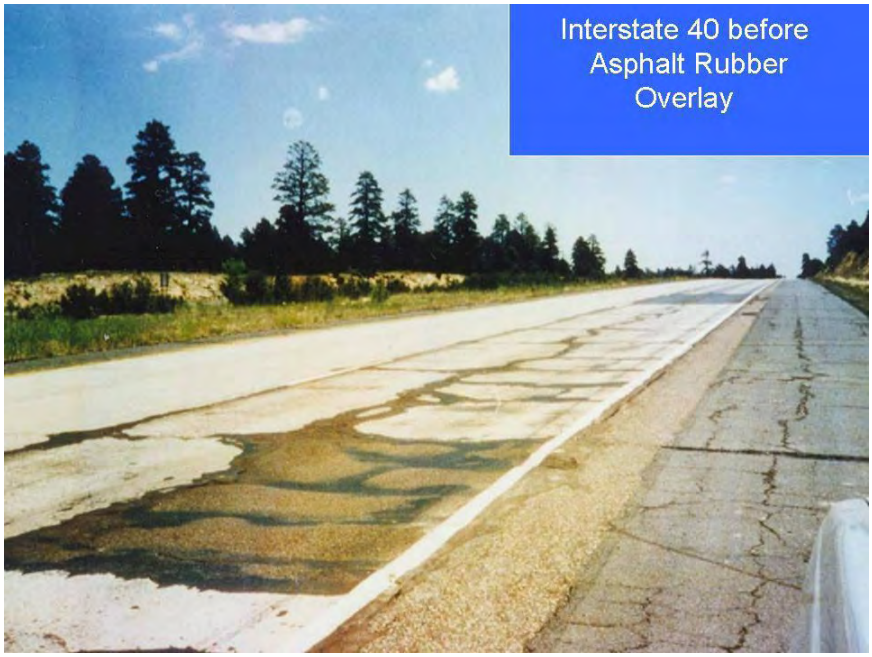



**Figure 55** – *Concrete pavement in 1989 before asphalt-rubber overlay*


**Figure 56** – *Interstate 40, 15 years after asphalt-rubber overlay*

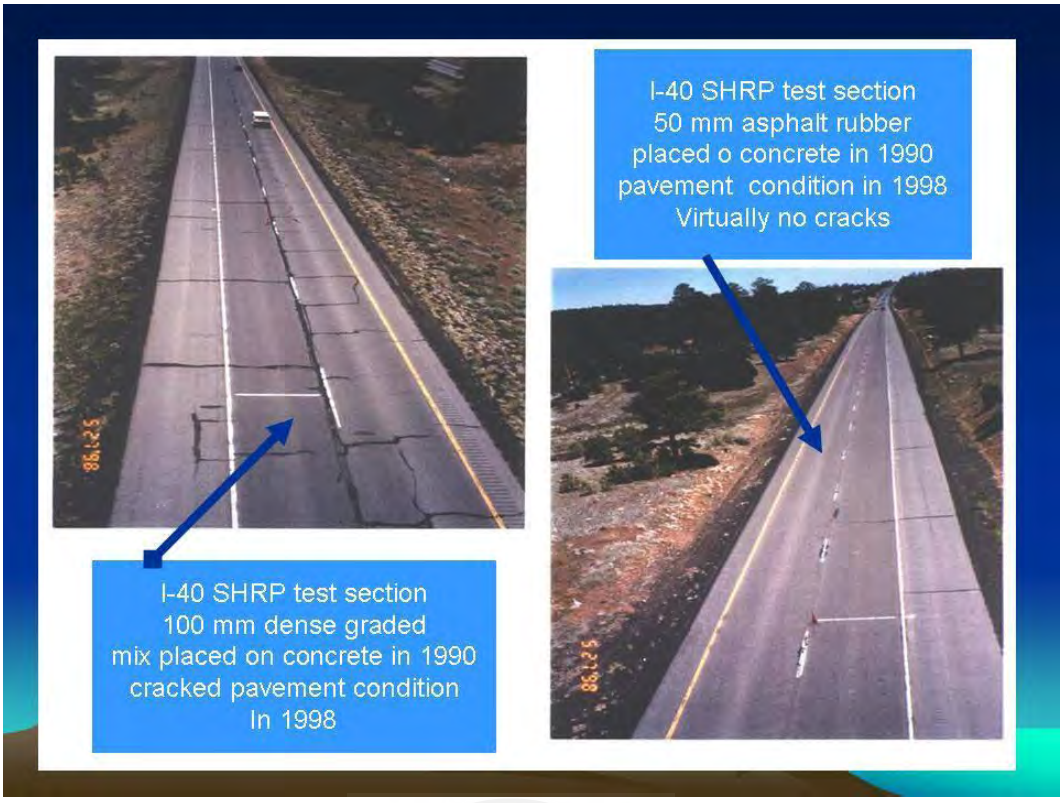



**Figure 57** – *Flagstaff SHRP test sections I-40, 50 mm asphalt-rubber no cracks*

The price of AR binder reduced significantly after the patents expired in the early 1990's. As the patents on AR binder ended, the price of the material dropped from about $450 dollars per ton to about $250 per ton. At present, up to seven companies supply AR in Arizona. The ADOT monitors the price of all the products it buys and has used asphalt-rubber only when its usage appeared to be well suited to the problem and cost effective. Table 11 shows the cost of AR HMA mixes compared to HMA made with neat unmodified asphalt binders [Zareh, 2009].

The cost of asphalt binder has gone up tremendously during 2008 as shown in Figure 58. Although the price or cost of asphalt may not vary directly with the cost or price of a barrel of oil it does track closely in the Arizona market. Given this change in the cost structure it is easy to observe that asphalt-rubber mixes are presently very attractive in cost when particularly examined in light of actual usage It is indeed possible that as the cost of asphalt continues to increase that asphalt-rubber will become very attractive. As Figure 59 shows the trade off in cost in a practical manner is close to even at about $300.

**Table 11** – *Total Cost (Dollars Per Sq. Meter, Per 25 mm thickness)*

| YEAR | AC | ARAC | ACFC | AR-ACFC |
|---|---|---|---|---|
| | | | | |
| 1992 | 1.89 | 3.71 | 2.09 | 3.18 |
| 1996 | 1.60 | 2.93 | 1.85 | 2.72 |
| 1997 | 1.59 | 2.99 | 1.84 | 2.56 |
| 1998 | 1.61 | 2.38 | 1.86 | 2.02 |
| 1999 | 1.64 | 2.77 | 1.84 | 2.10 |
| 2000 | 1.65 | 2.76 | 1.86 | 2.30 |
| 2001 | 1.66 | 2.99 | 1.90 | 2.49 |
| 2002 | 1.67 | 3.00 | 1.92 | 2.50 |
| 2003 | 1.68 | 3.02 | 1.93 | 2.52 |
| 2004 | 1.68 | 3.03 | 1.94 | 2.53 |
| 2005 | 1.71 | 3.15 | 1.99 | 2.59 |
| 2008 | 4.66 | 5.42 | 3.72 | 4.05 |
| 2008 | Dollars | Per | Square | Yard |
| 2008 | 3.88 | 4.52 | 3.10 | 3.38 |

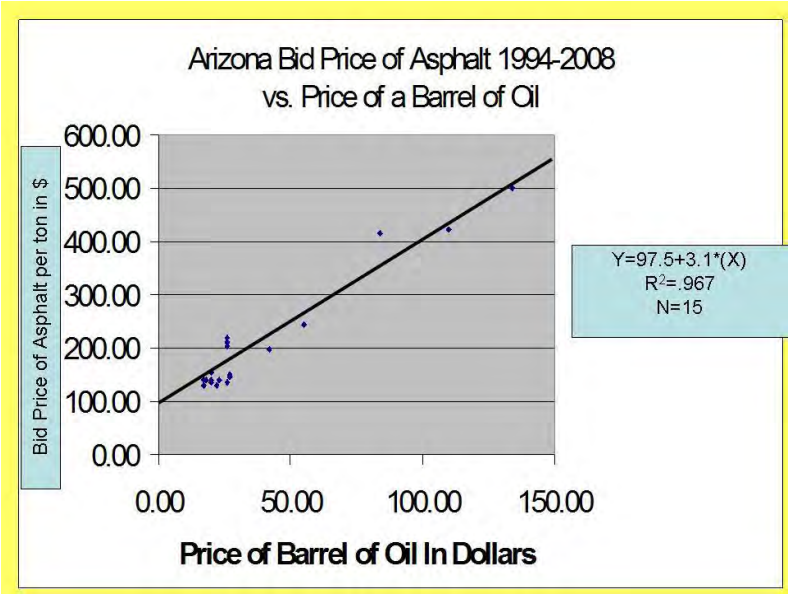



**Figure 58** – 2008 Comparison of *ADOT asphalt bid price to the price of a barrel of oil*

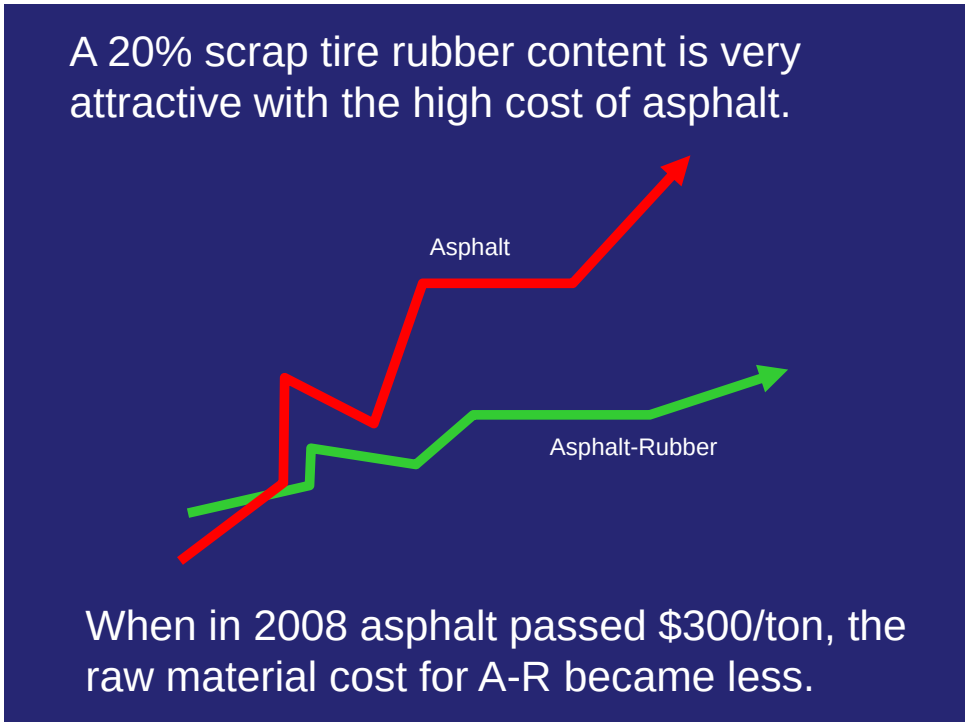



**Figure 59** – *Attractive tradeoff between asphalt-rubber and unmodified asphalt as asphalt price increases*

# Chapter 9 – Performance

Pavement performance has been routinely monitored by ADOT's pavement management system since 1972. Over that time a general trend of cracking, maintenance cost, rutting, ride and skid resistance have been observed [Zareh, 2009A]. Figure 60 shows a comparison of the average percent cracking for conventional overlay/inlay projects and those projects built with asphalt-rubber mixes.

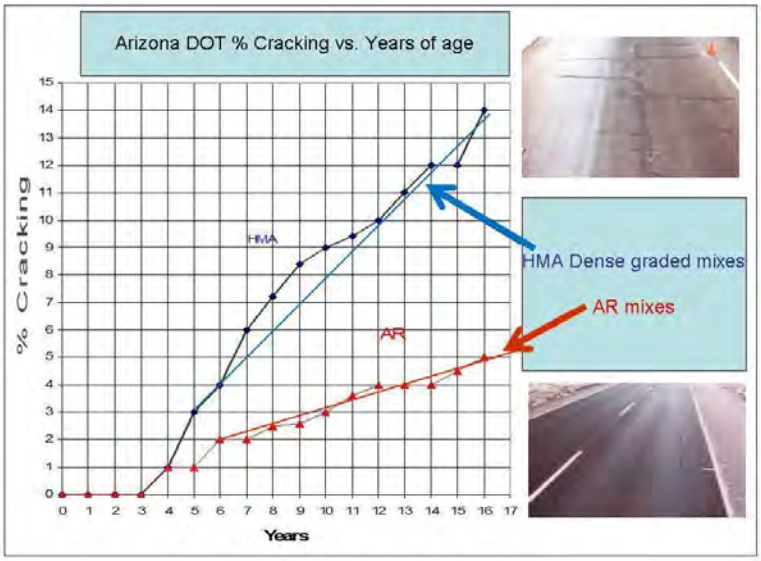



**Figure 60** – *Statewide cracking performance with and without asphalt-rubber*

As Figure 60 shows AR has reduced the amount of reflective cracking as expected and designed for. A value of ten percent cracking is considered as fatigue cracking, therefore virtually no fatigue cracking has been seen in the AR rubber projects.

A value of ($666 dollars of maintenance cost per lane mile ($400 per lane kilometer) per year is considered high and worthy of attention. Projects with AR typically need much less maintenance and rarely exceed the $400 threshold even after fifteen years of service as shown in Figure 61.

The average rut depth over the seventeen year period has been surprisingly better with asphalt-rubber mixes than expected considering their greater binder content, Figure 62. This could be due to less cracking as well as the use of a very stable stone structure in the ARFC and ARAC. Rut depths over the seventeen year period have generally stayed below 0.25 in. (6 mm) which is considered low and not of any major concern.

The average smoothness for AR projects over the seventeen year period has been very good with smoothness values below 93 inches per mile (1415 mm/km) which is considered very satisfactory and not in need of any correction, Figure 63. Generally ARFC is typically used as the final pavement surface and has produced some of the smoothness riding surfaces as measured as part of ADOT's smoothness specification.

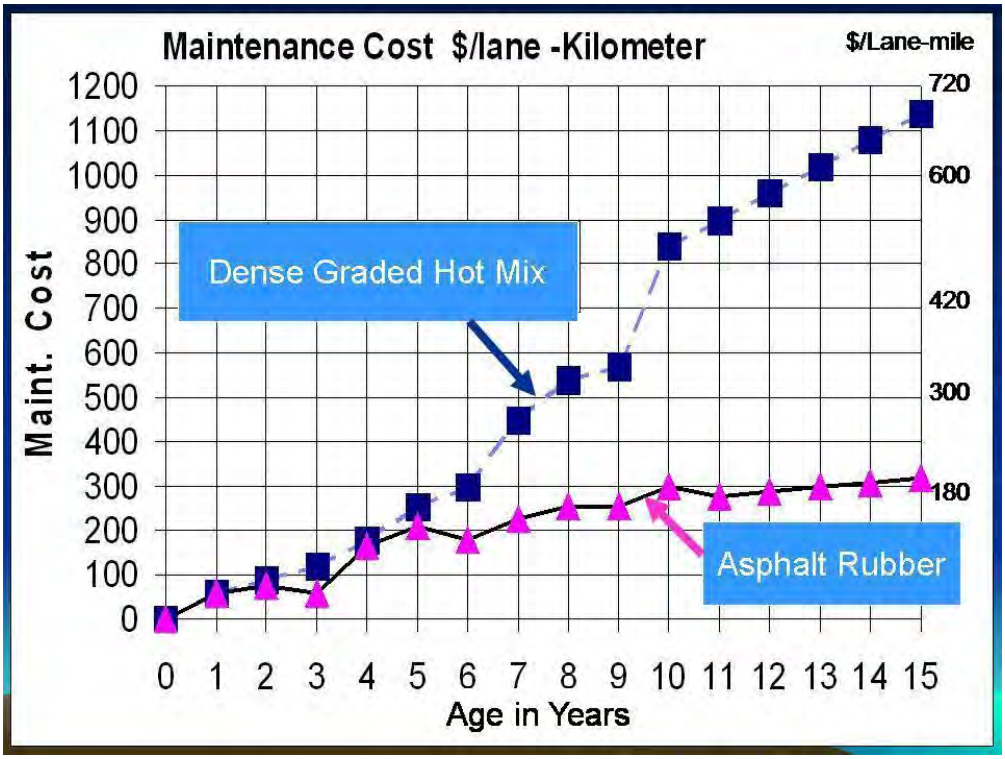



**Figure 61** – *Statewide Maintenance cost with and without asphalt-rubber*

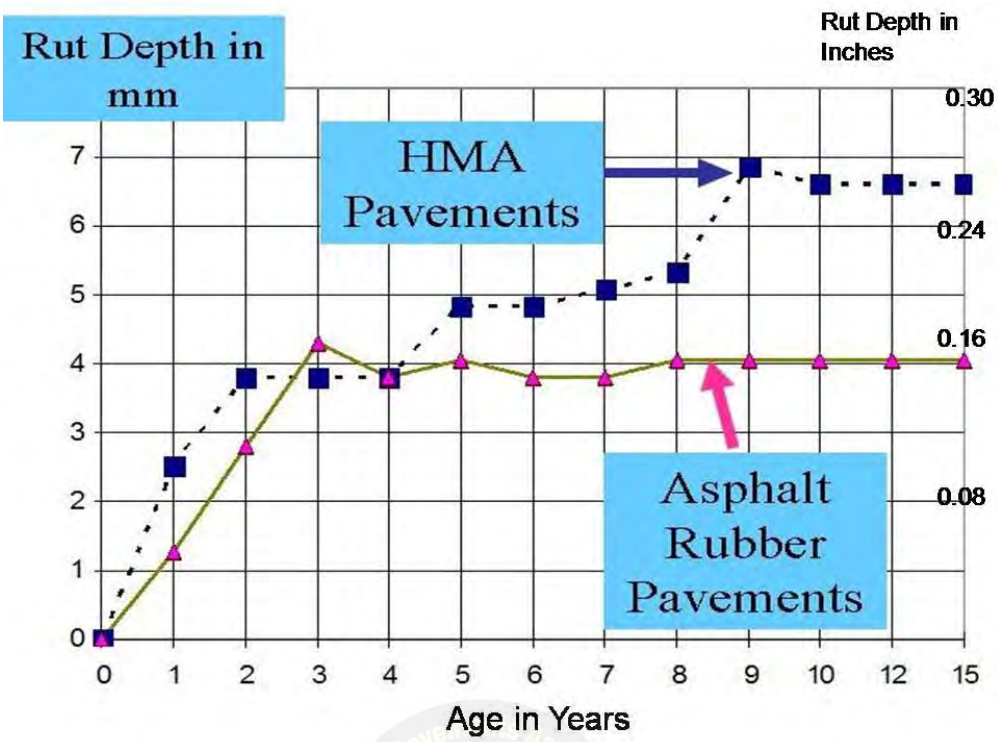



**Figure 62** – *Statewide rut depth with and without asphalt-rubber*

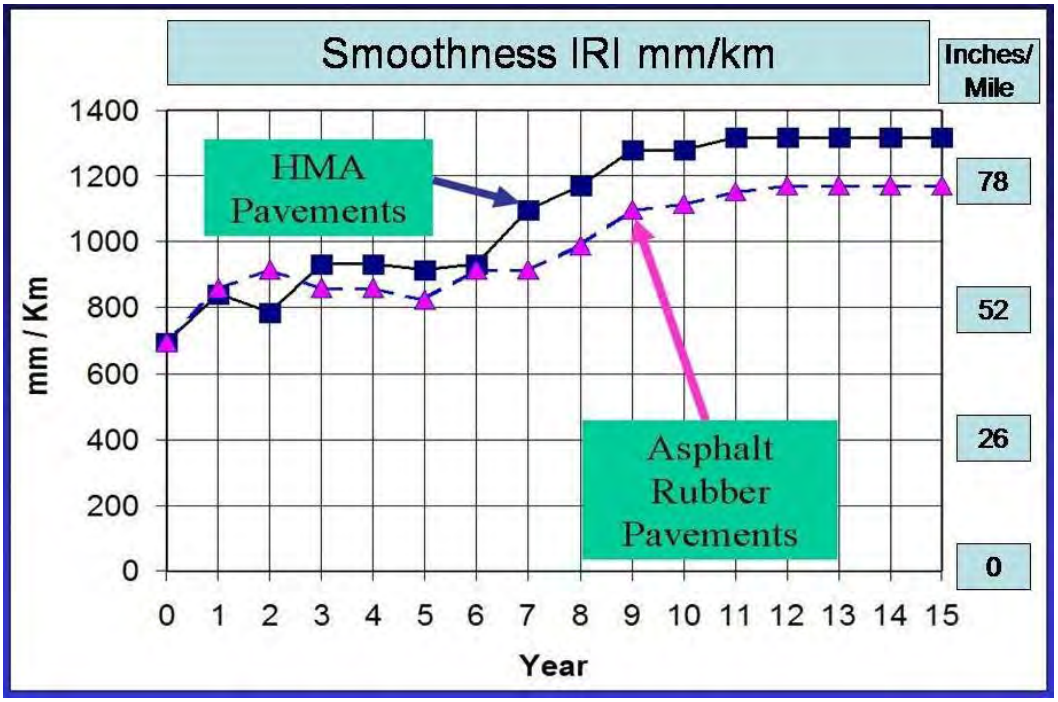



**Figure 63** – *Statewide pavement smoothness performance with and without asphalt-rubber*

The average skid resistance over time has been good as shown in Figure 64 and there is good splash and spray characteristics as shown in Figure 65.

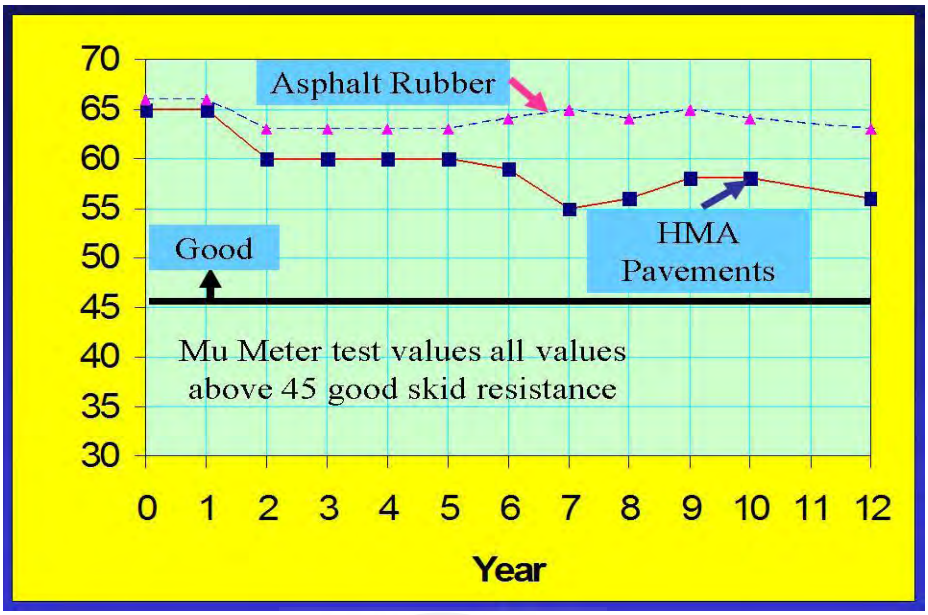



**Figure 64** – *Statewide skid resistance performance with and without asphalt-rubber*


**Figure 65** – *I-35, San Antonio Texas, Reduced splash and spray with asphalt-rubber porous friction course*

In addition to the reduction in splash and spray the Texas DOT noted a reduction in wet weather accidents when a concrete pavement was overlaid with an asphalt-rubber porous friction course as shown in Figure 66 and 67, [Rand, 2007] and [Rand, 2008].

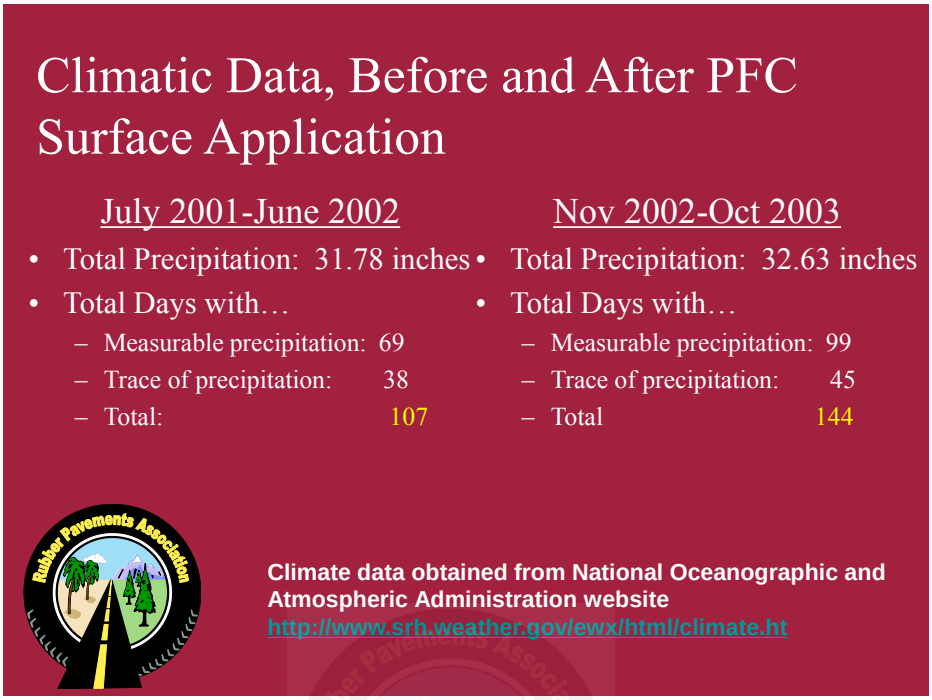



**Figure 66** – *I-35, San Antonio, Texas, climatic data*

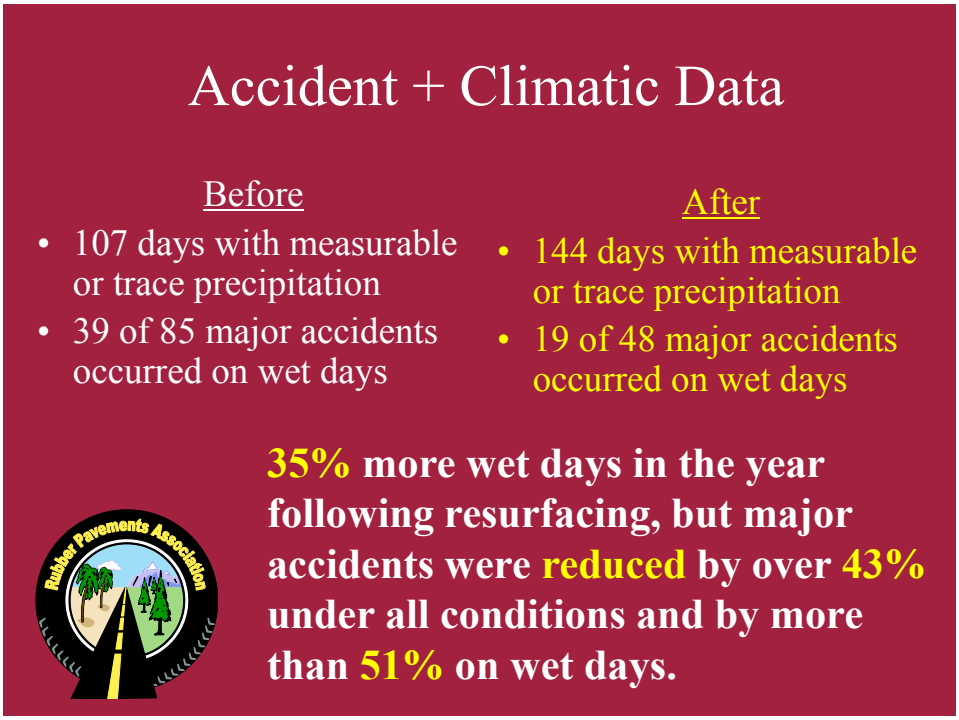



**Figure 67** – I-35, San Antonia, Texas, *accident data from San Antonio Police Department*

Asphalt-rubber has shown that it performs very well over a long period of time even though it is placed in relatively thin layers and on many types of pavements, both asphalt and concrete, and varying levels of traffic loading, interstate, state arterial and local streets**.** It has also been shown to provide a good surface in wet weather which helps to reduce wet weather accidents.

# Chapter 10 – Environmental Benefits

*Recycle Scrap Tires*

Approximately 900 million tires a year become scrap tires every year worldwide. These scrap tires are a potential site for the breeding of mosquitoes and undesirable vermin, both of which contribute to an unhealthy environment. In addition, stockpiles of scrap tires may catch on fire and cause considerable damage to the environment by releasing noxious gases into the air and pouring oil into the soil which can contaminate the underground water supply, Figure 68. By using scrap tires in asphalt pavements, the number and size of undesirable stockpiles can be reduced, thus reducing undesirable tire fires and removing the breeding ground for undesirable and unhealthy pests.

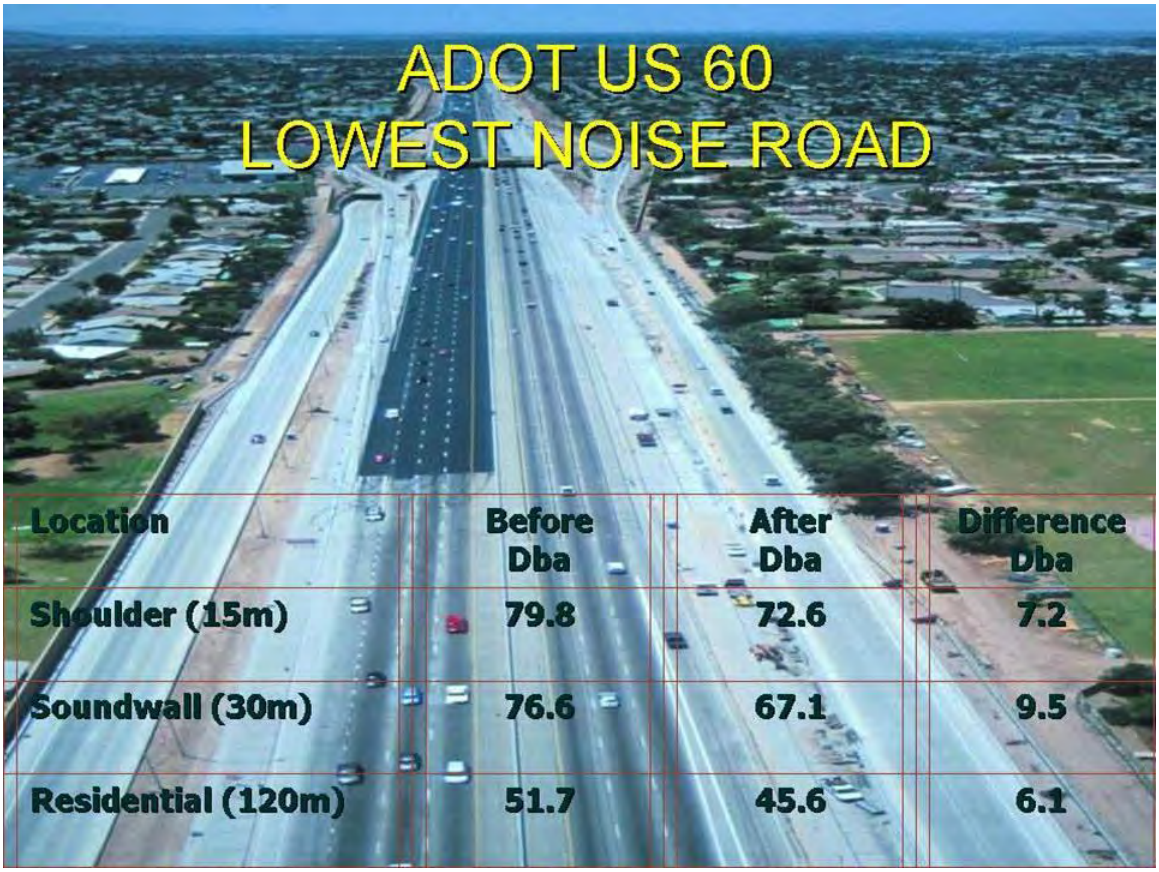

**Six to Eight million tires in flames**
**Filbin/Oxford, California, USA**
**Photo courtesy Sacramento Bee. September 1999**

**Figure 68** – *Unwanted scrap tire stockpile fire*

*Noise*

With regard to traffic noise, a 1996 Arizona Transportation Research Center study [ATRC, 1996], indicated that an ARFC can lower the noise by as much as 5.7 decibels. The report went on to say, "Human hearing can distinguish noise level differences of 3.0 decibels or more. Therefore, the ARFC overlay appears to be capable of noticeably reducing roadside noise levels in certain situations." In 2002 noise became a very big issue in the Phoenix, Arizona, metropolitan area. It became evident from a recently completed freeway concrete widening and overlay with an ARFC, that the pavement had become much quieter. The highway became so much quieter that it was decided to overlay all 150 miles (250 kms) of the Phoenix Metropolitan

concrete freeway system with the ARFC, Figure 69 [Zareh, 2009B]. Noise studies in Arizona and California found similar results shown in Figure 70, [Zareh, 2009B].




| Location | Before Dba | After Dba | Difference Dba |
|---|---|---|---|
| Shoulder (15m) | 79.8 | 72.6 | 7.2 |
| Soundwall (30m) | 76.6 | 67.1 | 9.5 |
| Residential (120m) | 51.7 | 45.6 | 6.1 |

**Figure 69** – *Noise reduced after one inch (25 mm) asphalt-rubber ARFC placed*

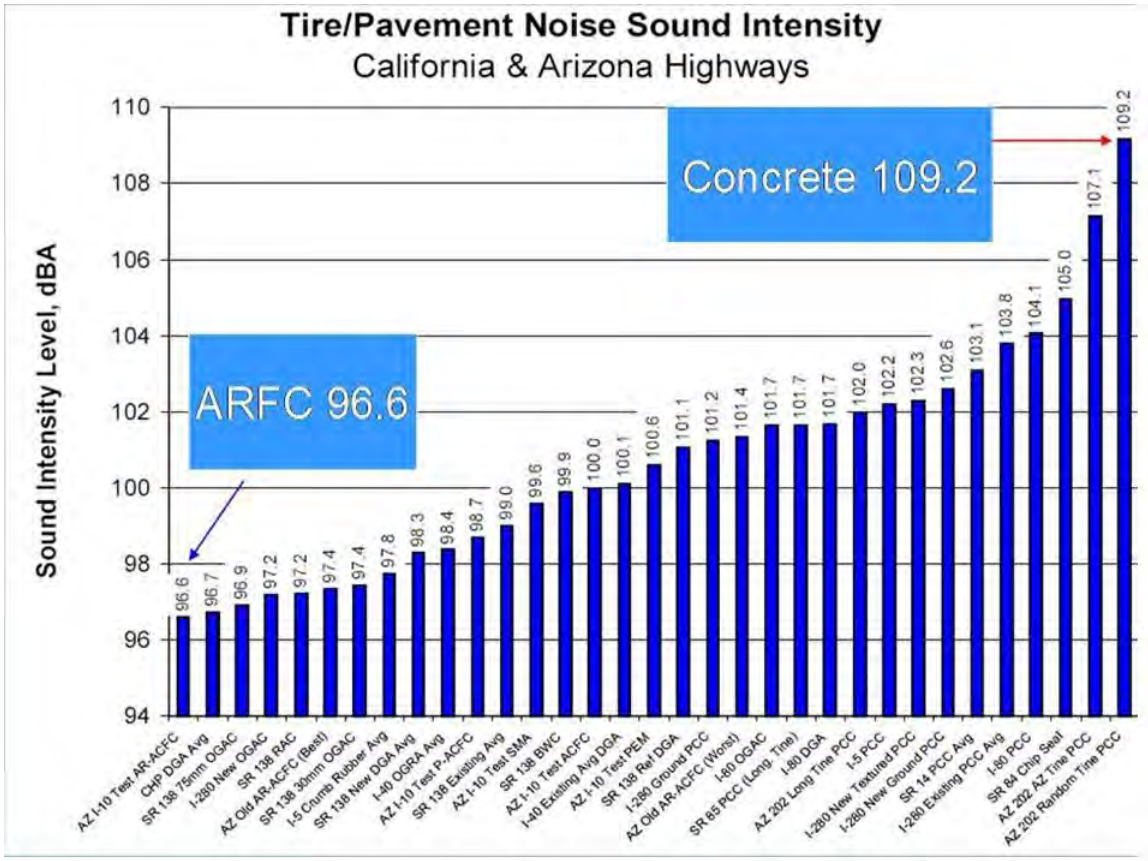



**Figure 70** – *Noise measurements for many surfaces asphalt-rubber ARFC the quietest*

*Energy and $CO_2$*

A study was conducted to compare the energy savings by using asphalt-rubber to other common uses of scrap tires, i.e., alternate daily cover and tire derived fuel [Sousa, 2009]. As shown in Figure 71 the use of asphalt-rubber provided substantial energy savings as well as $CO_2$ savings. This is primarily due to asphalt-rubber mixes being placed in relatively thin layers which reduce the amount of aggregate that needs mining, transport of the aggregate and the amount of hot mix that needs to be heated. A similar finding was reported in an ASU report presented at AR2009. Figure 72 shows the nature of the $CO_2$ savings as reported by ASU [White, 2009].

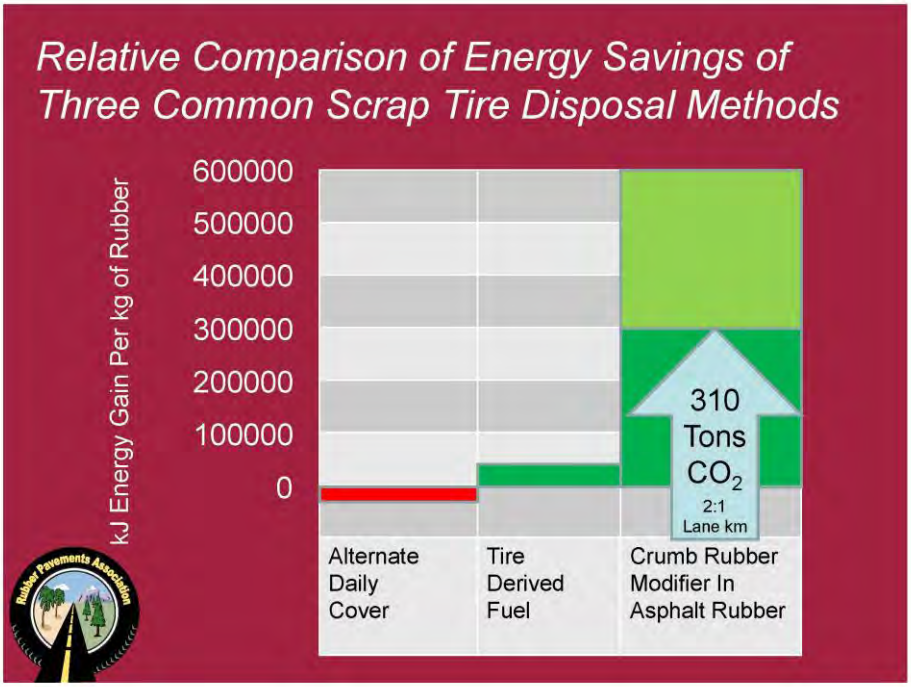



**Figure 71** – *Energy and $CO_2$ savings with asphalt-rubber*

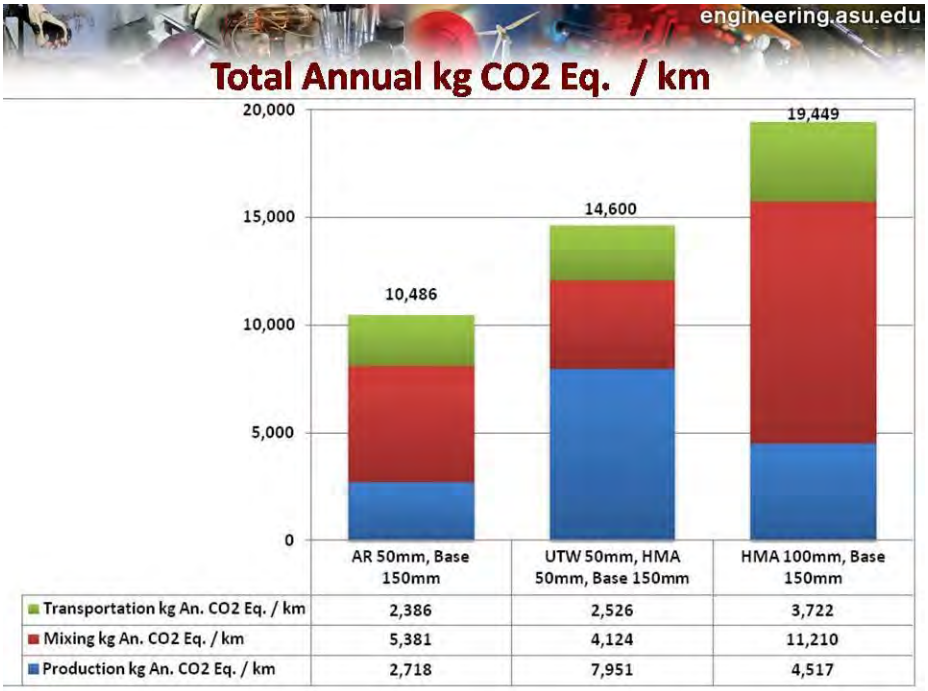



**Figure 72** – *Total Annual kg CO2 eq. / km for moderate traffic volume pavement designs*

*Recycling*

Over the years a number of states have recycled asphalt-rubber pavements as documented in a Caltrans report [Caltrans, 2005]. More recently, at the AR2009 Conference, results of the ADOT recycling project was reported [Zareh, 2009A]. An example of the ADOT project is shown in Figure 73. Both these reports note that an asphalt-rubber mix can be recycled in a conventional manner with routine mix design procedures and construction methods.


**Figure 73** – *Recycled ARFC pavement*

*Fumes*

A research study in 2003 [Stout, 2003] reviewed several studies where the potential pollution fumes from both conventional and asphalt-rubber hot mixes were measured an evaluated on the same project. The report reviewed the stack emission results from comparative studies conducted in Michigan, Texas and California within the USA, [Michigan, 1994], [Texas, 1995], [California, 2002]. In all three cases, the emissions from asphalt-rubber hot mixes were within the allowable limits and similar to the emissions from the production of conventional asphalt concrete. These data indicate that emissions from the production of asphalt-rubber are not significantly different than those from the production on conventional asphalt.

Another stack emission fume cooperative study was conducted in California and reported in 2006. The study participants included Caltrans, the California Air Resources Board, California North Coast Air Districts, RPA and the paving construction industry represented by Granite

Construction Company. Results of the study were reported by Granite Construction Company [Granite, 2006] and noted the following:

- Emissions resulting from the production of the three types of rubberized asphalt tested (including asphalt-rubber) are not significantly different than those resulting from the production of conventional asphalt.

In addition, an odor study was conducted on asphalt-rubber hot mixes and results reported on as follows [Granite, 2006]:

- Numerous (50-100) odor observations were made by CARB, Air Districts, CalTrans, and Granite using a common form.
- Odor intensity varied from weak to noticeable, and no observer rated the odor as "strong & offensive," or "extreme."
- "Noticeable" odors were generally confined in close proximity to loaded haul trucks.
- The odor observations "did not identify rubberized (asphalt-rubber mix) product odors as being significantly stronger than conventional asphalt products." (LCAQMD Summary Report).

*Tire Wear*

ASU conducted a tire wear study for the ADOT comparing the tire wear from a concrete pavement in a tunnel with the tire wear after an ARFC was placed over the same concrete pavement and tested one year after placement of the ARFC [Allen, 2006]. The study found the following conclusions.

Tire wear tracer compounds have been identified and quantified in representative tire wear composite samples from used tires in Arizona, ambient aerosol samples and aerosol samples collected from two roadway tunnels. Test extraction and separation protocols to determine the amounts of tire wear tracers in tire treads have been developed.

Emission rates of tire wear tracer compounds have been calculated. Emission rates of tire wear tracers were found higher at PCC road surface than at ARFC road surface. This finding supports the hypothesis that ARFC road surface layer results in significantly less tire wear than PCC road surface layer.

Emission rates of tire wear per kilometer driven have been calculated. Emission rates of tire wear per kilometer driven at PCC road surface are 1.4-2 times higher than emission rates of tire wear at ARFC road surface. These findings provide ADOT with tire wear emission data for use in the federally-mandated air quality modeling for the Phoenix air shed.

*Heat Island*

ASU has also been looking at the Heat Island effect of higher night time temperatures [Kaloush, 2008]. This effect has been noted in Phoenix, Arizona where the summer time night temperature has increased from 1950 to 2005 by 10°F (6°C), Figure 74. The cause of this increase in night time temperatures is attributed to the absorption of heat during the day time by concrete and

asphalt pavements, roofs, buildings and other manmade structures. ASU is conducting research to determine whether an open graded asphalt-rubber surface placed on top of a concrete surface can help to release the day time accumulation of heat during the day and thus help to reduce the degree of heat island effect, Figure 75.

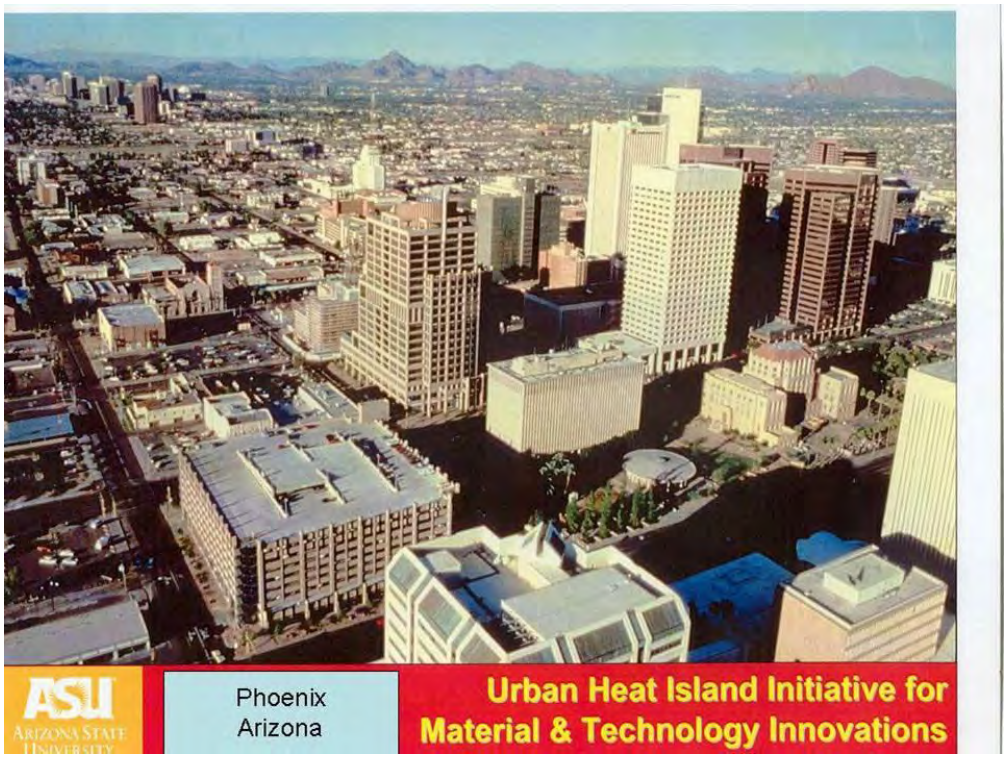



**Figure 74** – *Phoenix, Arizona*

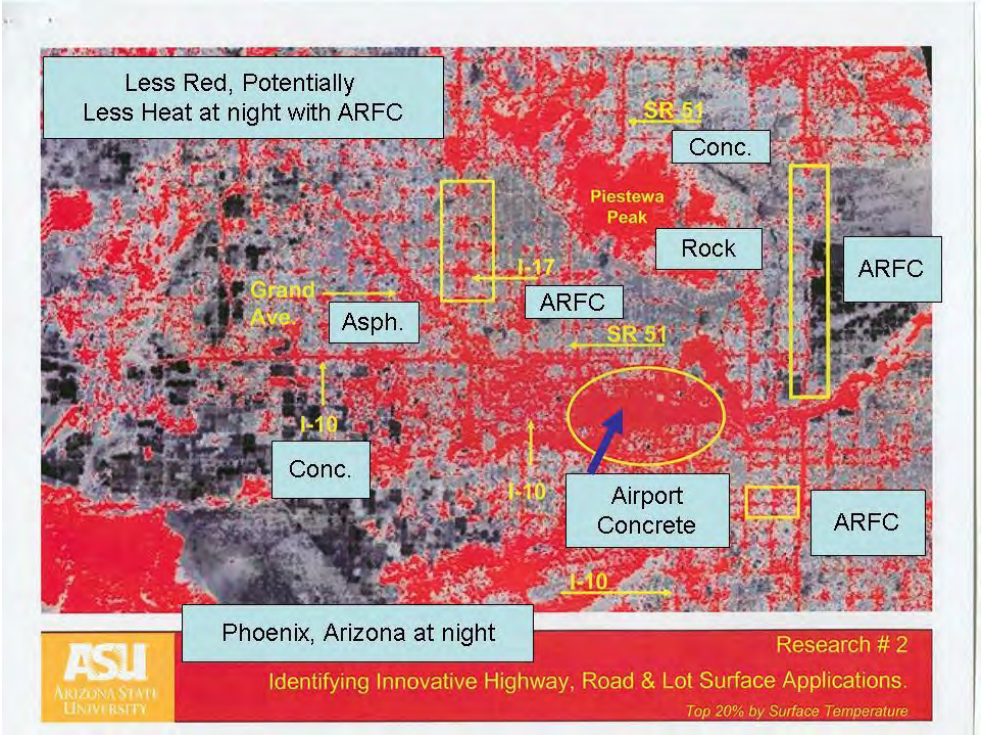



**Figure 75** – *Night time temperatures appear less for open graded asphalt-rubber surfaces*

# Chapter 11 – Closure

The story of asphalt-rubber began on or about the year 1965 with the simple goal of developing a maintenance patching material to hold together old crack pavements long enough to allow for the future overlaying or reconstruction of the pavement. In the intervening 40 plus years its use has grown an expanded into a myriad of areas and now is a routine seal coating and paving material in Arizona, California, Texas and Florida. Useful products from adding scrap tire crumb rubber to pavements will continue to be developed because pavements that last longer, use less material and need less maintenance will always be in demand.

In general, objective pavement performance measurements taken over time all indicate that asphalt-rubber is a very good modified asphalt binder which, when properly utilized, can impart a great deal of durability to a surface wearing course material. Asphalt-rubber mixes can generally be placed much thinner than conventional dense mixes and thus can be cost effective. With 40 plus years of successful service and cost effectiveness asphalt-rubber is a viable alternate form of modified asphalt binder. In addition, asphalt-rubber has the advantage of utilizing millions of scrap tires in an engineering beneficial and sustainable manner. Table 12 is a summary of benefits derived from using asphalt-rubber.

**Table 12** - *Asphalt-rubber benefits as a pavement surfacing material*

- Less reflective cracking, and cracking in general
- Greater durability
- Less thickness
- Less maintenance
- Less raveling
- Smooth ride
- Good rut resistance
- Good skid resistance
- Less splash and spray
- Provide a safe wet weather surface
- Good in hot and cold climates
- Less Noise
- Cost effective
- Beneficial use of scrap tires
- Recyclable
- Environmentally friendly
- Less energy consumption
- Less $CO_2$ produced
- Sustainable building material
- Compatible with routine construction practices
- Highly controlled material with modern computerization
- Standard specification by states and ASTM
- Warm Mix compatible

This practice is directed toward providing some basic information about asphalt-rubber binder; what it is, how it is made, how it is used and how it provides a wide variety of benefits. Like any asphalt binder to garner its full value involves proper engineering selection for its use, proper engineering design, proper testing, proper specifications and proper construction. Also, like any building material unforeseen problems, lack of care in design and testing, construction under adverse weather conditions or traffic, lack of quality control during construction, and lack of good engineering judgment and care can lead to failures. The information in this practice is directed toward providing the basis for the successful design and construction of asphalt-rubber pavement surfaces.

The authors thank you the reader for your kind attention and wish you only success with using asphalt-rubber binder. In addition we thank the Rubber Pavements Association for the opportunity of developing this guide.

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# Appendix A
## Glossary

**AASHTO** – American Association of State and Highway Transportation Officials.

**ADOT** – Arizona Department of Transportation.

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

**Ambient Ground Rubber** – processing where scrap tire rubber is ground or processed at or above ordinary room temperature.

**Asphalt** – any various natural or synthetic, dark colored, bituminous substances composed mainly of hydrocarbon mixtures. For purposes of this guide asphalt is the binder or asphalt cement used in various manners in the paving industry. It is a product derived from the petroleum refining industry which may contain various additives and modifiers before its final use in the paving industry. It is an adhesive, glue, or black and sticky material that is used in seal coating and hot mix paving.

**Asphalt-rubber** – is used as a binder in various types of flexible pavement construction including surface treatments and hot mixes. According to the ASTM definition (ASTM D 8, Vol. 4.03, "Road and Paving Materials" of the Annual Book of ASTM Standards 2001) asphalt-rubber is "a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles". In addition asphalt-rubber physical properties fall within the ranges listed in ASTM D 6114, "Standard Specification for Asphalt-rubber Binder," also located in Vol. 4.03. Recycled tire rubber or scrap tire crumb rubber is used for the reclaimed tire rubber portion of asphalt-rubber binder. The asphalt-rubber is formulated and reacted at elevated temperatures and under high agitation to promote the physical interaction of the asphalt cement and scrap tire crumb rubber constituents, and to keep the scrap tire crumb rubber particles suspended in the blend. Asphalt-rubber contains visible particles of scrap tire rubber. Asphalt-rubber is typically used as either a Type 1 or Type 2 formulation. For purposes of this guide both Type 1 and 2 are considered as equal.

**Asphalt-rubber Type 1** – consists of asphalt and crumb rubber from scrap tires only and no other additives, modifiers or extenders. Type 1 is primarily used in Arizona as well as Texas and Florida.

**Asphalt-rubber Type 2** – consists of a maximum of 85 % asphalt combined with a minimum of 15 % rubber. The rubber portion consists of 75% crumb rubber from scrap tires and 25% from a high natural rubber source. An extender oil is added to the combination of

asphalt and rubber. The amount of extender oil is generally about 2% of the total mixture. Type 2 is primarily used in California.

**ASU** – Arizona State University located in Tempe, Arizona.

**ARAC** – is asphalt-rubber asphalt concrete which consists of asphalt-rubber binder hot mixed with a gap graded aggregate. The resultant mixture is placed as a final wearing surface or base support layer. It is generally placed from 1-2 inches (25 to 50 mm) in thickness.

**ARFC** – is asphalt-rubber friction course which consists of asphalt-rubber hot mixed with an open graded aggregate. The resultant mixture is placed as a final wearing course. It is generally placed 0.5 to 1.0 inch (12.5 to 25 mm) in thickness.

**ASTM** – American Society for Testing and Materials.

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

**Bitumen** – is any of various natural substances, as asphalt, consisting mainly of hydrocarbons. For purposes of this guide asphalt, asphalt cement and bitumen refer to the binder used in various manners in the paving industry and is derived initially from the petroleum refining process.

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

**Caltrans** – California Department of Transportation. www.dot.ca.gov

**CIWMB** – California Integrated Waste Management Board, now called Department of Resources Recycling and Recovery (CalRecycle) www.calrecycle.ca.gov

**Crackermill** – apparatus typically used for ambient grinding and a process 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 4.75-millimeter to 425-micron [No.4 to No.40] sieve).

**Crumb Rubber Modifier** – a general term for scrap tire rubber that is reduced in size and is used as a modifier in asphalt paving materials.

**Cryogenic/Cryogenic grinding** – process that freezes the scrap tire rubber and crushes the rubber to the desired particle size. The process 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.

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

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

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

**Dry Process** – any method that mixes the crumb rubber modifier with the aggregate before the mixture is charged with asphalt binder. This process only applies to hot mix asphalt production.

**EPA** – Environmental Protection Agency responsible for administering all federal environmental rules and regulations nationwide.

**Extender oil** – aromatic oil used to promote the reaction of the asphalt binder and the crumb rubber modifier.

**FDOT** – Florida Department of Transportation,

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**FHWA** – Federal Highway Administration that administers all federal funded road building projects in accordance with federal laws and regulations. www.fhwa.dot.gov

**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 asphalt concrete.

**Gap-graded** – aggregate that is not continuously graded for all size fractions, typically missing or low on one or two of the finer sizes. Gap grading is used to promote stone-to-stone contact in hot-mix asphalt concrete. This type of gradation is most frequently used to make rubberized asphalt concrete-gap graded in Arizona and it is referred to as ARAC and in California RAC-G paving mixtures.

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

**Granulated rubber** – cubical, uniformly shaped, cut crumb rubber particle with a low surface area which are generally produced by a granulator.

**Ground Crumb Rubber Modifier (CRM)** – irregularly shaped, torn scrap rubber particles with a large surface area, generally produced by a crackermill.

**Granulator** – process that shears apart the scrap tire rubber, cutting the rubber with revolving steel plates that pass at close tolerance, reducing the size of the rubber to a crumb particle (generally 9.5-mm to 2.00-mm (3/8 in. to No. 10) sieve).

**HMA** – is hot mix asphalt. It is derived by mixing asphalt and aggregate and elevated in a hot plant and placing the resultant mix as the asphalt pavement. It may be referred to as asphalt paving or blacktop.

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

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

**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.

**Micro-mill** – process that further reduces a crumb rubber to a very fine ground particle, reducing the size of the crumb rubber below a 425-micron (No. 40) sieve.

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

**OGFC** – Open Graded Friction Course, see open-graded.

**PCC** – Portland Cement Concrete pavement.

**PG** – is a form of AASHTO and ASTM grading of asphalt by the climatic zone such that the asphalt meets the required properties for the climatic zone.

**Reaction** – is the interaction between asphalt cement and crumb rubber modifier (CRM), when blended together at a certain temperature for a certain period of time. The reaction, more appropriately defined as polymer swell, is not a chemical reaction. It is the absorption of aromatic oils from the asphalt cement into the polymer chains of the crumb rubber.

**Rubber Aggregate** – Crumb rubber modifier added to hot mix asphalt mixture using the dry process which retains its physical shape and rigidity.

**Recycled tire rubber** – rubber obtained by processing used automobile, truck, or bus tires (essentially highway or "over the road" tires). The Caltrans chemical requirements for scrap tire rubber are intended to eliminate unsuitable sources 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.

**RPA** – Rubber Pavements Association located in Tempe, Arizona. www.rubberpavements.org

**RTERF** – Recycled Tire Engineering Research Foundation located in Scottsdale, Arizona.

**Rubber-Modified Asphalt Concrete** – a hot mix asphalt concrete mixture with dense graded aggregates using a rubberized asphalt type of binder. (Note: The CRM percentage is generally low (5 to 10%) and is generally the finer mesh (30 mesh size or smaller).

**Rubberized asphalt** – is a general term that refers to a broad family of asphalt binder products that contain scrap tire rubber that may or may not comply with the ASTM definition of asphalt-rubber (ASTM D 8, Vol. 4.03). This terminology is often quoted in the press and may or may not be an asphalt-rubber product.

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

**Sieve Sizes** – Sieve sizes various nomenclature;

| Sieve Size | | Mesh |
|---|---|---|
| Metric | US Customary | |
| 25 mm | 1 inch | NA |
| 19 mm | 3/4 inch | NA |
| 12.5 mm | 1/2 inch | NA |
| 9.5 mm | 3/8 inch | NA |
| 6.4 mm | 1/4 inch | 3 |
| 4.75 mm | #4 | 4 |
| 2.36 mm | #8 | 8 |
| 2 mm | #10 | 9 |
| 1.68 mm | #12 | 10 |
| 1.18 mm | #16 | 14 |
| 0.8 mm | #20 | 20 |
| 0.6 mm | #30 | 30 |

| | | |
|---|---|---|
| 0.4 mm | #40 | 35 |
| 0.3 mm | #50 | 48 |
| 0.15 mm | #100 | 100 |
| 75 micron | #200 | 200 |

**SHRP** – Strategic Highway Research Program which is a long term research effort supported by the AASHTO and FHWA to develop new tools, tests and procedures to design and build longer lasting pavements.

**Stress Absorbing Membrane (SAM)** – the abbreviation for a Stress Absorbing Membrane. A SAM is used primarily to mitigate reflective cracking of an existing distressed asphalt or rigid pavement. It is usually associated with an asphalt-rubber binder sprayed on an existing pavement surface at .60 gallons per square yard (2.9 liters per square meter) and immediately followed by an application of a uniform pre-coated aggregate, which is then rolled and the aggregate is embedded into the binder layer. The nominal thickness normally ranges between 1/4 and 3/8 inch (6 and 9 mm).

**Stress Absorbing Membrane Interlayer (SAMI)** – for purposes of this guide a SAMI is an asphalt-rubber membrane beneath an overlay designed to resist the stress strain of reflective cracks and delay the propagation of the crack through the new overlay. It is noted, however, that the term SAMI has also been used to include an interlayer of asphalt-rubber chip seal (SAMI-R), fabric (SAMI-F), or fine unbound aggregate, thus care must be taken in reading reports to determine the type of SAMI being described.

**Shredding** – process that reduces scrap tires to pieces 6 inches (0.15 meter) square and smaller prior to granulation or ambient grinding.

**Terminal blend** – is a form of the wet process where scrap tire rubber is blended with hot asphalt binder at the refinery or at an asphalt binder storage and distribution terminal and transported to the asphalt concrete mixing plant or job site for use. This type of rubberized binder reportedly does not require subsequent agitation to keep the scrap tire rubber particles evenly dispersed in the modified binder. In the past, such blends normally contained 10 percent or less finely ground scrap tire rubber by mass (which does not satisfy the ASTM D 8 definition of asphalt-rubber) and other additives to eliminate the need for agitation. However, new formulations have reportedly been developed that contain 15 percent scrap tire rubber by total binder mass but may not meet the asphalt-rubber physical properties contained in ASTM D 6114. In addition the crumb rubber particles are reduced to such a small size by various means that they are not visible.

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

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

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

**TxDOT** – Texas Department of Transportation.

**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 binder production and it is used in rubberized asphalt concrete mixtures.

**Vulcanized rubber** – is a 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 primarily through the use of sulfur. The odor associated with asphalt-rubber is associated with the use of sulfur in the vulcanized rubber.

**Warm Mix Asphalt** – Warm mix asphalt (WMA) is the name given to certain technologies that reduce the production and placement temperatures of asphalt mixes. Generally, the placement temperatures should be between 185°F and 275°F for an asphalt to be considered warm mix asphalt.

**Wet process** – any method that blends scrap tire rubber with the asphalt cement before incorporating the binder into the asphalt paving materials. Although most wet process asphalt-rubber binders require agitation to keep the scrap tire rubber evenly distributed throughout the binder, terminal blends may be formulated in a wet process manner so as not to require agitation.

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

# APPENDIX B

## FHWA - Suggested Guide Specification For The Design Of Surface Treatments Using Asphalt-Rubber Binder

Reprinted from FHWA Report No. FHWA-SA-92-022, Reference 1 and updated to represent current practice.

A1.1 *Description:* This design guide evaluates the compatibility of the materials and determines the application rate for asphalt-rubber binder and cover aggregate for surface treatments.

A1.2 *Testing Standards*
ASTM C 29 Unit Weight and Voids in Aggregate.
ASTM C 127 Specific Gravity and Absorption of Coarse Aggregate
ASTM C 128 Specific Gravity and Absorption of Fine Aggregate

A1.3 *Materials Selection*
A1.3.1 Aggregate- Typically, a 9.5 millimeter [3/8 in.] nominal maximum aggregate gradation is specified for most applications. Other aggregate sizes such as 12.5 or 6.3 millimeter [1/2 to 1/4 in.] can be considered. Suggested gradations are as shown in Table XA.

Table AA – Asphalt-rubber seal coat aggregate gradations.

Percent Passing for Various Top Size Aggregate Gradations

| Sieve | 12.5 mm [1/2 in.] | 9.5 mm [3/8 in.] | 6.3 mm [1/4 in.] |
|---|---|---|---|
| 16 mm [5/8 in.] | 100 | | |
| 12.5 mm [1/2 in.] | 90-100 | 100 | |
| 9.5 mm [3/8 in.] | 0-20 | 70-100 | 100 |
| 6.3 mm [1/4 in.] | 0-5 | 0-10 | 70-100 |
| 2.36 mm [No.8] | 0-2 | 0-5 | 0-5 |
| 75 $\mu m$ [No. 200] | 0-1 | 0-1 | 0-1 |

A1.3.2 *Asphalt Cement:* The grade of asphalt selected will be based on the desired asphalt-rubber binder properties as noted in D 6114. The suggested grades of asphalt cement are as shown in Table AB.

Table AB – Grades of asphalt cement for asphalt-rubber binder

| CLIMATE | ASPHALT CEMENT GRADE |
|---|---|
| Cold | AC-2.5 or AC-5 / PG 52-28 Ref. 2 |
| Moderate | AC-5 or AC-10 / PG 58-22 |
| Hot | AC-10 or AC-20 / PG 64-16 |

A1.3.3 *Crumb Rubber Modifier* (CRM): The nominal maximum size of CRM (the recycled tire crumb rubber) is directly related to the size of aggregate selected. The nominal maximum size of CRM may be equal to or less than the values shown in Table AC.

Table AC – Size of recycled crumb rubber

| Nominal maximum particle size | |
|---|---|
| Aggregate | CRM (Recycled Rubber) |
| 12.5 mm [1/2 in.] | 2.36 mm [No. 8] |
| 9.5 mm [3/8 in.] | 1.18 mm [No. 16] |
| 6.3 mm [1/4 in.] | 600 $\mu m$ [No. 30] |

A1.4 *Aggregate Design:* The quantity of aggregate required to cover the road surface can be determined using the following equation:

S = (1*W) / Q Formula 1—SI units
[S = (27*W) / Q Formula 1—inch-pound units]

where: S = Quantity of aggregate sq. m. / cu. m. [sq. yd. / cu. yd.]
W = Dry loose unit weight kg / cu. m. [lbs. / cu. ft.]
Q = Spread rate of aggregate kg / sq. m. [lbs. / sq. yd.]

The aggregate spread rate is determined from the Board Test, which consists of placing a sufficient quantity of aggregate on a board with an area of 0.4 sq. m [1/2 sq. yd.] so that full coverage one stone in depth is obtained. Convert that quantity of aggregate to units of kg / sq. m [lbs. / sq. yd.].

A1.5 *Binder Design*
Determining the proportions of asphalt cement is a trial and error process. Over time, the design engineer should develop an understanding of the proportions which satisfy the binder criteria knowing the common sources of materials available to the area. Some general rules of thumb include:
(1) meeting the asphalt-rubber binder material specifications will normally require at least 15 percent CRM by weight of the asphalt consistent with D 6114;
(2) the typical CRM content will range from 15 to 25 percent by weight of asphalt;
(3) the standard blending / reaction temperature is 175°C [350°F];
(4) the time to achieve complete interaction (full reaction) is normally between 45 and 60 minutes.

The Brookfield Viscometer covered by ASTM D 2196 is used to monitor the reaction and establish the limits of the CRM content. Once these limits are determined, other binder tests can be used to measure the chosen CRM content, and any necessary adjustments in the CRM content made accordingly. For field control, a Rion- or Haake-type hand-held, high-range rotational viscometer may also be used (with Rotor No. 1) once the chosen device is correlated with the standard Brookfield device. However, in all cases the Brookfield shall be the referee method.

The quantity of asphalt-rubber required for the surface treatment can be determined using the following equation:

A = (0.465*E*T *(1- (W / (1410*G))) + V Formula 2—SI units
[A = (5.6*E*T *(1- (W / (62.4*G))) + V Formula 2—inch-pound units]

where:
A = Quantity of asphalt-rubber (L / $m^2$ [gal. / sq. yd.] at 16°C [60°F])
E = Embedment depth from Figure 1 (mm [in.]). The depth is a function of the maximum size of the aggregate. It is suggested for 12.5 mm [1/2 in.] top size the embedment is 5.6mm [0.22 in.] for a surface treatment (SAM). For 9.5 mm [3/8 in.] top size the embedment is 4.3 mm [0.17 in.], and for 6.3 mm [1/4 in.] top size the embedment is 3 mm [0.12 in.].
T = Traffic correction factor from Table AD
W=Dry loose unit weight (kg / sq. m [lbs. / sq. yd.])
G = Dry bulk specific gravity of aggregate
V = Surface condition correction from Table AE (L / $m^2$ [gal. / sq. yd.])

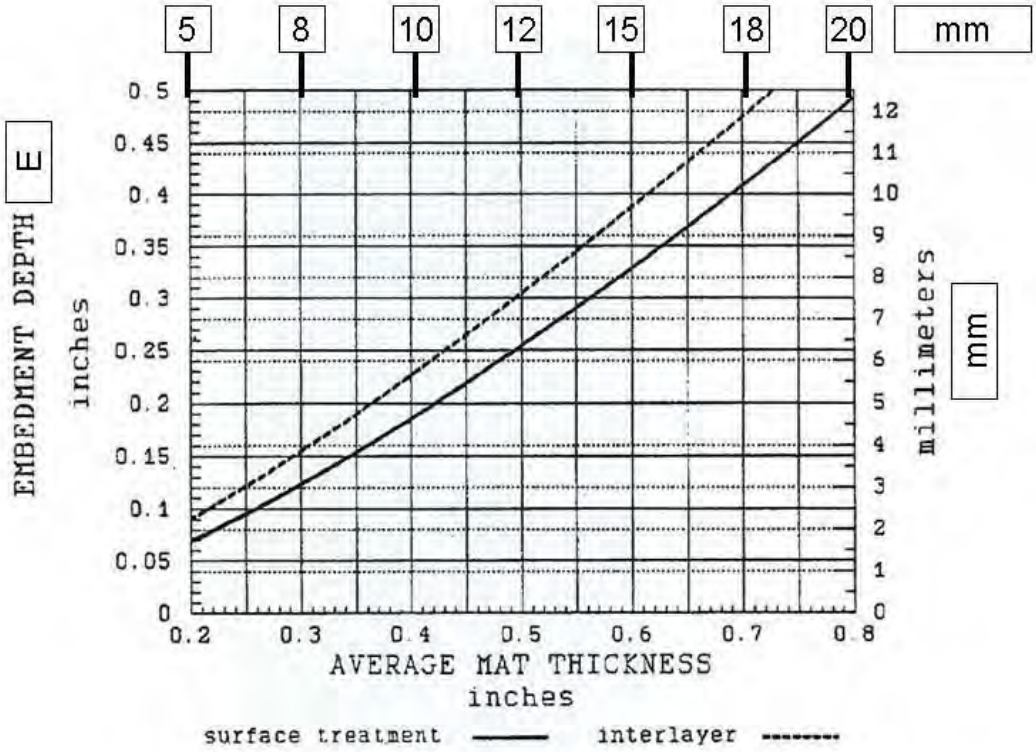



**FIGURE 1** EMBEDMENT DEPTH FACTOR

Table AD-Traffic Correction Factor

| Vehicles per day per lane | Traffic factor |
|---|---|
| **Over 1000** | **1.00** |
| **500-1000** | **1.05** |
| **250-500** | **1.10** |
| **100-250** | **1.15** |
| **Under 100** | **1.20** |

Table AE- Pavement Condition Correction

| Pavement Surface Condition | Asphalt Quantity Correction (V) |
|---|---|
| **Flush asphalt surface** | **-0.24 L/m$^2$ [-0.06 gal/sq. yd.]** |
| **Smooth, non-porous surface** | **-0.12 L/m$^2$ [-0.03 gal/sq. yd.]** |
| **Slightly porous, oxidized** | **0.00** |
| **Porous, oxidized, slightly pocked** | **+0.12 L/m$^2$ [+0.03 gal/sq. yd.]** |
| **Porous, oxidized, badly pocked** | **+0.24 L/m$^2$ [+0.06 gal/sq. yd.]** |

A1.6 *Example Binder Design*

As an example, a 12.5 mm [1/2 in.] maximum sized aggregate meeting requirements of Table AA produced a board test single layer capacity result of 11.4 kg / $m^2$ [25.0 lbs / sq. yd.], Reference 3. The material had a dry bulk specific gravity (G) of 2.59 and a dry, loose unit weight (W) of 53 kg / cu. m [88 lbs / cu. ft.].

The asphalt-rubber binder application rate using this aggregate for a SAM surface treatment according to the formula (using an average mat thickness of 11 mm [0.45 in.]) is 2.55 L / $m^2$ [0.56 gallons per square yard]. The following details this calculation:

Given an average mat thickness of 11 mm [0.45 in.]; go to Figure 1 and find the embedment depth for a surface treatment (SAM) which is 5.6mm [0.22 in.]. Thus E = 5.6 mm [0.22 in.].

Traffic Factor selected as over 1000 vehicles per day, Table AD. Thus T = 1.00.

W = 53 kg / cu. m. [88 pounds per cubic foot].

G = 2.59 bulk specific gravity.

Given a surface condition correction from Table AE, V = 0.0 for a slightly porous oxidized surface, then from the equation A is found to be as follows.

A = 2.55 L / $m^2$ [0.56 gal. / sq. yd.]

If this surface treatment was being used for a lower traffic volume (e.g. 250-500 vehicles per day) roadway that was porous, slightly pocked and sealed cracks, the binder application rate should be increased to 2.92 L / $m^2$ [0.65 gallons per square yard]. It is noted that these application rates are determined at 16°C [60°F].

T = 1.10 from Table XD, 250-500 vehicles.

V = 0.12 L / $m^2$ [0.03 gal. / sq. yd.], from Table AE for a very porous and slightly pocked surface.

A = 2.92 L / $m^2$ [0.65 gal. / sq. yd.]

This is a representative application rate for the condition shown in Appendix A1. Actual spray application rates at application temperatures between 150 and 205°C [300-400°F] should be increased by an appropriate volume correction factor to adjust for volume expansion of the asphalt-rubber binder. At 175°C [350°F], the correction factor is approximately 10 percent. Conventional asphalt cement correction factors are currently being used.


1. Heitzman, M.A., "State of the Practice-Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier," Federal Highway Administration, Report No. FHWA-SA-92-022, May 1992. Available through FHWA Technology Applications Library,
2. Arizona Department of Transportation, "Standard Specifications for Road and Bridge Construction," Pgs. 998, 2008.
3. Chehovits, James, G., R. Gary Hicks and James Lundy, "Crumb Rubber Modifier Workshop Notes, Design Procedures and Construction Practices," Session 10.0, Pgs. 10-25, March, 1993.

# Appendix C
# ARAC – Marshall Mix Design Overview

ARAC Mix Design Considerations

**ARAC: Purpose**

- Highly flexible lift
- High quality structural lift
- Typically nominal 50 mm lift

**ARAC: Aggregate**

- Gradation
- Sand Equivalent
- Crushed Faces
- Abrasion

**ARAC: Typical ARAC Specification Gradation**

| Sieve Size | Percent Passing Without admixture |
|---|---|
| 19.0 mm | 100 |
| 12.5 mm | 80-100 |
| 9.5 mm | 65-80 |
| 4.75 mm | 28-42 |
| 2.36 mm | 14-22 |
| 75 um | 0-2.5 |

**ARAC: Mineral Admixture**
1% Lime or Cement is mandatory

**ARAC: Sand Equivalent**

- Minimum SE=55

- To ensure that there are not excessive amounts of clay particles on the aggregate, done on washed aggregate

**ARAC: Crushed Faces**

- Minimum 95% Single Crushed Faces to insure good aggregate particle interlock

**ARAC: Abrasion**

- Maximum at 100 rev. 9
  at 500 rev. 40

- To insure that the aggregate will hold up to the wear and tear of traffic

**ARAC: Mix Design Steps**

- Prepare Aggregate

- Determine aggregate specific gravities

- Determine maximum theoretical specific gravity

- Compact mix, determine optimum binder content

**Check mix volumterics**

- Determine aggregate specific gravities for fine and coarse mineral aggregate

**Calculate combined specific gravities (oven dry, saturated surface dry, apparent**

- Determine the maximum theoretical specific gravity (Rice test)

- Done at 6.0% binder content and calculated to other binder contents as needed

- Compact with Marshall hammer at three binder contents

- Typically 6.5, 7.5, 8.5 or 6.0, 7.0, 8.0 depending on aggregate source

**Mix/Compact at 163°C**

- Check Volumetrics, select optimum binder content.

- Minimum VMA 19.0%

- Effective Voids 4.0 - 6.0%

**Maximum 1% binder absorption**

- Watch to make sure that the VMA is not being created by the binder

- Typically when VMA is being created by the binder, voids will drop

- VMA/Voids are very interrelated for this mix type

- If necessary, adjust gradation to improve VMA or voids. Repeat compaction process and re-measure maximum theoretical specific gravity.

- Typical binder content 6.5-8.5% by weight of mix depending on aggregate source and gradation

# Appendix D
# Detailed ARAC Marshall Mix Design Procedure

## ARIZ 815

MARSHALL MIX DESIGN METHOD
FOR ASPHALTIC CONCRETE (ASPHALT-RUBBER GAP GRADED MIX)
(A Modification of AASHTO T 245 or ASTM D 5581)

Scope

1. This method is used to design Section 413 Asphaltic Concrete (Asphalt-Rubber Gap Graded Mix) mixes using four-inch Marshall apparatus. Note: Figures 1-11 describe example report forms and calculations to complete the mix design.

Apparatus

2. The apparatus necessary includes all items required to perform the individual test methods referred to in this procedure as follows:

AASHTO T 27 Sieving of Coarse and Fine Graded Soils and Aggregates
ASTM C 136

AASHTO T 85 Specific Gravity and Absorption of Coarse Aggregate
ASTM C 127

AASHTO T 84 Specific Gravity and Absorption of Fine Aggregate
ASTM C 128

AASHTO T 245 Compaction and Testing of Bituminous Mixtures Utilizing
ASTM D 5581 Four-Inch (100 mm) Marshall Apparatus

AASHTO T 166 Bulk Specific Gravity of Compacted Bituminous Mixes
ASTM D 2726

AASHTO T 209 Maximum Theoretical Specific Gravity of Laboratory
ASTM D 2041 Prepared Bituminous Mixtures (Rice Test).

Materials

3. (a) Mineral Aggregate - The mineral aggregate for the asphaltic concrete shall be produced material from the source(s) for the project. Use of natural sand is not permitted in asphalt-rubber mixtures.

1) Mineral aggregate from each source shall be tested for compliance to the project requirements for Abrasion (AASHTO T 96).
2) The mineral aggregate shall be combined using the desired percentages of the different produced materials.
3) The composite blend of mineral aggregate shall be tested for compliance to the grading limits in Table 413-2 of the specifications according to (AASHTO T 27 or ASTM C 136) Gradation, modified so that the 2.36 mm sieve is the smallest coarse sieve.
4) The composite blend of mineral aggregate shall conform to the requirements of Table 413-3 of the specifications for Sand Equivalent (AASHTO T 176) and for Crushed Faces (ASTM D 5821)

(b) Bituminous Material - The bituminous material used in the design shall be the asphalt-rubber conforming to the requirements of Section 1009 of the specifications, which is to be used in the production of the asphaltic concrete. No dilution with extender oil, kerosene, or other solvents is allowed. The specific gravity of the bituminous material shall be determined in accordance with AASHTO T 228 and ASTM D 70.

(c) Mineral Admixtures - Mineral admixture is required in the amount of 1.0 percent by weight of the mineral aggregate and shall be the same type of material to be used on the project. Mineral admixture shall be either portland cement, blended hydraulic cement, or hydrated lime conforming to the requirements of Table 413-4 of the specifications.

Determination of Composite Gradation

4. The composite gradation of the mineral aggregate is determined using desired percentages. When mineral admixture is used, the composite of mineral aggregate and mineral admixture is also determined. When mix designs are performed using bin material a composite of the bin material is performed using the desired percentages, along with a composite of the stockpile material which feeds the bins at the desired percentages. For designs developed using both bin material and stockpile material the composite gradation of the bin material is used for the design aggregate gradation.

NOTE: The sieve analysis for the aggregate from each individual stockpile or bin shall be determined in accordance with AASHTO T 27 or ASTM C 136. The Pass 4.75 mm fraction of each aggregate shall then be screened into 2.36 mm and Pass No. 8 sizes, and the weights for each recorded. The proportion of the Pass No. 4.75 mm fraction which passes the 2.36 mm sieve is determined by dividing the weight of Pass 2.36 material by the total weight of the 2.36 mm and Pass 2.36 mm material. This value is multiplied by the Pass 4.75 mm from the sieve analysis to determine the actual Pass 2.36 mm, which is recorded to the nearest whole percent. This value is compared to the Pass 2.36 mm value from sieve analysis to provide a check on the representativeness of the fine sieve analysis. If the difference between the two Pass 2.36 mm values is greater than 4 the fine sieve analysis shall be adjusted by multiplying the percent pass for each sieve smaller than 2.36 mm by a factor obtained by dividing the actual Pass 2.36 by the Pass 2.36 from sieve analysis.

(a) The compositing of aggregate materials is performed as described in ARIZ 205, "Composite Grading", with the following exceptions: (An example of a composite done for mix design is given in Figure 1, which shows the procedure outlined below.)

1) The Pass 2.36 mm fraction is calculated for each type of aggregate by multiplying the % Pass 2.36 mm from the sieve analysis for the material by the "% of composite" that the type of aggregate represents and the total of each of the Pass 2.36 mm fractions is recorded as the "Composite of Pass 2.36 mm from Gradation of Each Stockpile or Bin".

2) The "Composite of Pass 2.36 mm From Gradation of Each Stockpile or Bin" is rounded to the whole % and recorded as the composite % Pass 2.36 mm sieve.

3) Adjust fractions of material passing the 2.36 mm sieve for each type of aggregate as necessary to correspond to the value for each calculated % Pass 2.36 mm.

4) After summing the % retained for each size fraction and rounding to the whole percent, any adjustments are made to the composite so that the calculated value for Pass 2.36 mm is not changed.

NOTE: If desired, the composite of aggregate materials may be adjusted using the method of "artificially grading" as shown in ARIZ 244.

(b) When mineral admixture is included in the mix the aggregate composite and gradation is adjusted to indicate the composite using the desired % mineral admixture "by weight of the aggregate". An example of the calculations is given in Figure 1.

1) The aggregate "% of composite" for each aggregate stockpile or bin is adjusted by the following:

$$\text{Adjusted Aggregate "\% of Composite"} = \frac{\text{Aggregate "\% of Composite"}}{100 + (\text{\% mineral admixture})} \times 100$$

Example (for coarse aggregate and 2% mineral admixture):

$$\text{Adjusted Aggregate \% of Composite} = \frac{26}{100 + 2} \times 100 = 25.49\% = 25\%$$

2) The percentage of mineral admixture in the adjusted composite is determined:

$$\text{Adjusted \% Mineral Admixture} = \frac{\text{\% mineral admixture}}{100 + (\text{\% of mineral admixture})} \times 100$$

Example (For 2% mineral admixture):

$$\text{Adjusted \% mineral admixture} = \frac{2}{100 + 2} \times 100 = 1.96\% = 2\%$$

3) The aggregate gradation (for % passing) is adjusted for mineral admixture by performing the following calculation for each sieve:

$$\text{Adjusted \% Pass Each Sieve} = \frac{\text{\% Pass From Aggregate} + \text{\% Mineral Composite Admixture}}{100 + (\text{\% of mineral admixture})} \times 100$$

Example (For No. 16 sieve, 1.18 mm sieve):

$$\text{Adjusted \% Pass} = \frac{36 + 2}{100 + 2} \times 100 = 37.25\% = 37\%$$

4) The % retained on each sieve is determined:

$$\text{\% Retained on Each Sieve} = \text{\% passing next larger sieve size} - \text{\% passing desired sieve size}$$

Example (For 1/4" sieve, 6.25 mm sieve):

% retained = 78% - 67% = 11%

(c) The composited gradation of the aggregate (and composite of aggregate and mineral admixture when used) is shown on the design card, along with the percentage of each material.

Preparing Samples for Mix Designs Using Stockpile Material

5. The samples necessary in the design are prepared and weighed up for testing utilizing the stockpile composite information.

(a) Representative samples, for each size fraction in the composite, are obtained for the tests necessary in the design. The size fractions which shall be utilized are individual sizes from each stockpile for material of 2.36 mm sieve size and larger, and minus 2.36 mm material from each stockpile. A weigh up sheet is shown in Figure 2, which gives an example illustrating the use of the composite information and the material sizes required.

NOTE: If the composite was accomplished using the "artificial grading" method, the preparation of samples will be as directed in ARIZ 244.

(b) The aggregate sample sizes, number of samples required for design tests, and other pertinent information in preparing the samples are given in Section 7.

Preparing Samples for Mix Designs Using Bin Material

6. When bin material is used for the mix design the samples are prepared and weighed up for testing as outlined below.

(a) The stockpile composite gradation shall be adjusted to the desired gradation of the bin composite. This is accomplished as outlined in ARIZ 244.

(b) Representative samples of bin material, for each size fraction in the bin composite, are obtained for performing the Marshall Stability/Flow and Density tests. Size fractions to be used are individual sizes from each bin for material of 2.36 mm sieve size and larger, and Pass 2.36 mm material from each bin.

(c) Representative samples of stockpile material, using the adjusted composite information obtained from "artificially grading" in ARIZ 244, are obtained for performing all other required tests (Sand Equivalent, Crushed Faces, Abrasion, Fine and Coarse Aggregate Specific Gravity/Absorption, Rice Test, and Immersion Compression Test). The size fractions to be used are individual sizes from each stockpile for material of 2.36 mm sieve size and larger; and for the Pass 2.36 mm material, the amount of each size fraction for Pass 2.36 mm to Retained No. 425 um, Pass 425 um to Retained 75 um, and 75 um. An illustration of the use of the above size fractions is shown in Figure 4 of ARIZ 244.

(d) The aggregate sample sizes, number of samples required for design tests, and other pertinent information in preparing the samples are given in Section 7.

Aggregate Sample Sizes

7. (a) The following table gives the aggregate samples sizes and the number of samples required for each test. The aggregate weight shown below for Maximum Theoretical Specific Gravity will provide 3 test samples and the amount shown for Density-Stability/Flow will produce 3 Marshall specimens.

| Test | Aggregate Sample Size | Number Samples |
|---|---|---|
| Fine Aggregate Specific Gravity/ Absorption | 1200 grams | 1 |
| Coarse Aggregate Specific Gravity/Absorption | * | 1 |
| Maximum Theoretical Specific Gravity (Rice Test) | 3000 grams | 1 |
| Density-Stability/Flow | **3000 grams | *** |

* Minimum weight of the test sample is determined by nominal maximum size of the aggregate, in accordance with AASHTO T 85 or ASTM C 127.

** Generally the weight shown will provide specimens of acceptable heights, but adjustments may be necessary in some cases. If the combined specific gravity of the coarse and fine mineral aggregate is known, the following equation will normally provide specimens within the specified criteria:

$$\text{Adjusted Weight of Aggregate} = \frac{\text{Combined Bulk O.D. Agg. Specific Gravity}}{2.650} \times \text{Approx. Sample Size Shown (3000 grams for Density-Stability/Flow)}$$

*** 1 Sample for each asphalt content desired to be tested.

NOTE: The proper amount of mineral admixture is added dry to the composited aggregate samples for Density-Stability/Flow specimens only. The mineral admixture and aggregate shall be thoroughly mixed together.

Aggregate Specific Gravities and Absorption

8. (a) The Bulk Oven Dry, S.S.D., Apparent specific gravities and absorption of the fine and coarse mineral aggregate shall be determined in accordance with AASHTO T 84 or ASTM C 128 and AASHTO T 85 or ASTM C 127 respectively.

NOTE: When different sources of fine mineral aggregate are to be used in the production of asphaltic concrete the specific gravity and absorption of each individual fine material shall be determined and recorded and the combined specific gravity and absorption calculated as specified in AASHTO T 84 or ASTM C 128. This allows for the combining of fine aggregates in varying amounts without having to composite a sample of the different sources and testing the combined materials. If "artificial grading" has been performed, the fine aggregate specific gravity and absorption shall be determined on a sample of the combined material from the different sources.

(b) The combined Bulk Oven Dry, S.S.D., Apparent specific gravities and combined absorption for the coarse and fine mineral aggregate are calculated by the following:

$$\text{Combined Specific Gravity} = \frac{100}{\frac{Pc}{Gc} + \frac{Pf}{Gf}}$$

Where: Pc = weight percent of coarse aggregate (Plus 4.75 mm)
Pf = weight percent of fine aggregate (Minus 4.75 mm)
Gc= specific gravity of coarse aggregate
Gf = specific gravity of fine aggregate

(Note the Pc and Pf are for aggregate material only. If mineral admixture is being used in the design, Pc and Pf shall be determined for composite of mineral aggregate only, not for the aggregate and mineral admixture composite.)

Example (For combined S.S.D. specific gravity):

$$\text{Combined S.S.D. Specific Gravity} = \frac{100}{\frac{41}{} + \frac{59}{}} = 2.614$$

2.597 2.626

$$\text{Combined Absorption} = \frac{\text{Combined S.S.D. Specific Gravity} - \text{Combined Bulk O.D. Specific Gravity}}{\text{(Combined Bulk O.D. Specific Gravity)}} \times 100$$

Example: Combined S.S.D. Sp. Gr. = 2.614
Combined Bulk O.D. Sp. Gr. = 2.576

$$\text{Combined Absorption} = \frac{2.614 - 2.576}{2.576} \times 100 = 1.48\%$$

Preparation of Specimens for Density and Stability/Flow Determination

9. Marshall specimens shall be prepared as follows, using apparatus shown in AASHTO T 245 or ASTM D 5581 and the attendant procedures with the modifications presented herein.

(a) The temperature of the asphalt and aggregate at the time mixing begins shall be 163 ± 3ºC.

(b) The aggregate and mineral admixture shall be dried to constant weight at the temperature required as shown in paragraph 6 (a). Bring samples to desired weight of approximately 3000 grams to make a batch of three Marshall specimens by adding a small amount of proportioned Pass 2.36 make up material.

NOTE: Normally a range of 3 different asphalt-rubber binder contents at 1.0 % increments will provide sufficient information, although in some cases it may be necessary to prepare additional sets of samples at other asphalt-rubber contents. Two series of binder contents are typically used: either 6.0, 7.0, and 8.0% asphalt-rubber by total mix weight; or 6.5, 7.5, and 8.5% asphalt-rubber by total mix weight.

(c) Before each batch is mixed, the asphalt-rubber binder shall be heated in a forced draft oven for approximately 2 hours or as necessary to reach a temperature of 163 to 177ºC. Upon removal from the oven, the asphalt-rubber shall be thoroughly stirred to uniformly distribute rubber particles throughout the binder before adding the designated proportion to the aggregate-admixture blend. If there is any delay before beginning of mixing the binder with the composite aggregate blend, thoroughly stir the asphalt-rubber again immediately before pouring.

**CAUTION**: Do not use a hot plate or open flame to heat the asphalt-rubber, to avoid damaging it. Once the asphalt-rubber temperature has reached 163ºC or the desired temperature, the container may briefly be moved to a hot plate for 3 to 5 minutes, if the asphalt-rubber is constantly stirred to avoid sticking or scorching, to maintain temperature and facilitate batching and mixing with aggregates and admixture. Do not heat the binder longer than necessary to complete batching and mixing operations, or damage by overheating. Properties of asphalt-rubber vary with time and temperature, and changes to the binder are likely to affect mixture volumetric properties.

NOTE: Before each batch is mixed, the mixing bowl and whip shall be heated to 163±3ºC.

(d) The aggregate, mineral admixture, and asphalt-rubber binder shall be mechanically mixed for 90 to 120 seconds in a commercial dough mixer with a minimum 10 quart capacity and equipped with a wire whip and then hand mixed as necessary to ensure thorough coating.

(e) After mixing, each batch shall be placed on a tarp or sheet of heavy paper and in a rolling motion thoroughly mixed and spread and distributed. The material shall be spread into a circular mass 1 1/2 to 2 inches thick. The circular mass shall be cut into 6 equal segments, taking opposite segments for each individual sample and using up the batch.

(f) Each sample shall be placed in a pan and allowed to cure for 2 hours ± 10 minutes at approximately 163 ± 3ºC. A mold assembly (baseplate, mold and collar) shall be heated to approximately 163 ± 3ºC. The face of the compaction hammer shall be thoroughly cleaned and heated on hot plate set at approximately 163 ± 3ºC.

(g) Lightly spray one side of a 100 mm (inch) paper disc with PAM (vegetable cooking spray used as release agent), and place the disc PAM-side up in the bottom of the mold before the mixture is introduced. Place the entire batch in the mold with a heated spoon. Spade the mixture vigorously with a heated flat metal spatula, with a blade approximately 25 mm wide and 150 mm long and stiff enough to penetrate the entire layer of material, 15 times around the perimeter and 10 times at random into the mixture, penetrating the mixture to the bottom of the mold. Smooth the surface of mix to a slightly rounded shape.

(h) Before compaction, put the mold containing the mix sample back in the 163ºC oven for 45 to 60 minutes to assure that the mixture shall be at the proper compaction temperature of 163 ± 3ºC.

(i) Lightly spray one side of a 100 mm (4 inch) paper disc with PAM, and immediately upon removing the mold assembly and mix from the oven, place the paper disc with PAM side down on top of mixture, place the mold assembly on the compaction pedestal in the mold holder, and apply 75 blows with the compaction hammer. Remove the base plate and collar, and reverse and reassemble the mold. Apply 75 compaction blows to the face of the reversed specimen.

NOTE: The compaction hammer shall apply only one blow after each fall, that is, there shall not be a rebound impact.

(j) Remove the collar and top paper disc and allow the compacted specimen to cool in a vertical position in the mold with base plate to approximately 25 to 32ºC. Rotate the base plate occasionally to prevent sticking.

NOTE: Cooling may be accomplished at room temperature, in a 25ºC. air bath, or if more rapid cooling is desired the mold and specimen may be placed in front of a fan until cool, *but do not turn the mold on its side*.

(k) Extrude the specimen from the mold on the same day that it is compacted, but not until it is time to test it.

NOTE: Care shall be taken in extruding the specimen from the mold, so as not to deform or damage the specimen. If any specimen is deformed or damaged during extrusion, the entire set of specimens at that asphalt-rubber content shall be discarded and a new set prepared.

(l) Immediately upon extrusion, measure the height of the specimen to the nearest 0.001 inch and its weight in air to the nearest 0.1 gram.

NOTE: Compacted specimens shall be 62.5 mm ± 0.1 mm in height. If this criteria is not met for the specimens at each asphalt content the entire set of specimens at that asphalt content shall be discarded and a new set prepared after necessary adjustments in the aggregate weight have been made.

(m) Follow the procedure in paragraphs (f) through (l) for all specimens required.

Specific Gravity/Bulk Density of Specimens

10. (a) Determine the specific gravity of the three specimens at each asphalt-rubber content in accordance with AASHTO T 166 or ASTM D 2726 except that paraffin coating cannot be applied to specimens that are to be tested for Marshall stability and the paraffin method shall not be used in the mix design. The determination of the "Weight in Water" and "S.S.D. Weight" of each specimen will be completed before the next specimen is submerged for its "Weight in Water" determination. <u>Note an alternate an superior method for of determining the Specific Gravity and Bulk Density of asphalt rubber gap graded mixes is the vacuum sealing method ASTM D 6752</u>

NOTE: Specimens fabricated in the laboratory that have not been exposed to moisture do not require drying after extrusion from the molds. The specimen weight obtained in 9(l) is its dry weight.

(b) Determine the density in kg/cubic meter, by multiplying the specific gravity of each specimen by 1000 kg/cubic meter.

NOTE: For each asphalt-rubber content the densities shall not differ by more than 35 kg/cubic meter. If this density requirement is not met the entire set of specimens at that asphalt-rubber content shall be discarded and a new set of specimens prepared.

(c) Determine the average specific gravity and bulk density values for each asphalt-rubber content and plot each on a separate graph versus asphalt-rubber content. Connect the plotted points with a smooth curve that provides the "best fit" for all values.

Stability and Flow Determination

11. The stability (including height corrections) and flow of each specimen shall be determined according to AASHTO 245 or ASTM D 5581, except that flow is recorded in units of 0.01 inch.

(a) Determine and record the average values for stability and flow for each asphalt content, and plot each on a separate graph using the same scale for asphalt-rubber content as used in Figure 11. Connect the plotted points with a smooth curve that provides the "best fit" for all values.

Maximum Theoretical Specific Gravity (Rice Test)

12. The maximum specific gravity of the mixture shall be determined in accordance with AASHTO T 209 or ASTM 2042 at 6.0% asphalt-rubber content and calculated for the other contents tested in the mix design.

Determination of Design Asphalt-Rubber Content

13. The design asphalt-rubber content is determined as follows in paragraphs (a) through (e).

(a) For each asphalt-rubber content used, calculate effective (air) voids (EV) according to ARIZ 424, and percent absorbed asphalt-rubber, voids in mineral aggregate (VMA), and voids filled with asphalt (VF) in accordance with the example given in Figures 8 and 9 for mixes including mineral admixture.

(b) Using a separate graph for each of the volumetric properties calculated in 13(a), plot the average value for each set of three specimens versus asphalt-rubber content. Connect the plotted points with a smooth curve that provides the "best fit" for all values.

NOTE: The percentage of absorbed asphalt-rubber (Pba) and the effective specific gravity of the aggregate (Gse) do not vary with asphalt-rubber binder content.

(c) The design asphalt-rubber content shall be the asphalt-rubber content which meets the Mix Design Criteria requirements in Table 413-1 of the specifications, and provides air voids as close as possible to the middle of the specified range.

(d) Use the effective (air) voids plot to select the asphalt-rubber content that yields the target air voids content in Table 413-1. Use the other plots to pick off the values of bulk density, VMA, VF, stability and flow that correspond to the selected asphalt-rubber content, and compare these with the limits in Table 413-1. Properties for which limits are not specified are evaluated by the Engineer for information only.

(e) If it is not possible to obtain specification compliance within the range of asphalt-rubber contents used, a determination must be made to either redesign the mix (different aggregate gradation) or prepare additional specimens at other asphalt-rubber contents for density, stability/flow testing, and voids relationships analysis.

(f) Calculate the maximum theoretical density for the design asphalt content by the equation below. This value is recorded on the design card as shown in Figure 10.

Bulk Density

$$\text{Maximum Density} = \frac{\quad}{100 - \%\ \text{Air Voids}} \times 100$$

Mix Design Gradation Target Values

14. The desired target values for the aggregate and mineral admixture in the asphalt-rubber mixture shall be from the composited gradation and shall be expressed as percent passing particular sieve sizes as required by the specifications for the project.

NOTE: The target values for aggregate with mineral admixture are shown on the design card. The gradation of samples taken for specification compliance are compared to the applicable target values, (e.g., a mix design requires mineral admixture and the mineral admixture is blended with the asphalt. The sample for specification compliance will be aggregate only and therefore is compared to the target values given without cement).

Report and Example

15. Report the test results and data obtained on the appropriate forms as an example shown in Appendix E. Liberal use of the remarks area to clarify and/or emphasize any element of the design is recommended.

# Appendix E
# ARAC – Mix Design Report

| Gradation (% Passing) | | |
|---|---|---|
| **Sieve Size** | **Grad. W/O Admixture** | **Grad. W/ Admixture** |
| 1.25" | 100 | 100 |
| 1" | 100 | 100 |
| 3/4" | 100 | 100 |
| 1/2" | 87 | 87 |
| 3/8" | 72 | 72 |
| 1/4" | 47 | 48 |
| #4 | 31 | 32 |
| #8 | 18 | 19 |
| #10 | 16 | 17 |
| #16 | 12 | 13 |
| #30 | 7 | 8 |
| #40 | 6 | 7 |
| #50 | 5 | 6 |
| #100 | 2 | 3 |
| #200 | 1.8 | 2.8 |

| **Properties** | **Result** | **Specification Requirement** |
|---|---|---|
| Mix: | | |
| Effective Air Voids (%) | 5.3 | 4.5 - 5.5 |
| Asphalt Absorption (%) | 0.61 | 1.0 max. |
| Marshall Density (lbs./cubic ft.) | 146.7 | |
| Stability | 2710 | |
| Flow | 11 | |
| Maximum Dens. (lbs/cubic ft.) | 154.9 at 7.5% | |
| Aggregate: | | |
| % Abrasion at 100 Rev.: | 5 | 9 max. |
| 500 Rev.: | 22 | 40 max. |
| Sand Equivalent: | 88 | 55 min. |
| % Single Crushed Faces | 98 | 70 min. |
| Flakiness | | max. |
| % Carbonates | | max. |
| O.D. Coarse Sp. Gr. | 2.721 | 2.35 - 2.85 |
| O.D. Fine Sp. Gr. | 2.825 | |
| O.D. Combined Sp. Gr. | 2.752 | |
| Comb. Water Absorption (%) | 1.60 | 2.50 max. |

Other Mix Properties:

**Aggregate Samples:**

| Lab: | Type | From | Date | Source | 1" | 3/4" | 1/2" | 3/8" | #4 | #8 | #40 | #200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -3/4" | STOCKPILE | | | 100 | 100 | 63 | 21 | 2 | 2 | 1 | 1.2 |
| | -3/8" | STOCKPILE | | | 100 | 100 | 100 | 100 | 24 | 3 | 2 | 1.3 |
| | FINE | STOCKPILE | | | 100 | 100 | 100 | 100 | 99 | 82 | 23 | 3.6 |

| Source | Description |
|---|---|

**Specific Gravity Tests:**

| Test # | Type | Source | O.D. Sp. Gr. | S.S.D. Sp. Gr. | Water Absorption | Used in Design? | Tested On: |
|---|---|---|---|---|---|---|---|
| 1 | Fine | | 2.825 | 2.857 | 1.13% | Yes | -#4 |
| 1 | Coarse | | 2.721 | 2.769 | 1.77% | Yes | +#4 |

**Rice Tests: (Without Admixture)**

| Test # | Date | % Asphalt | Maximum Density | Effective Sp. Gr. | Type of Flask | Used in Design? |
|---|---|---|---|---|---|---|
| 1 | | 5.0 | 161.1 | 2.796 | Small | Yes |

**Marshall Tests:**

| Test # | Method | Date | % Asphalt | % Admix | Bulk Dens. | Sta-bility | Flow | Used in Design? |
|---|---|---|---|---|---|---|---|---|
| 1 | Mech | | 6.5 | 1.0 | 146.0 | 2865 | 11 | Yes |
| 2 | Mech | | 7.5 | 1.0 | 146.7 | 2710 | 11 | Yes |
| 3 | Mech | | 8.5 | 1.0 | 146.6 | 2398 | 14 | Yes |

# Asphalt-Rubber Binder

**Materials**

| **Material** | **Asphlat Cement** | **Crumb Rubber** |
|---|---|---|
| Supplier | | |
| Grade/Identifier | AC-10 | Type II |
| % by Total Weight of Binder | 82.0% | 18.0% |
| % by Weight of Asphalt Cement | | 22.0% |

Laboratory Test Properties — Test Date:

| | **Lab Test Results** | | | | | | **Specification** |
|---|---|---|---|---|---|---|---|
| Reaction Time, Minutes | 30 | 60 | 90 | 180 | 360 | 1440 | 60 |
| Apparent Viscosity @ 350 deg. F: cPs Spindle 3.20 rpm (ASTM D 2196 Modified) | 2040 | 2880 | 3330 | 3630 | 3790 | 4440 | |
| Apparent Viscosity @ 350 deg. F: cPs (HAAKE) | | 2700 | | | 3360 | | 1500 - 4000 |
| Penetration @ 77 deg. F: 0.1 mm 100 g, 5 sec. (STM D5) | | 44 | | | 48 | 49 | |
| Cone Penetration @ 77 deg. F: 01. mm 100 g, 5 sec. | | 42 | | | 46 | 46 | 20 Minimum |
| Penetration @ 39.2 deg. F: 0.1 mm 200 g, 60 sec. (ASTM D 5) | | 27 | | | | | |
| Softening Point: deg. F (ASTM D 36) | | 142 | | | 146 | 142 | 125 Minimum |
| Resilience @ 77 deg. F: % (ASTM D 3407) | | 28 | | | 30 | 29 | 15 Minimum |
| Ductility @ 39.2 deg. F: cm 1 cm/minute (ASTM D 113) | | 7 | | | | | |
| TFOT Residue (ASTM D 1754) Penetration Retention @ 39.2 deg. F: % | | | | | | | |
| Ductility Retention @ 39.2 deg. F: % | | | | | | | |
| | | | | | | | |

**Asphalt-Rubber Specific Gravity @ 60 deg. F** **1.046**

***Rubber Gradation*** **<Test Date:**

| **Material** | **Crumb Rubber** | | | | |
|---|---|---|---|---|---|
| **% of Total Rubber** | **100.0%** | | | | |
| **Sieve Size** | | | | **Composite** | **Specification** |
| #4 | 100 | | | 100 | |
| #8 | 100 | | | 100 | |
| #10 | 100 | | | 100 | 100 |
| #16 | 94 | | | 94 | 75 - 100 |
| #30 | 37 | | | 37 | 25 - 100 |
| #40 | 23 | | | 23 | |
| #50 | 14 | | | 14 | 0 - 45 |
| #80 | 5 | | | 5 | |
| #100 | 3 | | | 3 | 0 - 10 |
| #200 | 0 | | | 0.0 | 0 - 5 |

# Appendix F
## ARFC – Mix Design Overview

**ARFC: Purpose**
- Final wearing surface
- Typically nominal 12.5 mm lift

**AR-ACFC: Aggregate**
- Gradation
- Flakiness
- Sand Equivalent
- Crushed Faces
- Abrasion
- Percent Carbonates

**ARFC: Gradation**

| Sieve Size | Percent Passing Without admixture |
|---|---|
| 9.5 mm | 100 |
| 4.75 mm | 30-45 |
| 2.36 mm | 4-8 |
| 75 um | 0-2.5 |

**ARFC: Mineral Admixture**
1% Lime or Cement is mandatory

**ARFC: Sand Equivalent**
- Minimum 55
- To insure that there are not excessive amounts of clay in the aggregate tested on washed aggregate

**AR-ACFC: Crushed Faces**

- Minimum 95% Single Crushed Faces
- To insure good particle interlock and good frictional characteristics

**AR-ACFC: Abrasion**

- Maximum at 100 rev. 9
  at 500 rev. 40
- To insure that the aggregate will hold up to the wear and tear of traffic

**AR-ACFC: Percent Carbonates**

- Maximum 30%
- To minimize the amount of limestone. LIMESTONE has a tendency to polish under traffic.

**AR-ACFC: Mix Design Steps**

- Prepare Aggregate
- Determine aggregate specific gravities
- Determine maximum theoretical specific gravity
- Check draindown

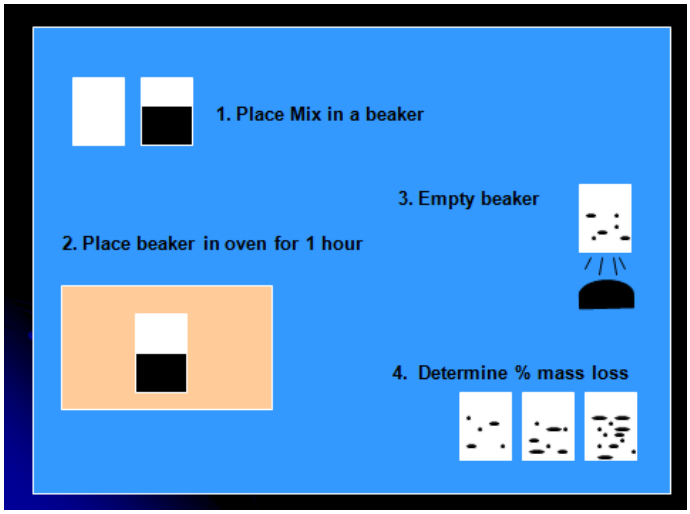
**Determine mix density**

- Determine aggregate specific gravities for fine and coarse mineral aggregate
- Calculate combined specific gravities (oven dry, saturated surface dry, apparent)
- Determine the maximum theoretical specific gravity (Rice test)
- Done at 3.5 to 4.0% binder content
- Determine the amount of asphalt absorption.
- Calculate Binder content:

((.38)(W) + 8.6)(2.620/C)= Binder content
W=% water absorption
C=combined oven dry specific gravity

- Check Draindown using the Schellenberg test

This test is performed in the laboratory in order to determine whether or not an unacceptable amount of binder drains down from the mix. Typically the test is performed at the mix design temperature,




Based on the results of the draindown test, adjust binder content if necessary

- Determine mix density
    - Compact with a Forney like static compactor with a load capacity of at least 25,000 pounds (11400 kg). Statically compact ARFC mix in a 4 inch (100 mm) diameter mold to 2000 psi (14 MPa).
    - Determine density by volumetrics
    - Information used for determining spread, may also calculate voids for information only

**ARFC Typical Design**

- Typically 2 stockpiles: 95% intermediates, 5% fines
- Typical binder content 9.2-9.3% (general range 8.7-9.7%), by weight of mix
- Over PCC consider adding 1% to design binder content

# Appendix G
## ARFC – Mix Design Report

| Gradation (% Passing) | | |
|---|---|---|
| **Sieve Size** | **Grad. W/O Admixture** | **Grad. W/ Admixture** |
| 1.25" | 100 | 100 |
| 1" | 100 | 100 |
| 3/4" | 100 | 100 |
| 1/2" | 100 | 100 |
| 3/8" | 100 | 100 |
| 1/4" | 61 | 61 |
| #4 | 30 | 31 |
| #8 | 9 | 10 |
| #10 | 8 | 9 |
| #16 | 6 | 7 |
| #30 | 4 | 6 |
| #40 | 4 | 6 |
| #50 | 3 | 4 |
| #100 | 2 | 3 |
| #200 | 1.6 | 2.6 |

| **Properties** | **Result** | **Specification Requirement** |
|---|---|---|
| Mix: | | |
| Bulk Density (lbs./cubic ft.) | 126.4 | |
| Asphalt Absorption (%) | 0.82 | 1.0 max. |
| Aggregate: | | |
| % Abrasion at 100 Rev.: | 5 | 9 max. |
| 500 Rev.: | 22 | 40 max. |
| Sand Equivalent: | 67 | 55 min. |
| % Single Crushed Faces | 100 | 70 min. |
| Flakiness | 15 | 25 max. |
| % Carbonates | 1.3 | 30 max. |
| O.D. Coarse Sp. Gr. | 2.732 | 2.35 - 2.85 |
| O.D. Fine Sp. Gr. | 2.862 | |
| O.D. Combined Sp. Gr. | 2.743 | |
| Comb. Water Absorption (%) | 1.82 | 2.50 max. |

Other Mix Properties:

**Aggregate Samples:**

| Lab: | Type | From | Date | Source | 1" | 3/4" | 1/2" | 3/8" | #4 | #8 | #40 | #200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -3/4" | STOCKPILE | | | 100 | 100 | 100 | 100 | 24 | 3 | 2 | 1.3 |
| | FINE | STOCKPILE | | | 100 | 100 | 100 | 100 | 99 | 82 | 23 | 3.6 |

| Source | Description |
|---|---|

**Specific Gravity Tests:**

| Test # | Type | Source | O.D. Sp. Gr. | S.S.D. Sp. Gr. | Water Absorption | Used in Design? | Tested On: |
|---|---|---|---|---|---|---|---|
| 1 | Fine | | 2.710 | 2.776 | 2.46% | No | -#4 |
| 2 | Fine | | 2.862 | 2.882 | 0.70% | Yes | -#8 |
| 1 | Coarse | | 2.724 | 2.777 | 1.95% | No | +#4 |
| 2 | Coarse | | 2.732 | 2.784 | 1.89% | No | +#8 |

**Rice Tests: (Without Admixture)**

| Test # | Date | % Asphalt | Maximum Density | Effective Sp. Gr. | Type of Flask | Used in Design? |
|---|---|---|---|---|---|---|
| 1 | | 5.0 | 161.1 | 2.796 | Small | Yes |

**Marshall Tests:**

| Test # | Method | Date | % Asphalt | % Admix | Bulk Dens. | Sta-bility | Flow | Used in Design? |
|---|---|---|---|---|---|---|---|---|
| 1 | Mech | | 6.5 | 1.0 | 146.0 | 2865 | 11 | Yes |
| 2 | Mech | | 7.5 | 1.0 | 146.7 | 2710 | 11 | Yes |
| 3 | Mech | | 8.5 | 1.0 | 146.6 | 2398 | 14 | Yes |

# The AR Journey Begins