Mississippi Transportation Research Center

U.S. Department of Transportation Federal Highway Administration

MISSISSIPPI DEPARTMENT OF TRANSPORTATION

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Open Graded Friction Courses for HMA Pavements

REPORT NO.
FHWA/MS-RD-13-207

Prepared by
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December 30, 2013

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FINAL REPORT

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Prepared in Cooperation with the Mississippi Department of Transportation and
the U.S. Department of Transportation, Federal Highway Administration

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Mississippi State, MS 39762

December 30, 2013

Technical Report Documentation Page

1.Report No. FHWA/MS-DOT-RD-13-207	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Open Graded Friction Courses for HMA Pavements		5. Report Date December 2013 6. Performing Organization Code
7. Author(s) Thomas D. White and James L. Hillabrand		8. Performing Organization Report No. MS-DOT-RD-13-207
9. Performing Organization Name and Address Mississippi State University Department of Civil Engineering P.O. Box 9546 Mississippi State, MS 39762		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Federal Highway Administration Mississippi Department of Transportation		13. Type Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A laboratory study was conducted to evaluate OGFC mixtures meeting current Mississippi specifications. In addition, materials included a second 12.5 mm gradation and an asphalt rubber binder. The additional 12.5mm gradation was selected to evaluate application of the asphalt rubber binder. Specifically, the asphalt rubber OGFC was included for its potential of noise reduction. Factors in the study included gravel and Gravel/Limestone aggregate combinations, three gradations, and two asphalt binders, PG 76-22 and Ground Tire rubber (GTR) PG 76-22.

Laboratory tests were conducted to evaluate the effect of design mixtures relative to aggregate type, gradation, and binder type. Tests included two permeability tests, MT-84 and White falling head test; Stripping, MT-63; sound absorption, ASTM E1050; dynamic modulus, AASHTO TP 62; and interface bond strength, direct shear.

17. Key Words Open Graded Friction Course, OGFC, Noise, Properties, Rubber		18. Distribution Statement Unclassified	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background

Open Graded Friction Courses (OGFC) decrease hydroplaning potential, spray, noise, underlying pavement temperature, and captures contaminants. Test sections of OGFC were built in Mississippi in the 1970's with local aggregate and neat asphalt. These sections performed poorly, exhibited stripping and sever raveling. As a result, only recently has OGFC been reconsidered for use by the Mississippi Department of Transportation (MDOT). Based on the renewed interest a test section of OGFC was built in the spring/summer of 2007. The test section is located on I-55 in Copiah County. Test section condition and in situ permeability were studied over a two year period in six month increments. Results of that study are reported by White and Ivy (2009).

Because of relatively high annual rainfall in the state, the potential for OGFC to address hydroplaning is the most important function for the driving public in Mississippi. Associated tire/vehicle generated spray is also a safety issue and its reduction increases visibility. Noise from tire/pavement acoustical coupling is becoming more important where highways pass through residential and urban areas. Decrease in the pavement temperature profile even a few degrees could increase underlying HMA stiffness a measurable amount. Contaminants dropped by and washed off vehicles and normally carried in dense pavement runoff are retained in the OGFC, which reduces surface water contamination.

A more in-depth laboratory and field evaluation of OGFC is needed that considers possible aggregate gradation and rubber modified binders.

1.2 Objectives

The initial objective of this project was to conduct a combined laboratory and field study to further document characteristics of OGFC meeting current and anticipated MDOT specifications, although, ultimately, the field sections were not constructed. In addition, materials to be evaluated were expanded to include two 12.5 mm gradations and the use of asphalt rubber binder. Inclusion of the additional 12.5mm gradations was to evaluate a larger maximum size aggregate mixture and application of ground tire rubber binder. Study of the ground tire rubber asphalt OGFC will address potential for noise reduction attributed to these mixtures. Noise reduction is becoming more important in residential and urban areas.

1.3 Approach

A laboratory study was conducted to evaluate OGFC materials and their performance. As shown in Table 1, aggregate materials included in the study were gravel and a gravel /limestone combination. Three gradations were utilized, the existing MDOT 9.5mm OGFC gradation, a new MDOT 12.5mm gradation, and a 12.5mm-coarse gradation. The 12.5mm-coarse gradation was adopted from the Florida Department of Transportation (FLDOT). Two binders were included in the study, PG 76-22 and PG 67-22 blended with ground rubber. The combinations of materials to be evaluated are shown in Table 1.1.

Table 1.1 Material Combination's Test Matrix

Type	Gradation	PG 76-22	PG 67-22/AR
Gravel	MS 9.5	X	
	MS 12.5	X	X
	MS 12.5-Coarse (FL FC-5)	X	X
Gravel/Limestone	MS 9.5	X	
	MS 12.5	X	X
	MS 12.5-Coarse (FL FC-5)	X	X

Gravel and Gravel/Limestone aggregate combinations were selected because these are the most likely aggregates to be utilized in Mississippi OGFC. The three initial gradations are shown in Table 1.2. A new coarse gradation was adopted in place of the FL FC-5. The reasons and process for its adoption will be discussed later in the report.

Table 1.2 OGFC Gradations

Sieve Size – mm (in)	Gradation		
	MS 9.5mm - %	MS 12.5mm - %	MS 12.5mm-Coarse (FL FC-5) - %
19 (3/4)			100
12.5 (1/2)	100	100	85-100
9.5 (3/8)	90-100	80-89	55-75
4.75 (#4)	15-30	15-30	15-25
2.36 (#8)	10-20	10-20	5-10
.075 (#200)	2-5	2-5	2-4

The MS 9.5mm gradation was used in the existing test section on I-55 in Copiah County. The MS 12.5mm gradation is only slightly coarser than the 9.5mm gradation while the MS 12.5-coarse (FLDOT FC-5) is significantly coarser.

Laboratory mixture designs were conducted to evaluate the effect of aggregate type, gradation, and binder type. Tests were also conducted to determine functional properties, performance, and structural evaluation. The tests are shown in Table 1.3.

Table 1.3 Specific Tests

Test	Laboratory	Test Methods
Permeability	X	MT-84, Corps of Engineers Falling Head Perm.
Stripping	X	MT-63
Noise	X	ASTM E1050
Dynamic Modulus	X	AASHTO TP 62
Interface Bond Strength	X	Direct Shear

Functional tests such as for permeability and noise were used to validate benefits of OGFC and provide data to evaluate aggregates, gradations, and binders as well as mix designs. OGFC permeability in the laboratory was conducted using MT-84 and a laboratory version of the device used to evaluate field permeability on the I-55 OGFC test section. Laboratory pavement noise absorption was measured with an impedance tube.

Material layer bond strength was determined in a direct shear test. Structural capacity was addressed by laboratory tests to characterize the OGFC layer in a way that inputs are obtained for the new pavement design guide.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This literature review will be broken into three sections. The first section will review plant mix seal coats, porous friction courses in general, and then specifically open graded friction course (OGFC). This section will also discuss binder, aggregate, and gradations. The next section will discuss ground tire rubber as an additive in both normal asphalt mixtures and in OGFC. The last section will discuss highway related noise. Both the use of OGFC and ground tire rubber has been shown to reduce highway related noise.

2.2 Open Graded Friction Course

Smith, et al (1974) and White (1975) reviewed development in the US of highway open graded friction courses and the parallel airfield porous friction course. Early applications for highways were in western and southwestern states as plant mix seal coats. There were several mix design methods, but in the early 1970s the Federal Highway Administration (FHWA) and the Federal Aviation Administration (FAA) developed mix design procedures and specifications for highways and airfields, respectively.

Smith listed benefits that had been assigned to open-graded surface courses.

1. High speed skid resistance during inclement weather.
2. Reduced hydroplaning potential.
3. Improved roadway smoothness.
4. Reduced splash and spray.
5. Reduced wheel path rutting.
6. Better visibility of painted pavement markings (day and night).
7. Reduced glare at night during wet weather.
8. Reduced highway noise.
9. Retardation of ice formation on surface.

Based on laboratory and field research White (1975) described functions of porous friction course (PFC), the terminology used for airfield OGFC mixtures.

1. High internal voids
   a. Provide internal pressure relief channels.
   b. Provides flow channels for internal drainage of surface water.
   c. Provides temporary storage of a small amount of surface water.
2. Coarse surface macro-texture.
   a. Provides pressure relief channels on the surface.
   b. Provides flow channels for surface water.
   c. Provides, in general, tire-pavement contact above surface water film.

Other reported benefits include:

1. Reduced temperatures in a vertical profile (White, 1976).
2. Reduced pollutants in run-off from pavements (Barrett and Stanard, 2008).

Continued engineering of OGFC has expanded accepted functions. Swan (2013) reported on an application to solve a surface storm water issue. In this application a thicker (3in) OGFC was combined with a drainable aggregate base. This has been an expanding area of OGFC applications. Smith and Stewart (2013) reported on use of a bonded OGFC overlay on a curve of a concrete pavement in Florida. The application greatly reduced the accident rate when grooving the concrete was unsuccessful in doing so.

2.2.1 Binder

Early applications of plant –mix seal coats and OGFC used conventional neat asphalt binder. Adjustments were made with harder grades recommended for higher traffic volumes and higher in service temperatures (Gallaway and Epps, 1976), (Smith, 1976). The performance of OGFC varied from good to poor (Triplett and White. 1976). Asphalt rubber binders evolved in the 1960s although wide spread use did not occur until the early 1990's. A more detailed discussion of use of rubber in asphalt mixes is given below. A polymer modified asphalt using neoprene was marketed in the early 1970's and the performance when used in PFC was good (Johnson and White, 1976). In the late 1980's and 1990's polymer modified asphalts use increased markedly both in conventional HMA and in OGFC. Polymer modified asphalt addressed HMA permanent deformation (rutting) that was being experienced on roads and highways from heavy vehicle loads and volumes. It also became the binder of choice for OGFC. The polymer modified binder was better able to hold aggregate in place, maintain permeability, and cushion aggregate when subject to high volumes of heavy traffic. Fiber addition in the OGFC mitigated the relatively high binder contents used in OGFC. Also, the fiber creates a pseudo mastic usually formed in dense HMA around the finer aggregate (-#40 sizes). As a result, desirable toughness and durability is imparted to the OGFC mixture,

2.2.2 Aggregate

Early investigations of aggregate for highway OGFC considered:

1. Particle shape
2. Number of crushed faces
3. Polishing
4. Toughness and durability

In general, for highway pavements, OGFC aggregate requirements were adopted consistent with aggregate requirements for dense HMA surface mixtures (Gallaway and Epps, 1976, and Smith, 1976). This is true today (MSDOT and FLDOT). The only real contrast was between highway and airfield aggregate requirements for toughness (LA Abrasion) where highway DOT requirements allowed coarse aggregate with LA Abrasion values of 40 to 45. The Federal Aviation Administration (FAA) specification limited LA Abrasion values to 25 (FAA Item 402). This limit was borrowed from a British standard for airfield porous friction course (PFC, i.e. OGFC). The lower LA Abrasion value has the effect of focusing on use of higher specific gravity aggregate.

Gradations of highway OGFC and airfield PFC mixtures are similar. To provide desired characteristics, the most important being permeability, the critical aggregate size for both mixtures is the No. 8 sieve. The percent passing the No. 8 ranges from 0 to 15 percent. The balance of the aggregate, 85 to 100 percent, typically is in the size range from 3/8in to 5/8in to the No.8 sieve, which is a narrow size range.

2.3 Ground Tire Rubber

This section discusses the use of rubber products, specifically use of ground tire rubber in asphalt pavements. Ground tire rubber usually comes from discarded tires that are processed by separating the casings, fabric, and steel. The extracted rubber can be ground to various gradations, but is usually ground to a coarse powder like form similar to the consistency of ground coffee (Figure 2.1). The benefits of using ground tire rubber in asphalt pavement are: 1) reduced noise, 2) increased durability (lifespan), 3) increased traction, and 4) decreased landfill use. The only drawback currently is increased initial costs. Two methods of incorporating crumb rubber into the asphalt mixture are the "wet process" and the "dry process."

In the wet process, the rubber is added to a bulk volume of the asphalt binder and mixed at high temperatures until the mixture is homogenous. Subsequently, the homogenous binder is added to and mixed with aggregate to produce an asphalt paving mixture. In the dry process, the rubber is added to the aggregate before the binder is added in the process of producing the asphalt paving mixture. The wet process is used to produce "asphalt rubber" and the dry process is used to make "rubberized asphalt."

The American Society for Testing 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 percent by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles," (ASTM D 6114 – Standard Specification for Asphalt Rubber Binder). Asphalt rubber is produced at temperatures between 177C/350°F and 191°C/375°F under high agitation to promote the physical interaction of the asphalt binder and rubber constituents as described by the California Department of Transportation (Caltrans, 2003).

Rubberized asphalt (produced by the dry process) is not defined by ASTM. In the dry process, ground tire rubber is considered part of the aggregate, not a binder additive. Asphalt plant mixing temperatures are usually between 160°C/320°F and 188°C/370°F. Field compaction temperatures are 149°C/300°F to 160°C/320°F.

Figure 2.1 Photo of Ground Tire Rubber (Morse, 2007)

Asphalt rubber materials were developed for joint sealing, patching, and as membranes starting in the late 1930s. In the early 1950s, Lewis and Welborn (1954) of the Bureau of Public Roads (BPR) conducted an extensive laboratory study to evaluate the effect of various rubber products on the properties of petroleum asphalts. It was their hope to capture the flexible nature of rubber in a longer lasting paving surface. These early asphalt-rubber formulations provided little or no benefit, and the result was a modified asphalt pavement that cost more and had a shorter service life than conventional asphalt. It wasn't until the 1960s that a successful formulation was developed by Charles H. McDonald.

Charles H. McDonald with the City of Phoenix, Arizona worked extensively with asphalt and rubber materials in the 1960s and 1970s and was instrumental in development of the "wet process" (also called the McDonald process) for producing asphalt rubber blends (Arizona Department of Transportation (ADOT), 2008). He was the first to routinely use asphalt rubber in hot mix patching and surface treatments for repair and maintenance (Epps, 1994). McDonald's early development occurred while traveling across the country inspecting highway material sources for the Bureau of Roads. His mobile trailer's roof cracked and he used asphalt as a quick patching material. However, eventually the asphalt oxidized, became brittle, and cracked from sunlight exposure and vehicle movement. He solved the cracking problem by incorporating rubber in the asphalt used for patching (Carlson & Zhu, 1999 and Winters, 1989).

California removed asphalt rubber from experimental status in 1990. Prior to 1990 federal funds could not be used on asphalt rubber paving projects (with some exceptions) due to its experimental status. The late Sonny Bono, then mayor of Palm Springs and later a US Congressman, spearheaded the effort to remove asphalt-rubber from experimental status in 1991 (Carlson & Zhu, 1999). Now 45 states routinely use rubberized asphalt.

Neither the dry or wet processes require significant plant modifications for use of the material in paving mixtures. In rubberized asphalt, unlike asphalt rubber, little, if any, reaction takes place between the rubber and asphalt. The lack of this reaction leaves the asphalt binder unmodified and does not allow the release of the ultraviolet inhibitors and anti-oxidants contained in the scrap tire rubber. After a lengthy study, the Florida DOT opted not to develop state specifications for the dry process for this reason (Asphalt Rubber Technology Information Center (ARTIC), 2008).

Rubberized asphalt pavement mixtures have generally been used as overlays and surface wearing courses. It has been marketed as having good skid resistance and de-icing properties. For these reasons, it was of some interest in cold regions such as Alaska. Laboratory wheel testing indicates that the higher rubber content mixes may potentially increase the incidence of ice cracking. (Oliver, 1981)

Oregon State University led a study of ground tire rubber modified asphalts sponsored by the FHWA and several states in 1995. They investigated both the "wet" and "dry" processes. However, only the "wet" process material was studied due to the lack of successful "dry" process projects throughout the nation. Currently, some "dry" processes are being marketed in California and other states as an equal to Asphalt-Rubber. Resulting projects have not been in service long enough to meet the "time tested and proven" performance achieved by the "wet" process. (ARTIC, 2008)

2.3.1 Production

Ground tire rubber comes primarily from discarded tires. Tires can be ground up and any metal reinforcement separated in a process such as the one shown in Figure 2.2. This type of separation process called “ambient grinding” is the most widely used. Another option for processing rubber tires is to dip them into liquid nitrogen which makes the rubber brittle and easily broken apart on a press (Figure 2.3). This is referred to as “The Cryogenic Process” and is carried out at very low temperatures (-87°C to -198°C). (Dantas, et al, 2006) Ground tire rubber particles from the cryogenic process are more regularly shaped and have a lower specific surface than the particles produced by the grinding process (Figure 2.4).

When ground, the rubber can be reduced to various particle sizes. Three of the most common grinding tools are a cracker mill, a granulator, and a micro-mill. A cracker mill tears apart scrap tire rubber by passing the material between rotating corrugated steel drums which reduces the size of the rubber to about 4.75 mm to 425 μm. A granulator shears apart the scrap tire rubber by cutting the rubber with revolving steel plates that pass at a close tolerance which reduces the rubber to cubicle particles generally 9.5 mm to 2.0mm in size. A micro-mill can further grind ground tire rubber particles to sizes smaller than 425 μm.

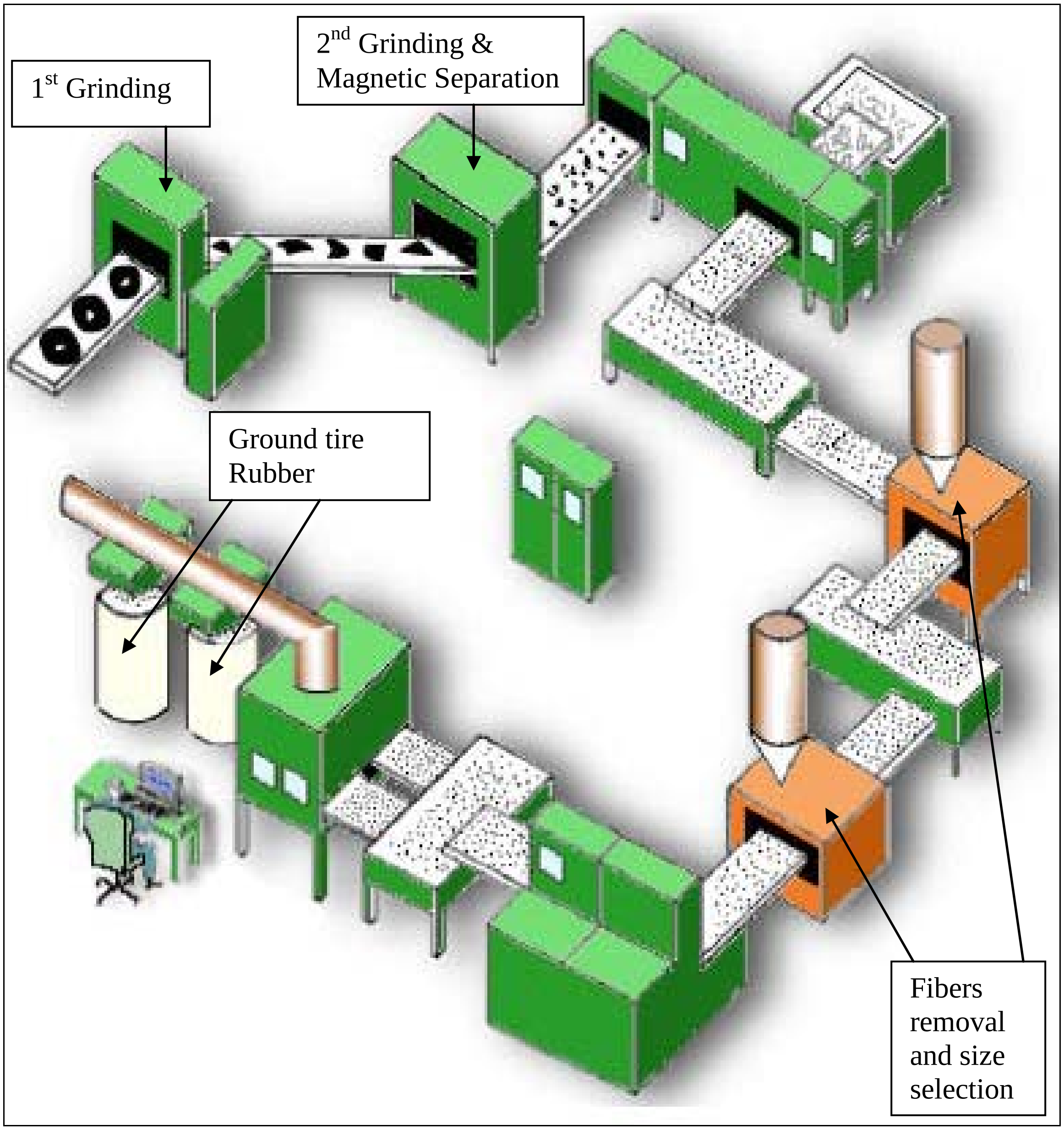

Figure 2.2 Schematic of Ground Tire Rubber Production (Dantas, et al, 2006)

Figure 2.3 Cryogenic Processes (Tire Fragmentation, Cryogenic Tunnel, Granulators, and Collection) (Dantas, et al, 2006)

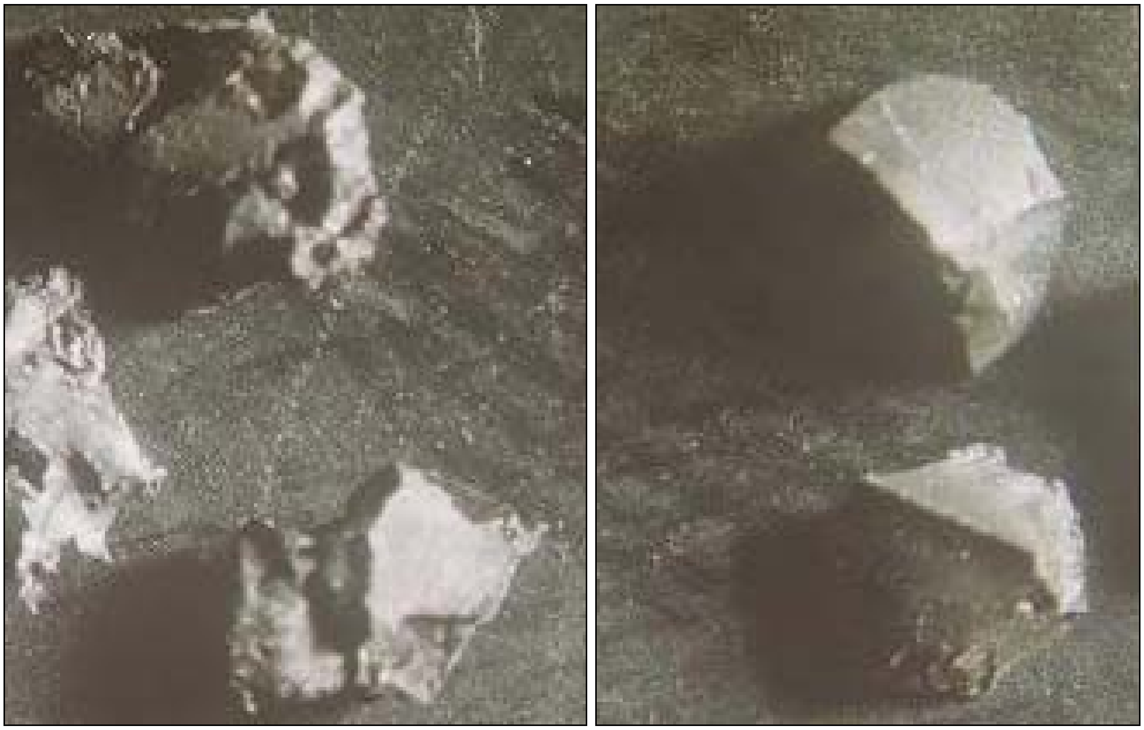

Figure 2.4 Ground Tire Rubber from Ambient Grinding Process (Right) vs. Cryogenic Process (Left) (Dantas, et al, 2006)

2.3.2 Application

Asphalt rubber (AR) or rubberized asphalt (RA) hot mixes are typically most effective as thin (one inch or less) maintenance overlays of flexible or rigid pavements. Also, AR and RA have been found to be most effective when used in open-graded or gap-graded mixes. These types of mixes have high voids that accommodate the asphalt coated rubber particles. In dense graded asphalt concrete (DGAC), the aggregate gradation produces relatively low voids. Also, performance of dense graded mixtures with AR/RA is not improved enough to justify the added cost (Caltrans, 2003).

Asphalt rubber or rubber asphalt products can be used wherever conventional asphalt concrete (AC) or asphalt surface treatments would be used. However, they provide better resistance to reflective cracking and fatigue than DGAC. Temperature is critical for compaction of AR or RA mixtures. Asphalt rubber is stiffer than RA or neat asphalt cement; therefore, higher placement and compaction temperatures are usually required for paving mixtures with AR. Both AR and RA materials are often difficult to hand work because of the stiffer binder and adhesion of the binder to tools.

In the wet process, ground tire rubber makes up about 15% by weight of the binder. The ground tire rubber is not treated as a binder replacement, but rather as a binder additive. In the dry process, more ground tire rubber is typically used than in the wet process, and the ground tire rubber is treated as an aggregate additive, typically between 1 and 3 percent by weight of the total aggregate. The target air voids content in either process for the asphalt mix is 2 to 4 percent, which is usually attained at asphalt binder content in the 7.5 to 9 percent range. (Heitzman, 1991)

2.3.3 Benefits

The primary reason for using asphalt rubber is that it provides improved engineering properties over conventional paving grade asphalt. Asphalt rubber binder can be engineered to perform in any type of climate although performance is better at intermediate to high temperatures. The rubber stiffens the binder and increases elasticity (proportion of deformation that is recoverable) over these pavement operating temperature ranges. As a result, binder temperature susceptibility decreases and pavement deformation (rutting) and fatigue resistance are improved with little effect on cold temperature properties. Asphalt rubber also provides good use of waste tires. Approximately 1,500 tires are used for every lane-mile of rubberized paving. (Caltrans, 2003)

Use of asphalt rubber in paving mixtures can lead to road related noise reduction. The traffic noise reduction shown in Table 2.1 and 2.2 from rubberized paving is similar to the results documented in several non-related studies conducted in recent years, both nationally and internationally. All studies indicate that the noise reduction qualities of rubberized paving do not diminish over time (Bollard and Brennan, Inc., 1999). Most literature on the subject of noise reduction does not differentiate between AR and RA forms in their effectiveness at reducing noise. Generally, it appears that either method reduces noise by 4 to 10 decibels. The gradation of the mix is also a likely factor in the noise reduction.

Table 2.1 Countries Using Rubberized Paving for Noise Reduction (Bollard and Brennan,Inc., 1999)

Country	Year	Reported Noise level Reduction
Belgium	1981	8-10 dB (65-85%)
Canada	1991	Shown noise reduction
England	1998	Project not completed
France	1984	2-3dB/3-5dB (50-75%)
Germany	1980	3dB (50%)
Austria	1988	3+ dB
Netherlands	1988	2.5dB

Table 2.2 States Using Rubberized Paving for Noise Reduction (Bollard and Brennan, Inc., 1999)

State	Counties & Cities	Year	Noise Level Reduction
Arizona	Phoenix, AZ	1990	10dB (88%)
	Tucson, AZ	1989	6.7dBs (78%)
California	Sacramento County	1993	7.7 - 5.1 dB
	Orange County	1992	3-5 dB on Open Graded asphalt
	Los Angeles County	1991	3-7 dB
	San Diego County	1998	Project in process
Texas	San Antonio	1992	Data not Provided
Oregon	Corvallis	1994	Data not Provided

In 1990, the Arizona Department of Transportation (ADOT) compared conventional and asphalt rubber overlays on Interstate 40 near Flagstaff, AZ. The overlay using conventional materials was four inches thick. The asphalt rubber test section was two inches thick. The section is located at about 7000 feet above sea level and experiences nearly 100 inches of annual snowfall. (Carlson & Zhu, 1999) Figure 4 shows the results of each test section. The photo in Figure 5 was taken in 1998 after the test sections had been in service eight years.

Figure 2.5 Comparison of Conventional Overlay (Left) to Asphalt Rubber Overlay (Right) (Carlson & Zhu, 1999)

2.3.4 Limitations

There are increased mobilization costs for AR or RA production, however if the project tonnage is large the unit costs may not be increased significantly. Also, increased costs may be offset by the increased service life, lower maintenance costs, and reduced lift thickness. For small projects, however, the resulting increase costs may not be offset. (Caltrans, 2003)

Construction with AR or RA can be more challenging because temperature is more critical. Asphalt rubber or rubber asphalt must be compacted at higher temperatures than DGAC because AR/RA are more temperature sensitive than typical asphalt binder. Also, open graded or coarse gap graded mixtures may be more resistant to compaction due to the “stone-on-stone” nature of the aggregate structure (Caltrans, 2003). Resistance to compaction will be gradation dependent as well as dependent on layer thickness.

Early or late season construction affects construction and subsequent performance of AR or RA mixtures as well as conventional mixtures. However, this effect is more significant with materials that have been modified to increase high temperature stiffness (such as AR, RA, or polymer modified asphalt) and are being placed in thin lifts. It is recommended construction with AR or RA binders be constrained for the following conditions: (Caltrans, 2003)

- Inclement weather.
- Cold weather with ambient or surface temperatures <13°C/55°F.
- Over pavements with severe cracks (more than 12.5 mm wide).
- Areas where considerable handwork is required.
- Where haul distances are too long to maintain required mix temperature.

2.3.5 Costs

The unit costs of AR or RA are higher than those of conventional or even polymer modified asphalt. The initial cost is one of the reasons AR or RA use is limited to thin lifts. However, this means AR or RA are generally cost effective when used in open-graded surface courses, overlays less than 60 mm thick, chip seals, and interlayer applications. In 2003 Caltrans summarized unit mix costs for HMA with neat asphalt, polymer modified asphalt, and AR. The summary is shown in Table 3. As noted above, in similar applications HMA with AR or RA typically requires less thickness than conventional HMA, and therefore less tonnage.

Table 2.3 Asphalt Costs (Caltrans, 2003)

Asphalt Type	Hot Mix \$/Ton	Chip Seal \$/m²
Conventional	33 -38	1.2-1.5
Polymer Modified	38-44	1.5-1.8
Asphalt Rubber	49-55	3.0-3.6

The equipment used to blend asphalt and rubber requires little, if any, modification to a standard hot mix asphalt plant. As shown in Figure 2.6. the equipment is typically trailer mounted and is transported to the asphalt plant site. Dedicated mixing and reacting tanks are used (AR only) and can be brought on site. Additionally, conventional paving equipment without modifications is used to place the material. The capital investment required for a fully operational asphalt rubber plant is anywhere from $500,000 to $750,000. (Carlson & Zhu, 1999)

Figure 2.6 Asphalt rubber blending unit (Carlson & Zhu, 1999)

A mixture in which RA is added is accomplished in a "dry process" described below. However, the ground tire rubber is treated as an aggregate. The only issue is that care is required in the metering process because of the relative small quantities of ground tire rubber used.

2.3.6 Environmental Considerations

The distinctive odor of asphalt rubber can trigger concerns about emissions because there is a natural tendency to think that strong odors indicate a hazard. This is not necessarily true. Plant "stack tests" were performed during asphalt rubber hot mix production in New Jersey (1994), Michigan (1994), Texas (1995), and California (1994, 2001). The results indicate emissions measured during production of hot mix with asphalt rubber are about the same as for conventional hot mix (Caltrans, 2003). Ground tire rubber is produced with various gradations. However, no gradations have rubber particles small enough to become airborne as particulate matter.

Fume emissions have been studied extensively in a number of asphalt-rubber projects since 1993 and in all cases been determined to be below the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limits. (Gunkel, 1994) A study conducted for the Michigan Department of Natural Resources in 1993 compared conventional HMA to Asphalt Rubber Hot Mix. Fifteen percent asphalt rubber grindings were added to the asphalt binder. The findings of this study were significant in that many of the conventional mix materials had higher, but still acceptable emissions. Very few emission studies were conducted following this report. (Carlson & Zhu, 1999)

The use of ground tire rubber in asphalt overlays will not solve the waste tire issue alone, but any contribution to solving the problem is beneficial. It is far better to remove tires from the waste stream, regardless of disposal method, than to allow the build up of uncontrollable waste tire stockpiles. The emissions from equipment and facilities that process waste tires will always be lower than the emissions from a waste tire fire burning out of control in the open demonstrated by Figure 2.7.

Figure 2.7 Tire Fire in Oxford, CA of approximately 6 to 8 Million Tires (Carlson & Zhu, 1999)

2.3.7 Production

Some equipment may differ among AR or RA types and manufacturers, but the processes are all still similar. Temperature is always critical during the production of AR or RA. Temperature gauges or thermometers should be readily visible. In AR production, augers are needed to agitate the asphalt rubber inside the tanks to keep the ground tire rubber particles well dispersed; otherwise the particles tend either to settle to the bottom or float near the surface. AR binder production methods are essentially the same for both hot mix and spray applications (Visser &Verhaeghe, 2000). Rubber asphalt production is nearly identical to conventional asphalt production except that the aggregate is heated slightly higher prior to the addition of the ground tire rubber (Figure

2.8, 2.9, and 2.10). Table 4 shows a summary of current ground tire rubber processes (not all are discussed in this report).

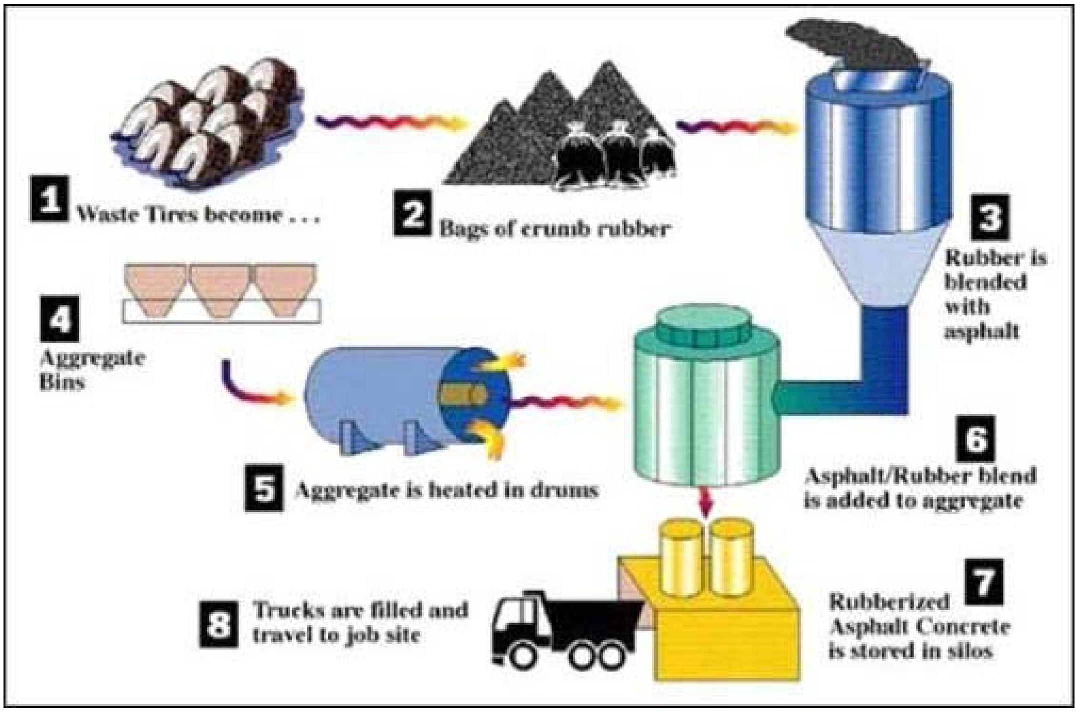

Figure 2.8 The Wet Process (Visser & Verhaeghe, 2000)

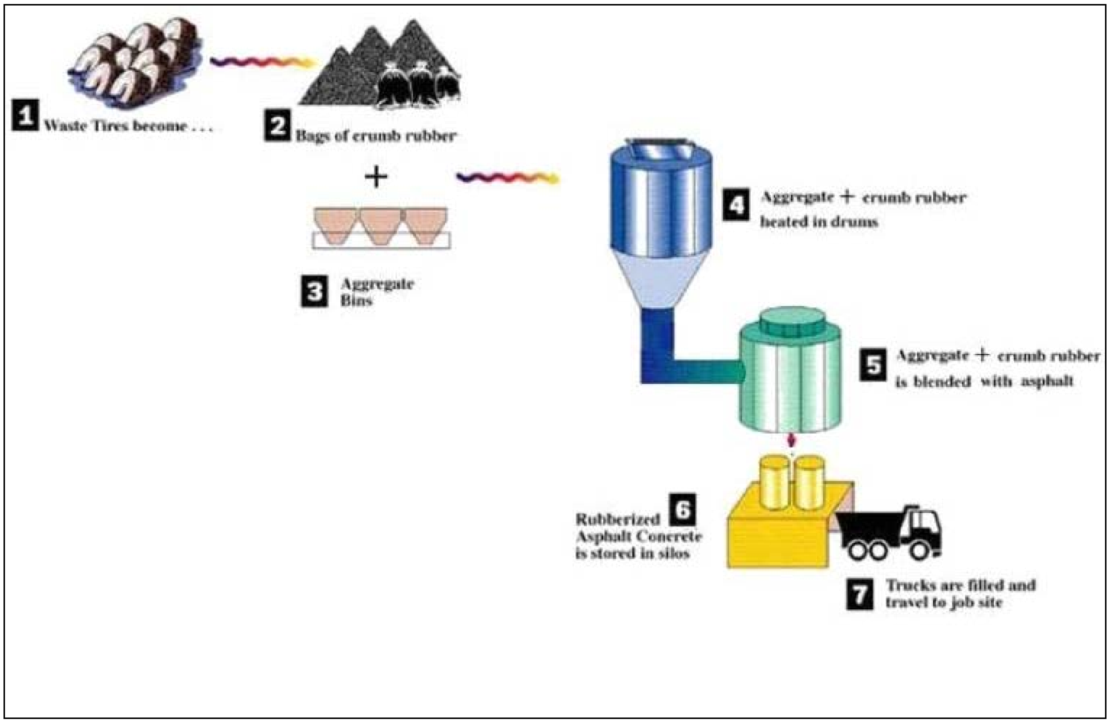

Figure 2.9 The Dry Process (Visser and Verhaeghe, 2000)

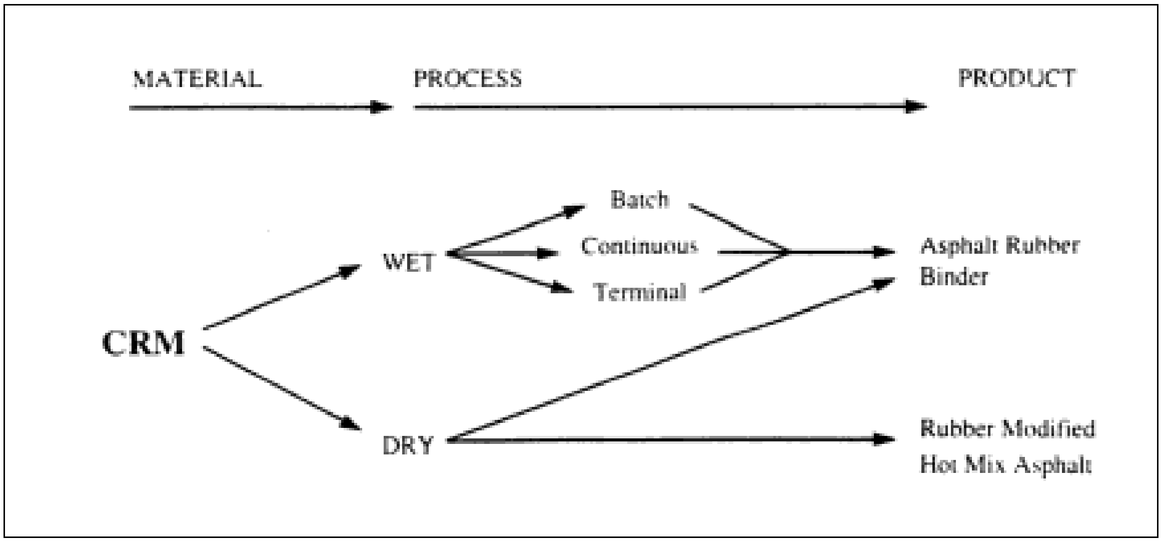

Figure 2.10 Types of Ground Tire Rubber (CRM) Process (Epps, 1994)

Table 2.4 Summary of Ground Tire Rubber Technologies (Epps, 1994)

Technology	Development Date and Location	Patented?	Marketing Firm
	Process/Product	Field Evaluation	
McDonald (1)	1960's - Arizona	patented (2)	(3)
	wet/batch/AR	extensive evaluation since 1970's	
pressure	1990 - Missouri	not patented	Dan Truax
	wet/batch/AR	has not been field-evaluated	
continuous blending	1989 - Florida	not patented	Rouse Rubber Industries (4)
	wet/continuous (terminal)/AR	limited evaluations since 1989	
terminal blending	1992 - Arizona - Washington	not patented	Neste U.S. Oil
	wet/terminal/AR	limited evaluations since 1992	
Ecoflex™	1992 - Canada	patented	Bitumar
	wet/terminal/AR	limited evaluations since 1992	
Flexochape™	1986 - France	patented	BAS Recycling (Beugnet)
	wet/terminal/AR	has not been field-evaluated in U.S.	
PlusRide™	1960's - Sweden	patented	EnvirOtire
	dry/RUMAC-gap	extensive evaluations since 1978	
generic dry (RUMAC)	1989 - New York	not patented	TAK (4)
	dry/RUMAC-gap, dense	limited evaluations since 1989	
chunk rubber	1990 - SHRP	not patented	CRREL
	dry/RUMAC-gap	has not been field-evaluated	
generic dry (AR)	1992 - Kansas	not patented	(4)
	dry/AR-open, gap, dense	limited evaluations since 1992	

2.3.8 Application Issues

Caltrans (2003) identified the following issues associated with AR or RA mixtures:

- Mixture segregation may be difficult to identify in some AR open graded mixtures since there are few fines and the AR can appear segregated even if it is not.

- Temperature segregation (hot or cold spots) may be checked with a heat gun or with an infrared camera. The primary concern is variation in temperature rather than exact values.
- If blue smoke appears then the mix is too hot.
- If white smoke appears then there is too much moisture. This may cause the mix to become tender and may contribute to compaction problems or later to pavement distress due to stripping.
- If the mix is too stiff then the mix may be too cool.
- A dull, flat appearance indicates insufficient mixing.
- A slumped and shiny appearance indicates a high AR binder content.

2.3.9 Performance

The wet process has the advantage that the binder properties are better controlled, while the dry process is often easier for an asphalt manufacturer to use. Currently, it appears that the dry process produces better results in terms of rutting resistance, fatigue life (cracking resistance), and noise reduction. This is believed to be due to the high ratio of rubber to bitumen in the mix. However, the dry process has yet to meet the time tested reliability of the wet process (Oliver & Alderson, 1998).

A recent study by the Oliver (199) suggests that for optimum performance when using the dry process, the overlay should be 14 mm thick, contain 8.0% binder, and 2.5% ground tire rubber (percentage of the total mass of the mix). The ground tire rubber should have a maximum particle size of 440 µm and maximum bulk density of 300 kg/m^3. No one has been this specific yet about an optimum mix using the wet process.

2.4 Noise

There are two sources of noise from highway vehicles, tire noise and mechanical noise. In general, there are also two perspectives for such noise, on-board and roadside. Characteristics and level of on-board noise can be affected by pavement type and texture, engine and other mechanical equipment, tires, and vehicle insulation. Road side noise affects roadway workers and adjoining property depending on weather, vegetation, terrain, and distance. The impact depends on outside and inside adjoining property use. Structure orientation and insulation will also mitigate noise.

For in service pavements or roadway test sections noise can be measured with sensors placed on a specific vehicle or a trailer. Sensors in these locations measure noise close to the source but have to be projected to predict noise characteristics and levels on adjoining property along the roadway. Roadside or by-pass noise can be also be measured by locating sensors at off-sets from the roadway. Both measurement locations can be utilized to evaluate characteristics and level of tire-pavement generated noise. As a result, contributions of either tires or pavement surfaces can be evaluated. Relative evaluation of pavement mixtures can also be done in the laboratory using ASTM E1050, Impedance and Absorption of Acoustical Materials Using a Tube.

The significance of noise from roadway use is that noise level standards exist for various inside and out activities and for various times of the day and night. Also, there is public recourse to requests for noise mitigation. In areas along roadways that developed over time, mitigation usually means construction of noise walls along the roadway right-of-way which can be unappealing and quite expensive. Sound dampening walls cost between 1 and 5 million USD/mile (Hanson et al, 2005).

2.5 Sound Basics

Sound is generated by small air pressure changes in the form of waves. Our ears detect these waves and our brains interpret them as sound. These sound waves can be measured with a microphone that is sensitive to these small air pressure changes (Figure 2.11). The changes in air pressure must be converted into an electrical signal that correlates to amplitude of the pressure change. The frequency of the air pressure changes must also be recorded to characterize the sound.

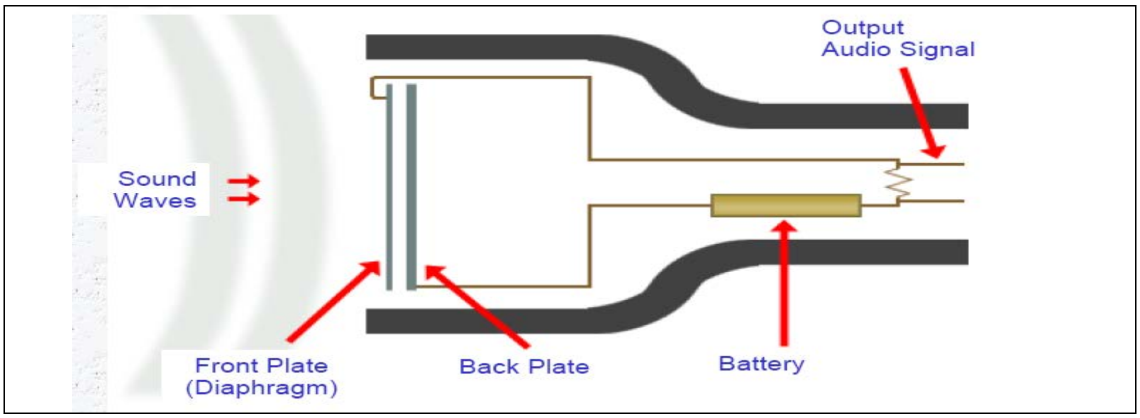

Figure 2.11 Microphone Schematic (Brüel &Kjaer, 2009)

2.5.1 Amplitude

Amplitude is measured in decibels (dB). The decibel (dB) is a logarithmic unit of measurement that expresses the magnitude or power of the sound waves. An analogy might be the height of an ocean wave relative to sea level. The human ear can generally detect no less than a 3 dB change in amplitude. If a given noise emission is doubled in magnitude this will result in an increase of approximately 3 dB.

Decibels are also affected by distance from the noise emitting source. Decibels are governed by the inverse square law in terms of distance. However, the inverse square law only applies to point sources and not line sources such as from a train or busy highway. Doubling the distance from a line source such as the subway train in Table 2.5 from 200 to 400 feet would lower the decibels from 95 dB to 92 dB not 89 dB. Traffic noise is assumed to be a line source even though at times it may be closer to a point source (Hanson et al, 2005).

Table 2.5 Examples of Common Noise Amplitudes (Hanson et al, 2005).

Source	Amplitude
Quiet library	30-40dB
Normal conversation (3-5 feet)	60-70dB
Vacuum cleaner at 10 feet	70dB
Garbage disposal at 3 feet	80dB
Blender at 3 feet	85dB
Diesel truck at 50 feet	90dB
Subway train at 200 feet	95dB
Level at which sustained exposure may result in hearing loss	**90 - 95dB**
Gas powered lawn mower at 3 feet	100dB
Power saw at 3 feet, Jet fly over at 1,000 feet	110dB
Pneumatic riveter at 4 feet	125dB
Pain begins	125-140dB
Level at which short term exposure can cause permanent damage	**140dB**
Jet engine at 100 feet, Gun blast	140dB
Death of hearing tissue	180dB
Loudest sound possible (Sonic Boom)	194dB

2.5.2 Frequency

In terms of sound measurement, frequency (hertz, Hz) is the number of sound waves per unit time (sec). The period is the duration of one wave cycle, so period is the reciprocal of the frequency. The frequency distribution of a noise forms what's called a pitch. An octave is the interval between one pitch and another with half or double its frequency (see Figure 2.12). Sound can be measured by how much amplitude is in every octave. More precise measurements often call for measurement in 1/3 octave bands. Many environmental, building acoustics, airport, and highway noise control applications require measurements in 1/3 octave bands. Traffic and tire pavement noise is most often measured and reported in 1/3 octave bands. Typically, the narrower a band that a noise meter measures, the more expensive it is.

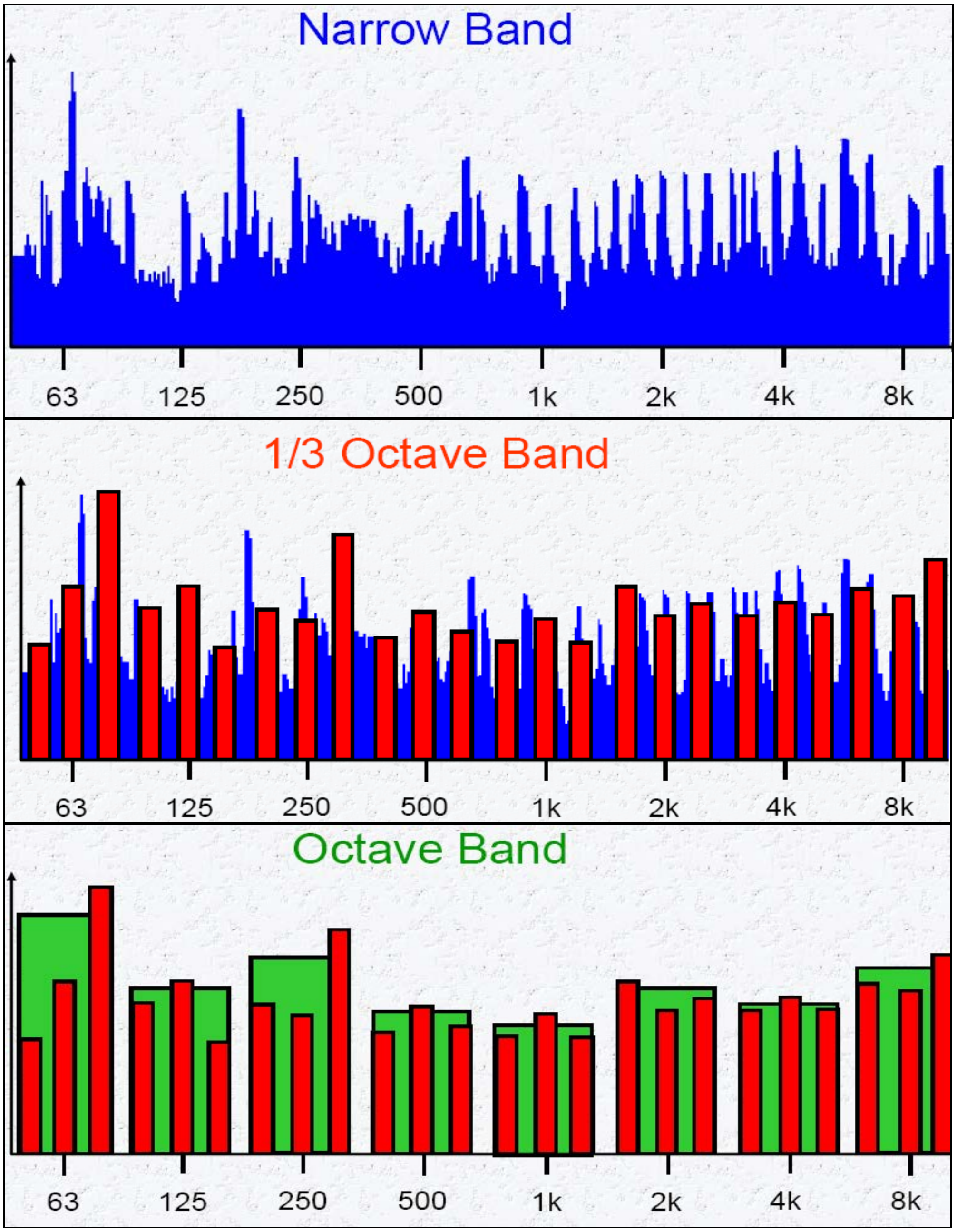

Figure 2.12 Narrow, 1/3, and 1/1 Octave Bands (ISQDH, 2005)

2.5.3 Frequency Weighting

Sounds can be filtered by using "frequency weighting". Frequency weighting is a way of emphasizing certain frequency ranges. Frequency weighting is categorized as A-, B-, or C-weighting. The weightings are shown in Figure 2.13. The most common frequency weighting is A-weighting and is used for measuring highway related noise.

The A-weighted filter is commonly used to emphasize frequencies around 2–5 kHz where the human ear is most sensitive, while attenuating very high and very low frequencies to which the ear is insensitive. Human ears are capable of detecting sounds all the way from 20 Hz to 20 kHz, but are most sensitive between 2 and 5 kHz (Ludwig, 1997).

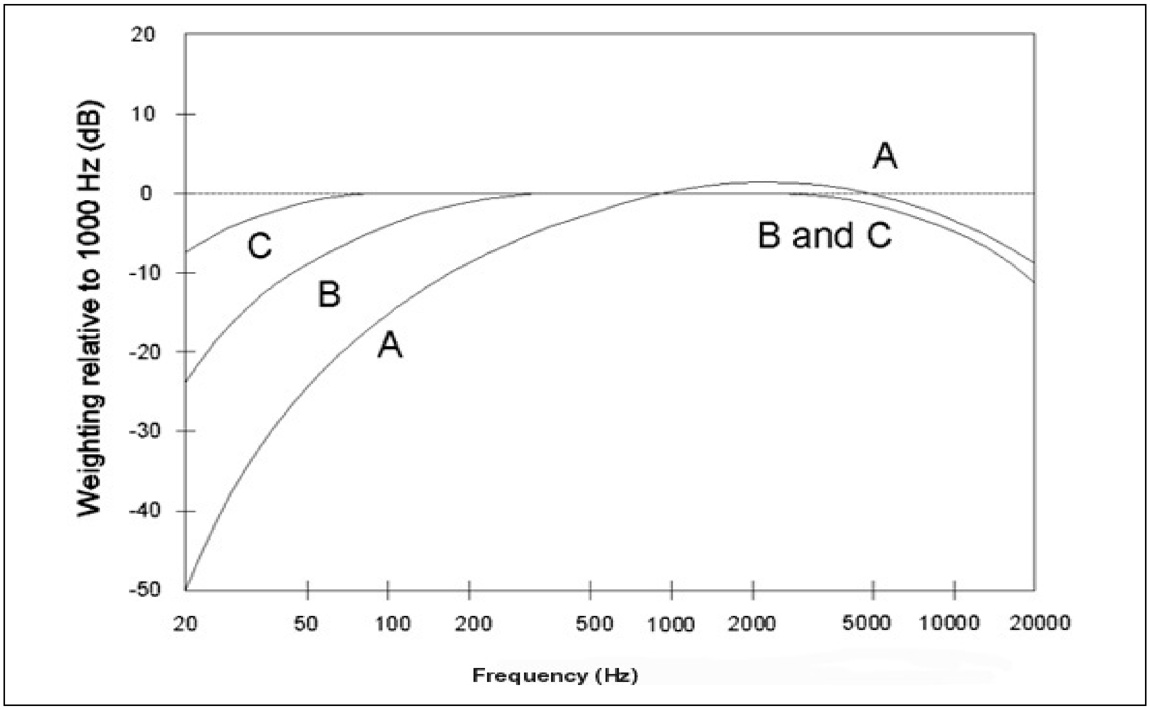

Figure 2.13 Frequency Weighting (FHWA, 2009)

2.6 Traffic Noise

"Throughout the world, sound caused by transportation systems is the number one noise complaint. Highway noise is one of the prime offenders. The main challenge in establishing noise abatement criteria is to balance noise levels that are desirable with those that are achievable." (Hanson and James, 2004)

2.6.1 Traffic Noise Analysis

In the US a traffic noise analysis is required for any FHWA Type I project. A Type I project is "a proposed Federal or Federal-aid highway project for the construction of a highway on new location or the physical alteration of an existing highway which significantly changes either the horizontal or vertical alignment or increases the number of through-traffic lanes." (CFR, 2009) Even if the project does not change ambient noise levels, Title 23 CFR Part 772, requires an analysis to determine if a traffic noise impact exists.

2.6.2 Traffic Noise Impact

A traffic noise impact occurs if:

- Predicted noise levels with the project change substantially (increase by 12 decibels or more) over existing ambient noise levels
- Predicted noise levels within the project approach to within 1 dB, or exceed the noise abatement criteria, as indicated in Table 2.

Table 2.6 Traffic Noise Impact Chart (CFR, 2009)

Land-use Activity Category	Hourly A-Weighted Noise Level	Description of Activities
A	57 dB Exterior	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B	67 dB Exterior	Picnic areas, recreation areas, playgrounds, active sport areas, parks, residences, motels, hotels, schools, churches, libraries, and hospitals.
C	72 dB Exterior	Developed lands, properties, or activities not included in Categories A or B above.
D	--	Undeveloped lands.
E	52 dB Interior	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, and auditoriums.

Some states may have even more stringent standards than the CFR. In Colorado, for example, impact is defined when 66 dB or higher is measured in residences, schools, and parks, or when 71 dB is measured near businesses and other commercial properties. A substantial impact occurs when there is a projected 10 dB increase over existing noise levels (Colorado DOT, 2005).

2.7 Noise Measurement Methods

2.7.1 Statistical Pass-By Method

The Statistical Pass-By (SPB) method (ISO 11819-1) is used to determine the roadside composite noise consisting of both tire/pavement and mechanical noise. It is done by placing microphones at offsets from the roadway at a specified height and distance from the vehicle lane of interest. The FHWA requires a microphone at an offset of 50 ft from the centerline of the lane of interest. The International Organization for Standardization (ISO) requires an offset of 7.5 m (25 ft) (FHWA, 2009; ISO 11819-1, 1997). Figure 4 shows the required microphone setup of ISO 11819-1. Both FHWA and ISO standards require the microphones to be at a height of 5 ft. Measurements are often made at additional points both higher and at greater offsets than required by the FHWA and ISO in order to better define the noise profile.

In the Statistical Pass-By (SPB) method, the maximum A-weighted sound pressure levels of a statistically significant number of individual vehicle pass-bys are measured at a specified road-side location together with the vehicle speeds. According to ISO 11819-1, each measured vehicle is classified into one of three vehicle categories: “cars”, “dual-axle heavy vehicles,” and “multi-axle heavy vehicles”. Other vehicle categories are not used for this evaluation, since they do not provide any additional information regarding road surface influence. At low speeds, mechanical noise produced by the vehicle power train dominates, but at high speeds the tire/pavement noise dominates. Therefore, measuring tire/pavement noise is only practical on highways with speed limits of 45 mph or greater (Hanson et al, 2005).

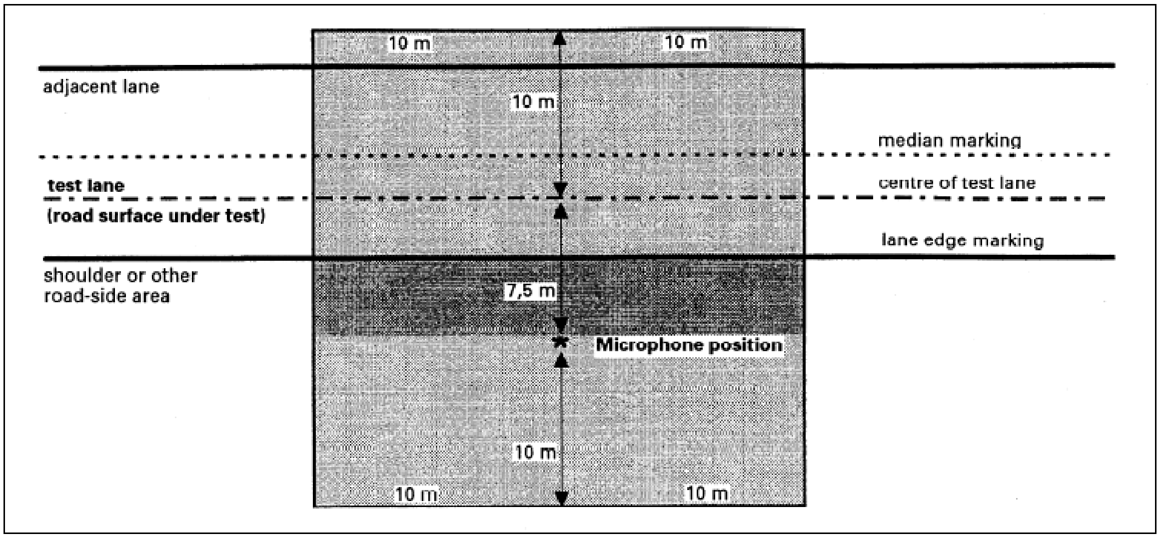

Figure 2.14 ISO-11819-1 Microphone Setup (ISO-11819-1, 1997)

In the ISO-11819-1 sensory setup;

"The sound level meter (or the equivalent measuring system) shall meet the requirements of a Type 1 instrument according to International Electrical Commission (IEC) IEC 60651. A windscreen shall be used and should be of a type specified by the microphone manufacturer as suitable for the particular microphone. It should be ascertained from the manufacturer that the windscreen does not detectably influence the performance of the sound level meter under the ambient conditions of the test. Frequency analysis of the measured sound using one-third-octave band resolution is recommended, but not mandatory. The frequency range of 50 Hz to 10 kHz (centre frequencies of one-third-octave bands) shall be covered. The one-third-octave-band filters shall conform to IEC 61260." (ISO, 1997)

The FHWA guidelines for the statistical pass by method are similar, but slightly different from ISO guidelines. The most notable difference being that the microphone is required to be at a distance of 50 ft not 25 ft from the center line of the lane being evaluated. The height requirement of 5 ft is the same as shown in Figure 2.15 and 2.16. Also the sound level meter is only required to be type 2, but type 1 is preferred. (FHWA, 2009)

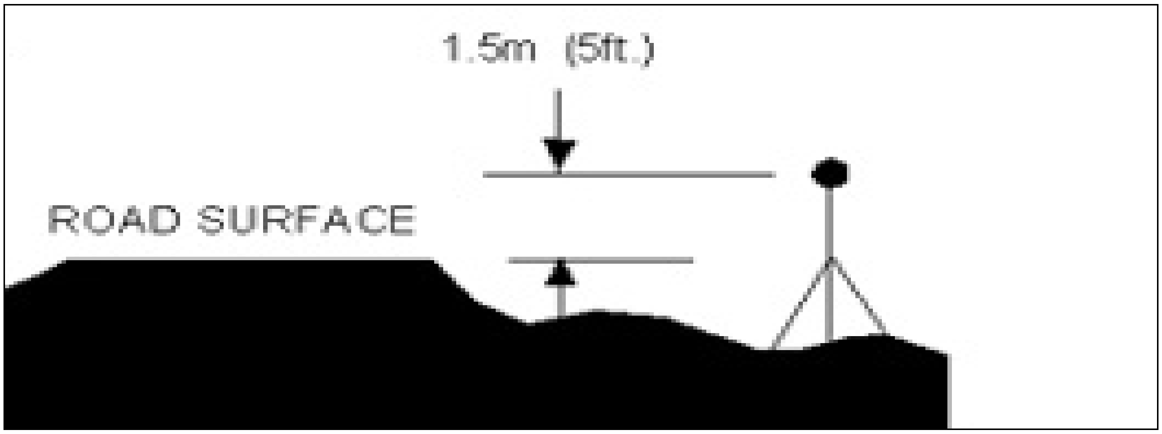

Figure 2.15 Microphone Height Requirements of FHWA and ISO (FHWA, 2009)


Figure 2.16 Statistical Pass-By Method (M+P Consulting Engineers, 2008)

2.7.2 Close-Proximity Method

The close-proximity or on-board method consists of measuring sound levels at or near the tire/pavement interface. The requirements for the close-proximity method are given in ISO-11819-2. In this close-proximity method microphones are attached to a vehicle or trailer and placed near the road surface. The ISO standard calls for microphones to be placed eight inches from the center of the tire and four inches from the surface of the road. The microphones are mounted in an acoustical chamber to isolate them from passing traffic as shown in Figure 2.17.

The advantages of the close-proximity method are:

- It is on board and therefore portable.
- The number of external factors such as background noise is reduced.
- Noise contributed by tires, pavement surface and combined tire/pavement surface are easy to separate.

The disadvantages are:

- It cannot be relied upon to determine if a sound wall is needed.
- The noise measurement is confined to that produced by whatever vehicle or trailer the microphone is attached to.

Figure 2.17 Close Proximity Measurement (M+P Consulting Engineers, 2008)

2.8 Noise Meters

Highway noise measurement methods have advanced significantly in the last decade. Figure 2.18 represents a typical setup of ten years ago. Today this setup can be captured in one instrument (Figure 2.19).

Noise meters come with a range of features and corresponding prices. There two types: Type 1 or Type 2 (Type 1 is more precise). They can measure 1/1 octave or 1/3 octave for more precision. They can store data and be downloaded to common computer software such as Excel. They may be able to be connected to more than one microphone at a time (multi-channel). A Type 2, 1/1 octave, non data storing, single channel noise meter can be purchased for as little as $100. However, a Type 1, 1/3 octave, data storing, multi-channel noise meter can be as much as ~ $10,000. However, costs and unit size are going down with time. Units can be bought or rented.

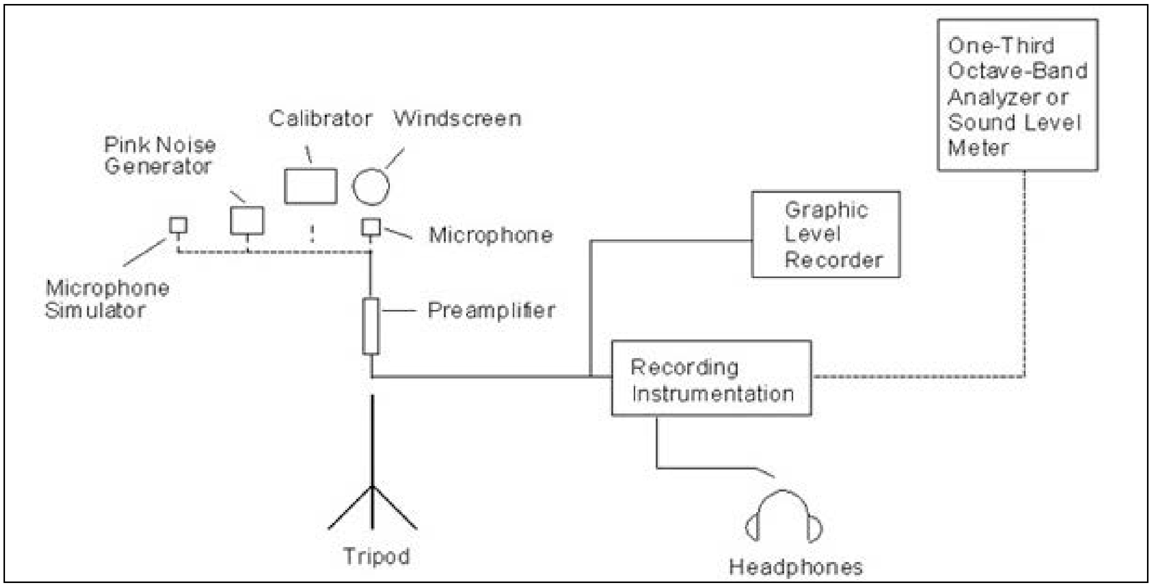

Figure 2.18 Typical Noise Measurement Instrumentation Parts (FHWA, 2009)

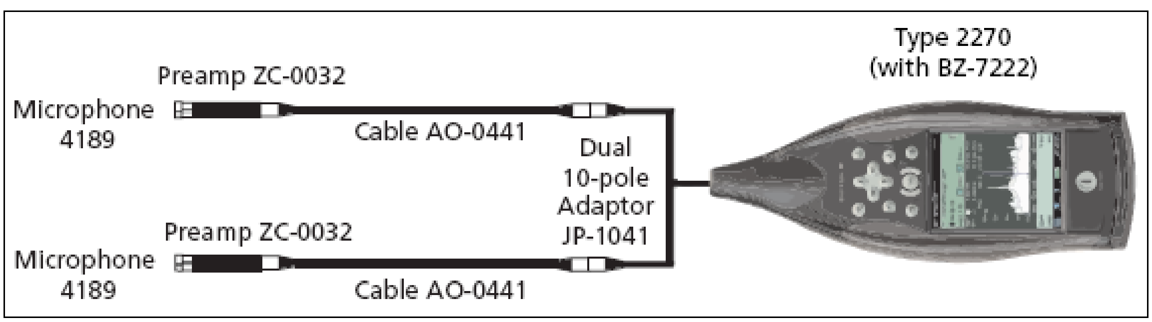

Figure 2.19 Noise Measurement Instrument with Two Microphone Attachments (Brüel & Kjaer, 2009)

2.9 Computer Modeling

The FHWA has developed software to predict noise. The FHWA's Highway Traffic Noise Prediction Model (FHWA-RD-77-108), or "108 Model," was developed and used in the 1970s until the FHWA adopted the Traffic Noise Model (TNM), Version

1.0 in March 1998. The TNM was developed as an aid for being in compliance with FHWA regulations. The most current version, Version 2.5 was released in April 2004 (FHWA, 2007). The software is described as: "The TNM is an entirely new, state-of-the-art computer program used for predicting noise impacts in the vicinity of highways. The TNM uses advances in personal computer hardware and software to improve upon the accuracy and ease of modeling highway noise, including the design of effective, cost-efficient highway noise barriers." (FHWA, 2007)

The TNM contains the following components: (FHWA, 2007)

- Models for five standard vehicle types as well as user-defined vehicles. The five standard vehicles are automobiles, medium trucks, heavy trucks, buses, and motorcycles.
- Models for both constant-flow and interrupted-flow traffic.
- Models for different pavement types.
- Output for one-third octave-band data.
- Interactive, graphic noise barrier design and optimization.
- Attenuation over/through rows of buildings and dense vegetation.
- Multiple diffraction analyses.
- Parallel barrier analysis.
- Contour analysis.

The TNM database is made up of over 6,000 individual pass-by events measured at 40 sites across the country. The TNM has a Microsoft Windows interface. Data input is menu-driven using a digitizer, mouse, and/or keyboard. Users also have the ability to import Stamina 2.0/Optima files, as well as roadway design files saved in CAD, DXF format. (FHWA, 2007)

2.9 Laboratory Noise Measurement

Sound absorption coefficients can also be measured in the laboratory on cores from in service pavements or on cores prepared in the laboratory. ASTM E1050 is a standard test method using an apparatus consisting of a tube with microphones at two heights. The surface being tested is located at one end of the tube. The tube is long relative to its diameter. A digital frequency analysis system is used to determine the test material's sound absorption coefficients and acoustic impedance ratios. Because of the specimen’s orientation to the tube the properties measured are “normal” or perpendicular to the material’s surface.

It is recognized that on an in service pavement, returned sound is from a larger area and is random and is affected by many environmental factors. However, the impedance tube measurements provide acceptable data for relative comparison of materials. NCAT and Robinson (2005) report use of impedance tube data to evaluate OGFC surfaces. The impedance tube is shown in Figure 2.20.

Figure 2.20 ASTM E1050 Testing Device (Robinson, 2005)

2.10 Summary

OGFC has been shown to reduce hydroplaning and noise reduction. With stiffer binders and the addition of cellulose fibers, OGFC has become more durable to the effects of environment and traffic. Ground tire rubber has been used has an additive in both normal asphalt blends and in OGFC.

Use of ground tire rubber in asphalt pavement reduces noise, increases durability (lifespan), increases traction, and decreases landfill use. Asphalt with ground tire rubber is more sensitive to climate (temperature and moisture) when being mixed and placed, but after placement can provide excellent performance. The two primary methods of incorporating ground tire rubber into the asphalt mixture are the wet process (AR) and the dry process (RA). The wet process is a proven technology, but recent testing indicates that the dry process may also perform well. The dry process typically uses more tire rubber which is advantageous in reducing disposal problems.

Mobilization costs for AR or RA production is high, but for large projects, the unit price is lower and can be further offset by performance benefits, lower maintenance costs, and reduced lift thickness. For small projects, however, the resulting increase in unit price may not be fully offset.

Sound is defined by its amplitude (dB) and by its frequency (Hz). Frequency weighting is applied to filter out the frequencies of non-interest and attenuate those to which the human ear is most sensitive (2-5 kHz). There are two ways of measuring in service highway related noise, the statistical pass by method and the close proximity method. Noise meters have improved significantly since the turn of the century and come in a wide range of abilities and price ranges. Pavement noise can be measured in the laboratory using the impedance tube method (ASTM E1050).

Analysis of site noise impact can be done using the FHWA noise model (TNM). The TNM can help predict the need for noise barriers based on anticipated traffic, location, and pavement type. Sound dampening walls are usually very costly; therefore, quieter pavements are often a viable solution.

CHAPTER 3

MATERIALS AND MIXTURE DESIGN

3.1 Introduction

Materials included in this study include PG 76-22(SBS modified) and GTR PG 76-22 (crumb rubber modified PG-67-22), cellulose fiber, chert gravel and crushed limestone aggregates, hydrated lime, and crumb rubber. Individual designs were conducted on each mixture.

3.2 Materials

3.2.1Asphalt Binder

In selecting a source of asphalt binders a decision was made to use the same source for both the standard PG 76-22 (SBS modified) and AR asphalt (GTR PG 76-22, PG 67-22 with 12% ground tire crumb rubber). Blacklidge Emulsions Inc., Tampa, FL markets both binders in Mississippi from an office in Gulfport, Ms. They also market in Florida where there has been significant use of AR asphalt over a number of years. Therefore the decision was made to use their products. The AR asphalt came pre-blended with crumb rubber meeting FLDOT specifications as shown in Table 3.1. The data sheet showing results of tests to grade the AR modified asphalt is shown as Figure 3.1.

The cellulose fiber used in the mixtures was obtained from Interfibe Inc., Portage, MI. The cellulose fiber is processed from recycled paper. The fiber have a diameter of 40 microns with a specific gravity of approximately 1.1. The product literature describes it as a grey fibrous powder, biodegradable, and non-toxic.

Table 3.1 Ground Tire Rubber (Global Tire Recycling, Wildwood, FL)

Physical Properties			
Specific Gravity	1.148		
Moisture Content, %	0.3		
Metal	None Detected		
Gradation, % Passing	Sieve	Specifications*	Actual
	No. 30	100	100
	No. 50	40-60	52
Chemical Properties			
	Acetone, %	9.8	
	Ash,%	5.2	
	Rubber Hydrocarbon, %	54.5	
	Natural Rubber (Isoprene), %	34.3	
	Carbon Black, %	28.7	

*Section 919, Florida Standard Specifications for Roads and Bridge Construction

BETA RESEARCH & DEVELOPMENT

Tested by: Trinh Ho	Date: June 25, 2010
Requested by : Scott Watson	Date Returned: July 12, 2010
Work Request #: 10-0771	Project: TPA-03-01-008

Materials: GTR Modified PG 76-22

Objective: SHRP full grading, elastic recovery and separation

Instructions: Evaluate for full SHRP Grading plus elastic recovery and separation

Results for full PG grading:

PROPERTIES			METHOD	SPECIFICATIONS	RESULTS
ORIGINAL BINDER:					
SUPERPAVE PG Asphalt Binder Grade			AASHTO M 320	-	PG76.4-26.6 UTI 103.0
Flash Point, COC °C			AASHTO T 48	230 min	324°C
Rotational Viscosity, cPs		275°F	AASHTO T 316	3000 max	1525
Dynamic Shear, k Pa (G*/sin δ, 10 rad/sec)		76 °C	AASHTO T 315	1.0 min	1.08
Dynamic Shear, Phase Angle		76 °C			77.6°
		P/F		PASS/FAIL TEMPERATURE	76.8
RTFO RESIDUE:					
Mass Loss, %			AASHTO T 240	1.0 max	-0.154
Dynamic Shear, k Pa(G*/sin δ, 10 rad/sec		76°C	AASHTO T 315	2.2 min	2.30
		P/F		PASS/FAIL TEMPERATURE	76.4
Elastic Recovery, % 5cm/min, 10 cm elongation		25°C	AASHTO T 301	report	70%
PRESSURE AGING RESIDUE:			AASHTO R 28		
Dynamic Shear, k Pa(G*·sin δ, 10 rad/sec		25°C	AASHTO T 315	5,000 max	2770
		22°C			3990
		19°C			5640
		P/F		PASS/FAIL TEMPERATURE	20.0°
Creep Stiffness	Stiffness, MPa(60 sec)	-12°C	AASHTO T 313	300 max	136
	m value			0.300 min	0.334
	Stiffness, MPa(60 sec)	-18°C		300 max	255
	m value			0.300 min	0.290

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Figure 3.1 GTR PG 76-22 QC Test Results

3.2.2 Aggregates

Two types of aggregates were used in this study, chert gravel and limestone. Bulk samples were obtained from 1/2in maximum and 3/4in maximum stockpiles of chert gravel and from a 3/4in maximum stockpile of limestone (No. 78). All aggregate was acquired from APAC, Inc., Columbus, MS. These aggregate were selected because they are widely used in MDOT surface HMA mixtures. Pictures of the stockpiles are shown in Figures 3.2-3.4. Specific gravities and absorption results from APAC QC tests are shown in Table 3.2. The QA stockpile gradations are given in Table 3.3.

Figure 3.2 1/2 inch Gravel (APAC, Inc., Columbus, MS)

Figure 3.3 3/4 inch Gravel (APAC Inc., Columbus, MS)

Figure 3.4 No. 78 Limestone (APAC, Inc., Columbus, MS)

Table 3.2 Aggregates Specific Gravity and Absorption (APAC, Inc., Columbus, MS)

	78 Limestone	1/2 Gravel	3/4 Gravel
Apparent Gravity	2.752	2.650	2.612
Bulk Dry Gravity	2.705	2.403	2.398
Absorption	0.63	2.388	2.342

Table 3.3 Stockpile Gradations, APAC, Columbus, MS

Sieve Size, mm (in/No.)	Percent Passing		
	19mm (3/4in) Chert Gravel	12.5mm (1/2in) Chert Gravel	No. 78 Limestone
19.0mm (3/4in)	100	100	100
12.5mm (1/2in)	77.8	100.0	95.5
9.5mm (3/8in)	57.6	94.3	72.0
4.76mm (No.4)	26.5	46.2	13.5
2.38mm (No. 8)	14.8	24.3	3.8
1.19mm (No. 16)	10.0	14.5	1.9
0.6mm (No. 30)	7.0	9.8	1.7
0.3mm (No. 50)	5.5	6.8	1.6
0.15mm (No. 100)	4.4	5.2	1.5
0.074mm (No. 200)	3.6	4.2	1.3

3.3 OGFC Mixture Designs

In developing the plan of test for this project, aggregate types, binders, and gradations of primary interest were identified. Since OGFC is a surface mixture the aggregates used in Mississippi for surface mixtures are crushed chert gravel and limestone. Chert gravel is widely available in the state and its use is desirable. Limestone is available in adjoining states and is used for skid resistance qualities in surface mixtures. The matrix in Table 3.4 was designed to include mixture combinations of primary interest to MDOT. The approach was to only include mixture combinations likely to be utilized by MDOT. Exclusion of MS 9.5 mixtures with PG 76-22 (AR) is based on potential incompatibility of the binder with the nominal 9.5mm maximum aggregate size gradation.

Table 3.4 Test Matrix for Study

Aggregate Type	Gradation (Nominal Maximum Aggregate Size, mm)	Binder Type and Grade	
		PG 76-22 (SBS)	GTR PG 76-22 (AR)
Chert Gravel	MS 9.5	X	
	MS 12.5	X	X
	MS 12.5-Coarse (Modified FL FC-5)	X	X
Chert Gravel/Limestone	MS 9.5	X	
	MS 12.5	X	X
	MS 12.5-Coarse (Modified FL FC-5)	X	X

In the above table an MS 12.5mm-Coarse gradation is listed. This is a gradation adopted after evaluation of the Florida FL FC -5 gradation. The FLDOT specifies the FL FC-5 gradation with asphalt rubber binder (GTR PG 76-22). The mixture incorporating the FL FC-5 gradation proved not to be durable as will be shown below. As a result, the MS 12.5-Coarse gradation was adopted. Gradations indicated in Table 3.4 are shown in Table 3.5.

Table 3.5 OGFC Gradations

Sieve Size, mm (in/No.)	OGFC Gradations, % Passing			
	MS 9.5mm	MS 12.5mm	FL FC-5 (12.5mm)	MS 12.5mm-Coarse
19.0mm (3/4in)	100	100	100	100
12.5mm (1/2in)	100	100	85-100	85-100
9.5mm (3/8in)	90-100	80-89	55-75	55-75
4.76mm (No.4)	15-30	15-30	15-25	15-25
2.38mm (No. 8)	10-20	10-20	5-10	10-16
1.19mm (No. 16)	---	---	---	---
0.6mm (No. 30)	---	---	---	---
0.3mm (No. 50)	---	---	---	---
0.15mm (No. 100)	---	---	---	---
0.074mm (No. 200)	2-5	2-5	2-4	2-5

All mixtures in the study included 1% hydrated lime as a mineral aggregate fraction and 0.3% fiber based on total mass.

An initial evaluation of mixtures indicated in Table 3.4 was conducted. The exception was that rather than a mixture with the MS 12.5-Coarse (Modified FL FC-5) gradation, a mixture with the FL FC-5 gradation given in Table 3.5 was evaluated. The initial evaluation of the mixtures was done based on results given in Table 3.6.

A mixture design asphalt content based on data in Table 3.6 would be the lowest asphalt content that satisfies all criteria of each column (i.e. VCA_{dry}/VCA_{mix}, Air Voids, Permeability, Unaged Abrasion, and Aged Abrasion). To assist in understanding the evaluation, the values for each mixture that fail the criteria are highlighted. Also, the lowest asphalt content passing the criteria for each mixture is highlighted. A design asphalt content could be identified for all mixtures except the mixture prepared with the Florida FC-5 gradation, crushed gravel aggregate, and GTR binder. The mixture with a GTR binder content of 7.2% is highlighted although it failed the aged abrasion test. It was identified because it failed at the lowest percent aged abrasion loss of 46.2%.

After evaluating the abrasion results a decision was made to adjust the 12.5mm Florida gradation. The adjusted gradation is designated as MS 12.5mm-Coarse and is given in Table 3.5. The gradation is designated as "Coarse" because the gradation is coarser than the MS 12.5mm gradation. As can be seen by evaluation of the gradations in the table, the ranges of percent passing are adjusted from the No. 4 sieve through the No.200 sieve. The critical sieve was taken to be the No. 8 and the increase in the range of percent passing on this sieve inherently increases the percent finer on the finer sieves. A consequence of the increased finer material is that there is an increase in toughness of the mastic portion of the OGFC mixture. The coarse aggregate is surrounded by mastic consisting of the fine aggregates and asphalt binder. By increasing the amount of fine aggregate, binder mixed with the aggregate will migrate to the finer aggregate because it has a larger surface area than the coarse aggregates. It is the combination of fine aggregate and binder that toughens the mastic and would be expected to improve abrasion resistance.

Another series of mixtures were prepared for the adjusted FL FC-5 gradation (MS 12.5-Coarse) using both GTR and SBS binders. Results for these mixtures are shown in Table 3.7. Again, results failing the criteria and the lowest asphalt content satisfying the criteria are highlighted. These results are interesting in that the marginal asphalt content (7.2%) selected in Table 3.6 for the FL FC-5 crushed gravel mixture prepared with the GTR modified asphalt is the same design asphalt content as for the MS 12.5-Coarse gradation mixture with the same binder. The abrasion resistance is improved compared to the FL FC-5 mixture.

Table 3.6 Selection of Design Asphalt Content

		AC, %	VCA_{dry}/VCA_{mix}	Air Voids, %	Permeability, m/d	Unaged Abrasion, %	Aged Abrasion, %
	Criteria		<1.0	>15	>40	<30	<40
	Asphalt Binder Type						
12.5 LS/CG	GTR	5.9	0.96	17.6	79.5	29.5	26.7
		6.4	0.96	16.6	60.5	18.9	20.2
		6.9	0.95	15.5	54.2	13.3	10.9
		7.4	0.94	14.8	34.3	10.8	13.3
	SBS	5.9	0.96	18.3	98.1	26.0	30.1
		6.4	0.96	17.3	82.8	19.2	22.3
		6.9	0.95	16.4	72.2	14.3	24.6
		7.4	0.94	15.7	56.5	12.0	21.0
12.5 CG	GTR	6.2	0.96	18.9	85.3	33.9	41.3
		6.7	0.96	18.4	84.5	30.8	31.9
		7.2	0.96	17.8	74.7	18.7	23.4
		7.7	0.96	16.8	48.1	18.4	17.7
	SBS	6.2	0.95	18.4	129.4	43.7	39.3
		6.7	0.94	17.1	99.7	29.3	27.7
		7.2	0.94	16.5	87.0	19.6	21.7
		7.7	0.94	16.0	80.9	23.9	20.2
FL LS/CG	GTR	5.9	1.00	18.8	129.8	31.2	41.0
		6.4	0.99	18.1	133.3	26.2	33.9
		6.9	0.99	17.4	106.5	15.0	18.2
		7.4	0.97	16.1	88.0	13.8	17.8
	SBS	5.9	1.01	19.2	169.7	35.8	36.2
		6.4	1.01	18.6	145.2	29.8	27.9
		6.9	0.99	17.2	136.8	27.6	23.1
		7.4	0.99	16.8	103.2	14.5	20.5
FL CG	GTR	6.2	0.96	20.9	163.8	61.3	76.6
		6.7	0.96	20.2	158.5	37.8	79.5
		7.2	0.96	17.7	140.9	25.4	46.1
		7.7	0.95	18.4	123.5	18.9	46.6
	SBS	6.2	0.95	19.4	179.2	54.5	60.5
		6.7	0.94	18.7	153.9	47.6	48.6
		7.2	0.94	18.4	149.3	51.6	53.0
		7.7	0.94	17.6	115.9	29.9	29.2
9.5 LS/CG	GTR						
	SBS	5.9	0.90	18.4	93.1	19.9	21.4
		6.4	0.89	17.6	72.2	18.3	17.0
		6.9	0.88	16.5	57.0	14.6	13.5
		7.4	0.89	16.2	57.4	12.2	13.6
9.5 CG	GTR						
	SBS	6.2	0.92	19.9	122.7	43.0	36.8
		6.7	0.92	19.0	113.2	31.2	26.4
		7.2	0.91	18.1	96.7	27.7	21.5
		7.7	0.90	17.5	77.3	19.8	18.6

Table 3.7 Evaluation of MS 12.5-Coarse (Adjusted FL FC-4) Mixtures

		AC, %	VCA_{dry}/VCA_{mix}	Air Voids, %	Permeability, m/d	Unaged Abrasion, %	Aged Abrasion, %
	Criteria		<1.0	>15	>40	<30	<40
	Asphalt Binder Type						
MS 12.5-Coarse CG	GTR	6.2	1.02	20.9	163.8	37.5	41.1
		6.7	1.01	20.2	158.5	36.8	33.8
		7.2	0.97	17.7	140.9	29.9	25.0
		7.7	1.00	18.4	123.5	22.8	20.4
	SBS	6.2	1.00	19.4	179.2	39.1	37.5
		6.7	1.00	18.7	153.9	36.2	32.5
		7.2	1.00	18.4	149.3	30.2	30.9
		7.7	1.00	17.6	115.9	24.7	23.3

Similarly, there is agreement of the design asphalt content (7.7%) for the FL FC-5 mixture prepared with the SBS modified asphalt and the design asphalt content selected for the MS 12.5-Coarse gradation mixture prepared with the same binder. In the latter case the asphalt content is again selected that most closely satisfies the criteria. The mixture with the design asphalt content (7.7%) has a marginal VCA_{dry}/VCA_{mix} value of 1.00, but the Aged abrasion is improved compared to the FL FC-5 mixture.

A summary of design asphalt contents is shown in Table 3.8. This table includes results for combinations of aggregate, gradations, and binders of interest. These are the mixtures tested and evaluated in subsequent chapters.

Table 3.8 Design Binder Content Summary

Aggregate Type	Gradation (Nominal Maximum Aggregate Size, mm)	Design Asphalt Content, %	
		PG 76-22 (SBS)	GTR PG 76-22 (AR)
Chert Gravel	MS 9.5	7.2	
	MS 12.5	6.7	7.2
	MS 12.5-Coarse (Modified FL FC-5)	7.7	7.2
Chert Gravel/Limestone	MS 9.5	5.9	
	MS 12.5	5.9	5.9
	MS 12.5-Coarse (Modified FL FC-5)	6.9	6.4

3.4 Modifications to MDOT OGFC Specification

There are modifications recommended for the current MDOT OGFC specification. These modifications include addition of the MS 12.5mm-Coarse gradation for use with a GTR modified asphalt and requirements for the GTR based on the FLDOT specifications. The MS 12.5mm-Coarse gradation is shown in Table 3.5 above. Proposed modifications are shown in Appendix A.

Another modification is the expansion of the table of values in the current MDOT specifications for estimating the minimum asphalt content based on the combined aggregate bulk specific gravity. That table is shown here as Table 3.9. The estimated binder content is provided for a range of aggregate bulk specific gravity from 2.40 to 2.85. In the current study combined aggregate bulk specific gravity for the MS 12.5mm and MS 12.5mm-Coarse blends of chert gravel were 2.35 and 2.34. As a result, the data in Table 3.9 was plotted and fitted with a second order polynomial as shown in Figure 3.5. The polynomial was used to predict minimum asphalt content for aggregate bulk specific gravities of 2.35 and 2.30. The predicted asphalt contents are 6.7 and 6.9 percent, respectively. These values are added to the table in the proposed specification modifications shown in Appendix A.

Table 3.9 Combined Aggregate Bulk Specific Gravity and Asphalt Content

Combined Aggregate Bulk Specific Gravity ($G_{sb)}$	Minimum Asphalt Content, %
2.40	6.6
2.45	6.5
2.50	6.3
2.55	6.2
2.60	6.1
2.65	6.0
2.70	5.9
2.75	5.8
2.80	5.7
2.85	5.6

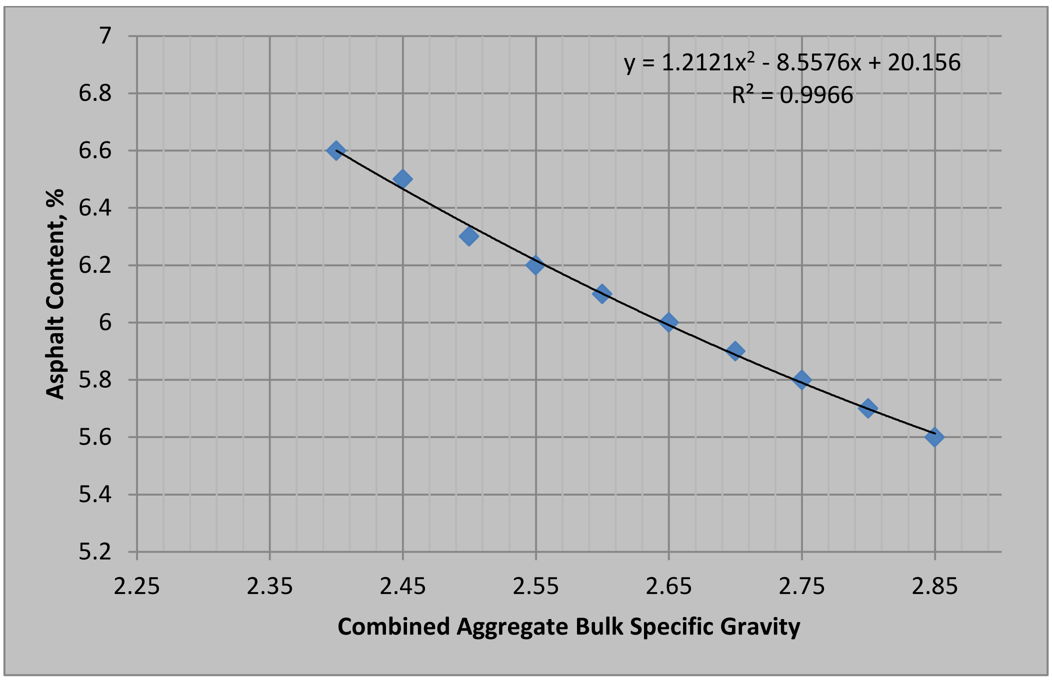

Figure 3.5 Relation to Estimate Minimum Asphalt Content

CHAPTER 4

OGFC MIXTURE TESTS

4.1 Introduction

The Mississippi DOT has constructed a limited number of OGFC surfaces. Two very similar gradations except for the nominal maximum aggregate size (9.5mm and 12.5mm) are allowed in the current specification. In this specification, the specified binder is PG 76-22 and is a polymer modified asphalt. These gradations and asphalt along with a ground tire rubber modified asphalt and a 12.5mm gradation to accommodate the GTR modified asphalt have been included in this study. Tests conducted as part of this study are used to evaluate the potential performance of these OGFC mixes.

4.2 Sample Preparation

Two types of test specimens were prepared in the study. Full height OGFC cores were prepared using the Superpave gyratory compactor. These specimens were used for indirect tensile tests, MT-84 permeability tests, and dynamic modulus tests. Composite specimens consisting of a ¾ inch OGFC cap compacted on a previously compacted core of dense HMA were used to evaluate White falling head permeability and interface shear strength.

The full height cores for indirect tensile testing were compacted to a height of 3.75 inches with air voids at the design asphalt content. Mass of mix compacted was adjusted to achieve the target air voids at the reduced specimen height. Full height OGFC specimens for dynamic modulus determinations were compacted to a height of approximately 170mm. The target air voids was taken as the mix design air voids plus 2 percent. Since the target air voids of dynamic modulus specimens for dense HMA is 7 percent plus or minus 0.5 percent and the OGFC air voids are twice that of dense HMA specimen, the tolerance for OGFC target air voids was taken as plus or minus 1 percent. In practice, meeting the 1 percent tolerance was not difficult.

When the 150mm diameter by 170mm high dynamic modulus specimens are compacted in the Superpave gyrator compactor, the resulting cores have a density gradient that varies from the outside of the core to the center. The center density is higher. To minimize the density gradient, the 150mm diameter specimens are cored with a 100mm core barrel centered on the axis of the original core. Finally, the ends of the 100mm core are sawn so that they are parallel. The purpose of these steps is to reduce the gradient of the air voids. The specimen is required to have a diameter of between 100 and 104 mm and an average height of between 147.5 and 152.5 mm. The air voids for each specimen is required to be the target air voids plus or minus 1 percent.

From previous experience (White, et al, 2007) using the Superpave gyratory compactor to compact the 150mm diameter sample, the compaction had to be to a slightly higher air void target (1 percent higher) to achieve the target air voids in the 100mm diameter test specimen. The process also varies from mix to mix.

The MDOT MT-84, Laboratory Falling Head Test was conducted on the OGFC specimens. However, the geometry and boundary conditions are not representative of in service OGFC surfaces. White (1975, 1976) developed a falling head permeability device specifically for laboratory and field evaluation of porous friction course (PFC) surfaces. Porous friction course is the terminology used for airfield porous surfaces analogous to OGFC. Sandiford, et al (1985) conducted an evaluation of equipment for determining permeability of porous surfaces and recommended the apparatus and test procedure developed by White.

The White apparatus consists of a 2 inch inside diameter, 13 inch high plastic stand pipe mounted on a 4 inch diameter base plate. A schematic is shown in Figure 4.1. The key feature of the device is that it can be used on an in service pavement as well as a 6 inch diameter core. The core can be a field core or a laboratory prepared core. The test is a falling head test. When the test is conducted on a thin OGFC surface over a dense underlying pavement, water flows into the OGFC layer and then flows horizontally with significant flow coming to the surface around the base plate perimeter. This is exactly the path of pressurized water trapped between a moving vehicle’s tire and pavement surface.

Field OGFC compaction is based on a method specification, i.e. so many passes of a specified roller. Also, there is no current laboratory standard for compaction of the ¾ inch OGFC layer on a dense base. White (1975) used a standard Marshall hammer with a fabricated 6 inch diameter foot and CBR mold to produce the desired specimens. A compaction effort was

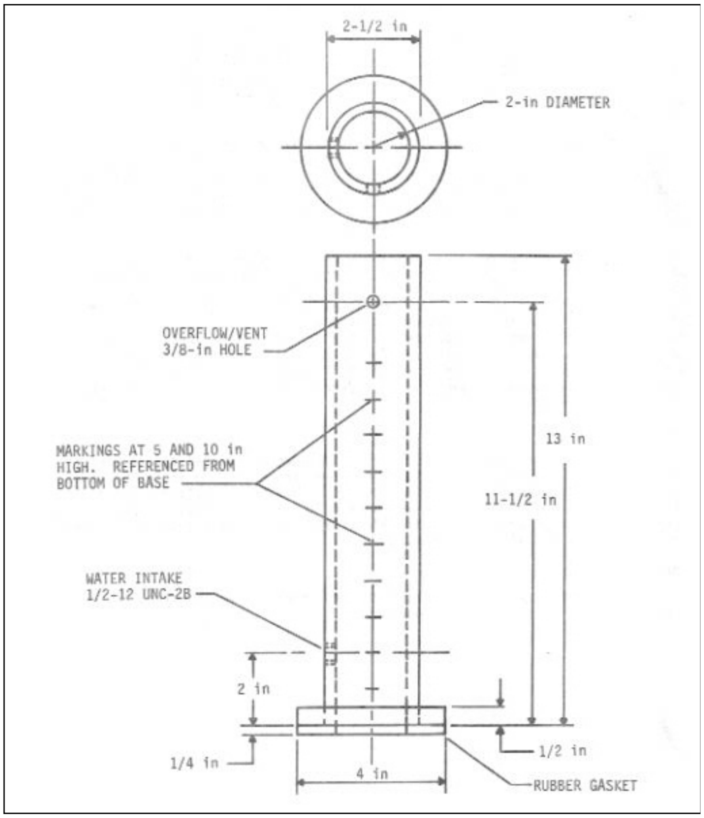

Figure 4.1 White Permeability Apparatus (1976)

selected to achieve a minimum permeability based on evaluation of varying amounts of asphalt. At that time asphalts were unmodified and mix compaction characteristics were markedly different to current mixes using modified asphalts.

To develop a compaction effort for producing the OGFC/dense base composite specimen, consideration was given to the concept that permeability of a standard OGFC would be a measure of compaction. A candidate “standard OGFC” was the OGFC test section on Mississippi I-55 that was evaluated over a period of time after it was constructed. Approximately one mile was constructed in both the south and north bound lanes. The evaluation is reported by White and Ivy (2009). The evaluation included falling head permeability using the above apparatus. The field test being conducted on the I-55 OGFC section is shown in Figure 4.2.

Figure 4.2 In Service Pavement Testing, I-55 (White and Ivy, 2007)

In the field evaluation, permeability tests were conducted every 1/10 mile in and between both wheel paths. The test procedure for each station included positioning the stand pipe at the desired transverse test location so that it was vertical under the reaction bar attached to the rear of a van. With extensions, the reaction bar spans the width of the lane. A screw jack is used to apply a load of 100 lbs. to insure the foam gasket on the bottom of the base plate provides a complete seal between the base plate and OGFC surface. Water from a reservoir in the van was pumped into the stand pipe and allowed to fall between timing marks. The test was run to prewet the OGFC and then run three times for record. A result is the average of the three tests.

The first set of permeability tests between wheel paths was of most interest because of having been subjected to minimum traffic. Also for a longer period of time fuel and oil from vehicles could contaminate the OGFC between the wheel paths. The average times to fall for the set of tests are shown in Table 4.1.

Table 4.1 Average Permeability Between wheel paths, Nov. 27, 2007

Direction	Lane	Average Time to fall, seconds
South	Driving	7.20
South	Passing	9.90
North	Driving	9.04
North	Passing	9.90

The first ½ of the first lane constructed (south bond driving lane) had times to fall lower than 5 seconds which markedly decreased the average time to fall of the lane. As a result, the average of the other three lanes was taken as a target time to fall on which to base selection of the laboratory compaction effort. The average time to fall of the three lanes is 9.6 seconds.

Dense base cores were compacted and subsequently OGFC mixtures using aggregate and asphalt grade and content matching the plant produced OGFC for the I-55 test section was compacted on the dense base cores. The OGFC mixture was mixed by hand. The unheated dense base cores were placed in a six inch diameter Marshall mold and compacted with a six inch Marshall hammer. Specimens were compacted with 40, 50, 60, and 75 blows. Times to fall were measured using a laboratory setup of the White permeability apparatus shown in Figure 4.3. Results of the tests are given in Table 4.2. Figure 4.4 shows a plot of the same data.

Table 4.2 Time to Fall for 6 inch OGFC Caps

Number of Blows	Average Time to Fall, seconds
40	5.87
40	7.37
60	8.81
70	9.27
75	9.77

Figure 4.3 Laboratory Permeability Apparatus

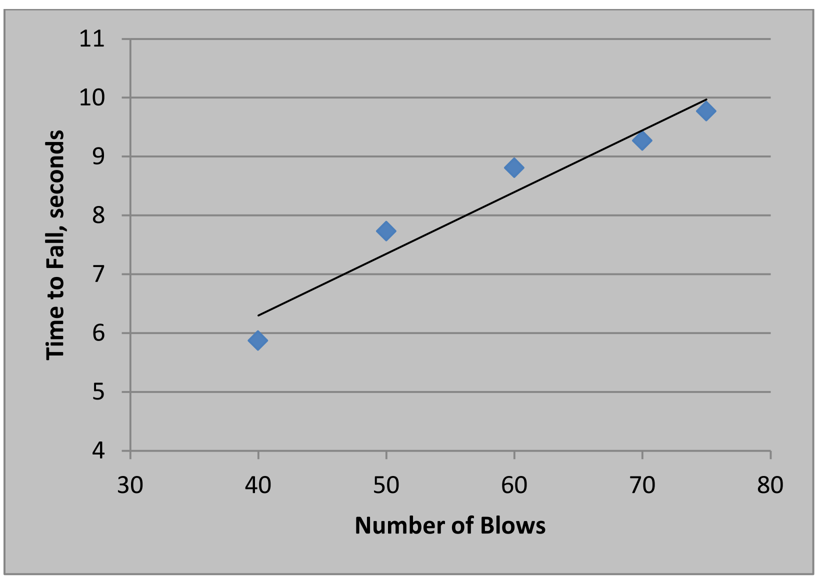

Figure 4.4 Time to fall for increasing Number of Blows with 6 inch Marshall Hammer

Examination of the tabular data and figure indicates the 75 blow compaction effort will produce a time to fall of about 9.8 seconds. On this basis the 75 bow compactive effort was adopted for preparing the composite cores consisting of a ¾ inch OGFC cap on a dense HMA base.

4.3 MT-84 Falling Head Permeability Tests

Mississippi DOT evaluates the permeability of OGFC mixtures with a falling head test (MT-84). Configuration of the test is such that water is forced to flow through the full depth of a core compacted with the Superpave gyratory compactor. Permeability is reported in meters/day. Results of permeability tests at design asphalt contents of the OGFC mixtures evaluated in this study are given in Table 4.3.

Table 4.3 Falling Head Permeability (MT-84)

Aggregate Type	Gradation	Permeability meters/day	
		Binder	
		PG 76-22	GTR PG 76-22
Gravel	MS 9.5	96.7	NT
	MS 12.5	99.7	74.7
	MS 12.5-Coarse	101.6	88.1
Limestone/Gravel	MS 9.5	93.1	NT
	MS 12.5	98.1	79.5
	MS 12.5-Coarse	136.8	133.3

NT – Not Tested

There does not appear to be a large difference in MT-84 permeability among the mixtures except for the MS 12.5-Coarse mixture with limestone and gravel aggregate. All mixtures with the GTR PG 76-22 binder have a slightly lower permeability than the mixtures with the PG 76-22 (SBS) binder.

4.4 White Falling Head Permeability Tests

The White falling head permeability test described above can be used to test in service pavements, 6 inch diameter cores of in-service pavements, and laboratory prepared 6 inch diameter cores. As noted, the laboratory cores are prepared by compacting ¾ inch OGFC layer on a dense mixture base. Boundary conditions of the laboratory test are in close agreement with an in service OGFC pavement. Permeability is reported as time to fall in seconds. However, the time to fall can be converted to a permeability based on geometry of the apparatus (White, 1975). Table 4.4 gives time to fall at the design asphalt content of the OGFC mixtures studied.

Table 4.4 White Falling Head Test

Aggregate Type	Gradation	Time to Fall, seconds	
		Binder	
		PG 76-22	GTR PG 76-22
Gravel	MS 9.5	8.0	NT
	MS 12.5	12.2	11.3
	Ms 12.5-Coarse	10.4	17.0
Limestone/Gravel	MS 9.5	12.7	NT
	MS 12.5	13.0	17.5
	Ms 12.5-Coarse	12.7	15.0

NT – Not Tested

In Table 4.4, the MS 12.5, GTR PG 76-22 mix exhibits a higher permeability (lower time to fall) than other mixes with the GTR PG 76-22 binder. This may be the result of variability of mixing and compaction of the laboratory specimens. The issue may be resolved by testing in situ test sections. Also, on average, the mixtures with PG 76-22 binder exhibited higher permeability than those with GTR PG 76-22 binder.

Results of the White falling head permeability test are similar to those of MT-84. In the test a lower time to fall indicates a higher permeability. The advantage of the White device is that the test can be used to evaluate in service pavements and cores from in service pavements.

4.5 OGFC Dynamic Modulus Tests

Dynamic modulus tests were conducted on the ten OGFC mixtures studied in this project. Samples were compacted using the Superpave gyratory compactor. Test specimens were prepared, instrumented, and tested as described by White, et al (2007). Table 4.5 gives the results for predicting dynamic modulus of the OGFC mixtures. The 9.5mm mixtures were tested at **-10**°C, **4**°C, **21**°C, **37**°C, and **54**°C for mixtures with both SBS and GTR binders. However, the 12.5 mixtures could not be tested at **54**°C and some of the remaining results were questionable. These results can be seen in an examination of the prediction equation coefficients in Table 4.5. The problem is that the integrity of the larger maximum aggregate mixtures can decrease rapidly at the high test temperatures.

Table 4.5 Coefficients for Prediction Equation and Shift Coefficients

OGFC Mix	Coefficients				Shift Factors				
	δ	**α**	**β**	**γ**	**-10**°C	**4**°C	**21**°C	**37**°C	**54**°C
MS 9.5 G SBS	3.1329	3.2345	-1.0438	0.3204	4.6841	2.3052	0	-2.0236	-3.8794
MS 9.5 LS SBS	2.4815	3.9919	-1.0760	0.2641	5.1303	2.4040	0	-0.9949	-3.0665
MS 12.5 G SBS	4.9018	1.1320	2.2997	2.7213	6.0183	2.4131	0	0.5654	_
MS 12.5 G GTR	-5.3739	11.7352	-2.5345	0.3215	4.5946	2.1603	0	-0.8560	_
MS 12.5 LG SBS	-39.6555	45.7127	-4.1566	0.5828	5.6345	1.7464	0	-0.6378	_
MS 12.5 LG GTR	-4.4946	10.719	-2.4934	0.34301	4.2166	2.0503	0	-0.9382	_
MS 12.5-Coarse G SBS	-37.1106	43.1300	-4.1438	0.6663	9.4095	1.8159	0	-0.5093	_
MS 12.5-Coarse G GTR	-20.9449	27.1080	-3.5894	0.3741	5.0022	2.0824	0	-1.3987	_
MS 12.5-Coarse LG SBS	4.7279	1.4062	0.4963	0.7295	3.9116	2.1417	0	-1.8023	_
MS 12.5-Coarse LG GTR	5.0772	0.9591	1.8931	2.4531	2.6376	1.6946	0	0.5391	_

4.6 Indirect Tensile Strength

Moisture in an asphalt mixture can reduce the bond of asphalt binder to aggregate because some aggregates have a greater affinity for water than asphalt. The loss of bond leads to loss of inherent tensile strength which can be quantified by the indirect tensile strength test. The phenomenon leading to the loss of asphalt to aggregate bond is referred to in the paving industry as stripping.

Indirect tensile tests can be conducted on laboratory compacted specimens and field sampled pavement cores. In tests of laboratory compacted cores, sets of cores are tested. One set is cured at room temperature. The second set is saturated under vacuum and cured in water at 140°F for 24 hrs. Both sets of specimens are brought to a temperature of 77°F and tested using an indirect tensile apparatus. The apparatus consists of a constant rate loading system and narrow metal strips contacting the specimens. The metal strips are longer than the height of the specimen and have a contact surface curvature equal to the specimen’s radius of curvature. In preparation for testing, the specimen is positioned in the test apparatus with the cylindrical axis horizontal. Load is applied to the specimen at a constant rate through the loading strips. The loading strips are diametrically opposite each other so that load is applied along a specimen diameter.

As the load increases and approaches specimen failure, a crack occurs along the specimen's vertical diameter. The crack develops because tensile stress across the crack exceeds the tensile strength. The tensile stress at failure is calculated from the failure load and specimen geometry (Mississippi DOT MT-63).

Results of the test are tensile strengths for conditioned and unconditioned specimens. The ratio of tensile strengths for conditioned specimens to unconditioned specimens is the tensile strength ratio (TSR). A lower TSR ratio indicates the mixture is more susceptible to damage from water. MDOT limits the ratio to 0.85. If the ratio is below 0.85 then an additive to mitigate the effect of moisture is required. Subsequently, the mixture with an acceptable additive can be reevaluated with a new series of tests. However, no subsequent evaluations of the mixtures with additional anti-stripping agents were conducted.

After the indirect tensile tests, samples can be split along the crack and the failed surfaces examined. In the visual examination, the relative percent of uncoated aggregate can be estimated. MDOT has a limit on the percent of aggregate retaining a coating of at least 95 percent.

Both indirect tensile tests and subsequent visual examinations were conducted on the OGFC mixtures being evaluated in this study. All mixtures included hydrated lime which some agencies allow to treat mixture stripping tendencies.

Results of the indirect tensile tests of unconditioned and conditioned specimens are in Table 4.6. The results are the average of duplicate tests. Tensile strength ratios are shown as well as visual estimates of percent of stripping (uncoated aggregate). In the latter case, each specimen was inspected by three research assistants and the results shown are the averages of their observations. Table 4.7 gives TSR and stripping for the mixture test matrix. Figure 4.5 shows an example of specimen surfaces inspected.

Table 4.6 Indirect Tensile Test Results

Gradation	Binder Type	Conditioning	Tensile Strength, psi	Tensile Strength Ratio, %	Stripping, %
MS 12.5 L/G	GTR	Unconditioned	38.1	93.8	8.9
		Conditioned	35.7		
	SBS	Unconditioned	66.6	86.0	3.9
		Conditioned	57.3		
MS 12.5 G	GTR	Unconditioned	57.4	82.1	10.8
		Conditioned	47.1		
	SBS	Unconditioned	84.2	81.6	6.0
		Conditioned	68.8		
MS 12.5-Coarse L/G	GTR	Unconditioned	51.4	53.2	12.7
		Conditioned	27.4		
	SBS	Unconditioned	62.1	75.9	2.7
		Conditioned	47.2		
MS 12.5-Coarse G	GTR	Unconditioned	53.7	56.8	12.0
		Conditioned	30.5		
	SBS	Unconditioned	71.0	81.2	5.7
		Conditioned	57.7		
MS 9.5 L/G	GTR	Unconditioned	68.0	NT	NT
		Conditioned	40.9		
	SBS	Unconditioned	102.3	75.1	5.7
		Conditioned	76.8		
MS 9.5 G	GTR	Unconditioned	42.5	NT	NT
		Conditioned	24.3		
	SBS	Unconditioned	67.3	82.0	5.7
		Conditioned	55.2		

NT – Not Tested

Table 4.7 TSR and Stripping for Mixture Test Matrix

Aggregate	Gradation	Binder			
		PG 76-22		GTR PG 76-22	
		TSR	% Stripping	TSR	% Stripping
Gravel	MS 9.5	82	5.7	NT	NT
	MS 12.5	81.6	6.0	82.1	10.8
	MS 12.5-Coarse	81.2	5.7	56.8	12.0
Limestone/Gravel	MS 9.5	75.1	5.7	NT	NT
	MS 12.5	86	3.9	93.8	8.9
	MS 12.5-Coarse	75.9	2.7	53.2	12.7

NT – Not Tested

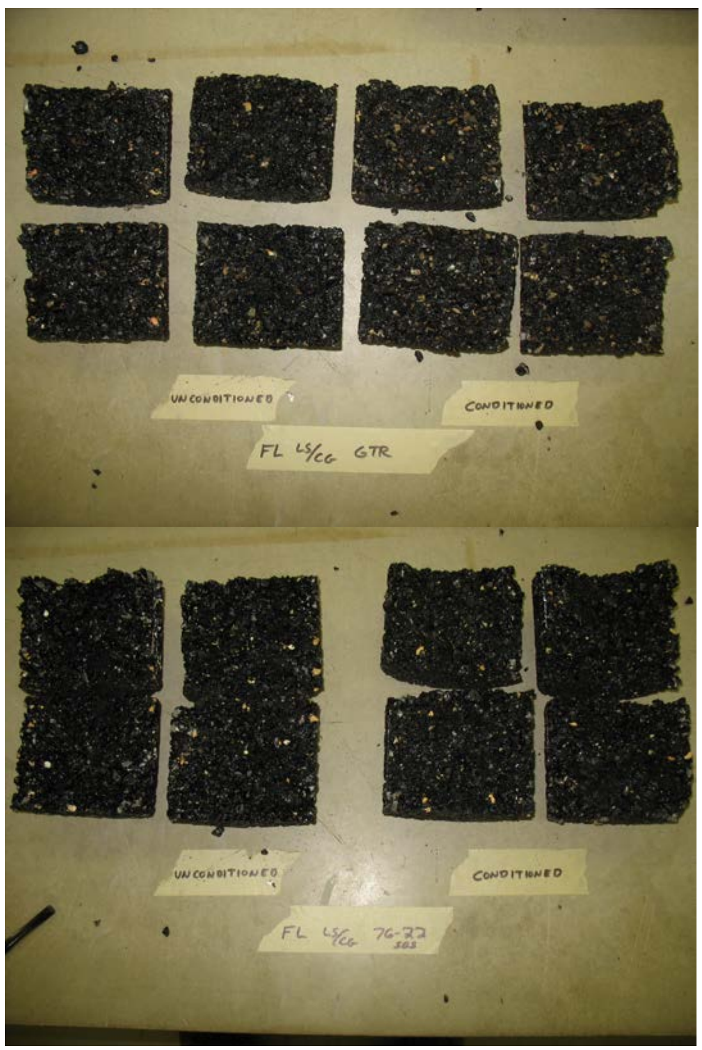

Figure 4.5 Split Indirect Tensile Specimens for Visual Inspection

Of the mixtures evaluated, the MS 12.5 L/G mixture barely passed both the TSR and stripping criteria. The other mixtures were slightly below the criteria except for the new MS 12.5-Coarse mixtures with the GTR PG 76-22 binder. This mixture with both limestone/gravel and gravel aggregates exhibited results much lower than the criteria.

4.7 Direct Shear Tests

Early MDOT experience with OGFC mixtures (White and Ivy, 2009) was that OGFC exhibited raveling and delamination. Factors contributing to these problems include traffic, binder characteristics and amount, and aggregate type and gradation. The direct shear test is used in this study to evaluate integrity and bonding of the thin OGFC surface to underlying dense HMA mixtures. The result is an evaluation directly or indirectly of the OGFC mixtures and their components to adequately perform under traffic.

4.7.1 Test Apparatus

As part of the test a direct shear apparatus was fabricated and techniques developed for its use. The apparatus is designed to test a six inch diameter composite core consisting of a ¾ inch thick OGFC cap compacted on a 3 inch dense mixture base core. The compaction is discussed above. The test apparatus has two parts. One part is fixed and the other part is moveable. During the test, the specimen axis is horizontal with the dense mixture base inserted into the fixed part of the apparatus. Specimens are positioned so that the juncture of the two parts of the mold is aligned with the OGFC/dense mixture base interface. The test temperature is 140°F (60°C). A reference specimen with a temperature sensor is used to insure the target test temperature is attained. After the sample is conditioned, a constant load is applied normal to the OGFC/ dense base interface. Subsequently, a transverse load is applied to the moveable section of the apparatus at a rate of 0.001 in/sec, shearing the specimen at the interface. Figure 4.6 shows the apparatus.

Direct shear testing was conducted on specimens of the ten mixtures focused on after the preliminary OGFC mix design evaluation. The specimens consisted of three inch thick dense HMA cores compacted in a Superpave gyratory compactor. The compacted dense core is then placed in a six inch Marshall mold. The OGFC material was placed in the mold and compacted on top of the dense mixture base with a six inch Marshall hammer to produce a composite specimen with the ¾ inch thick OGFC cap.

4.7.2 Test Procedure

In preparation for testing an assembly with an attached low profile hydraulic ram is inserted into the fixed section of the two-part mold. Length of the assembly is adjusted to accommodate the specimen length. The adjustment is made so that the ¾" cap extends out of the fixed apparatus section and the edge of the fixed mold lines up with the interface of the OGFC and the dense mixture base. The juncture of the two sections defines the shear plane during the test (Interface of the OGFC cap and dense mixture base). Finally, the load cell assembly is bolted in place. Figure 4.6 shows the internal assembly and length adjustment.

Figure 4.6 Direct Shear Apparatus Internal Assembly

Sample conditioning and testing are done in a temperature chamber shown in Figure 4.7. Samples and the dummy specimen used to monitor temperature are placed in the chamber at 140°F (60°C). Temperature conditioning takes about six hours. The dummy specimen is simply a specimen of the same size as the test samples but has a temperature sensor embedded at its center (Figure 4.8). Once the desired internal temperature of 140°F (60°C) is achieved, the test can then be run.

Figure 4.7 Environmental Test Chamber

Figure 4.8 Dummy Specimen

Because of the temperature sensitivity of asphalt mixtures it is important to minimize the time that the chamber door is open. This can be accomplished by using the access ports in the chamber door for handling the specimens and test set up. The test is conducted using an Interlaken closed loop, electro-hydraulic machine. The test machine is computer controlled and has preprogrammed software that was utilized to conduct the direct shear test. Several test routines are available in the master software. The routine for conducting the direct shear test is selected and the parameters are adjusted. Parameters for the direct shear test are load, stroke, and rate of loading. Data sampling frequency is also set.

In preparation for the test, the two parts of the test apparatus are aligned so that the specimen can be inserted. The dense mixture base end of the specimen is inserted first so that it is in the fixed part of the apparatus and in contact with the end where the hydraulic ram for applying the normal load is located. Finally, a plate is bolted in place and a hand operated pump is connected to the load cell. Figure 4.9 shows the sequence of these steps.

Figure 4.9 Direct Shear Preparation Sequence

In preparation for conducting the tests, the pump was calibrated so that the desired normal load could be applied by achieving a target pressure on the pump pressure gage. Shear tests were conducted on specimens with normal pressures of 30, 60, and 90 psi, respectively. These pressures corresponded to loads of 848.2lbs, 1696.5lbs, and 2544.7lbs, respectively.

Data recorded was stroke or deformation and load in the direction of the plane of shear (interface). There were a total of thirty tests conducted. Each of the ten mixtures were tested at three normal pressures. A plot of load versus stroke was plotted for each test. To obtain an estimate of a yield load, tangents were drawn for the initial slope and upper yield slope and the intersection was used to define a yield load. The initial and yield slopes were poorly defined in the tests at 30psi and 60psi normal pressures for all mixtures. However, well defined curves were obtained for tests at 90psi normal pressure for all mixtures. Also, it was felt that the 90psi normal pressure more closely approximates truck tire pressures and therefore, the associated shear test would be better for comparing the interface bond of the OGFC mixtures.

4.7.3 Test Results

Results of the tests are shown in Table 4.8.

Table 4.8 Direct Shear Yield Load

Aggregate Type	Gradation	Normal Pressure (psi)	Yield Load, lbs	
			Binder	
			PG 76-22	GTR PG 76-22
Gravel	9.5	30	1219	NT
		60	2450	
		90	3650	
	MS 12.5	30	1213	1325
		60	1750	2250
		90	2875	3400
	MS 12.5-Coarse	30	F	875
		60	F	2088
		90	F	2675
Limestone/Gravel	9.5	30	1490	NT
		60	2450	
		90	3425	
	MS 12.5	30	1425	1194
		60	1500	1613
		90	3288	3300
	MS 12.5-Coarse	30	F	1200
		60	F	2000
		90	F	3575

NT – Not Tested, F – Interlaken test equipment data system failed to store data

In the above table, the shear load at the 90psi normal pressure is highlighted. Range of the shear load for all mixtures is from 2675lbs to 3650lbs. There does not appear to be any difference between mixtures or between binder types. For example, the average shear load of mixtures with PG 76-22 binder is 3310lbs, the average shear load of mixtures with GTR PG 76-22 binder is 3238, and the average of all mixtures is 3274lbs.

4.8 Sound Absorption

An attribute of OGFC pavement surfaces is that they are known to mitigate tire and vehicle noise. The high, connected air voids of in service OGFC surfaces facilitate the noise reduction. Air voids of OGFC are typically above 15 percent depending on the method by which they are measured. Sound waves enter the voids of an OGFC surface where they are absorbed. A dense HMA surface with much lower percent air voids (4 to 8 percent) has a correspondingly lower absorption. The result is that tire and vehicle noise is reflected and becomes undesirable ambient highway noise.

As discussed in the literature review, noise mitigating characteristics of highway surfaces can be measured for in service pavements as well as in the laboratory. The current study examines several OGFC mixtures with varying aggregates, binders and gradations. The goal of the study is to compare the noise mitigate characteristics of the mixtures. For this reason the mixes were evaluated in the laboratory using an impedance tube.

Impedance tube testing was conducted at the National Center for Asphalt Technology (NCAT), Auburn University. Theory and fabrication of the impedance tube are discussed by Vissamraju (2005). The tube is metal and has a six inch inside diameter. A six inch diameter core specimen is placed at one end of the tube and a speaker at the other. Two microphone pickups project through the tube wall at fixed positions along its length. Sound is generated from the speaker and travels in the tube toward the specimen. Depending on the specimen’s sound absorption characteristics more or less sound is reflected from the specimen’s surface. The sound generated and reflected are captured by the microphone pickups and used to determine the reflectivity and complement, absorption coefficient (α).

There are operating limitations of impedance tubes. According to Vissramraju (2005) the six inch diameter tube has a practical working range of from 200 to 1250 Hz. However, the peak frequency of noise generated by automobiles on interstate highways is about 900 Hz. Therefore, the pavements absorption coefficient at that frequency is important.

Specimens tested consisted of a ¾ inch OGFC cap on a dense HMA base. The base was compacted first and then at a later date the OGFC cap was compacted on the base. The specimens were transported to NCAT for testing. Figure 4.10 shows specimens organized for testing. Duplicate specimens were tested over a frequency range of from 315 to 1600Hz. Figure 4.11 shows a specimen inserted in the tube base and the tube in the background.

Figure 4.10 Specimens for Sound Testing

Figure 4.11 Preparations for Impedance Tube Testing

Output of the tests consists of discrete frequencies and corresponding absorption coefficients. The data for the duplicate tests were averaged and plotted. A typical plot is shown in Figure 4.12.

From the plot, the absorption coefficient at 900 Hz is 0.23. Absorption coefficients for OGFC mixtures tested are given in Table 4.9.

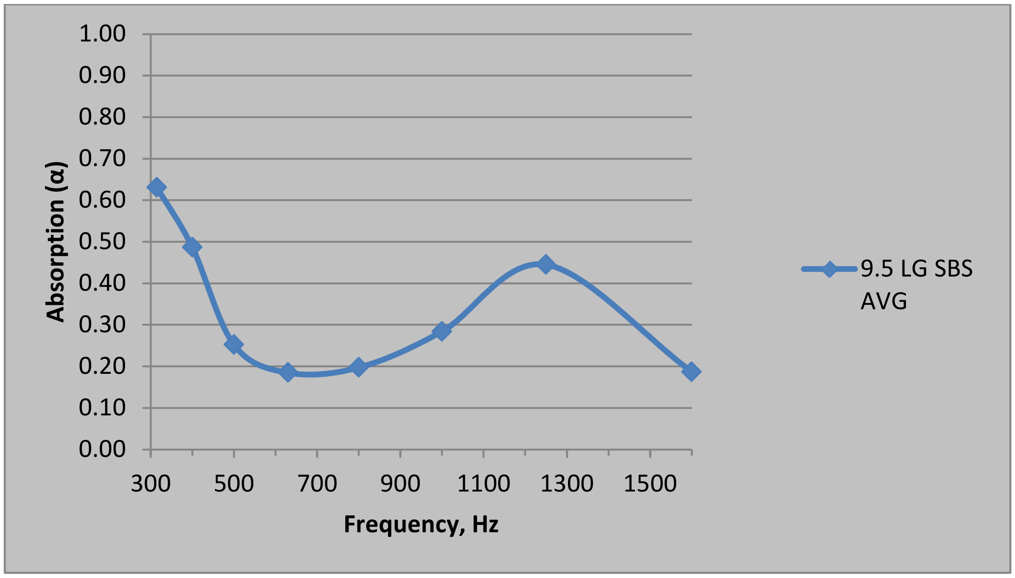

Figure 4.12 Absorption Coefficient vs. Frequency Sweep

Table 4.9 Coefficient of Sound Absorption at 900Hz

<table>
<tr><td rowspan="2">Aggregate Type</td><td rowspan="2">Gradation</td><td colspan="6">Coefficient of Absorption (α)</td></tr>
<tr><td colspan="3">PG 76-22</td><td colspan="3">GTR PG 76-22</td></tr>
<tr><td></td><td></td><td></td><td>Avg</td><td>Avg.</td><td></td><td>Avg.</td><td>Avg.</td></tr>
<tr><td rowspan="3">Gravel</td><td>MS 9.5</td><td>0.20</td><td rowspan="3">0.203</td><td rowspan="6">0.215</td><td>NT</td><td rowspan="3">0.265</td><td rowspan="6">0.250</td></tr>
<tr><td>MS 12.5</td><td>0.22</td><td>0.25</td></tr>
<tr><td>MS 12.5-Coarse</td><td>0.19</td><td>0.28</td></tr>
<tr><td rowspan="3">Limestone/Gravel</td><td>MS 9.5</td><td>0.23</td><td rowspan="3">0.227</td><td>NT</td><td rowspan="3">0.24</td></tr>
<tr><td>MS 12.5</td><td>0.22</td><td>0.23</td></tr>
<tr><td>MS 12.5-Coarse</td><td>0.23</td><td>0.25</td></tr>
</table>

NT – Not Tested

An examination of data in the above table indicates that all mixtures with GTR PG 76-22 binder have higher coefficients of sound absorption than mixtures with PG 76-22 binder.

CHAPTER 5

CONCLUSIONS

In this laboratory study of OGFC mixtures several conclusions have been drawn. These conclusions are made based on application of standard tests and new tests with new apparatus developed as part of this study.

Specimens for standard tests are prepared with the Superpave gyratory compactor. However, for tests that were conducted on specimens requiring geometry of in service OGFC layers, a compaction effort was needed to produce an OGFC/dense base composite specimen. As a standard, consideration was given to the concept that permeability of a standard OGFC would be a measure of compaction. Permeability of the I-55 MDOT test section determined by the White falling head device was used as a target. On this basis, a 75 bow compactive effort with the six inch Marshall hammer was adopted for preparing the composite cores consisting of a ¾ inch OGFC cap on a dense HMA base. This compactive effort appears reasonable.

For the MT-84 permeability tests, there does not appear to be a large difference in permeability among the mixtures except for the MS 12.5-Coarse mixture with limestone and gravel aggregate. All mixtures with the GTR PG 76-22 binder have a slightly lower permeability than the mixtures with the PG 76-22 (SBS) binder.

Results of the White falling head permeability test are similar to those of MT-84. In the test, a lower time to fall indicates a higher permeability. The advantage of the White device is that the test can be used to evaluate in service pavements and cores from in service pavements. Adoption of this test as a standard for field and laboratory evolutions is recommended.

In the dynamic modulus tests, the 9.5mm mixtures were tested at **-10**°C, **4**°C, **21**°C, **37**°C, and **54**°C for mixtures with both SBS and GTR binders. However, the 12.5 mixtures could not be tested at **54**°C and some of the remaining results were questionable. The problem is that the integrity of the larger maximum aggregate OGFC mixtures is lost at high test temperatures.

Of the mixtures evaluated, the MS 12.5 L/G mixture barely passed both the TSR and stripping criteria. The other mixtures were slightly below the criteria except for the new MS 12.5-Coarse mixtures with the GTR PG 76-22 binder. This mixture with both limestone/gravel and gravel aggregates exhibited results much lower than the criteria. In normal mixture design evaluations it is likely all of the OGFC mixtures will require anti-stripping additives.

In the direct shear test results, the failure shear load at 90psi normal pressure was selected to evaluate OGFC/dense base bond. Range of the failure shear load for all mixtures ranged from 2675lbs to 3650lbs. There does not appear to be any difference between mixtures or between binder types. For example, the average shear load of mixtures with PG 76-22 binder is 3310lbs, the average of mixtures with GTR PG 76-22 is 3238, and the average of all mixtures is 3274lbs. The failure shear load variation between OGFC mixtures does not seem to be large.

In the laboratory sound study, gravel mixtures have a slightly higher sound absorption coefficient than limestone/gravel mixtures. Also, mixtures with GTR PG 76-22 binder have a higher sound absorption coefficient than mixtures with PG 76-22 binder. As a result, the potential for OGFC mixtures with GTR modified binder to reduce ambient highway related noise appears to be valid.

Ultimately, tests sections combined with a monitoring program will be required to verify satisfactory performance of OGFC included in this study.

CHAPTER 6

REFERENCES

Arizona Department of Transportation (ADOT) (2008), “What is Rubberized Asphalt?”, http://www.azdot.gov/Highways/index.asp

Asphalt Rubber Technology Information Center (ARTIC) (2008), Asphalt-Rubber/ “Rubberized Asphalt - There Is a Difference!”, http://www.asphaltrubber.org/library/difference.asp

ASTM D6114-09, “Standard Specifications for Asphalt Rubber Binder”.

ASTM E1050-10, “Impedance and Absorption of Acoustical Materials Using a Tube”.

Barrett, M. and Stanard, C. (2008), “Effects of the Permeability Friction Course (PFC) on Highway Runoff”, *Proceedings*, 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

Bollard & Brennan, Inc. and Sacramento County Department of Environmental Review and Assessment (1999), “Report on the Status of Rubberized Asphalt Traffic Noise Reduction in Sacramento County” November 1999, http://www.rubberpavements.org/Library_Information/4_6_Sac_County_Noise_Study.pdf

Brüel & Kjaer Instruments (2009), Nærum, Denmark.

Caltrans (California Department of Transportation) (2003), Asphalt Rubber Usage Guide, Division of Engineering Services, January, 2003, http://www.asphaltrubber.org/ari/California_AR_Design_Guide/Caltrans_Asphalt_Rubber_Usage_Guide.pdf

Carlson, D.D. and Zhu H, (1999), Third Joint UNCTAD/IRSG Workshop on Rubber and the Environment International Rubber Forum, Veracruz, Mexico, October 1999.

CRF (Code of Federal Regulations), (2009), TITLE 23, Part 772, PROCEDURES FOR ABATEMENT OF HIGHWAY TRAFFIC NOISE AND CONSTRUCTION.

Colorado Department of Transportation (CDOT) (2005), “Noise FAQs”, http://www.dot.state.co.us/environmental/CulturalResources/Noise.asp

Dantas, N.S.A., Farias, M.M., Pais, J.C., and Pereira, P.A.A. (2006), “Influence of Crumb Rubber Gradation on Asphalt-Rubber Properties”, *Asphalt Rubber*, http://www.civil.uminho.pt/highways/publications/2006_(AR2006)_Neto_Farias_Pais_Pereira.pdf

Epps, J. A. (1994), Uses of Recycled Rubber Tires in Highways, *NCHRP Synthesis 198*, TRB, National Research Council. Washington, DC.

Federal Aviation Administration (FAA) (2008), "Integrated Noise Model", http://www.faa.gov/about/office_org/headquarters_offices/aep/models/inm_model/

Federal Highway Administration (FHWA) (2007), "FHWA Traffic Noise Model", http://www.fhwa.dot.gov/environment/noise/tnm/tn_backg.htm

Federal Highway Administration (FHWA) (2009, "Measurement of Highway Related Noise", http://www.fhwa.dot.gov/environment/noise/measure/toc.htm

Gallaway, B. M. and Epps, J.A. (1976), "Porous Pavement Laboratory and Field Observations", *Proceedings*, International Symposium on Porous Asphalt, Study Centre for Road Construction, The Netherlands, pp. 48-90.

Gunkel, K.O. (1994), "Evaluation of Exhaust Gas Emissions and Worker Exposure From Asphalt Rubber Binders in Hot Mix Asphalt", Wildwood Environmental Engineering Consultants, Inc., Michigan Department of Transportation, March 1994.

Hanson D.I., James R.S. (2004), "COLORADO DOT TIRE/PAVEMENT NOISE STUDY", Report No. CDOT-DTD-R-2004-5, Department of Transportation, http://www.dot.state.co.us/publications/PDFFiles/tirenoise.pdf

Hanson D.I., James R.S., Waller B., (2005), "Kansas Tire/Pavement Noise Study", Kansas Asphalt Pavement Association, June 2005, http://www.quietpavement.com/docs/Kansas_Tire-Pavement_Noise_Study.pdf

Heitzman M. (1991), "Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier." *Transportation Research Record No.1339*, Transportation Research Board, Washington, DC, 1991, pp. 1-8.

ISQDH (Institute for Safe Quiet and Durable Highways) (2005), "Noise 101 What is a dB? What are Hz?", Quiet Asphalt 2005 Tire/Pavement Noise Symposium, Purdue University.

IEC (International Electrical Commission), IEC 60651, "Standard for Sound Level Meters".

International Organization for Standardization (ISO) (1997), "Acoustics - Measurement of the influence of road surfaces on traffic noise - Part 1: Statistical Pass-By method" ISO 11819-1:1997(E), First edition 1997-09-15, ISO publications. Geneva, Switzerland.

Johnson, E.A. and White, T.D. (1976), "Porous Friction Course Solves Airport Hydroplaning Problem," *Civil Engineering*, Volume 46, No. 4, pp. 90-92.

Lewis J.Y. and Welborn W.J. (1954), "Properties of Petroleum Asphalts," *Public Roads*, vol. 28, No. 4, October, 1954.

Ludwig A.C., (1997), “Music and the Human Ear”, http://www.silcom.com/~aludwig/EARS.htm

Mississippi DOT Test Method, MT-63, “Resistance of Bituminous Paving Mixtures to Stripping (Vacuum Saturation Method)”.

Mississippi DOT Test Method, MT-84, “Laboratory Falling Head Permeability”.

Morse E. (2007), “Durable Rubberized Asphalt Proves Its Worth in Phoenix”, *Better Roads*, August 2007. http://www.betterroads.com/content/Issue-Story.45.0.html?&no_cache=1&tx_magissue_pi1%5BshowUid%5D=909

M+P Consulting Engineers. (2008). “Road traffic noise”. http://www.mp.nl/themas/themepage.php?langID=2&theme=road

Oliver J.W.H. (1981). “Modification of Paving Asphalts by Digestion with Scrap Rubber.” *Transportation Research Record No. 821*, Transportation Research Board, Washington, DC, 1981.

Oliver, J.W.H. and Alderson, A.J. (1998), Crumb rubber asphalt study: final report, Austroads Pavement Research Group (APRG), Document 98/28(MA).

Oliver J.W.H. (1999), “The Use of Recycled Crumb Rubber”, Austroads Pavement Research Group (APRG), APRG Technical Note 10, July 1999. http://www.austroads.com.au/pdf/TechNotes/aprgTN10.pdf

Robinson, William Jeremy. (2005). “Design and Performance of Open Graded Friction Course Hot Mix Asphalt,” MS Thesis, Department of Civil Engineering, Mississippi State University.

Sandiford, Daniel L., Graul, Richard A., and Lenke, Larry R, (1985), Permeability Equipment for Porous Friction Surfaces,” Federal Aviation Administration/USAF Engineering & Services Center, New Mexico Engineering Research Institute, Albuquerque, NM, Interim Report, DOT?FAA?PM-85/31, ESL-TR-85-22.

Smith, R.W., Rice, Jim, and Spelman, S.R. (1974), “Design of Open-Graded Asphalt Friction Course, “RD-74-2, FHWA, Office of Research and Development, Washington, DC.

Smith, R. W. (1976), “Examination of Factors Related to the Development and Performance of Open-Graded Asphalt Friction Course”, *Proceedings*, International Symposium on Porous Asphalt, Study Centre for Road Construction, The Netherlands, pp. 91-135.

Smith, B. and Stewart, J. (2013), “OGFC Boosts Safety”, *Asphalt Pavements*, July/August, pp 24-29.

Summers, C.J. (2009), "The Idiots' Guide to Highway Maintenance" http://www.highwaysmaintenance.com/skidtext.htm

Swan, J. L. (2013), "Porous Asphalt Manages Difficult Drainage for BP Refinery", *Asphalt Pavements*, July/August, pp 16-19..

Triplett, G. S. and White, T. D. (1976), "Friction Course," *Proceedings*, Canadian Technical Asphalt Association Conference, Calgary, Alberta, pp. 283-305.

Turner-Fairbank Highway Research Center. (2005), "Pilot Program Evaluates Quiet Pavements in Arizona" *Focus*.

Vissamraju, Krishnasudha (2005), "Measurement of Absorption Coefficient of Road Surfaces Using Impedance Tube Method", MS Thesis, Auburn University, Auburn, AL.

Visser A.T. and Verhaeghe B. (2000), "Bitumen rubber: Lessons learned in South Africa", *Proceedings*, Asphalt Rubber 2000, Portugal, 2000, p. 33-52.

Volpe National Transportation Systems Center (2009), "Projects - Federal Aviation Administration (FAA) Integrated Noise Model, Ongoing", http://www.volpe.dot.gov/acoustics/af-faa.html#aedt-ongoing

White, T. D. (1975), "Porous Friction Surface Course", Miscellaneous Paper S-75-12, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

White, T.D. (1976). "Field Performance of Porous Friction Surface Course" Miscellaneous Paper S-76-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

White, Thomas D., Littlefield, Joshua C., Pittman, Jamie, Plummer, Robert C., Easterling, Jonathan R., Owens, James R., and Buchanan, M. Shane (2007), "Hot Mix Asphalt (HMA) Characterization For The 2002 AASHTO Design Guide," Report No. FHWA/MS-DOT-RD-07-166, Mississippi Transportation Research Center (MTRC), Department of Civil Engineering, Mississippi State University, Mississippi State.

White, Thomas D and Ivy, Joe (2009), "I-55 OGFC Field Permeability Testing"," MS-DOT-RD-090201, Mississippi Transportation Research Center, Mississippi State University, Mississippi State, MS.

Winters R.E. (1989). "The Conception and Development of Asphalt Rubber," Presentation to the National Seminar on Asphalt Rubber. Kansas City, Missouri. October 1989.

APPENDIX A

SUGGEST MODIFICATIONS TO MDOT OGFC SPECIFICATIONS

SUGGESTED MODIFICATIONS - SECTION 907-402 –- OPEN GRADED FRICTION COURSE (OGFC)

(Note: It is proposed that the term “crumb rubber” be replaced by “ground tire rubber (GTR)” or “asphalt rubber (AR)”. The term “ground tire rubber” will be used in the following recommendations.)

Replace the following subsections of Section 907--402

907-402.02.1.2.2--Combined Aggregate Blend. Allowable OGFC gradations are provided in the following table. Natural sand shall not be used in OGFC mixtures. All gradations are based on percent passing by weight. Gradation MS 12.5mm-Coarse applies to OGFC mixtures with GTR modified binder.

Sieve Size	MS 12.5mm	MS 12.5mm-Coarse	MS 9.5mm
19 mm	100	100	100
12.5 mm	100	85-100	100
9.5 mm	80-89	55-75	90-100
4.75 mm	15-30	15-25	15-30
2.36 mm	`10-20	10-16	10-20
75 □m	2-5	2-5	2-5

907-402.02.1.3--Bituminous Materials. Bituminous materials shall meet the applicable requirements of Section 702 for the grade specified. A PG 76-22 asphalt binder shall be used for OGFC mixtures with MS 9.5mm and MS 12.5mm gradations. A ground tire rubber modified PG 76-22 asphalt binder shall be used with the MS 12.5mm-Coarse gradation. For durability, the asphalt content (by weight of total mix) shall be based on the bulk specific gravity of the combined aggregate blend (Gsb) to ensure a constant asphalt binder volume in the mix. The relationship between Gsb and the minimum asphalt binder content by weight of total mix is provided in the following table.

.

Combined Aggregate Bulk Specific Gravity, G_{sb}	Minimum Asphalt Content (%)
2.30	6.9
2.35	6.7
2.40	6.6
2.45	6.5
2.50	6.3
2.55	6.2
2.60	6.1
2.65	6.0
2.70	5.9
2.75	5.8
2.80	5.7
2.85	5.6

Tack coat shall meet the requirements of Subsection 907-402.03.1.2.

907-402.02.1.6 Polymers and Ground Tire Rubber. Polymers or ground tire rubber for use in OGFC shall meet the requirements of Subsection 708.08.3.

The following sections are recommended modifications to Subsection 708.08.3.

-708.08.3 Polymers and Asphalt Rubber Binder.

-708.08.4 Polymers. The polymer…

-708.08.5 Asphalt Rubber Asphalt—Description. Blend of ground tire rubber asphalt binder for use in Open Graded Friction Course.

-708.08.5.1— Materials.

-708.08.5.1.1—Superpave PG Asphalt Binder. The binder grade will be PG 67-22 and meet the requirements of AASHTO M 320.

-708.08.5.1.2—Ground Tire Rubber. Ground tire rubber (GTR) used as a modifier shall meet the following additional requirements:

(1) Ground tire rubber shall be produced by ambient grinding methods.
(2) The GTR shall be sufficiently dry so as to be free flowing and to prevent foaming when mixed with asphalt cement.
(3) The GTR shall be free of contaminants including fabric, metal, minerals and other non-rubber substances. Up to four percent, by weight of rubber, of talc, such as magnesium silicate or calcium carbonate, may be added to prevent sticking and caking of the particles.
(4) The GTR shall be tested in accordance with AASHTO Designation: T 27 with the following exceptions: a 100-gram sample size and up to 25% dusting agent (talc). Rubber balls may also be used to aid in the sieving of finely ground rubber. The resulting rubber gradation shall meet the gradation limits shown herein.

Gradations of Ground Tire Rubber		
Sieve Size	Percent Passing	
	Type A	Type B
No. 10	--	--
No.16	--	--
No.20	--	--
No.30	--	100
No.40	100	--
No. 50	--	40-60
No.60	98-100	--
No.80	90-100	--
No.100	/0-90	--
No.200	35-60	--

The specific gravity of the rubber shall be 1.15 ±0.05 when tested in accordance with ASTM Designation: D 297, pycnometer method.

The moisture content shall be determined in accordance with AASHTO Designation: T 255, with the exception that the oven temperature shall be 140±5°F and the weight of the sample shall be 50 grams. The moisture content shall not exceed 0.75% by weight.

No more than 0.01% metal particles shall be detected when thoroughly passing a magnet through a 50-gram sample.

The chemical composition of the crumb rubber shall be determined in accordance with ASTM Designation: D 297 and shall meet the following requirements:

Acetone Extract.. Maximum 25 percent
Rubber Hydrocarbon Content .... 40 to 55 percent

Ash Content .... Maximum 10 percent
Carbon Black Content .... 20 to 40 percent
Natural Rubber .... 16 to 34 percent

Ground tire rubber meeting these specifications shall be supplied in moisture resistant packaging such as either disposal bags or other appropriate bulk containers.

Each container or bag of ground tire rubber shall be labeled with the manufacturer's designation for the rubber and the specific type, maximum nominal size, weight and manufacturer's batch or lot designation.

The producer of the GTR modified asphalt cement shall furnish the State Materials Engineer one copy of the manufacturer’s certified test results covering each shipment of GTR. These reports shall indicate the results of tests required by this specification. The reports shall also include a certification that the material conforms with the specifications, and shall be identified by manufacturer's batch or lot number.

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