NCAT Report No. 2000-01

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April 2000

Paper prepared for presentation at the annual meeting of the Association of Asphalt Paving Technologists to be held in Reno, Nevada (March 13-15, 2000)

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ABSTRACT

Open-graded friction course (OGFC) has been used by several state departments of transportation (DOT) since 1950. While many DOTs report good performance, many other states stopped using OGFC due to unacceptable performance and/or lack of adequate durability. A vast majority of the states reporting good experience use polymer modified asphalt binders and a relatively coarser aggregate gradation compared to the other states reporting unsatisfactory performance. Obviously, there is a need to develop an improved mix design procedure to help the highway agencies in successful use of OGFC.

The primary objectives of this study are to evaluate the performance of OGFC in the laboratory with different gradations and types of additives, and recommend a rational mix design procedure for the new-generation OGFC mixes. Additionally, the construction and performance of six OGFC pavements (constructed prior to this study) are discussed. These mixes generally meet the requirements for gradation band and Cantabro abrasion recommended in the new mix design system.

Several polymers and fibers were used in OGFC mixes. The mixes were evaluated for draindown, permeability, Cantabro abrasion, rutting, and moisture susceptibility. A tentative mix design system for the coarse new-generation OGFC has been recommended. Based upon the evaluation of six OGFC field pavements, it has also been shown that OGFC mixes meeting the new mix design requirements are constructible and have exhibited good performance.

KEY WORDS: open-graded friction course, OGFC, mix design, polymer modified binder, fiber, draindown, abrasion, permeability, moisture susceptibility

INTRODUCTION

Open-graded friction course (OGFC) has been used since 1950 in different parts of the United States to improve the surface frictional resistance of asphalt pavements. OGFC improves wet weather driving conditions by allowing the water to drain through its porous structure away from the roadway. The improved surface drainage reduces hydroplaning, reduces splash and spray behind vehicles, improves wet pavement friction, improves surface reflectivity, and reduces traffic noise. The Federal Highway Administration (FHWA) developed a mix design procedure for OGFC (1) in 1974, which was used by several state departments of transportation (DOTs). While many DOTs reported good performance, many other states stopped using OGFC due to unacceptable performance and/or lack of adequate durability (2). However, significant improvements have been made during the last few years in the gradation and binder type used in the OGFC. Recently, a survey (3) on the experience of states with OGFC was conducted by the National Center for Asphalt Technology (NCAT). Although experience of states with OGFC has been varied, half of the states surveyed in this study indicated good experience with OGFC. More than 70 percent of the states which use OGFC reported service life of eight or more years. About 80 percent of the states using OGFC have standard specifications for design and construction. A vast majority of states reporting good experience use polymer modified asphalt binders. Also, gradations of aggregates used by these states tend to be somewhat coarser compared to gradations used earlier and gradations used by other states. It seems that good design and construction practice is the key to improved performance of OGFC mixes. There is a need to develop an improved mix design procedure to help the states in successful use of OGFC. A well-designed and well-constructed OGFC should not have raveling/delamination problems and should reasonably retain its high permeability and macro texture.

Objective

The primary objective of this study was to evaluate the laboratory performance of OGFC with different gradations and types of additives, and based upon this work recommend a rational mix design system for a new-generation OGFC. Additionally, the construction and performance of six OGFC pavements (constructed prior to this laboratory study) are discussed. These mixes generally meet the requirements for gradation band and Cantabro abrasion recommended in the new mix design system.

SCOPE OF WORK

The major performance problems associated with OGFC can be classified into two categories: raveling in OGFC and stripping in underlying asphalt courses. The major causes of raveling in OGFC are believed to be inadequate asphalt binder film thickness, excessive aging of binder, and loss of asphalt-aggregate adhesion under freeze-thaw conditions. When OGFC was promoted by the Federal Highway Administration (FHWA) in the 1970s, many states either adopted FHWA's mix design method (1) or used a recipe mix composition. Since polymer modified asphalt binders were not available at that time, and no fibers were used, design asphalt contents in OGFC mixes were kept relatively low because of binder draindown problems during storage and/or transportation. Some states also experienced significant loss in permeability of OGFC after 2-3 years because of clogging of voids by deicing materials or other debris.

The following questions were raised to develop a test plan for evaluating different gradations and additives in this study:

1) What is a good gradation for OGFC to provide
   a) adequate permeability to drain water quickly and maintain a reasonable permeability during service life?

   b) adequate stability through stone-on-stone contact to minimize rutting?

2) What kind of additive(s) is needed to
   a) prevent draindown of binder at binder contents needed to provide sufficient binder film thickness?
   b) improve rutting resistance and decrease temperature susceptibility?
   c) resist excessive aging?

To answer these questions, the study was divided into two main parts. First, a laboratory study was conducted to evaluate different OGFC gradations and types of additives. Based upon this laboratory work, a new OGFC mix design system was to be recommended. Within the new design system, gradation bands, volumetric properties, and performance related tests were to be identified. The second part of the study entailed identifying OGFC pavement sections that would closely resemble OGFC mixes resulting from the recommended mix design system and document construction and performance.

Laboratory Study

A flow chart for the laboratory study test plan is shown in Figure 1. In the first phase of the study blends were prepared with gradations similar to and coarser than the FHWA recommended (1) gradation for OGFC mixes. Table 1 and Figure 2 give the FHWA gradation and the other three new gradations evaluated in this study. The FHWA gradation has 40 percent material passing the 4.75 mm sieve, and the coarsest of the other three gradations has 15 percent material passing the 4.75 mm sieve. The coarsest gradation is very similar to the gradation that is being used by many states reporting good experience with OGFC mixes (such as Georgia). Mixes were prepared for these blends with an unmodified PG 64-22 asphalt binder. The properties of aggregate and asphalt binder are shown in Tables 2 and 3, respectively. Mix designs were conducted according to FHWA procedures (1). These four blends were evaluated for stone-on-stone contact with voids in the mineral aggregate (VMA) and voids in the coarse aggregate (VCA) plots, and VCA data from dry rodded tests with coarse aggregates fraction only. The VCA concept is used in the design of stone matrix asphalt (SMA) mixtures (4).

Samples prepared with FHWA gradation and coarser gradations were tested for draindown potential, permeability, abrasion resistance, aging potential, and rutting. The test procedures are discussed later. All samples were initially compacted with 100 gyrations of Superpave gyratory compactor, which were considered to be equivalent to 50 blows of Marshall hammer in SMA mix design. The primary objective of phase 1 was to evaluate the relative improvements in mix characteristics when the FHWA gradation is made coarser and coarser.

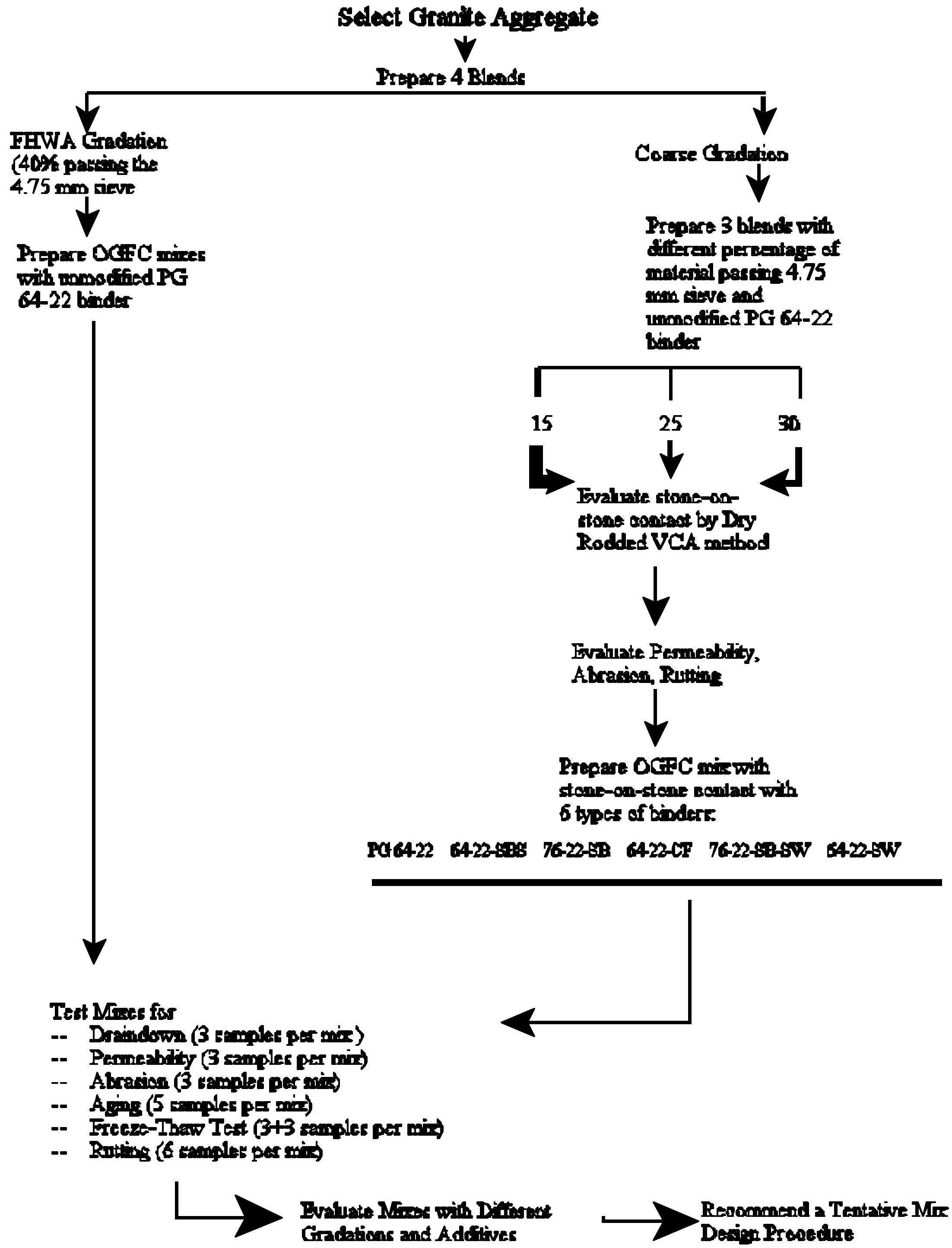

Figure 1. Test Plan.

Table 1. Gradations Used

Sieve Size	Percent Passing				
	Original FHWA Gradation	Gradation Similar to FHWA Used	New Gradation #1	New Gradation #2	New Gradation #3
19 mm	---	100	100	100	100
12.5 mm	100	95	95	95	95
9.5 mm	95-100	65	65	65	65
4.75 mm	30-50	40	30	25	15
2.36 mm	5-15	12	7	7	7
0.075 mm	2-5	4	3	3	3

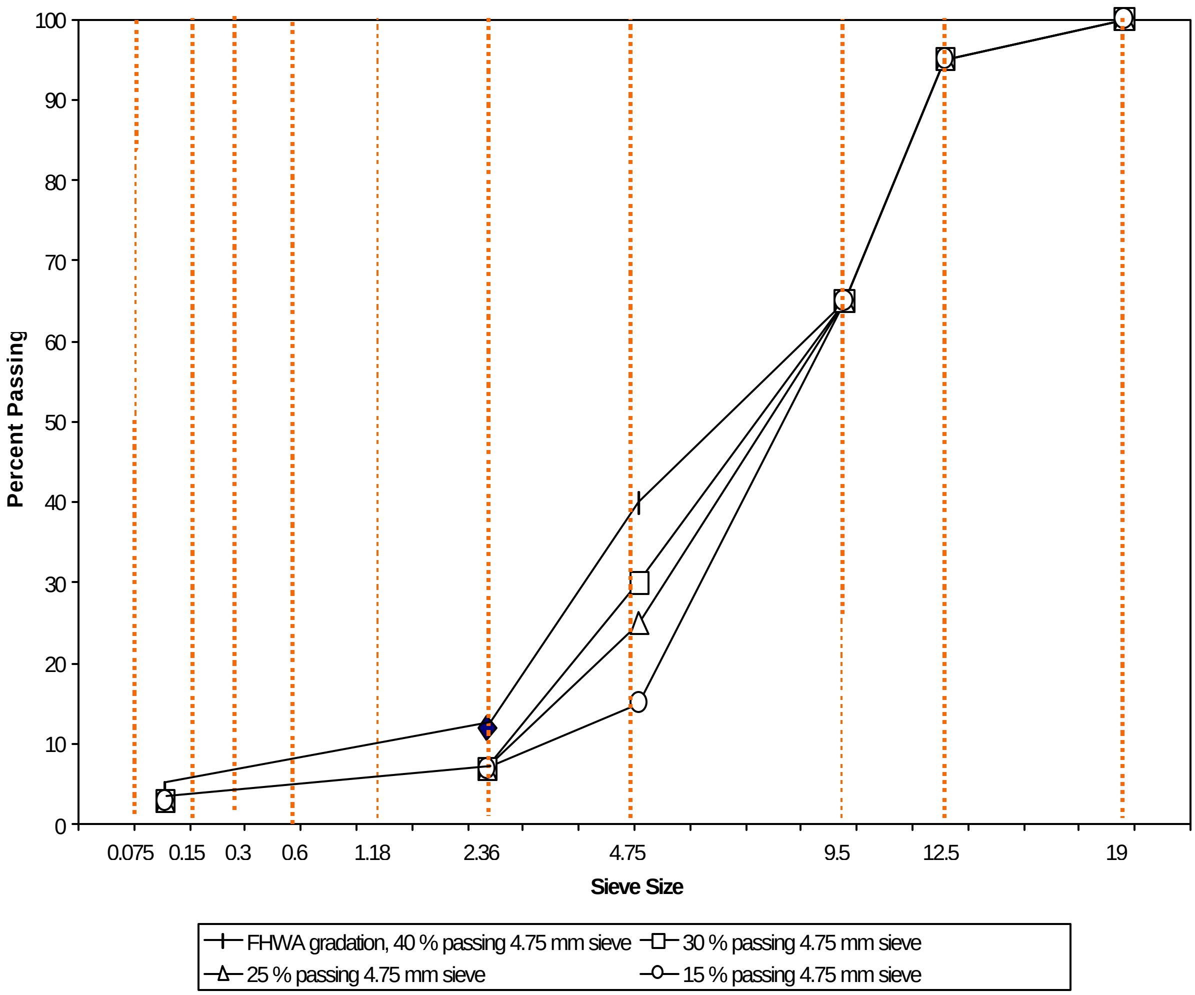

Figure 2. Gradations used in the study

Table 2. Properties of Aggregates

Aggregate	Size	Property	Value
Granite	Fine	Bulk Specific Gravity	2.712
		Water Absorption, percent	0.63
		Fine Aggregate Angularity	49.5
	Coarse	Bulk Specific Gravity	2.688
		Water Absorption, percent	0.58

Table 3. Properties of PG 64-22 and 76-22 (with SB) Asphalt Binder

Asphalt Binder (PG)	High Temperature properties			Low Temperature Properties				
	Temperature °C	Original DSR, G*/Sin ä (kPa)	RTFOT DSR, G*/Sin ä (kPa)	Temperature °C	RTFOT + PAV, DSR, G*Sin ä (Mpa)	Temperature °C	RTFOT + PAV Creep Stiffness, S (MPa)	RTFOT + PAV m (slope)
64-22	64	1.784	3.258	22	4426	-12	240	0.317
76-22 (with SB)	76	1.478	2.356	31	4450	-12	155	0.32

In the second phase of the study, mixes were prepared with the coarsest gradation (gradation #3 in Table 1) and six different binders: PG 64-22, PG 64-22 plus Styrene-Butadiene-Styrene or SBS (referred to hereinafter as PG 64-22-SBS), PG 76-22 containing Styrene Butadiene or SB (referred to as PG76-22-SB), PG 64-22 plus cellulose fiber (referred to as PG 64-22-CF), PG 76-22 containing Styrene Butadiene and slag wool (referred to as PG 76-22-SB-SW) and PG 64-22 plus slag wool (referred to as PG 64-22-SW). Both SBS and SB were added to the asphalt binder at 4 percent by weight of binder. The PG 64-22 and 76-22 (with SB) binders were the base binders, to which the different additives were added. The properties of PG 64-22 and 76-22 (with SB) binders are shown in Table 3. Cellulose and mineral fiber (slagwool) were added at 0.37 percent by weight of the total mix. The primary objective of the second phase was to evaluate the performance of various additives in the OGFC mix. Based on discussion with personnel from the Georgia Department of Transportation (GDOT), these mixes were prepared with 6.5 percent asphalt binder, and compacted with 50 gyrations to match air void contents of OGFC core samples obtained from the field where similar gradation had been used. These mixes were also tested for the different properties mentioned earlier. Resistance to moisture damage was also evaluated in phase 2.

Field Study

To validate the potential for the new mix design system, OGFC pavements were found that would closely meet requirements for the new mix design system. Six OGFC pavement sections were located on Interstate 75 south of Atlanta, Georgia. These sections were constructed in 1992 and consist of OGFC mixes with different types/combinations of asphalt additives.

Construction of these six pavements was documented in a GDOT report (5). Additionally, representatives of NCAT performed a visual distress survey. During the survey, rut depths for each section and three cores per section were obtained. The cores were used to measure density and laboratory permeability.

LABORATORY TEST PROCEDURES

The following test procedures were used in the laboratory study.

Voids in Coarse Aggregate (VCA)

Similar to stone matrix asphalt (SMA), OGFC must have a coarse aggregate (retained on No. 4.75 mm) skeleton with stone-on-stone contact to minimize rutting (4). The condition of stone-on-stone contact within an OGFC mix is defined as the point at which the voids in coarse aggregate (VCA) of the compacted OGFC mixture is less than the VCA of the coarse aggregate alone in the dry rodded test (AASHTO T19).

The VCA of the coarse aggregate only fraction (VCA_{DRC}) is determined by compacting the stone with the dry-rodded technique according to AASHTO T19. When the dry-rodded density of the stone fraction has been determined, the VCA_{DRC} can be calculated using the following equation:

$$VCA_{DRC} = \frac{G_{CA}\gamma_w - \gamma_s}{G_{CA}\gamma_w} \times 100$$

where:

G_{CA}	=	bulk specific gravity of the coarse aggregate (AASHTO T85)
γ_s	=	unit weight of the coarse aggregate fraction in the dry-rodded condition (kg/m^3) (AASHTO T19)
γ_w	=	unit weight of water (998 kg/m^3)

Draindown Characteristics

The NCAT draindown test method (4) was used. A sample of loose asphalt mixture to be tested is prepared in the laboratory or obtained from field production. The sample is placed in a wire basket which is positioned on a plate or other suitable container of known mass. The sample, basket, and plate or container are placed in a forced draft oven for one hour at a pre-selected temperature. At the end of one hour, the basket containing the sample is removed from the oven along with the plate or container and the mass of the plate or container is determined. The amount of draindown is then calculated.

This test method can be used to determine whether the amount of draindown measured for a given asphalt mixture is within acceptable levels. The test provides an evaluation of the draindown potential of an asphalt mixture during mixture design and/or during field production. This test is primarily used for mixtures with high coarse aggregate content such as porous asphalt (OGFC) and SMA. A maximum draindown of 0.3 percent by weight of total mix is recommended for SMA and is also considered applicable to OGFC.

Permeability

The Florida DOT falling-head laboratory permeability test was used. This test uses a falling head concept to determine permeability (6).

Resistance to Abrasion

The resistance of compacted OGFC specimens to abrasion loss was analyzed by means of the Cantabro test (7). This is an abrasion and impact test carried out in the Los Angeles Abrasion machine (ASTM Method C131).

In this test, an OGFC specimen compacted with 50 blows on each side is used. The mass of the specimen is determined to the nearest 0.1 gram, and is recorded as P_1. The test specimen is then placed in the Los Angeles Rattler without the charge of steel balls. The operating temperature is usually 25°C. The machine is operated for 300 revolutions at a speed of 30 to 33 rpm. The test specimen is then removed and its mass determined to the nearest 0.1 gram (P_2). The percentage abrasion loss (P) is calculated according to the following formula:

$$P = \frac{P_1 - P_2}{P_1} 100$$

The recommended maximum permitted abrasion loss value for freshly compacted specimens is 20 percent (5). However, some European countries specify a maximum value of 25 percent.

Resistance to abrasion usually improves with an increase in binder content. However, this resistance is also related to the rheological properties of the binder. For a given gradation and binder content, mixes containing unmodified binders generally have less resistance to abrasion than mixes containing polymer-modified binders.

Aging

Both unaged and aged compacted OGFC were subjected to Cantabro abrasion test to evaluate the effect of accelerated laboratory aging on resistance to abrasion. Because of very high air void contents the asphalt binder in OGFC is prone to hardening at a faster rate than dense-graded hot mix asphalt (HMA), which may result in reduction of cohesive and adhesive strength leading to raveling. Therefore, the mix design should be subjected to an accelerated aging test (7).

Aging was accomplished by placing five Marshall specimens compacted with 50 blows in a forced draft oven set at 60EC for 168 hours (7 days). The specimens are then cooled to 25EC and stored for 4 hours prior to Cantabro abrasion test. The average of the abrasion losses obtained on 5 aged specimens should not exceed 30 percent, while no individual result should exceed 50 percent.

Freeze and Thaw Test for Resistance to Moisture Damage

Raveling of the OGFC may take place due to stripping in the mix, especially from freeze and thaw cycles in northern tier states with cold climates. Modified Lottman test (AASHTO T283) was used in this study. Instead of using one freeze/thaw cycle used for dense-graded HMA, 5 cycles were used for OGFC. Since the air void content is higher in the OGFC compared to dense-graded HMA, more severe conditioning was deemed necessary to evaluate the stripping potential.

Rutting

The potential for rutting of OGFC was evaluated with the Asphalt Pavement Analyzer (APA) which is a modified version of Georgia loaded wheel tester. Cylindrical OGFC specimens were loaded at 64EC (both dry and under water) for 8000 cycles and rut depth measured.

DEVELOPMENT OF MIX DESIGN PROCEDURE

A summary of data and analyses used to develop the mix design system are presented in the following sections.

Phase One

Two blends with coarse aggregate only were prepared according to the AASHTO T19 procedure to determine the dry rodded voids in coarse aggregate (VCA_{DRC}). Next, three blends were prepared for each gradation with 15%, 25%, 30% and 40% passing 4.75 mm sieve. As mentioned earlier, the 40% passing 4.75 mm sieve represented FHWA gradation and the remaining three gradations were all coarser than the FHWA gradation (Figure 2, Table 1). Since, in general, the NCAT survey indicated good performance of mixes with gradations coarser than the FHWA gradation (3), it was decided not to use any gradation finer than the FHWA gradation. Mixes were prepared with PG 64-22 asphalt binder and compacted with 100 gyrations of the Superpave gyratory compactor (SGC). The asphalt contents were determined by the FHWA method (1). The FHWA method consists of the following steps: (1) determination of surface capacity of aggregate fraction retained on 4.75 mm sieve by oil absorption method, and (2) determination of asphalt content from an empirical formula with the surface constant (obtained in step 1). The following formula is used:

$$Asphalt\ \ content = (2K_c + 4.0) \times \frac{2.65}{Apparent\ \ sp.\ \ gr.\ \ of\ \ aggregate}$$

Table 4 gives the mix design data using the FHWA procedure. Unfortunately, the optimum asphalt content is based on the oil absorption of the material retained on 4.75 mm sieve only. Therefore, the optimum asphalt contents are very similar for all four gradations, which is not logical. Obviously, the FHWA formula was developed for one gradation band.

Table 4. FHWA Mix Design Data (Phase One)

Gradation (% passing 4.75 mm sieve)	Percent Oil Retained (POR)	Surface Constant, Kc	Asphalt Content, percent
15	1.890	0.856	5.55
25	1.839	0.836	5.51
30	1.808	0.823	5.48
40	1.724	0.789	5.42

The average air voids or voids in total mix (VTM), voids in mineral aggregate (VMA), voids in coarse aggregate (VCA), and voids filled with asphalt (VFA) data for the four different mixes are shown in Table 5. The VCA_{DRC} is also shown in Table 5. Plots of VTM, VMA, and VCA are shown in Figures 3 and 4. Although there is a difference of only 0.13% in asphalt content between the mixes with four gradations, there is a significant range in voids (VTM, VMA and VCA). The VTM and VMA generally decrease with an increase in percent passing 4.75 mm sieve. Hence, the coarser the mix, the higher is the VTM and VMA. The dry rodded coarse aggregate VCA (VCA_{DRC}) falls between the compacted mix VCA values for gradations with 15% and 25% passing the 4.75 mm sieve. This indicates that stone-on-stone contact begins at some point between 25% and 15% (approximately at 22%) passing the 4.75 mm sieve.

Also, the VMA curve starts to curl upward (VMA increases) at about 30% passing 4.75 mm sieve. The reduced slope in VMA indicates stone-on-stone contact is beginning to be lost, and further increases in the amount of the fine aggregate do not bring the aggregates any closer. High VTM

Table 5. Summary of Mix Volumetric Properties

Gradation (% passing 4.75 mm sieve)	Asphalt Content	TMD*	Compacted OGFC Mix			
			VTM, %	VMA, %	VCA, %	VFA, %
15	5.55	2.475	15.1	26.3	37.3	42.6
25	5.51	2.512	14.3	24.5	43.3	41.7
30	5.48	2.511	13.6	24.0	46.6	43.3
40	5.42	2.487	12.5	23.9	54.1	47.3

* TMD = Theoretical maximum density
Dry rodded VCA = 41.7%.

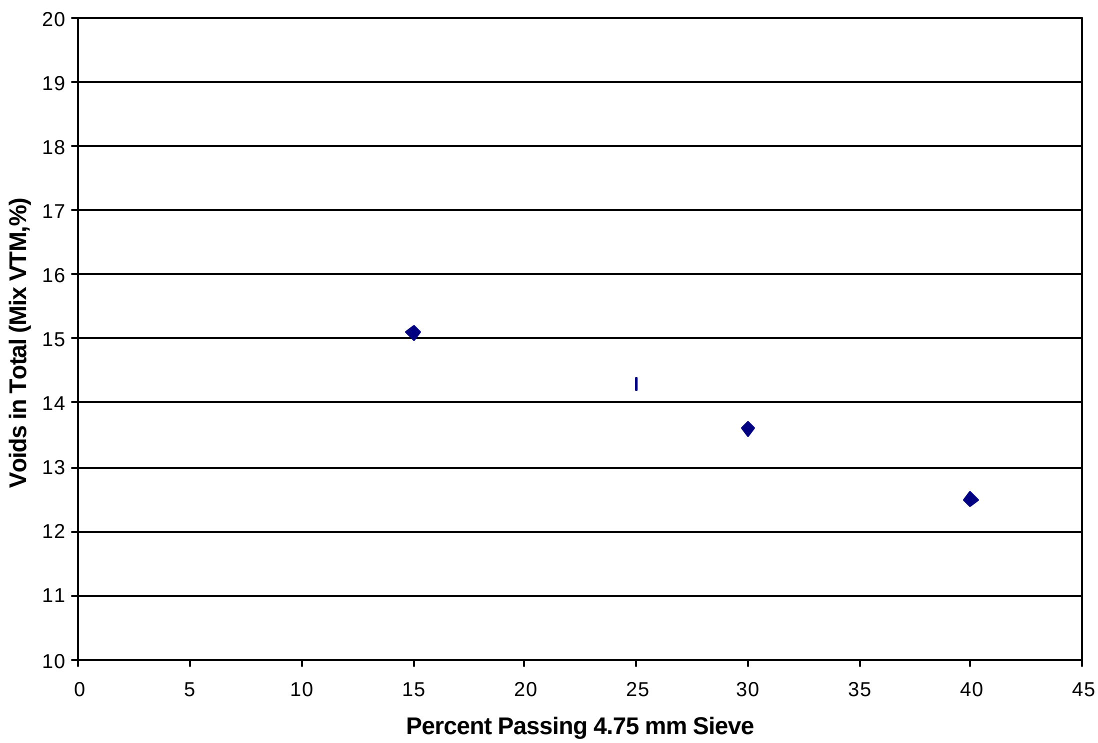

Figure 3. Percent passing 4.75 mm sieve versus voids in total mix
Note: samples compacted with 100 gyrations of SGC

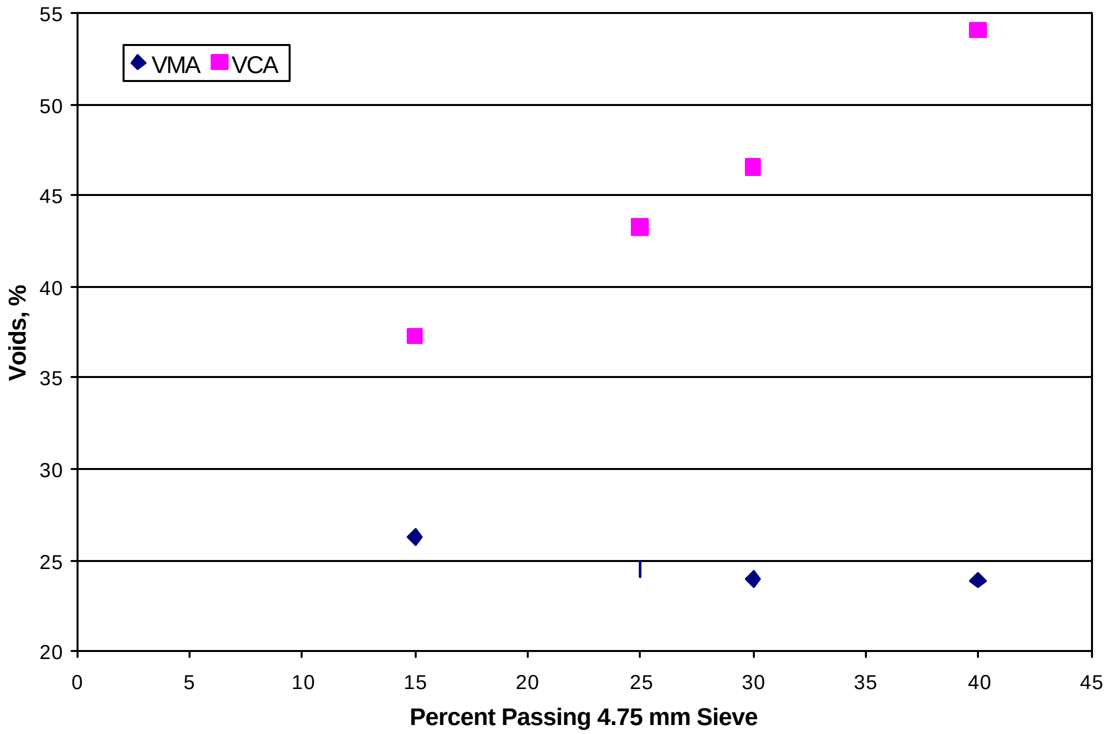

Figure 4. Percent passing 4.75 mm sieve versus VMA and VCA
Note: Dry rodded VCA = 41.7%

associated with the coarser gradation will also facilitate better drainage of water. A preliminary, crude test carried out by holding compacted OGFC specimens under water tap indicated almost free flow of water through the mix with 15% passing the 4.75 mm sieve, moderate flow through mix with 25% passing 4.75 mm sieve, and very poor or no flow through mixes with 30% and 40% passing the 4.75 mm sieve.

Draindown

In hot mix asphalt, the coarser the gradation, the greater is the potential of draindown of asphalt binder during storage and/or transportation. Draindown causes deficient binder in part of the mix (resulting in raveling) and excessive binder in the other part of the mix causing bleeding loss of permeability, and potential for flushing and rutting. Draindown tests were conducted on uncompacted OGFC mixes (with PG 64-22 binder) at 160EC and 175EC according to the NCAT draindown test method. The Schellenberg drainage test used in Europe is conducted at 175EC (7). The results of NCAT draindown test are shown in Table 6. The maximum permissible draindown is 0.3%. As expected, the mix with 15% passing 4.75 mm sieve showed the maximum draindown. The mix with 25% passing 4.75 mm sieve showed a draindown of less than 0.3% at 175EC. However, when tested with PG 76-22 binder, the mix with 15 percent passing the 4.75 mm sieve, showed significantly less draindown. It should be noted that the temperatures used for draindown tests in this study are significantly higher than typical production temperatures. OGFC mixes containing polymer modified binders such as SB or SBS are commonly produced at 150EC. It is recommended to conduct the draindown test at the proposed mixing temperature. Nonetheless, the test data in Table 6 gives the relative draindown potential of different mixes.

Table 6. Summary of Draindown Test Results

Gradation (percent passing 4.75 mm sieve)	Draindown (%)			
	160EC		175EC	
	PG 64-22	PG 76-22	PG 64-22	PG 76-22
15	0.45	0.05	1.27	0.30
25	0.10		0.25	
30	0.11		0.24	
40	0.12		0.19	

Abrasion Test

The Cantabro abrasion test was conducted on mixes with different percentages of material passing the 4.75 mm sieve. First, the unaged samples were tested. Next, samples were aged and tested for abrasion loss. The results are shown in Table 7. The data show that under both aged and unaged conditions the abrasion loss increases as the mix is made coarser, the mix with 15% passing 4.75 mm sieve shows the highest abrasion loss. Although, the mix with 15% passing 4.75 mm sieve satisfies the Cantabro abrasion criteria (7) of 20% maximum for unaged specimens and 30% maximum for aged specimens, the loss can be reduced further by using a modified binder and increasing the asphalt content by use of fibers. This was investigated in the second phase of the study reported later.

Table 7. Summary of Abrasion Test Results

Gradation (percent passing 4.75 mm sieve)	Loss, % (Unaged)	Loss, % (Aged)	Difference due to aging (%)
15	14.7	29.3	14.6
25	12.1	19.6	7.5
30	11.7	17.2	5.5
40	8.1	15.5	7.4

Permeability

The permeability of mixes with different percentages of material passing the 4.75 mm sieve were tested with a falling head permeameter. The coefficients of permeability obtained for the different mixes are shown in Table 8. As expected, the mixes with lower percentage of material passing the 4.75 mm sieve show higher permeability. There is a significant increase in permeability between the mix with 30 percent passing the 4.75 mm sieve and the mix with 15 percent passing the 4.75 mm sieve. For comparison, coarse graded Superpave mixes have been found to have permeability in the range of 1.5 m per day to 8.8 m per day with voids ranging from 6.4 to 8.8 percent (tested with the Florida Permeability Test Method) (6).

Table 8. Summary of Permeability Data

Gradation (percent passing 4.75 mm sieve)	Permeability (coefficient, m/day)
15	117
25	88
30	28
40	21

Rutting

Rut tests were conducted on the four mixes at design asphalt contents. The Asphalt Pavement Analyzer (APA) was used to rut the mixes under a wheel load of 445 N (100 lb), and a hose pressure of 690 kPa (100 psi). The mixes were tested at 64EC, since the PG grade of the asphalt was PG 64-22. Table 9 shows the results of rut tests. The rut depths at 8,000 cycles do not show a wide range, nor does it show any particular trend with percent passing the 4.75 mm sieve. However, all of the rut depths are very small, less than 5 mm, and are considered acceptable.

Table 9. Summary of Rut Data

Gradation (percent passing 4.75 mm sieve)	Rut Depth at 8000 cycles, mm
15	4.05
25	3.83
30	4.29
40	3.41

Phase Two

In the next phase of the laboratory study, mixes were prepared with 15 percent passing the 4.75 mm sieve and 6.5 percent asphalt content using six different binder/additive combinations. Test samples for the six mixes were compacted with the SGC, using the number of gyrations required to achieve air voids closer to those found in the field at the time of construction (about 18 percent).

A study was carried out to determine the required number of gyrations. Three samples of each mix were compacted with 100 gyrations of the SGC and 50 blows of Marshall hammer. The air voids at different gyrations were compared to air voids generally found in the field and the air voids of the sample compacted with 50 blows Marshall (Figure 5). It was determined that about 50 gyrations with the SGC and 50 blows with the Marshall hammer produce about 18 percent air voids generally found in the field. The mixes were prepared with six different types of binder as described earlier: PG 64-22, PG 64-22-SBS, PG76-22-SB, PG 64-22-CF, PG 76-22-SB-SW and PG 64-22-SW. The samples were tested for volumetric properties, draindown, aging, rutting, and moisture susceptibility. The volumetric properties are shown in Table 10. Results from other tests are discussed in the following paragraphs.

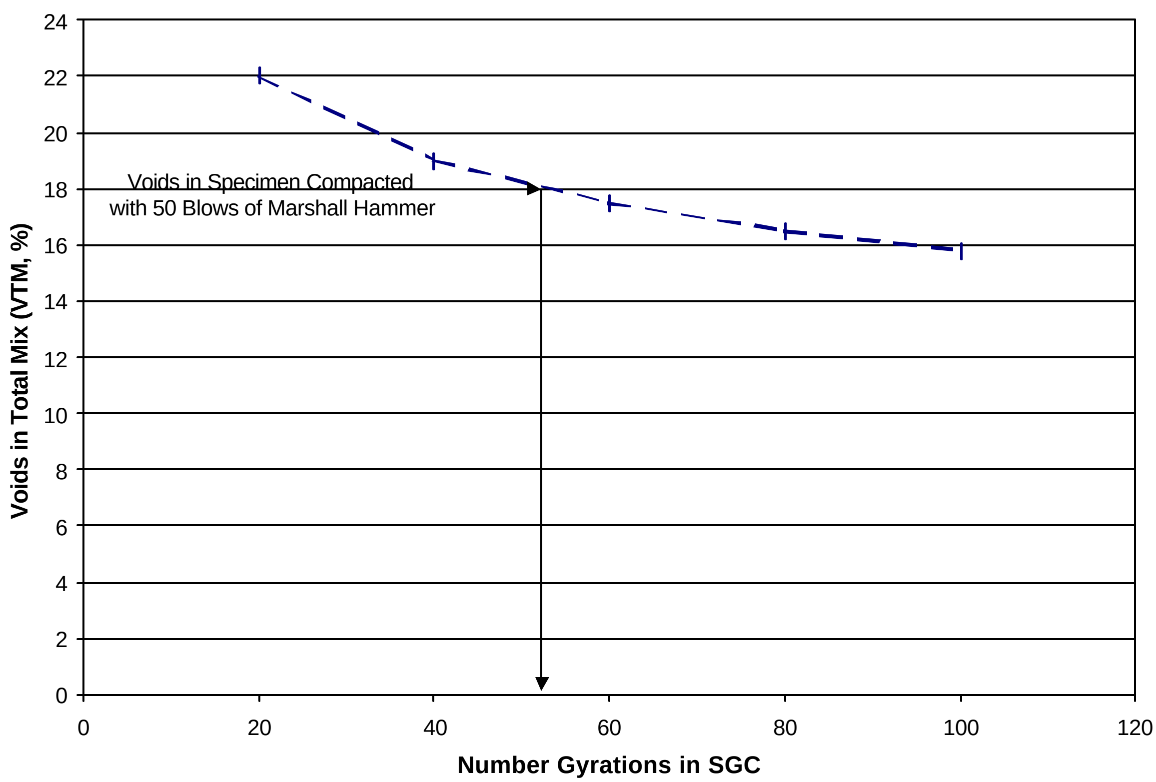

Figure 5. Gyrations versus VTM plot

Table 10. Volumetric Properties of Mixes With Different Binders (Average Values)

Binder	Bulk Sp. Gr.	TMD	VTM	VMA	VCA
PG 64-22	2.044	2.441	16.3	29.0	37.3
PG 64-22 with cellulose	2.043	2.441	16.3	29.0	37.3
PG 64-22 with slagwool	2.071	2.441	15.2	28.1	37.3
PG 64-22 with SBS	2.026	2.441	17.0	29.6	37.3
PG 76-22-SB	2.002	2.441	18.0	30.5	37.3
PG 76-22 with slagwool	2.046	2.441	16.2	28.9	37.3

Draindown

The average draindown values at 157EC (315EF) are shown in Table 11. The test temperatures were reduced in Phase 2 to represent production temperatures generally used in the field. Results from a multiple comparison test are also shown in Table 11. These results indicate whether there is any significant difference between the different means and if there is, provides the ranking of the different mixes based on the means. Table 11 indicates that the draindown values are significantly higher for all mixes with the PG 64-22 and the PG 76-22-SB and also do not meet the criteria of 0.3 percent maximum. It seems that SBS, slagwool, and cellulose are more effective in reducing the draindown at higher temperatures.

Table 11. Results of Draindown Tests From Mixes With Different Binders

Draindown at 157EC (315EF)		
Duncan Grouping	Mean (%)	Asphalt Binder
A	1.3585	PG 64-22
A	1.1845	PG 76-22-SB
B	0.5405	PG 64-22 with SBS
B	0.1245	PG 76-22-SB with slagwool
B	0.0510	PG 64-22 with slagwool
B	0.0040	PG 64-22 with cellulose

Aging Test

Samples of mixes prepared with different binders were tested with the Cantabro abrasion test to determine the effect of aging. All of the samples were aged at 160EC for 168 hours (7 days). Table 12 shows the test values and the results of multiple comparison test. The results show that the mixes with unmodified PG 64-22 binder have the highest abrasion loss, and the mixes with PG 76-22-SW have the lowest abrasion loss, with the other mixes having values in between. In general, mixes with PG 64-22 plus SBS and the PG 76-22-SB binders show less abrasion than mixes with the other binders. Although all mixes meet the maximum loss criteria of 30 percent, it appears that the combined use of polymer modified binder and fiber will minimize the abrasion loss from aging and thus increase the durability of the OGFC.

Table 12. Abrasion Loss (Aged Samples) for Mixes With Different Types of Binder

Duncan Grouping		Mean (%)	Asphalt Binder
	A	26.2	PG 64-22
B	A	19.3	PG 64-22 with slagwool
B	A	18.8	PG 64-22 with cellulose
B	C	15.7	PG 76-22-SB
B	C	13.0	PG 64-22 with SBS
	C	9.0	PG 76-22 with slagwool

Rutting Test

Rutting tests were conducted on samples of mixes with different binders with the APA using identical procedures as phase 1. Table 13 shows the means and the results of multiple comparison test. The results show that in general mixes with PG 76-22-SB binder show less rutting compared to mixes with PG 64-22 binder. Of the mixes with different PG 64-22 binders, the mixes with the unmodified binder showed the highest amount of rutting, while the one with SBS showed the least amount of rutting. The lowest rut depth was obtained in case of SB modified PG 76-22 with slagwool. Again, the combined use of a polymer-modified binder and fiber resulted in the lowest rut depth.

Table 13. Rut Depth for Mixes With Different Types of Binder

Duncan Grouping		Mean (%)	Asphalt Binder
A		6.28	PG 64-22
B	A	5.24	PG 64-22 with cellulose
B	C	5.00	PG 64-22 with slagwool
B	C	4.70	PG 64-22 with SBS
D	C	3.81	PG 76-22-SB
D		2.70	PG 76-22 with slagwool

Moisture Susceptibility Test

Moisture susceptibility of mixes was evaluated by conducting tensile strength test on conditioned (5 freeze/thaw cycles) and unconditioned compacted samples (air voids 7±1 percent) of mixes with different binders. This test was included in phase 2 to evaluate the effect of binder type and fibers on the moisture susceptibility of OGFC mixes. Table 14 shows the average values of tensile strength ratios obtained for the different mixes. The results show that mixes with PG 64-22-SBS show the highest TSR (100 percent), whereas the mixes with unmodified PG 64-22 show the lowest TSR (below 70 percent). In general, all the mixes, except those with unmodified PG 64-22 and PG 64-22-SW show TSR values greater than 80 percent. It appears that both polymer-modified binder and fiber should be used especially in the northern tier states of the U.S., which experience cold climates and freeze/thaw cycles.

Table 14. TSR Values for Mixes With Different Binders

Asphalt Binder	Mean (%)
PG 64-22 with SBS	100
PG 76-22 with slagwool	98
PG 64-22 with cellulose fiber	91
PG 76-22-SB	87
PG 64-22 with slagwool	75
PG 64-22	62

SUMMARY OF LABORATORY STUDY

The following observations can be obtained from the laboratory study:

1. A gradation with no more than about 20 percent passing the 4.75 mm sieve is required to achieve stone-on-stone contact condition and provide adequate permeability in OGFC mixes.

2. Mixes with 15 percent aggregates passing the 4.75 mm sieve are susceptible to significant draindown of the binder. Therefore, it is necessary to provide a suitable stabilizer such as fiber in the mix to prevent excessive draindown.

3. Abrasion loss of OGFC mixes resulting from aging can be reduced significantly with the addition of modifiers. In this study, all of the modified binders had significantly lower abrasion loss than the unmodified binder. The use of both polymer-modified binder and fiber can minimize the abrasion loss and thus increase the durability of OGFC.

4. For the binders used in this study, rut depths as measured with the APA did not vary over a wide range. However, within the range of rut values obtained, the mixes with modified binders had significantly less rutting than mixes with unmodified binders. A higher PG binder grade seems to have a greater effect in reducing rutting than a lower PG binder grade. A polymer-modified asphalt with fiber gave the least amount of rutting.

5. Moisture susceptibility, as measured by TSR values, is lower for mixes with modified binders than mixes with unmodified binders. All of the modifiers except slagwool (with PG 64-22) produced mixes which had TSR values in excess of 80 percent. Again, both polymer-modified binder and fiber should be most effective especially in cold climates with freeze/thaw cycles.

Tentative OGFC Mix Design Procedure

The following tentative mix design system is recommended for the new-generation OGFC mixes on the basis of the laboratory study, observation of in-place performance of OGFC mixes in Georgia, and experience in Europe. The system can be refined further as more experience is gained in the future.

Step 1. Materials Selection

The first step in the mix design process is to select materials suitable for OGFC. Materials needed for OGFC include aggregates, asphalt binders, and additives. Additives include asphalt binder modifiers, such as polymers and fibers.

Guidance for suitable aggregates can be taken from recommendations for SMA (4). The binder selection should be based on factors such as environment, traffic, and expected functional performance of OGFC. High stiffness binders, such as PG 76-xx, made with polymers are recommended (5) for hot climates or cold climates with freeze-thaw cycles, medium to high volume traffic conditions, and mixes with high air void contents (in excess of 22 percent). The addition of fiber is also desirable under such conditions and also have been shown to significantly reduce draindown. For low to medium volume traffic conditions, either polymer modified binders or fibers may be sufficient.

Step 2. Selection of Design Gradation

Based upon this laboratory study and recent experiences in Georgia, the following master gradation band is recommended.

Sieve	Percent Passing
19 mm	100
12.5 mm	85-100

9.5 mm	55-75
4.75 mm	10-25
2.36 mm	5-10
0.075 mm	2-4

Selection of the design gradation should entail blending selected aggregate stockpiles to produce three trial blends. It is suggested that the three trial gradations fall along the coarse and fine limits of the gradation range along with one falling in the middle. For each trial gradation, determine the dry-rodded voids in coarse aggregate of the coarse aggregate fraction (VCA_{DRC}). Coarse aggregate is defined as the aggregate fraction retained on the 4.75 mm sieve.

For each trial gradation, compact specimens at between 6.0 and 6.5 percent asphalt binder using 50 gyrations of a Superpave gyratory compactor. If fibers are a selected material, they should be included in these trial mixes. Determine the voids in coarse aggregate (VCA) for each compacted mix. If the VCA of the compacted mix is equal to or less than the VCA_{DRC}, stone-on-stone contact exists. To select the design gradation, choose a trial gradation that has stone-on-stone contact combined with high voids in total mix.

Step 3. Determine Optimum Asphalt Content

Using the selected design gradation, prepare OGFC mixes at three binder contents in increments of 0.5 percent. Conduct draindown test on loose mix at a temperature 15EC higher than anticipated production temperature. Compact mix using 50 gyrations of a Superpave gyratory compactor and determine air void contents. Conduct the Cantabro abrasion test on unaged and aged (7 days @ 60EC) samples. Rutting tests with the Asphalt Pavement Analyzer and laboratory permeability testing are optional. Insufficient data was accumulated in this study to recommend a critical rut depth. However, laboratory permeability values greater than 100 m/day are recommended. The asphalt content that meets the following criteria is selected as optimum asphalt content.

1. **Air Voids.** A minimum of 18 percent is acceptable, although higher values are more desirable. The higher the air voids are the more permeable the OGFC.

2. **Abrasion Loss on Unaged Specimens.** The abrasion loss from the Cantabro test should not exceed 20 percent.

3. **Abrasion Loss on Aged Specimens.** The abrasion loss from the Cantabro test should not exceed 30 percent.

4. **Draindown.** The maximum permissible draindown should not exceed 0.3 percent by

total mixture mass.

If none of the binder contents tested meet all four criteria, remedial action will be necessary. Air voids within OGFC are controlled by the binder content. If air voids are too low, the asphalt binder content should be reduced. If the abrasion loss on unaged specimens is greater than 20 percent, more asphalt binder is needed. Abrasion loss values of aged specimens in excess of 30 percent can be remedied by either increasing the binder content or changing the type of binder additive. If draindown values are in excess of 0.3 percent, the amount of binder and/or type of binder additive can be adjusted. Fiber stabilizers are typically incorporated into the mix at a rate of 0.2 to 0.5% of the total mix.

Step 4. Evaluate Mix for Moisture Susceptibility

The mix designed with Step 1 through 3 should be evaluated for moisture susceptibility using the modified Lottman method (AASHTO T283) with five freeze/thaw cycles in lieu of one cycle. The retained tensile strength (TSR) should be at least 80 percent.

CONSTRUCTION OF TEST SECTIONS

In 1992, the GDOT initiated a field study to evaluate OGFC mixes (5). The primary objective of this study was to compare GDOT conventional OGFCs with coarser OGFCs modified with different binder additive combinations. This was accomplished by constructing six test sections using a coarser gradation with six combinations of polymer/additive on I-75 south of Atlanta, Georgia.

The six test sections were characterized as a coarse OGFC (D), coarse OGFC with 16 percent crumb rubber (D16R), coarse OGFC with cellulose fibers (DC), coarse OGFC with mineral fibers (DM), coarse OGFC with SB polymer (DP), and coarse OGFC with SB polymer and cellulose fibers (DCP). Mix designs for each of these mixes was conducted using the "Method of Determining Optimum Asphalt Content for Open-Graded Bituminous Paving Mixtures," which is a standard procedure for GDOT (GDT-114).

Job-mix-formula (JMF) data for each of the six mixes are presented in Table 15. This table shows that all six OGFC mixes had identical gradations and only differed by respective asphalt contents. Of interest, the JMF gradation falls within the gradation band recommended in the new mix design system (Figure 6).

Tests conducted in addition to the mix design included the Cantabro abrasion and Schellenberg Drainage tests. Results of the Cantabro abrasion test indicated that all six of the OGFC mixes would meet the requirement of 20 percent loss maximum recommended in the proposed mix design system.

Table 15. Laboratory Test Results for the Six OGFC Mixes (6)

Test	D	D16R	DM	DC	DP	DCP
Percent passing 19.0 mm	100	100	100	100	100	100
Percent passing 12.5 mm	99	99	99	99	99	99
Percent passing 9.5 mm	75	75	75	75	75	75
Percent passing 4.75 mm	18	18	18	18	18	18
Percent passing 2.36 mm	8	8	8	8	8	8
Percent passing 0.075 mm	2	2	2	2	2	2
Percent Asphalt Binder of Total Mix						
% AC	6.0	6.6	6.3	6.4	6.2	6.4
Other Test Data						
Cantabro (% Wear)	13.5	8.6	5.7	5.8	8.6	8.2
Drainage (% Loss)	0.37	0.05	0.06	0.06	0.34	0.04

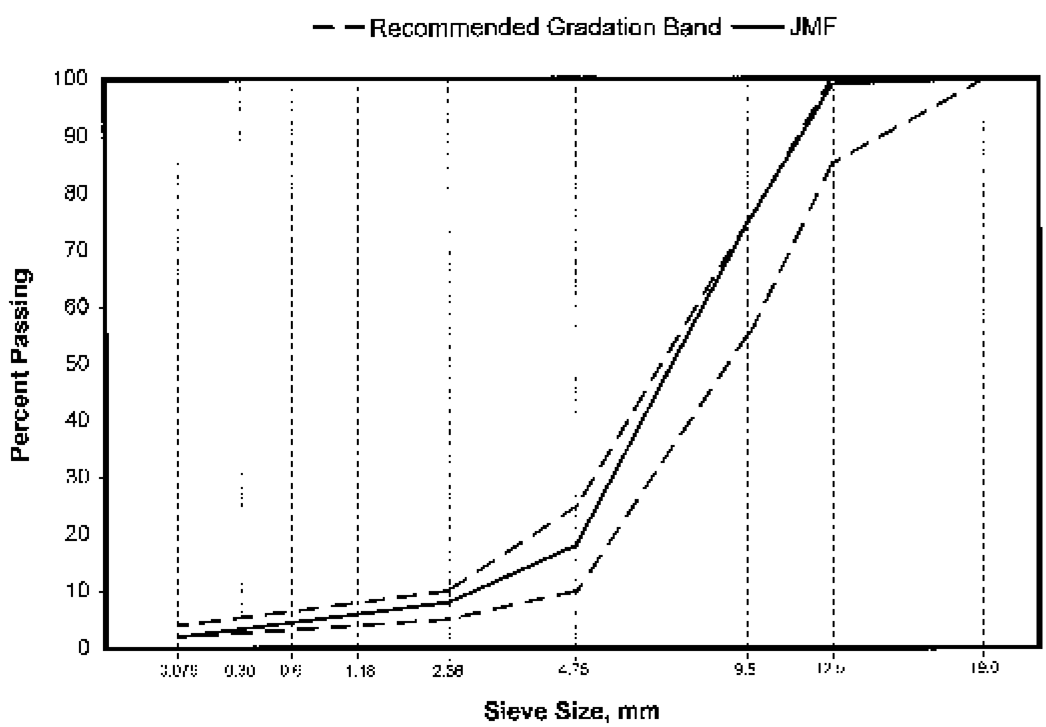

Figure 6. Gradation of OGFC Field Test Sections

In fact, for the five mixes containing binder additives, abrasion loss values were all less than 9 percent. Though the Schellenberg Drainage test is not identical to the NCAT draindown test (4), four of the six mixes met typical Schellenberg drainage requirements of 0.3 percent by total binder mass. Of the two mixes not meeting the 0.3 percent draindown, one used no polymers/additives (D) and the other used just a polymer (DP).

Production of the mixes in the field was accomplished with a double-barrel drum plant. The plant was modified slightly in order to incorporate the crumb rubber and fibers into the mixing process.

During production, truck samples were obtained to determine asphalt content, gradation, air voids, and Cantabro abrasion loss values. Table 16 presents the results of this testing.

Table 16. Laboratory Test Results for Field Produced OGFC Mixes (6)

Sample Type	JMF	D	DM	DC	DCP	DP	D16R
Sieve Size, mm	Total Percent Aggregate Passing by Weight						
19.0	100	100	100	100	100	100	100
12.5	99	98.3	98.9	96.7	97.0	99.1	96.3
9.5	75	70.0	76.2	64.0	68.6	69.9	60.3
4.75	18	21.0	23.9	19.0	19.1	23.1	15.7
2.36	8	8.7	9.0	7.7	7.8	8.4	7.4
0.075	2	3.6	3.1	2.8	2.4	3.1	2.6
Miscellaneous Test Data							
Asphalt Content	Extracted	5.85	6.22	6.16	6.14	6.25	6.41
TMD	---	2.484	2.445	2.429	2.424	2.476	2.451
VTM	---	12.2	11.4	11.5	10.9	14.1	12.0
Cantabro (% Wear)	---	10.3	8.1	14.7	7.0	15.9	7.6

Based on Table 16, five of the produced mixes were finer than the JMF gradation on the 4.75 mm sieve. Only one gradation (DM) did not meet the recommended gradation band within the new mix design procedure. However, this mix only varied from the band by 1.2 percent on the 9.5 mm sieve. Asphalt contents ranged from 5.9 to 6.4 percent. Air void contents of lab compacted samples using 25 blows per face of a Marshall hammer ranged from 10.9 to 14.1 percent and are lower than would be anticipated on the roadway. Cantabro abrasion loss values ranged from 7.0 to 15.7 percent and are all lower than the suggested 20 percent maximum criteria.

In addition to testing truck samples, cores were obtained from each of the six test sections.

Testing of these samples included asphalt contents and gradations by extraction and air void calculations. An additional test conducted was the in-place permeability of each section. Results of this testing are presented in Table 17.

Table 17. Laboratory Test Results for Roadway Core Samples from OGFC Test Sections

Sample No.	JMF	D	DM	DC	DCP	DP	D16R
Sieve Size, mm	Total Percent Aggregate Passing by Weight						
19.0	100	100	100	100	100	100	100
12.5	99	99.3	98.6	99.2	97.6	99.3	99.2
9.5	75	77.3	77.2	75.5	73.1	76.5	76.7
4.75	18	28.1	28.3	28.0	26.9	27.8	28.0
2.36	8	13.1	13.6	13.7	13.0	13.1	13.1
0.075	2	3.8	4.1	3.5	3.9	3.8	3.4
Miscellaneous Test Data							
Asphalt Content	Extracted	5.51	5.87	6.18	5.27	5.85	5.69
VTM	---	17.8	17.2	16.4	16.0	17.6	18.1
Permeability (m/day)	---	46	82	71	71	84	67

Of note in Table 17 are the in-place air void contents of the compacted mixes. Air void contents ranged from 16.0 to 18.1 percent which relate well to the data accumulated in the laboratory part of this study (Table 10). These values also seem to validate the selection of 18 percent air voids minimum during the new mix design system as mixes meeting the gradation requirements can be constructed to have 18 percent air voids. Permeability values obtained from the six test sections ranged from 46 to 84 m/day and appear to correspond reasonably well with permeability data from the laboratory work in this study (Table 8).

Data obtained from this GDOT field study indicate that OGFC mixes meeting the gradation requirements of the recommended mix design procedure can be produced successfully in the field. Also, because of the testing procedures used by GDOT in their field study, it is believed that the six mixes would be similar to OGFC mixes designed using the new mix design procedure. Therefore, the performance of these mixes in the field should provide valuable information on how mixes designed with the new procedure would perform.

PERFORMANCE OF TEST SECTIONS

During 1998 (six years after construction), representatives of NCAT performed a visual distress survey on the six OGFC test sections (8). The survey consisted of evaluating each section for surface texture, rutting, cracking, and raveling. During the course of the survey, cores were obtained from each section and used to determine the laboratory permeability. Also reported in this section are the results of friction testing conducted by the GDOT 3.5 years after construction (5).

Visual Distress Survey

Surface Texture

All six test sections had experienced some coarse aggregate popout. The D16R section appeared to have the most while the DC, DM, and DP sections all had a very low amount. Another surface texture item was the existence of small fat spots on the pavement surface. Each of the six sections had these fat spots. However, none were larger than approximately 15 cm diameter. The D and DCP appeared to have the most but were not deemed significant.

Rutting

Rut depth measurements were made for each section using a stringline. Rut depths ranged from 0.0 mm for the DP section to 4.1 mm for the DC section. None of the sections were characterized as having significant amounts of rutting.

Cracking

The primary form of cracking on all six sections was reflective from a Portland cement concrete pavement underlying each section. Table 18 presents descriptions and percentages of reflective cracks encountered. Percentages were determined by counting the number of transverse cracks visible at the pavement surface.

Table 18. Severity and Percentage of Transverse Reflective Cracks

Section	Description	% Cracks Showing
D	Low to medium severity	75
D16R	Low to high severity	87
DM	Low severity	55
DC	Low severity	45
DP	Low to medium severity	61
DCP	Low to medium severity	65

Table 18 shows that five of the six sections had low to medium severity reflective cracking. The two OGFC mixes containing only fibers (DM and DC) had the least amount (and severity) of cracking while the D16R section had the highest amount and severity cracking. Reflective longitudinal cracks were also observed on five sections. Only the D and D16R sections had what could be characterized as medium severity longitudinal cracking.

Besides reflective cracking, only the D16R section showed any other type of cracking. Secondary cracking around some reflective cracks had occurred.

Raveling

All six sections showed some signs of raveling. However, all raveling was minimal except the D16R section which showed some medium severity raveling next to some cracks.

Permeability Testing of Cores

Three 150 mm cores were obtained from each of the six sections. Table 19 presents the average laboratory permeability values from each section as well as average in-place air void contents. Statistically, no significant differences exist between the permeability values; however, the DC and DCP sections did have the highest average permeability at 74 and 70 m/day, respectively. In-place air void contents ranged from 15 to 19 percent. Bulk specific gravity measurements were determined by volumetric measurements. It is interesting that this range of air void contents correspond well with the roadway core air void contents (at the time of construction) presented in Table 17. Again, this appears to provide validity to the selection of 18 percent air voids minimum in the new mix design system. This criteria appears to be related to air void contents at both construction and during the life of an OGFC pavement. Additionally, it appears that the mix design procedure used by GDOT in this experiment resulted in OGFC mixes with stone-on-stone contact even though it was not specifically tested.

Table 19. Average Permeability and In-Place Air Void Contents for the Six Test Sections

Section	Avg. Permeability m/day	Avg. In-Place Air Voids, %
D	25	16.7
D16R	38	15.8
DM	28	19.9
DC	74	16.2
DP	16	13.9
DCP	70	19.2

Friction Testing

Friction testing was conducted by GDOT 3.5 years after construction according to ASTM E274 procedures (5). Results of this testing indicated that friction values for the six sections ranged from 49 to 51. These values were deemed satisfactory (5).

CONCLUSIONS

Results of this study showed that a coarser gradation for OGFC mixes provides a better performing OGFC pavement. Gradations near 15% passing the 4.75 mm sieve performed much better than finer gradations in the laboratory. Modifiers, whether polymer and/or fibers, were also shown to enhance the performance of OGFC mixes. Using this knowledge, a new mix design system for OGFC mixes was recommended.

Construction and performance data for six OGFC pavements that would closely resemble mixes resulting from the new mix design system were also discussed. Based upon the information obtained from both the laboratory and field work, it is concluded that the new-generation OGFC will provide a better performing mixture.

REFERENCES

1. Smith, R.W., J.M. Rice, and S.R Spelman. Design of Open-Graded Asphalt Friction Courses. Report FHWA-RD-74-2, Federal Highway Administration, January 1974.

2. Smith, H.A. Performance Characteristics of Open-Graded Friction Courses. NCHRP Synthesis of Highway Practice 180, TRB, 1992.

3. Kandhal, P.S., and R.B. Mallick. Open-Graded Friction Course: State of the Practice. Transportation Research Circular Number E-C005, TRB, December 1998.

4. Brown, E.R., and L.A. Cooley. Designing Stone Matrix Asphalt Mixtures for Rut-Resistant Pavement. NCHRP Report 425, TRB, 1999.

5. Santha, Lanka. Comparison of Standard Open-Graded Friction Courses with Modified Open-Graded Friction Courses. Georgia Department of Transportation Research Project No. 9110, Final Report, April 1997.

6. Florida Department of Transportation. "Florida Method of Test for Measurement of Water Permeability of Compacted Asphalt Paving Mixtures." FM 5-565, March 1999.

7. Porous Asphalt. Manual 17, Sabita Ltd, Roggebaai, South Africa, November 1995.

8. Cooley, Jr., L.A. and E.R. Brown. “Evaluation of OGFC Pavements Containing Cellulose Fibers.” National Center for Asphalt Technology. Prepared for Interfibe Corporation. April 1999.