Asphalt Rubber
Open Graded Friction Course

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***ABSTRACT**: Historically open graded friction course hot mix materials have had poor performance when utilizing conventional asphalt cement or polymer modified asphalt cement as the binder. High air void contents (14 – 18 %) can lead to moisture damage and premature aging which will accelerate the stripping of the mix from the roadway and inevitably unsafe driving conditions. This lack of long-term performance along with required increased maintenance activity and costs caused many jurisdictions to curtail use of this type of rehabilitation strategy.*

This paper will discuss the use of asphalt rubber materials as the binder for open graded friction course applications. Proper binder design, mix design and construction procedures will be discussed and applied to the benefits concerning the use of asphalt rubber open graded friction course (AR-OGFC).

KEY WORDS: Asphalt cement, crumb rubber modifier, asphalt rubber, binder and mix properties, noise reduction, open graded friction course.

I. Introduction

While the earliest roads can be traced as far back as 1500 B.C., the first architects of modern roads were the Romans. They built over 50,000 miles of roadways between 300 B.C. and A.D. 300. The Roman roads were well-planned and beautifully built and many remain today. In 1599 the first classification of asphalt and attempts to trace the connection between asphalt and petroleum were made. In 1777 the first exposition of the modern theory concerning the origin of asphalt was performed by P.C. Lesage in France. In 1780 the first asphalt composition of prepared roofing was constructed in Sweden. In 1802 rock asphalt was used in France for flooring, bridge deck surfacing and sidewalk surfacing. In 1815 John L. McAdam began building and improving roadways with an interlocked and compacted stone surface. This "macadam" innovation would have a profound impact on the roadways of the future. In 1858 the first modern asphalt road was placed in Paris, in 1869 the first compacted asphalt pavement was placed in London and in 1870 the first United States asphalt roadways were placed in Newark, New Jersey.

With the development of the automobile in the late 1800's the need arose to provide smoother and safer highways. These highways needed to handle heavier vehicles capable of higher speeds than the horse drawn wagons previously used. Developments critical to the success of the automobile included the discovery of crude oil and the manufacture of a temperature stable rubber from latex materials. Both of these events took place in the latter years of the 1800's. The major problem for the early refining industry was that the production of fuels from crude petroleum was not very efficient and created a substantial waste product with serious disposal problems. This waste product we know as asphalt and was found to be useful in the stabilization of soils and when combined with particular gravel materials, as proven by McAdam, improved the performance of the early roadways that were constructed. The refining industry realized that if the cost of this waste asphalt were subsidized they could essentially eliminate their disposal problem and at the same time provide improved highways. This in turn would lead to increased use of motor vehicles and higher demands for fuel. Through tremendous research and experimentation with this "stable rubber" the tire was developed for the automobile. The tire manufacturing industry, the automobile industry or the general public had no concept as to the solid waste disposal problem that would evolve over the years, from scrap or used tires.

Evolvement of asphalt rubber technology will be discussed as a continuance regarding the development of hot mix asphalt materials, particularly as the concept of asphalt rubber binder and the open graded friction course was conceived, tested and implemented.

II. Asphalt Rubber Binder

As defined by ASTM D8, standard definitions of terms relating to materials for roads and pavements, "asphalt rubber is a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15% by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles."

Asphalt rubber binder materials have been used in spray apply membrane applications since the late 1960's and as a binder in hot mix materials since the mid 1970's. The use of asphalt rubber as a binder in open graded friction course began during this timeframe, but did not gain acceptance as a viable and predictable material until the mid 1980's. Construction evaluated research (CER) lasted nearly 10 years. The binder is usually made up of asphalt cement, an asphalt extender oil (if necessary) and reclaimed ground tire rubber. The asphalt cement is usually SHRP graded to co-inside with the climatic region that the open graded friction course would be placed, as shown in Table 1.

Table 1: Asphalt Cement Requirements

Property	Type 1 Hot Climate	Type 2 Moderate Climate	Type 3 Cold Climate
Grade of Base Asphalt Cement	PG 64-16	PG 58-22	PG 52-28
Rotational Viscosity: 350°F (177° C); pascal seconds	1.5 – 4.0	1.5 – 4.0	1.5 – 4.0
Penetration: 39.2° F (4° C), 200 g, 60 sec. (ASTM D 5); minimum	10	15	25
Softening Point (ASTM D 36); ° F (° C), minimum	135	130	125
Resilience: 77° F (25° C) (ASTM D 5329); %, minimum	30	25	15

The extender oil is specified as a resinous, high flash point, aromatic hydrocarbon meeting the requirements in Table 2. It is important to note that the extender oil is not routinely used as part of the binder unless the low temperature properties of the asphalt cement need to be further adjusted or modified.

Table 2: Asphalt Extender Oil Requirements

Viscosity, SUS, at 100° F (38° C) (ASTM D 88)	2500 minimum
Flash Point, COC, ° F (° C) (ASTM D 92)	390 minimum
Molecular Analysis (ASTM D 2007):	
Asphaltenes, Weight %	0.1 maximum
Aromatics, Weight %	55.0 maximum

The Crumb Rubber Modifier (CRM) is produced primarily from the processing of automobile and/or truck tires by ambient grinding methods. Included in the specifications are limits on the fiber content (maximum of 0.5 % by weight), moisture content (maximum of 0.75 % by weight), mineral contaminants (maximum of 0.25 %) metal contaminants (no visible metal particles as indicated by thorough stirring of a 50 gram sample with a magnet) and maximum particle length at 3/16 of an inch (4.76 mm). When tested in accordance with ASTM C 136 utilizing a minimum 50 gram sample, the resulting CRM gradation, will meet the requirements in Table 3.

Table 3: Crumb Rubber Modifier (CRM) Gradation Limits (Percent Passing)

Sieve Size	Type 1	Type 2
No. 8 (2.36 mm)	100	---
No. 10 (2.00 mm)	95 - 100	100
No. 16 (1.18 mm)	40 - 60	70 – 100
No. 30 (600 µm)	0 - 20	25 – 60
No. 50 (300 µm)	0 - 10	0 – 20
No. 100 (150 µm)	0 - 4	0 – 10
No. 200 (75 µm)	---	0 - 5

The asphalt rubber binder design is generally performed by the asphalt rubber manufacturer, who is normally required to supply a binder formulation to the project Engineer a minimum of 10 days before pavement construction is scheduled to begin. This information consists of the type, source and grade of the asphalt cement to be used along with the recommended percentage of asphalt cement by total weight of the asphalt rubber binder. The same information is required for the CRM material. The proportion of CRM is specified to be between 15 and 23 percent by total weight of the asphalt rubber binder mixture. The asphalt rubber binder is required to be uniformly blended and reacted and shall meet the physical parameters listed in Table 4 for the type of binder specified.

Table 4: Specifications for Asphalt Rubber Binder

Climate Type	---	Hot	Moderate	Cold
Apparent Viscosity, 350° F (177° C) Spindle 3, 20 RPM, cP, (ASTM D 2196)	Min Max	1,500 5,000	1,500 5,000	1,500 5,000
Penetration, 77° F (25° C), 100g, 5 sec.: 1/10 mm. (ASTM D 5)	Min Max	25 75	25 75	25 75
Penetration, 39.2° F (4° C), 200g, 60 sec.: 1/10 mm. (ASTM D 5)	Min	10	15	25
Softening Point: ° F(° C): (ASTM D 36)	Min	135	130	125
Resilience, 77° F (25° C): %: (ASTM D 3407)	Min	25	20	15
TFOT Residue, (ASTM D 1754) Penetration Retention, 39.2° F (4° C): %	Min	75	75	75

The climatic regions referred to in Table 4 will have the following ranges of temperature:

Hot Climate	Average monthly maximum 110° F (43° C) or greater. Average monthly minimum 30° F (-1° C) or greater.
Moderate Climate	Average monthly maximum 110° F (43° C) or lower. Average monthly minimum 15° F (-9° C) or greater.
Cold Climate	Average monthly maximum 80° F (26° C) or lower. Average monthly minimum 15° F (-9° C) or lower.

The physical properties of the asphalt rubber binder depend on the physical and chemical properties of the individual components used along with the interaction conditions. These components, as previously discussed, are an important consideration and should be utilized to allow the asphalt rubber binder to have the appropriate stability of properties. Other modifiers may be added to further enhance the desired properties of the binder such as non-tire rubber materials, surfactant additives and polymeric additives. The interaction that takes place between the asphalt cement, the CRM and other additives (if required) is time and temperature dependent. Higher temperatures result in a quicker interaction and may result in greater amounts of swelling of the CRM particles. Therefore, testing of an asphalt rubber blend should be performed at a variety of interaction periods to evaluate stability and retention properties. It has been established and accepted by the asphalt rubber industry that the viscosity of the reacted binder relates directly to the desired physical and chemical properties established during the laboratory binder design process. Either digital or dial reading viscometers may be used in the laboratory and all measurements are recorded at the peak of the reading. For LV series models, use spindle 3 at 12 rpm. For RV and HA models, use spindle 3 at 20 rpm. It is important to note that for field testing of viscosity that the Haake-type viscometers may be substituted.

III. Asphalt Rubber Binder – Mixing and Production

The asphalt cement and the CRM are combined and blended together in a blending unit that has a two stage continuous mixing process capable of producing a homogeneous mixture of asphalt cement and CRM, at the mix design specified ratios. The unit is equipped with a CRM feed system capable of supplying the asphalt cement feed system, as not to interrupt the continuity of the blending process and shall be capable of fully blending the individual CRM particles with the asphalt cement. In conjunction with the asphalt rubber blending equipment an asphalt rubber storage/reaction tank is utilized that is equipped with a heating system to maintain the temperature of the binder between 325° F (163° C) and 375° F (191° C) during the reaction, pumping and combining the binder with the aggregate. This equipment shall have an internal mixing device, oriented horizontally in the tank, capable of maintaining a uniform mixture of the asphalt cement and CRM. Finally, a supply system is utilized which is equipped with a pump and a direct interlock/metering device capable of delivering the asphalt rubber binder by volume to the hot mix plant at the percentage required by the job-mix formula.

The intensity of mixing during the interaction time period can influence the asphalt cement and CRM blend properties. Differences in mixing and shearing intensity can vary from low speed agitation that gently keeps the rubber particles in suspension to a high speed shearing that can mechanically break down the rubber particles. With low speed agitation, the asphalt components are simply absorbed as the rubber particles swell with little exchange of the rubber polymer into the asphalt cement. During high intensity mixing, the rubber particles swell and soften due to the asphalt cement absorption, and the high energy mixing tends to shear off the softened rubber outer surfaces and produces a dissolved rubber component in the asphalt phase of the material. This is a very important factor regarding the overall properties of the asphalt rubber binder material and why the CRM gradation is very important along with the type of blending equipment that is utilized. Having the rubber particles suspended in the liquid phase of the asphalt cement as one aspect of the overall modification and at the same time having that liquid phase modified through the blending process allows for a “double modification” of the asphalt rubber binder.

The procedure for the blending and reacting of the various components is quite simple. The temperature of the asphalt cement is required to be between 375° F (191° C) and 450° F (232° C) at the addition of the CRM. The blending of the two components takes place as previously discussed, as does the transfer of the blend into the reaction vessel. The temperature of the asphalt rubber mixture is maintained at a minimum of 350° F (177° C) during the reaction period. After the binder has reacted for a minimum of 30 minutes, has been tested for viscosity and has met the viscosity requirements, the asphalt rubber material is metered into the mixing chamber of the asphalt concrete production plant at the percentage required by the job-mix formula.

IV. Asphalt Rubber Open Graded Friction Course – Production

Open Graded mixtures using asphalt rubber binder can be classified into three basic types depending on the binder content used. The Free Draining Friction Course provides a friction course which has skid resistance and draining characteristics similar to a conventional open graded friction course. The use of asphalt rubber binder will provide improved durability and permits the use of higher mix temperatures for cool climatic conditions. The typical asphalt rubber binder contents for this type of open graded friction course range from 7 to 8.5 percent by aggregate weight and normally contain 16 to 19 percent air voids when compacted using a 50 blow per side Marshall procedure at 275° F (135° C). This procedure is used for all three types of mixtures. The Durable Friction Course utilizes a binder content that ranges from 8.5 to 10 percent by aggregate weight. This mix type has much higher binder film thickness which results in increased durability, but with somewhat lessened drainage capacity, and has an air void range from 11 to 15 percent. The Plant Mix Seal utilizes a binder content that ranges from 9 to 11 percent by weight of aggregate and generally has from 8 to 12 percent air voids. The high binder content produces a mix with improved aging resistance, durability and resistance to reflective cracking. Other types of testing have been performed on the open graded mixtures such as binder drain off tests, permeability tests and stripping (moisture sensitivity) tests. The use of asphalt rubber binder has shown a significant improvement in binder drain off even with the increased binder contents. The reduced drain off, even at higher temperatures, is due to the higher viscosities of the asphalt rubber binder materials. Permeability testing has shown that when comparing asphalt rubber open graded mixtures to conventional open graded mixtures that the permeability is equal or better for the asphalt rubber mixes, even at higher binder contents. Different types of stripping tests have been used some considered less severe than others. Every type of test that has been used does show a benefit when asphalt rubber binder is used in open graded mixes. Much of this improvement is due to the higher binder contents and resulting increase in film thickness.

The aggregate utilized for the production of the asphalt rubber open graded friction course is composed of hard durable particles of crushed stone, crushed gravel, crushed slag, or expanded clay lightweight aggregate. This material is required to be free from clay balls or lumps, organic or decomposed materials, soft particles, adhered dust or deleterious coatings. Mineral filler, if used, shall meet the requirements of ASTM D 242 or AASHTO M 17. The gradation of the aggregate shall meet the limits listed in Table 5, when tested in accordance with ASTM C 136 or AASHTO T 11 and T 27.

Table 5: Aggregate Gradation Requirements (Percent Passing)

Sieve Size	3/8 inch (9.525 mm)	1/2 inch (12.70 mm)
1/2 inch (12.70 mm)	100	95 - 100
3/8 inch (9.525 mm)	85 - 100	75 – 95
No. 4 (6.35 mm)	22 - 55	20 – 45
No. 8 (2.36 mm)	5 - 15	5 – 15
No. 30 (600 µm)	0 - 10	0 – 10
No. 50 (300 µm)	-----	-----
No. 200 (75 µm)	0 - 5	0 - 5

The mineral admixture (if required) is mechanically mixed with the mineral aggregate prior to mixing the mineral aggregate and the asphalt rubber binder. A direct spray of water may be required to control the loss of the mineral admixture or to comply with any mix design stipulation for wet mixing of the aggregate and admixture.

It is important that the design gradation be selected on the course side of the band so that sufficient voids are available to accommodate the CRM particle size, increased binder content and greater film thickness generally associated with asphalt rubber open graded friction course paving materials. The overall aggregate quality is also very important to the performance of the asphalt rubber open graded friction course. The increased stone to stone contact of these types of hot mix materials requires the use of hard and durable crushed stone or gravel. The following requirements for aggregates to be utilized in asphalt rubber open graded friction course materials are listed in Table 6.

Table 6: Physical Requirements for Aggregate Materials

Fractured Faces (Retained on No. 8)	2- fractured faces 1- fractured face	90 % minimum 95 % minimum
Abrasion Loss (AASHTO T 96)	100 revolutions 500 revolutions	8 % maximum 35 % maximum
Sand Equivalent (AASHTO T 176)		55 minimum
Clay Lumps & Friable Particle in Aggregate (ASTM C 142)		1.0 % maximum
Moisture Absorption		2.5 % maximum

If the specifying agency uses other testing perimeters not shown here which eliminate poor quality aggregates, any such test and appropriate limits should also be included in the proposed specification to insure the overall quality of the aggregates used to manufacture the asphalt rubber open graded friction course hot mix material.

There are basically two types of hot mix asphalt plants, the Batch and Drier Drum type. The addition and mixing of the asphalt rubber binder should be accomplished with one of these two types of plants. The Batch mix plant normally consists of a cold aggregate storage and feed system, an aggregate weigh hopper and a twin-shaft pugmill mixing unit. This type of plant may be equipped with surge or storage bins for short term holding of the open graded friction course until spreading. The Drier Drum mix plant normally consists of a cold aggregate storage and feed system, an automatic weighing system, drier-drum mixer and surge or storage bins for the short term holding of the open graded friction course material until spreading. Both types of hot mix plants should be capable of producing a paving mixture meeting all of the requirements contained in the project specifications. Fundamentally, the plant will provide the proper aggregate gradation, asphalt rubber binder content and mixing temperature.

V. Asphalt Rubber Open Graded Friction Course – Application Procedures

Trucks for the hauling of the open graded friction course material from the hot plant to the lay down site can be end dump, belly or bottom gate dump or moving bottom (horizontal discharge). The truck beds should be clean of prior hauled materials such as dirt, mud and aggregates. Just prior to the loading of the mixture, the truck bed is sprayed with a light application of soapy solution or silicone emulsion to reduce sticking of the mixture to the bed of the truck. Oiling of the beds with kerosene or diesel fuel is not permitted and can cause adverse effects on the asphalt rubber open graded friction course hot mix material. If an end dump type of truck is used it is important not to allow the bed of the truck to push down on the receiving hopper of the paving machine or have too short of a bed which could result in mixture spillage in front of the paving machine. If a belly or bottom gate dump is used the hot mix material is not dumped at a distance greater than 150 feet in front of the paving machine. The loading equipment or pickup machine is self-supporting and shall not exert any vertical load on the paving machine.

The application of the asphalt rubber open graded friction course is accomplished by means of a self-propelled, mechanical spreading lay down machine. This machine should have a tamping bar, vibratory screed or strike-off assembly capable of distributing the material, without segregation, to not less than the full width of a traffic lane and to the depth needed to achieve the minimum compacted thickness or finished grade as required. The screed is required to be equipped with a heating unit that maintains the temperature needed to prevent tearing, shoving or gouging of the paving mixture, which is major concern when placing the asphalt rubber open graded friction course. Paving equipment that leaves ridges, indentations or other marks that cannot be eliminated by adjustment in the operation of this equipment or by the breakdown or finish rolling, should not be used.

The compaction of the asphalt rubber open graded friction course is normally accomplished by the use of three static wheel compactors, operating with the drive wheel in the forward position and weighing a minimum of eight tons (7.26 t). These compactors are equipped with a watering system to prevent sticking of the open graded friction course material to the steel drums. The drums are required to be of sufficient width that when staggered, two compactors can cover the entire width of the paving lane with one pass. Two compactors are utilized for the initial breakdown and are maintained no more than 300 feet (91.44 m) behind the paving machine. The remaining compactor shall follow as closely behind the initial breakdown as possible. As many passes as can be achieved should be made with the compactors, resulting in a smooth surface that is reasonably true to the required lines, grades, and dimensions. The compactive effort should be complete before the temperature of the asphalt rubber open graded friction course falls below 220° F (104° C). In many cases when the final smoothness is an incentive the contractor may add an additional finish compactor to achieve the maximum smoothness possible. At no time will pneumatic compactors be allowed due to the increased adhesiveness of the asphalt rubber open graded friction course to the rubber tires on these types of compactors.

Transverse joints are made the same as with conventional hot mix materials. Longitudinal joints are made by overlapping onto the previously placed and compacted lane, two or three inches. The raker should then move the two or three inches of overlap hot mix just past the edge of the previously placed lane and leave this extra material there! Do not throw it two or three feet on top of the new lane! This extra material needs to be left at the longitudinal joint to make a good tight joint. The breakdown compactor should stay approximately one foot away from the new longitudinal joint area until the rest of the new lane has been compacted at least one pass. Then the breakdown compactor should then roll the one foot joint area until a smooth joint is made. This procedure will assure enough material is at the longitudinal joint area to be well compacted by the steel wheel compactors to produce a more dense and longer lasting longitudinal joint.

The hot plant, lay down machine and the haul trucks should be coordinated to insure a steady, consistent project flow. Each stage of the process must operate consistently at the same pace. The hot plant should produce material at a steady rate, not at so high a rate that the haul trucks back up at the paving site. In some cases, mix production may be stopped to wait for the trucks to return. This situation usually hampers the paving operation also. Generally the paving machine operator speeds up in order to get the backed up trucks back to the hot plant and then sits idle waiting for their return. This hurry-up and wait routine causes inconsistency at the hot plant, and with the lay-down and compaction work on the roadway. This also adversely effects the production, causes undue wear and tear on the paving equipment and most importantly produces a lower quality pavement. If the paving machine is going to be stopped for more than 10 minutes it should be moved forward to keep the hot mix material in the auger and under the screed of the paving machine from cooling too much.

VI. Conclusions

The use of CRM as a modifier in asphalt cement can allow for a duel modification of the blended binder. The CRM also has specific additives contained in it as part of the tire manufacturing process. These additives allow for the binder to be resistant to aging and to maintain viscoelastic properties for a much longer period of time as compared to conventional asphalt or other modified asphalt binder materials.

The asphalt rubber binder is typically designed for three nominal climatic ranges – hot, moderate and cold. The increased viscosity allows for increased film thickness which enhances aggregate retention, eliminates drain-down problems, increases resistance to moisture damage, increases resistance to bleeding, flushing and deformation and reduces aging of the mix.

Proper selection of mineral aggregate is very important for the production of asphalt rubber open graded friction course applications.

Asphalt rubber open graded friction course materials utilize higher binder contents than conventional hot mix materials, which increases their durability and flexibility (resistance to cracking). The increased stiffness of the asphalt rubber binder at high temperatures along with the improved flexibility at low temperatures (range of performance), and the improved stone to stone contact of these types of open graded mixes provides increased resistance to rutting.

Other benefits include: cost effectiveness compared to other types of rehabilitation strategies along with ease of construction, noise level decrease, increased skid resistance, water draining characteristics and the tolerance to higher stress and strains from the underlying pavement.

The industry has over 35 years of experience concerning the asphalt rubber binder design and formulation. We have over 20 years of experience, including construction evaluated research (CER), concerning open graded friction course design and placement. It has been proven that open graded friction course mixes containing CRM are no harder to work with in the field than the same mixes manufactured with conventional paving grade asphalt cement or other modified asphalt cement. By using reasonable care to assure adequate placement temperature, compaction and good construction practice we can build cosmetically appealing, very high quality pavements containing asphalt rubber binder and at the same time utilize an abundant resource, scrap tires.

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VIII. Bibliography/References

[FED 93] FEDERAL HIGHWAY ADMINISTRATION, Crumb Rubber Modifier – Workshop Notes. Design Procedures and Construction Practices; Reno, Nevada, March 1993.

[CHE 82] CHEN, N.J., DIVITO, J.A., AND MORRIS, G.R. “Finite Element Analysis of Arizona’s Three Layer System of Road pavements to prevent Reflective Cracking”. Proceedings, AAPT, Vol. 51, 1982, p.p. 150 – 168.

[VAN 86] VANKIRK, J.L. “The Effect of Fibers and Rubber on the Physical Properties of Asphalt Concrete” California Department of Transportation, Report Number CA/TL – 85/18 June 1986.

[CHE 89] CHEHOVITS, J.G. “Design Methods for Hot-Mixed Asphalt-Rubber Concrete Paving Materials” Proceedings, National Seminar on Asphalt Rubber, Asphalt Rubber Producers Group, Kansas City, Missouri October 1989.

[AND 92] ANDERTON, G. “Physical Properties and Aging Characteristics of Asphalt Cement and Asphalt Rubber Binders”. Asphalt Rubber Producers Group, Phoenix Arizona February 1992

[USA 92] U.S. ARMY CORPS OF ENGINEERS AND ASPHALT RUBBER PRODUCERS GROUP. “Summary of Research on Asphalt-Rubber Binders and Mixes (CPAR) Program”. July 1992.

[ISI 94] INTERNATIONAL SURFACING, INC. “Guide Specification for Open and Gap Graded Asphalt-Rubber Concrete Pavements”. February 1994

[MAT 00] MODIFIED ASPHALT TECHNOLOGIES, INC. “Placement and Compaction Procedures for Crumb Rubber Modified (CRM) and Asphalt Rubber Concrete (ARC) Pavements – Open, Gap and Dense Graded”. Revised January 2000.

[DEC 99] HICKS R.G. AND EPPS J. A. “Quality Control for Asphalt Rubber Binders” Rubber Pavements Association (RPA) December 1999.

[FEB 99] WAY G. B. “Asphalt Rubber – The Arizona Experience” Arizona Department of Transportation Materials Group, Asphalt Rubber 1999: A Global Summary of Practices. Rubber Pavements Association (RPA) International Symposium, Tempe Arizona. February 3, 1999.

[FEB 92] SHIRLEY, E. “Memorandum to all District Directors” CalTrans Reduced Thickness Guidelines When Utilizing Asphalt Rubber Hot Mix – Gap Graded (ARHM-GG)”. February 1992

[OCT 98] HICKS R.G. AND EPPS J. A. “Life Cycle Costs for Asphalt-Rubber Paving Materials” Rubber recycling 98, Toronto Canada. October 22 and 23, 1998.

[ ] THE ASPHALT INSTITUTE. “Asphalt Handbook - Manuel Series No. 4 (MS-4)” 1989 Edition.

[ ] GENAT, R. MOTORBOOKS INTERNATIONAL “Road Construction” 1995 Edition.