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DESIGN OF NEW-GENERATION OPEN-GRADED FRICTION COURSE

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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.

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.

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

DESIGN OF NEW-GENERATION OPEN-GRADED FRICTION COURSE

Prithvi S. Kandhal and Rajib B. Mallick

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 macrotexture.

OBJECTIVE

The objectives of this study are to evaluate the performance of OGFC with different gradations and types of additives, and recommend a rational mix design procedure for OGFC.

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. Delamination of OGFC from the underlying pavement course has also been reported.

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?

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 gradation similar to and gradation 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

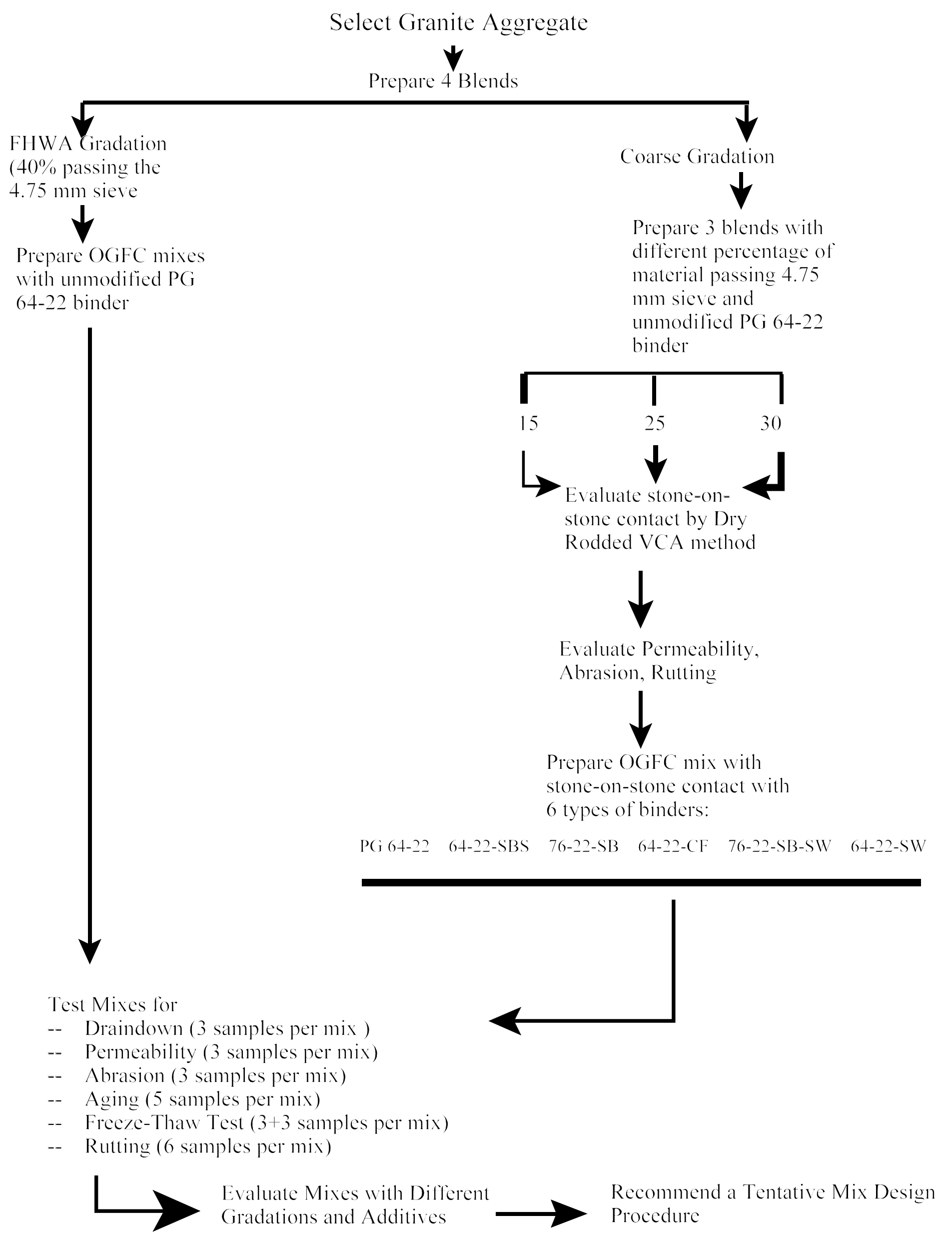

Figure 1. Test Plan

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) given in Appendix A. 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). An example of determining VCA is given in Appendix B.

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

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.

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 content 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.

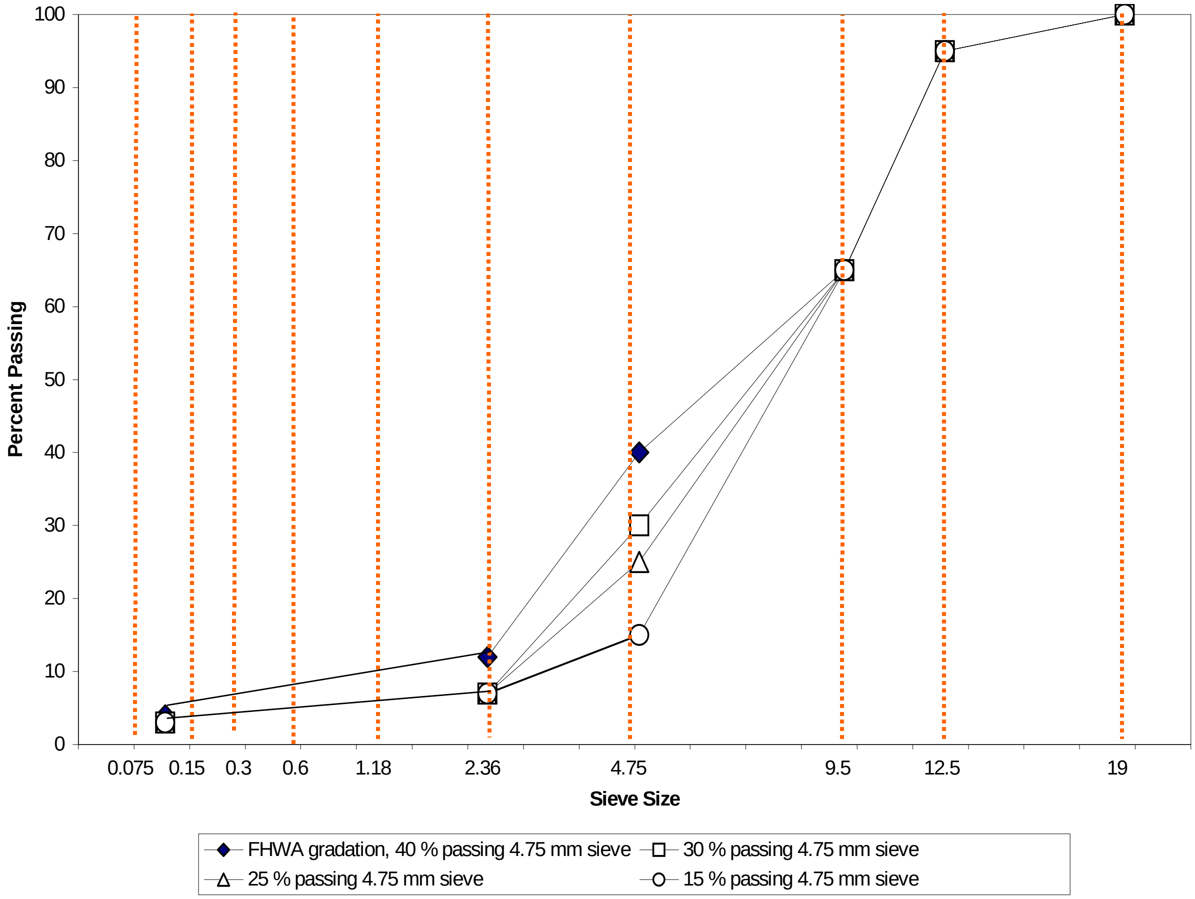

Figure 2. Gradations Used in the Study

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 * (kPa)	RTFOT DSR, G*/Sin * (kPa)	Temperature °C	RTFOT + PAV, DSR, G*Sin * (Mpa)	Temperature °C	RTFOT + PAV	
							Creep Stiffness, S (MPa)	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

TEST PROCEDURES

The following test procedures were used in this study.

Voids in Coarse Aggregate (VCA)

Similar to stone matrix asphalt (SMA), the 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)

An example of determining VCA_{DRC} and VCA (of the compacted OGFC mixture) is given in Appendix B.

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 stone matrix asphalt (SMA). A maximum draindown of 0.3 percent by weight of total mix is recommended for SMA and is also considered applicable to OGFC. The complete test method is given in Appendix C.

Permeability

The Florida DOT falling-head laboratory permeability test was used. The detailed test procedure is given in Appendix D.

Resistance to Abrasion

The resistance of compacted OGFC specimens to abrasion loss was analyzed by means of the Cantabro test (5). 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 (5).

Aging was accomplished by placing five Marshall specimens compacted with 50 blows in a forced draft oven set at 60°C for 168 hours (7 days). The specimens are then cooled to 25°C 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 64°C (both dry and under water) for 8000 cycles and rut depth measured.

TEST RESULTS AND ANALYSIS

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% percent 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) given in Appendix A. 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.

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

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

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%.

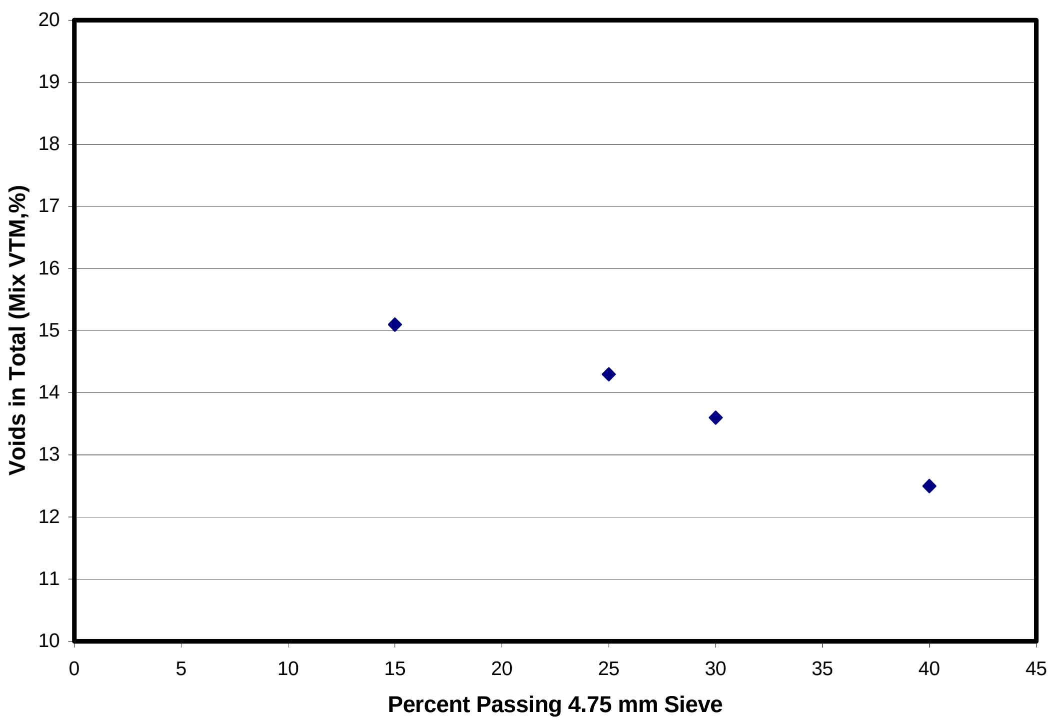

Figure 3. Percent Passing 4.75 mm Sieve Versus Voids in Total Mix
Note: Samples Compacted with 100 Gyrations of SGC

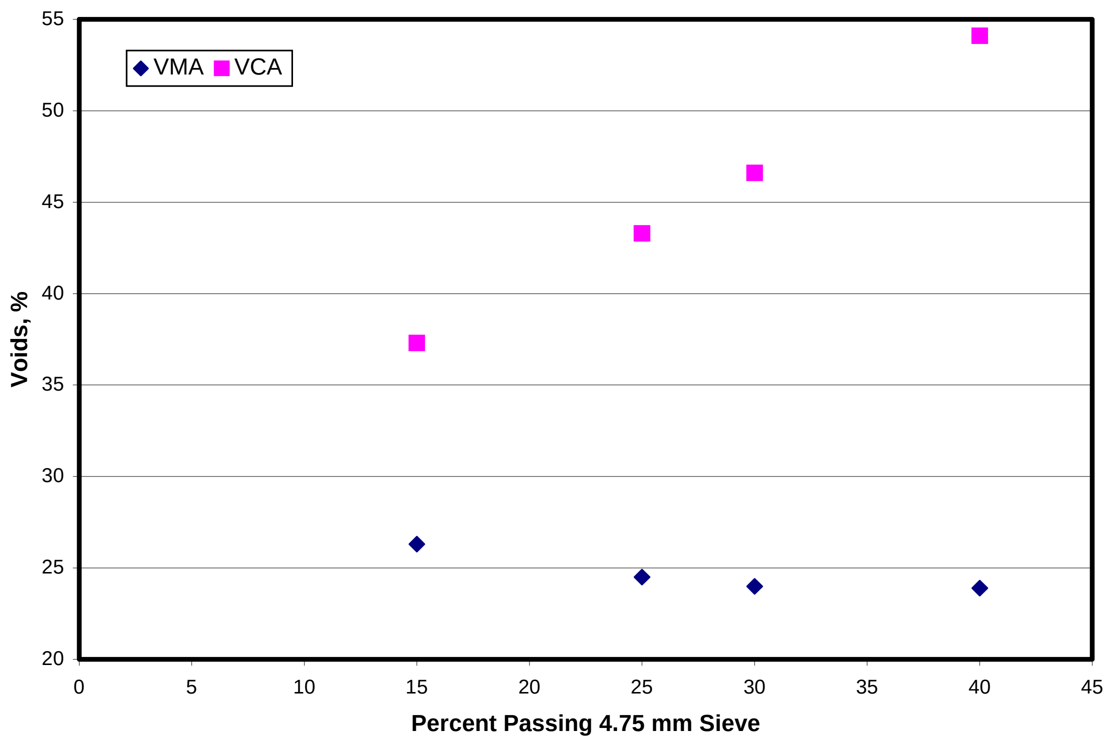

Figure 4. Percent Passing 4.75 mm Sieve Versus VMA and VCA
Note: Dry Rodded VCA = 41.7%

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 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 160°C and 175°C according to the NCAT draindown test method (Appendix C). The Schellenberg drainage test used in Europe is conducted at 175°C (6). 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 175°C. 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 150°C. 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 (%)			
	160°C		175°C	
	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 (5) 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 (Appendix D). 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).

Table 8. Summary of Permeability Data

Gradation (percent passing 4.75 mm sieve)	Permeability, 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 64ºC, 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.

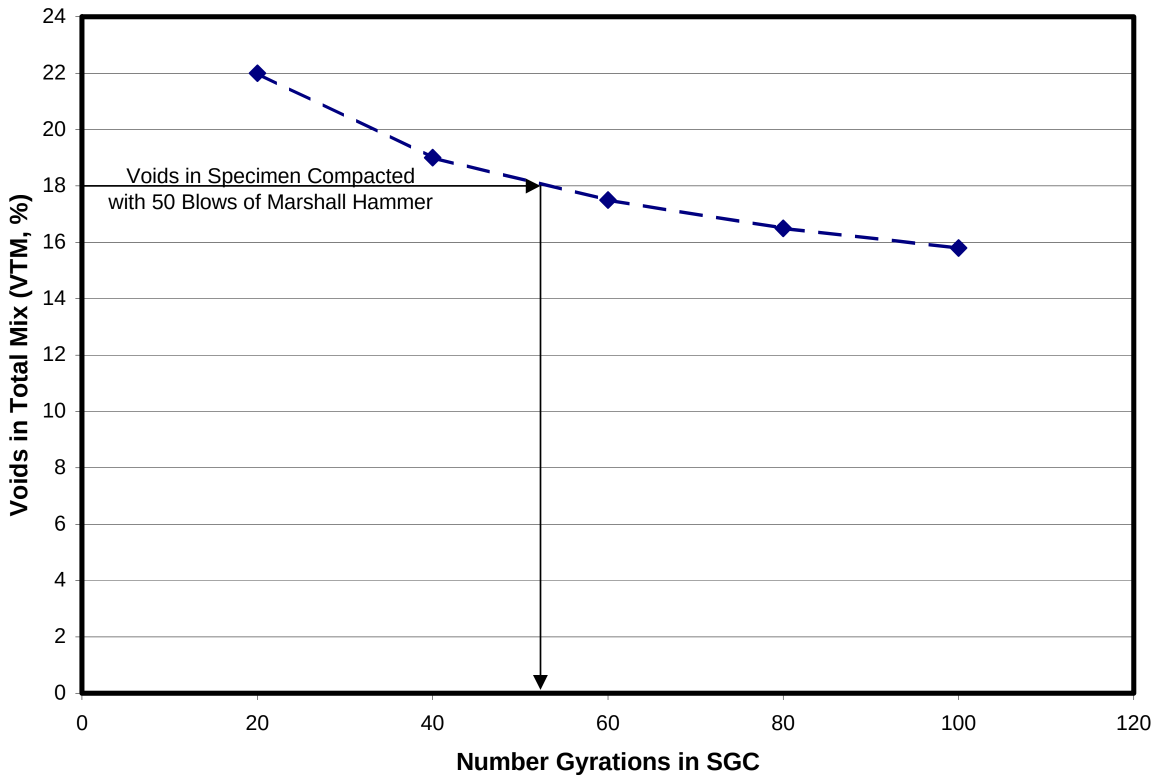

Figure 5. Gyrations Versus VTM Plot

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 157°C (315°F) 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 157°C (315°F)		
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 160ºC 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). 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

CONCLUSIONS AND RECOMMENDATIONS

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.

The following tentative mix design system is recommended for the new-generation OGFC mixes on the basis of conclusions from this 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 (see example in Appendix B). 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 (Appendix C) on loose mix at a temperature 15°C 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 @ 60°C) samples. Rutting tests with the Asphalt Pavement Analyzer and laboratory permeability testing (Appendix D) 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 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, 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 percent 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.

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Appendix A

FHWA Procedure for Design of Open Graded Friction Courses (OGFC)

Material Requirements

1.1 It is recommended that relatively pure carbonate aggregates or any aggregates known to polish be excluded from the coarse-aggregate fraction (material retained on the No. 8 sieve). In addition, the coarse-aggregate fraction should have at least 75 percent (by weight) of particles with at least two fractured faces and 90 percent with one or more fractured faces. The abrasion loss (AASHTO T 96) should not exceed 40 percent.

1.2 Recommended Gradation for Open-Graded Asphalt Friction Course.

Sieve Size[a]	Percent Passing[b]
1/2 in.	100
3/8 in.	95-100
No. 4	30-50
No. 8	5-15
No. 200	2-5

[a] U. S. Sieve Series.
[b] By volume. (This is the same as by weight unless specific gravities of aggregates being combined are different.)

1.3 The recommended grade of asphalt cement is AC-10, AC-20, or AR-40, AASHTO M 226. For AC-10 and AC-20, the M 226 Table 2 requirements should apply where such asphalt is available. AR-40 requirements are given in Table 3 of M 226.

Preliminary Data

2.1 Test coarse and fine aggregates as received for the project for gradation unless otherwise provided. If mineral filler is submitted as a separate item, it should also be tested for specification compliance. Analyze gradation results to determine if proportions of aggregates and batching operations proposed by the contractor will meet the job-mix formula and the specification limits of step 1.2.

2.2 Determine bulk and apparent specific gravity for the coarse- and fine-aggregate fractions (retained and passing the No. 8 sieve) for each type of material submitted. Additional specific gravity tests are not warranted when the only distinction between aggregates is size of grading. Using the information verified in step 2.1, mathematically compute the bulk and apparent specific gravity for the coarse- and fine-aggregate fractions (retained and passing the No. 8 sieve) for the proposed job-mix gradation.

2.3 Test the asphalt cement to be used for specification compliance (AASHTO M 226), viscosity-temperature data, and specific gravity at 77.0 F.

Asphalt Content

3.1 Determine the surface capacity of the aggregate fraction that is retained on a No. 4 sieve in accordance with the following procedure.

Note: For highly absorptive aggregates, use the procedure described in step 3.3.

K_c is determined from the percent of SAE No. 10 oil retained, which represents the total effect of superficial area, the aggregate's absorptive properties, and surface roughness.

3.1.1 Quarter out 105 g representative of the material passing the 3/8-in. sieve and retained on the No. 4 sieve.

3.1.2 Dry sample on hot plate or in 230 ± 9 F oven to constant weight and allow to cool.

3.1.3 Weigh out 100.0 g and place in a metal funnel (top diam 3-1/2 in., height 4-1/2 in., orifice 1/2 in., with a piece of No. 10 sieve soldered to the bottom of the opening).

3.1.4 Completely immerse specimen in SAE No. 10 lubricating oil for 5 min.

3.1.5 Drain for 2 min.

3.1.6 Place funnel containing sample in 140 F oven for 15 min of additional draining.

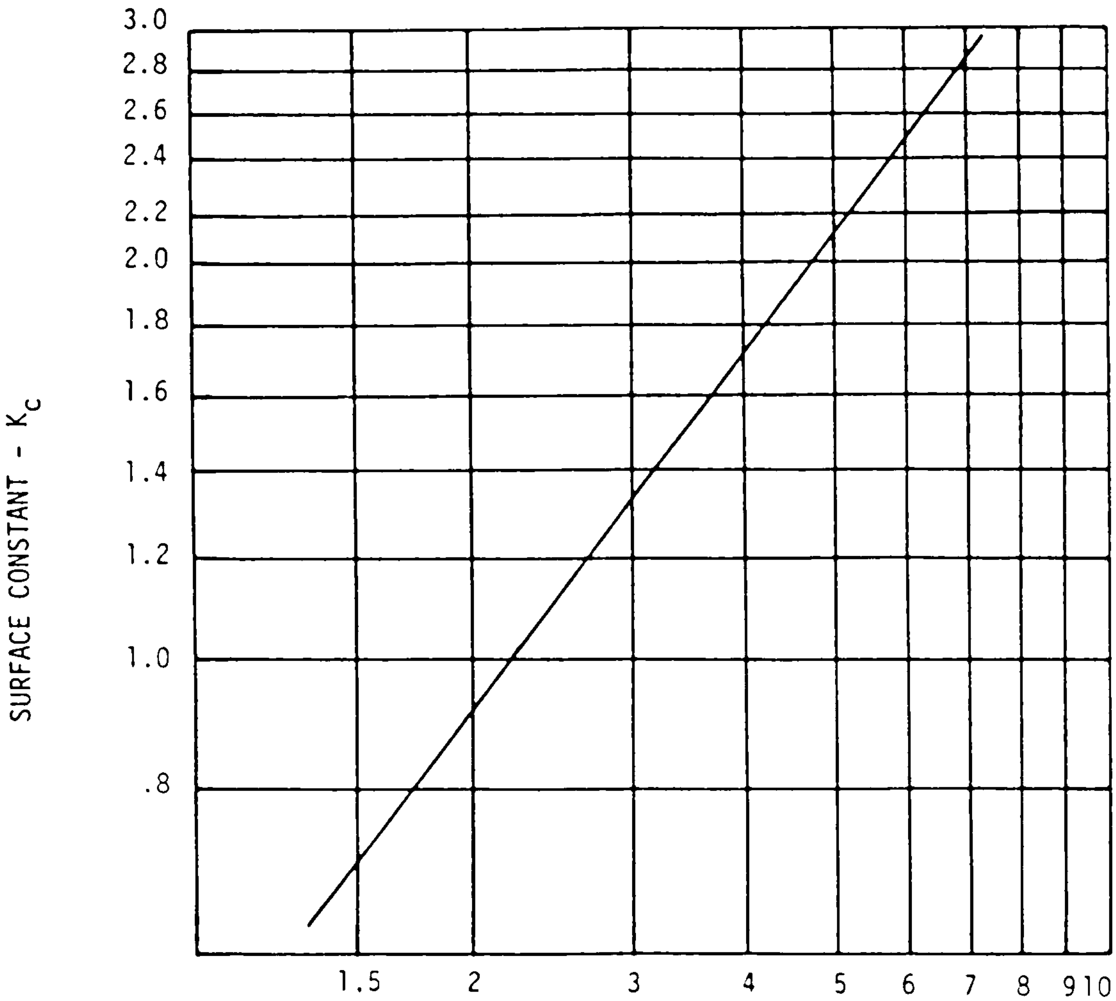
3.1.7 Pour sample from funnel into tared pan; cool, and re-weigh sample to nearest 0.1 g. Subtract original weight and record difference as percent oil retained (based on 100 g of dry aggregate).

3.1.8 Use chart shown in Figure A-1 for determination of K_c.

(a) If specific gravity for the fraction is greater than 2.70 or less than 2.60, apply correction to oil retained, using formula at bottom of chart in Figure A-1.

(b) Start at the bottom of chart in Figure A-1 with the corrected percent of oil retained; follow straightedge vertically upward to intersection with the diagonal line; hold point, and follow the straightedge horizontally to the left. The value obtained is the surface constant for the retained fraction and is known as K_c.

3.2 Determine the required asphalt content, which is based on weight of aggregate, from the following relationship:



PERCENT OIL RETAINED--CORRECTED FOR SPECIFIC GRAVITY OF AGGREGATE

Material used: Aggregate--passing 3/8-in. sieve, retained on No. 4 sieve
Oil--SAE No. 10

$$\text{Oil Retained Corrected (\%)} = \text{Oil Retained (\%)} \times \frac{\text{apparent specific gravity of coarse aggregate}}{2.65}$$

Figure A-1. Chart for determining surface constant (K_c) of coarse aggregate.

$$\textit{Percent asphalt} = (2.0\ K_c + 4.0) \times \frac{2.65}{(SG)ca}$$

Where K_c = surface constant
(SG)ca = apparent specific gravity of coarse aggregate (3/8 in. to No. 4)

3.3 For highly absorptive aggregates, use the following procedure for determining K_c and asphalt content.

3.3.1 Follow the recommended design procedure from step 3.1 through step 3.1.3.

3.3.2 Follow the instructions in step 3.1.4, except immerse the specimen for 30 min.

3.3.3 Follow the recommended procedure from step 3.1.5 through step 3.1.7.

3.3.4 Pour the sample onto a clean, dry, absorptive cloth; obtain a saturated surface dry condition; pour sample from cloth into a tared pan; re-weigh sample to nearest 0.1 g. Subtract original weight of aggregate and record difference as percent oil absorbed (based on 100 g of aggregate).

3.3.5 Subtract the percent oil absorbed value (see 3.3.4 above) from the percent oil retained value (see 3.3.3 above), and obtain the percent (free) oil retained value. This value represents the percent oil retained value that would have been obtained had the aggregate been a nonabsorptive type. The above technique allows one to evaluate the aggregate's surface and shape characteristics without the overwhelming influence of a large quantity of absorbed oil.

3.3.6 Follow the procedure recommended in steps 3.1.8 and 3.2. The only exception is that the percent (free) oil retained value is used (from step 3.3.5) to obtain K_c. Thus, the asphalt quantity determined is the "effective" asphalt content.

3.3.7 Follow the recommended procedure indicated through sections 4 and 5. Because asphalt absorption is not presently included in the formula for the determination of fine aggregate content, it is particularly desirable that the effects of oil absorption in the K_c test be excluded in the case of the highly absorptive aggregate.

3.3.8 Prepare a trial mixture using an asphalt content equal to or somewhat greater than (try to estimate amount that will be absorbed) the effective asphalt content determined in step 3.3.6 and also using the aggregate gradation as determined in step 3.3.7. Using a suitable technique, such as the test for maximum specific gravity of asphalt mixtures (AASHTO T 209), determine the actual quantity of asphalt absorbed (in percent, based on total weight of aggregate).

3.3.9 Determine the total asphalt content of the subject mixture by adding the effective asphalt content (from step 3.3.6) to the absorbed asphalt content (from step 3.3.8).

3.3.10 Follow the recommended procedure indicated in sections 6 and 7, using the total asphalt content for all subsequent computations and trials (from step 3.3.9).

Void Capacity of Coarse Aggregate

4.1 Use the following procedure to determine the vibrated unit weight and void capacity of the coarse-aggregate fraction (material retained on a No. 8 sieve) of the proposed job-mix gradation.

4.1.1 Apparatus

Rammer-A portable electromagnetic vibrating rammer as shown in Figure A-2, having a frequency of 3,600 cycles per min, suitable for use with 115-V ac. The rammer shall have a tamper foot and extension as shown in Figure A-3.

Mold-A solid-wall metal cylinder with a detachable metal base plate and a detachable metal guide-reference bar as shown in Figure A-4.

Wooden Base-A plywood disc 15 in. in diam, 2 in. thick, with a cushion of rubber hose attached to the bottom. The disc shall be constructed so it can be firmly attached to the base plate of the compaction mold.

Timer-A stopwatch or other timing device graduated in divisions of 1.0 sec and accurate to 1.0 see and capable of timing the unit for up to 2 min. An electric timing device or electrical circuits to start and stop the vibratory rammer may be used.

Dial Indicator-A dial indicator graduated in 0.001-in. increments and having a travel range of 3.0 in.

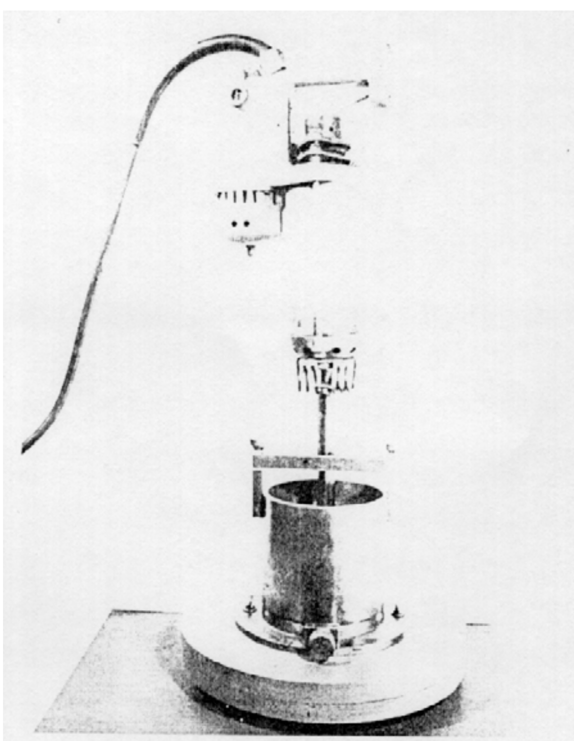


Figure A-2. FHWA vibratory compaction apparatus.

Figure A-3. Tamper foot and extension.

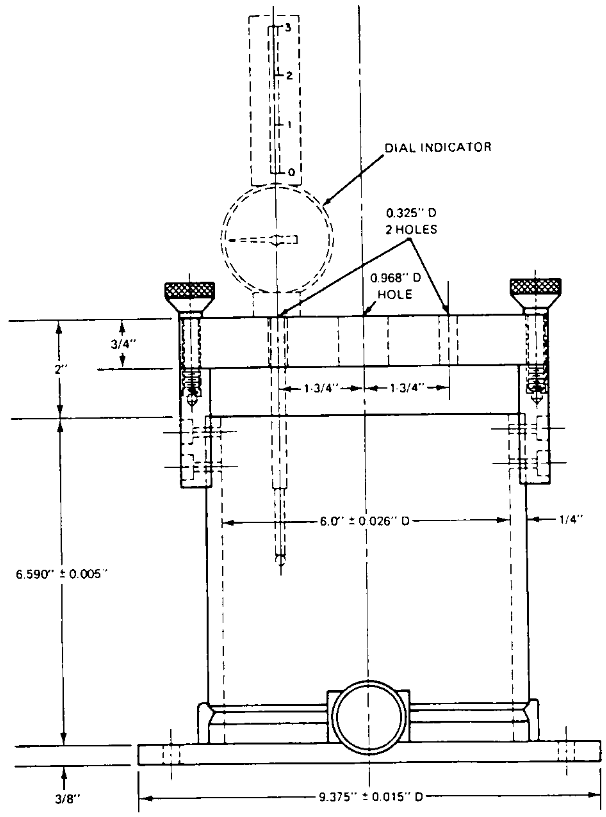


Figure A-4. Cylindrical mold for testing granular materials.

4.1.2 Sample: Select a 5-lb sample of the coarse-aggregate fraction from the proposed job-mix formula as verified in step 2.1.

4.1.3 Procedure

(a) Pour the selected sample into the compaction mold and place the tamper foot on the sample.

(b) Place the guide-reference bar over the shaft of the tamper foot and secure the bar to the mold with the thumb screws.

(c) Place the vibratory rammer on the shaft of the tamper foot and vibrate for 15 sec. During the vibration period, the operator must exert just enough pressure on the hammer to maintain contact between the sample and the tamper foot.

(d) Remove the vibratory rammer from the shaft of the tamper foot and brush any fines from the top of the tamper foot. Measure the thickness (t) of the compacted material to the nearest 0.001 in.

<u>Note</u>: The thickness (t) of the compacted sample is determined by adding the dial reading, minus the thickness of the tamper foot, to the measured distance from the inside bottom of the mold and the end of the dial gauge when it is seated on the guide-reference bar with stem fully extended.

4.1.4 Calculations

Calculate the vibrated unit weight (X) as follows:

$$X = 6912(w)/ \pi (d)^2 t \ (lb/ft^3)$$

Where w = wt of coarse-aggregate fraction (lb)
d = diam of compaction mold (in.)

If w = 5 lb and d = 6 in.:

$$X = 305.58/t \ (lb/ft^3)$$

Where t is in inches

Determine the void capacity (VMA) as follows:

$$VMA = 100 (l - X/U_c) \text{ (in percent)}$$

where U_c = bulk solid unit weight (lb/ft^3 of the coarse-aggregate fraction. U_c is calculated from bulk specific gravity, as determined in step 2.2, multiplied by 62.4 lb/f t^3.

Optimum Content of Fine Aggregate

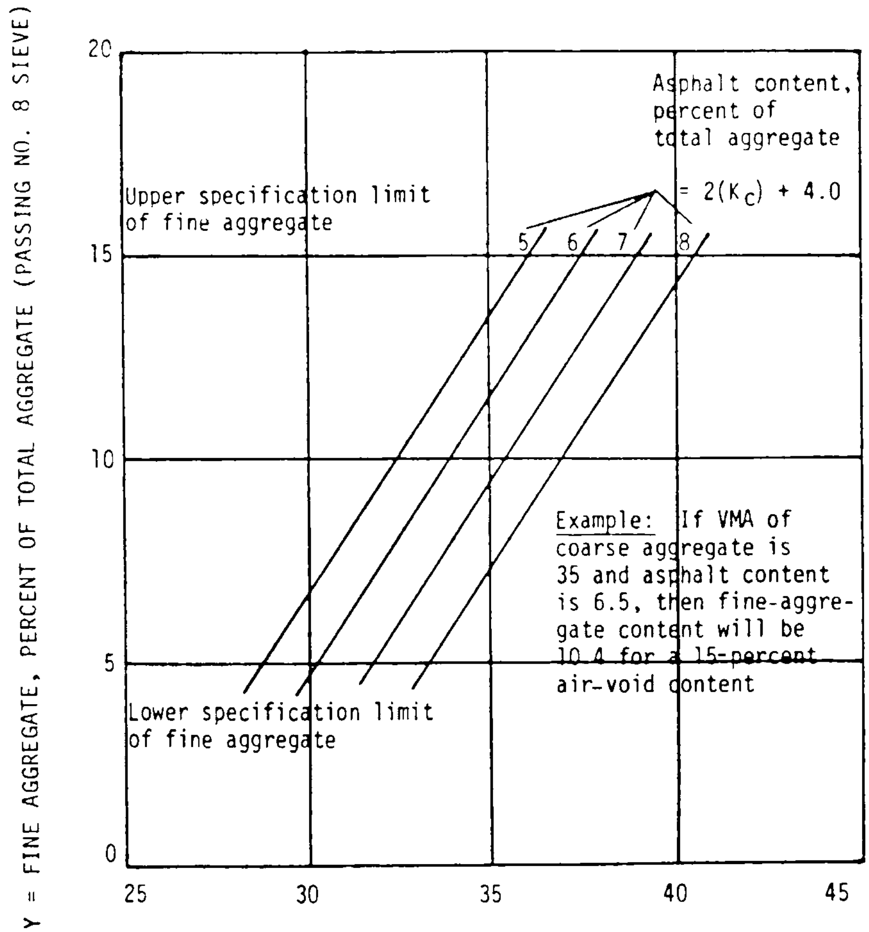
5.1 Determine the optimum content of fine-aggregate fraction using the following relationship:

$$Y = \frac{[\% \ VMA - V] - [(\% \ AC)(X)/U_a]}{[(\% \ VMA - V)/100] + [(X)/U_f]}$$

Where:
Y = Percent passing the No. 8 sieve (by weight)
X = Actual vibrated unit weight of coarse aggregate (retained on the No. 8 sieve)
U_f = Theoretical bulk dry solid unit weight of fine aggregate (passing the No. 8 sieve)
U_a = Unit weight of asphalt cement
%AC = Percent asphalt by total weight of aggregate $(2.0 \ Kc + 4.0) \ \dfrac{2.65}{(SG)ca}$
V = Design percent air voids (15.0 percent)
% VMA = Percent voids mineral aggregate of the coarse aggregate (retained on the No. 8 sieve), which is 100 - (100)(X)/U_c
U_c = Theoretical bulk dry solid unit weight of coarse aggregate (retained on the No. 8 sieve)
<u>Note</u>: X, U_a, U_c, and U_f are in pounds per cubic foot.

In the above relationship, asphalt absorption by aggregate has been assumed to be negligible. Because asphalt absorption requirements are considered in the test for K_c (see step 3.1), the estimated air voids of 15 percent in the mixture will actually be greater by an amount equivalent to the volume of asphalt absorbed, in percent. This condition provides, if anything, an additional safety factor.

As an alternative to the use of the mathematical relationship, one may use the design chart shown in Figure A-5, provided that the assumptions used in designing the chart are satisfied; that is, the specific gravity values (bulk dry) for the coarse- and fine-aggregate fractions do not deviate beyond the limits of 2.600 to 2.700.



PERCENT VOIDS (VMA) IN COARSE AGGREGATE (RETAINED ON NO. 8 SIEVE)

Assumptions Used in Deriving Chart:
U_c = 165.4 lb/ft^3 (SG = 2.650)
U_f = 165.4 lb/ft^3 (SG = 2.650)
U_a = 62.4 lb/ft^3 (SG = 1.000)
V = 15.0 percent

Figure A-5. Determination of optimum fine-aggregate content.

If the value thus obtained for fine-aggregate content is greater than 15 percent, a value of 15.0 percent shall be used.

5.2 Compare the optimum fine-aggregate content (Y) determined in step 5.1 to the amount passing the No. 8 sieve of the contractor's proposed job-mix formula. If these values differ by more than plus or minus 1 percentage point, reconstruct a revised or adjusted job-mix formula using the value determined for optimum fine-aggregate content.

Recompute the proportions of coarse and fine aggregates (as received) to meet the revised job-mix formula for submission to the contractor.

Note: If the proposed and revised job-mix gradations are significantly different, it may be necessary to rerun portions of this procedure.

Optimum Mixing Temperature

6.1 Prepare a 1,000-g sample of aggregate in the proportions determined in section 5. Mix this sample at the asphalt content determined in step 3.2 at a temperature corresponding to an asphalt viscosity of 800 centistokes determined in step 2.3. When the mixture is completely coated, transfer it to a pyrex glass plate (diam 8 to 9 in.) and spread the mixture with a minimum of manipulation. Return it to the oven at the mixing temperature. Observe the bottom of the plate after 15 and 60 min (Fig. A-6). A slight puddle at points of contact between aggregate and glass plate is suitable and desirable. Otherwise, repeat the test at a lower mixing temperature, or higher if necessary.

Note: If asphalt drainage occurs at a mixing temperature that is too low to provide for adequate drying of the aggregate, an asphalt of a higher grade should be used.

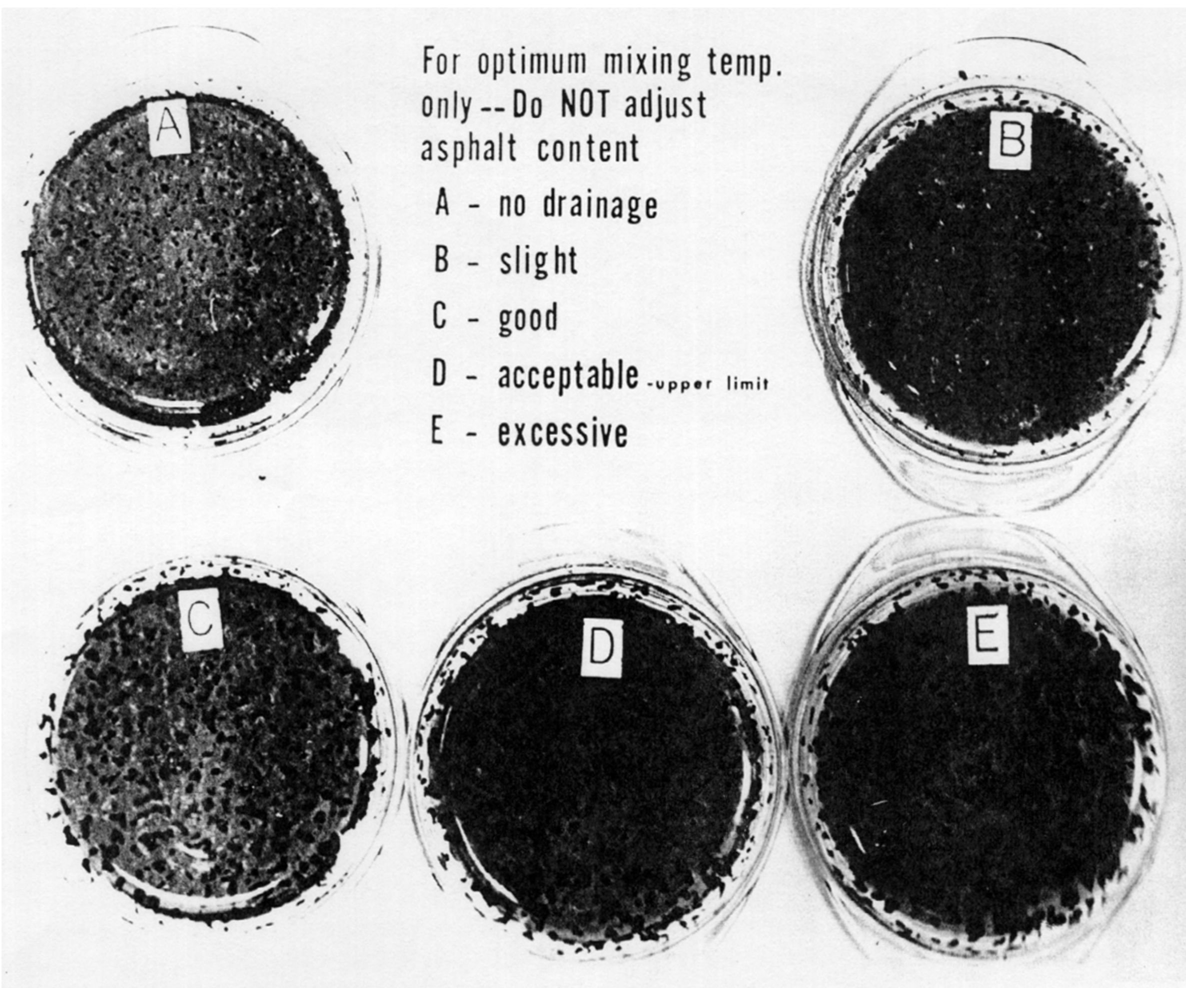


Figure A-6. Drainage test results.

Resistance to Effects of Water

7.1 Conduct the Immersion-Compression Test (AASHTO T 165 and T 167) on the designed mixture. Prepare samples at the optimum mixing temperature determined in step 6.1. Use a molding pressure of 1,000 psi rather than the specified value of 3,000 psi.

After a four-day immersion at 120 F, the index of retained strength shall not be less than 50 percent unless otherwise permitted.

Note: Additives to promote adhesion that will provide adequate retained strength may be used when necessary.

REPORT ON OPEN-GRADED ASPHALT FRICTION COURSE DESIGN

1. Aggregates

   A. Proposed Proportions (by weight)

   B. Proposed Job-Mix Gradation

Sieve Size	Specification limits	Percent Passing			Job-Mix Blend
1/2 in.		___	___	___	___
3/8 in.	95-100	___	___	___	___
No. 4	30-50	___	___	___	___
No. 8	5-15	___	___	___	___
No. 16		___	___	___	___
No. 200	2-5	___	___	___	___

   C. Specific Gravity—Unit Weight

	Apparent SG	Bulk SG (dry basis)	Bulk Solid Unit Weight (lb/ft^3)
Coarse aggregate (retained on No. 8 sieve)		___	___(U_c)
Fine aggregate (passing No. 8 sieve)		___	___(U_f)
3/8 in. - No. 4 sieve fraction	___		

   D. Void Capacity of Coarse Aggregate

   Unit weight (vibrated, lb/ft^3) = ________________________(X)

   Voids mineral aggregate (%) = ________________________(VMA)

   E. K_c Determination

   Oil retention (g oil per 100 g aggregate) = ___________

   Oil retention (corrected, 2.65 SG) = ___________

   K_c (from chart) = ___________

2. ASPHALT

   A. Specific Gravity--Unit Weight

   Specific gravity at 77°F (25°C) = ___________

   Unit weight (lb/ft^3) = ___________ (U_a)

   B. Viscosity--Temperature

   Asphalt grade = ___________

Temperature (°F)	Viscosity (centistokes)
290	___________
275	___________
260	___________
245	___________
230	___________
215	___________
Target: (-)	(700 - 900)

C. Asphalt Content (AC, %)

Percent asphalt (aggregate basis) =

$$(2.0\ K_c + 4.0) \times \frac{2.65}{\textit{apparent SG of coarse aggregate } (3/8\text{-}in. \textit{ to No. } 4 \textit{ sieve})}$$

3. MIXTURE DESIGN

A. Optimum Fine-Aggregate Content (Y)

Using: Formula ___________ Chart ___________

Where: X = ___________ lb/ft^3 VMA = ___________ %

U_f = ___________ lb/ft^3 AC = ___________ %

U_c = ___________ lb/ft^3 V = ___________ %

U_a = ___________ lb/ft^3

Find: Y = ___________ % (Specs limit: 5 < Y < 15)

Remarks:

B. Optimum Mixing Temperature

Temperature	Viscosity (centistokes)	Drainage	Use
___________	___________	___________	___________
___________	___________	___________	___________
___________	___________	___________	___________

C. Maximum Specific Gravity of Mixture (AASHTO T209)

Specific gravity (vacuum saturation) = ___________

Unit weight (vacuum saturation) = ___________ lb/ft^3

D. Resistance to Effects of Water (AASHTO T 165 and T 167, 2000 psi)

Air dry strength (psi) = ___________

Wet strength (psi) = ___________ 4 days at 120°F

Retained strength (%) = ___________ 50% minimum

Air voids (%) = ___________ Bulk volume by dimensional measurement

Remarks:

4. DESIGN SUMMARY

A. Aggregate Proportions (by weight)

B. Job-Mix Gradation

Percent Passing	
Sieve Size	Job-Mix Blend
1/2 in.	__________
3/8 in.	__________
No. 4	__________
No. 8	__________
No. 16	__________
No. 200	__________

C. Asphalt Content

Aggregate basis (%) = __________

Mixture basis (%) = __________

D. Mixing Temperature

Target value (°F) = __________

Range = __________

E. Additives

F. Recommendations   Accepted _____   Rejected _____

Appendix B

Example of Determining VCA_{DRC} and VCA for Checking Stone-on-Stone Contact in OGFC Mixtures

Three trial gradations were selected for evaluation as shown in Table B-1.

Determination of Voids in the Coarse Aggregate - Dry-Rodded Condition (VCA_{DRC})

VCA_{DRC} was determined for Trial Blend 1 coarse aggregate fraction according to AASHTO T 19. The VCA_{DRC} was determined for the aggregate fraction coarser than the 4.75 mm sieve. Two replicates for each test were performed. The average results are given in Table B-2.

Table B-1. Gradations of the Three Trial Blends

	Percent Passing by Volume		
Sieve Size (mm)	Trial Blend 1	Trial Blend 2	Trial Blend 3
19.0	100	100	100
12.5	95	95	95
9.5	65	65	65
4.75	15	25	30
2.36	7	7	7
1.18	6	6	6
0.60	5	5	5
0.30	4	4	4
0.15	3.5	3.5	3.5
0.075	3.0	3.0	3.0
G_{CA}	2.688	2.688	2.688

G_{CA} - coarse aggregate bulk specific gravity

Table B-2. Density and VCA_{DRC} for the Three Trial Blends

Blend No.	VCA_{DRC} (%)	Dry Rodded Unit Weight
1	41.6	1564.27 kg/m^3

The calculation for VCA_{DRC} for blend 1 is shown below.

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

$$VCA_{DRC} = \left(\frac{(2.688)(998) - 1564.27}{(2.688)(998)} \right) x\, 100$$

$$VCA_{DRC} = 41.6\%$$

where,

$(_s$ = unit weight of the coarse aggregate fraction in the dry rodded condition (kg/m^3)
$(_w$ = unit weight of water (998 kg/m^3), and
G_{CA} = combined bulk specific gravity of the coarse aggregate (Table B-1).

Compact Specimens

For each of the trial blends, three samples were produced at 5.5% asphalt binder by total mix mass using the Superpave Gyratory Compactor (SGC). The bulk specific gravities (Gmb) of these specimens were then determined after compaction according to AASHTO T 166. Also for each trial blend the maximum theoretical specific gravity (G_{mm}) was determined for one sample according to AASHTO T 209. The air voids, VMA, and VCA were then determined. These results are summarized in Table B-3.

Table B-3. Test Results for Three Trial Gradation Blends

Property	Trial Blend 1	Trial Blend 2	Trial Blend 3
G_{mb}	2.102	2.153	2.172
G_{mm}	2.475	2.512	2.511
Air Voids, %	15.1	14.3	13.5
VMA, %	26.3	24.5	23.9
VCA, %	33.5	39.9	43.4

An example of the VCA calculation for the compacted OGFC mixtures is given here for blend 1.

$$VCA = 100 - \left[\frac{G_{mb}}{G_{CA}} x\, P_{CA} \right]$$

$$VCA = 100 - \left(\frac{2.102}{2.688} x\, (85.0) \right)$$

$$= 33.5\%$$

where,

G_{CA} = combined bulk specific gravity of the coarse aggregate (Table B-1)
G_{mb} = bulk specific gravity of compacted OGFC specimens
P_{CA} = percent coarse aggregate in the total mixture

Based on Table 3, trial blends 1 and 2 meet the requirements for VCA ($VCA<VCA_{DRC}$) and do have stone-on-stone contact. Trial blend 3 did not meet the VCA requirements.

Appendix C

Standard Test Method for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures

1. SCOPE

1.1 This test method covers the determination of the amount of draindown in an uncompacted asphalt mixture sample when the sample is held at elevated temperatures comparable to those encountered during the production, storage, transport, and placement of the mixture. The test is particularly applicable to mixtures such as porous asphalt (open-graded friction course) and stone matrix asphalt (SMA).

1.2 The values stated in SI units are to be regarded as the standard.

1.3 This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

2.1 ASTM Standards:

C 670 - Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials.

D 979 - Standard Practice for Sampling Bituminous Paving Mixtures.

D 1559 - Standard Test Method for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus.

D 4753 - Evaluating, Selecting, and Specifying Balances and Scales, for Use in Testing Soil, Rock, and Related Construction Materials.

E 11 - Standard Specification for Wire-Cloth Sieves for Testing Purposes.

3. DEFINITIONS

3.1 *Draindown*—For the purpose of this test method, draindown is considered to be that portion of material which separates itself from the sample as a whole and is deposited outside the wire basket during the test. The material which drains may be composed of either asphalt binder or a combination of asphalt binder, additives, or fine aggregate.

4. SUMMARY OF METHOD

4.1 A sample of the 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 force 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 containing the drained material, if any, is determined. The amount of draindown is then calculated.

5. SIGNIFICANCE AND USE

5.1 This test method can be used to determine whether the amount of draindown measured for a given asphalt mixture is within specified 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 (open-graded friction course) and stone matrix asphalt (SMA).

6. APPARATUS

6.1 Forced draft oven, capable of maintaining the temperature in a range from 120-175°C. The oven should maintain the set temperature to within ±2°C.

6.2 Plates or other suitable containers of appropriate size. The plates or containers used should be of appropriate durability to withstand the oven temperatures. Cake pans or pie tins are examples of suitable types of containers.

6.3 Standard basket meeting the dimensions shown in Figure C-1. The basket shall be constructed using standard 6.3 mm sieve cloth as specified in ASTM E 11.

6.4 Balance—A balance readable to 0.1g and conforming to the requirements of specification D4753, GP2.

7. SAMPLE PREPARATION

7.1 Laboratory Prepared Samples

7.1.1 *Number of Samples*—For each mixture tested, the draindown characteristics should be determined at two different temperatures. The two temperatures should be the anticipated plant production temperature as well as 10°C above (Note 1). For each temperature, duplicate samples should be tested. Thus for one asphalt mixture, a minimum of four samples will be tested.

7.1.2. Dry the aggregate to constant mass and sieve it into appropriate size fractions as indicated in ASTM D 1559.

7.1.3 Determine the anticipated plant production temperature for the specific mix to be tested based on the specifications, mix design, or recommendations of the binder supplier.

7.1.4 Place into separate pans for each test sample the amount of each size fraction required to produce completed mixture samples having a mass of 1200±200 grams. The aggregate fractions shall be combined such that the resulting aggregate blend has the same gradation as the job-mix formula. Place the aggregate samples in an oven and heat to a temperature not to exceed the temperature established in 7.1.1.

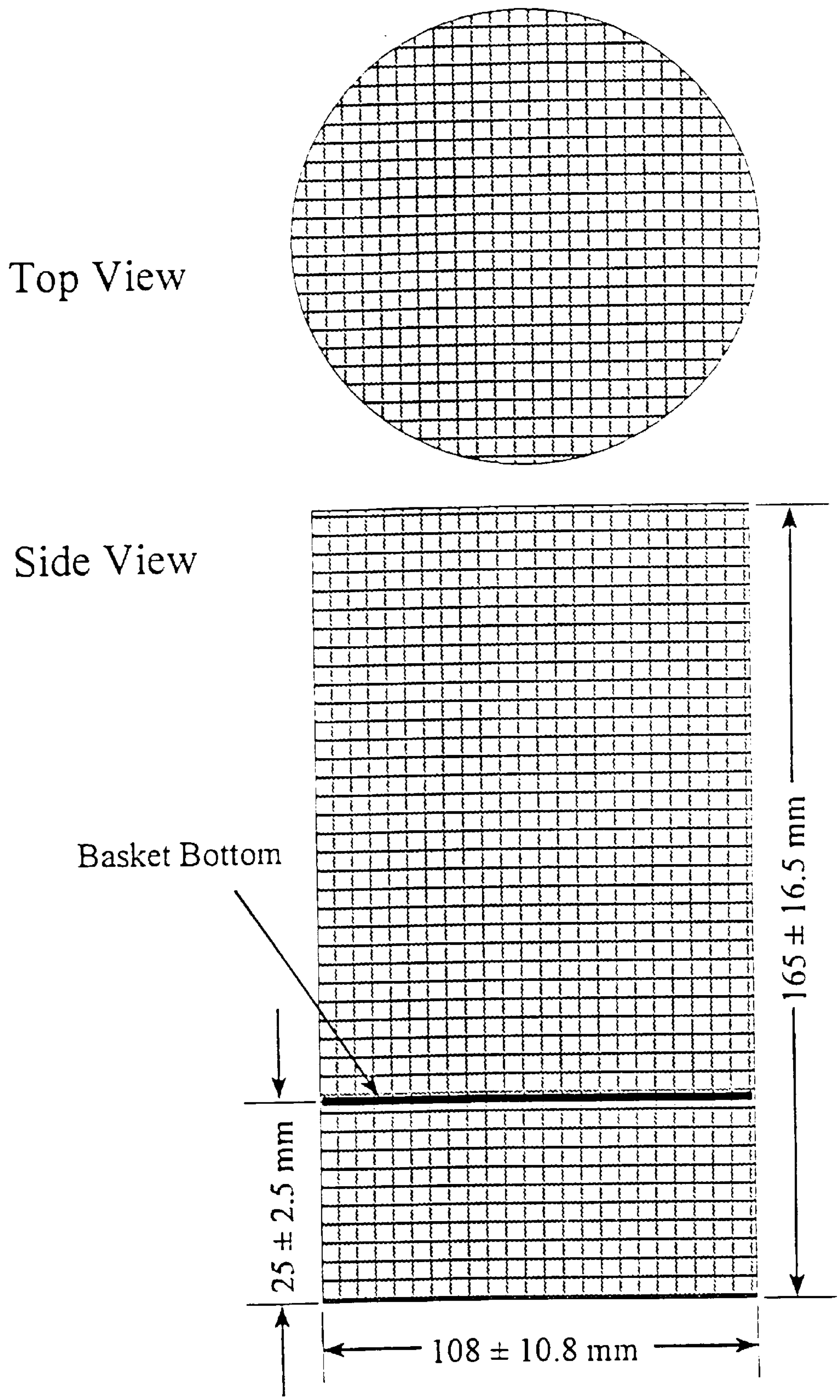


Figure C-1. Wire basket assembly (not to scale).

7.1.5 Heat the asphalt binder to the temperature established in 7.1.1.

7.1.6 Place the heated aggregate in the mixing bowl. Add any stabilizers (Note 2) and thoroughly mix the dry components. Form a crater in the aggregate blend and add the required amount of asphalt binder. The amount of asphalt binder shall be such that the final sample has the same asphalt content as the job-mix formula. At this point, the temperature of the aggregate and asphalt binder shall be at the temperature determined in 7.1.1. Mix the aggregate (and stabilizer if any) and asphalt binder quickly until the aggregate is thoroughly coated.

7.2 Plant Produced Samples

7.2.1 *Number of Samples*—For plant produced samples, triplicate samples should be tested at the plant production temperature.

7.2.2 Samples should be obtained in accordance with ASTM D 979 during plant production by sampling the mixture at any appropriate location such as the trucks prior to the mixture leaving the plant. Samples obtained during actual production should be reduced to the proper test sample size.

Note 1—When using the test as part of the mixture design procedure, the test should be performed at two temperatures in order to determine the potential effect that plant temperature variation may have on the mixture during production. When the test is used in the field during production, it should be necessary to perform the test at the plant production temperature only.

Note 2—Some types of stabilizers such as fibers or some polymers are added directly to the aggregate prior to mixing with the asphalt binder. Other types of stabilizers are added directly to the asphalt binder prior to blending with the aggregate.

8. PROCEDURE

8.1 Weigh the empty wire basket described in 6.3 (Mass A). Transfer the laboratory produced or plant produced uncompacted mixture sample to the wire basket as soon as possible. Place the entire sample in the wire basket. Do not consolidate or otherwise disturb the sample after transfer to the basket. Determine the mass of the wire basket plus sample to the nearest 0.1 gram. (Mass B).

8.2 Determine and record the mass of a plate or other suitable container to the nearest 0.1 gram at ambient temperature (Mass C). Place the basket on the plate or container and place the assembly into the oven at the temperature as determined in 7.1.1 or 7.2.1 for 1 hour ±5 minutes.

8.3 After the sample has been in the oven for 1 hour ±5 minutes, remove the basket and plate or container from the oven. Let cool to ambient temperature. Determine and record the mass of the plate or container plus drained material to the nearest 0.1 gram (Mass D).

9. CALCULATIONS

9.1 Calculate the percent of mixture which drained to the nearest 0.1 percent as follows:

Draindown (percent) = (D-C)/(B-A) x 100

where A = mass of the empty wire basket,
B = mass of the wire basket and sample,
C = mass of the empty catch plate or container, and
D= mass of the catch plate or container plus drained material.

10. REPORT

10.1 Report the average percent drainage at each of the test temperatures to the nearest 0.1 percent.

11. PRECISION AND BIAS*

11.1 Precision statements for mixtures with draindown values of less than 1.0 percent. (Note 3).

Test & Type Index	Coefficient of Variation (% of mean)[A]	Acceptable Range of Two Test Results (% of mean)[A]
Single operator precision: Draindown, percent	32.5	92.0
Multilaboratory precision: Draindown, percent	68.2	193.0

[A] These numbers represent, respectively, the (1s%) and (d2s%) limits as described in ASTM practice C670.

NOTE 3—These precision statements are based on an analysis of a round-robin study conducted by the National Center for Asphalt Technology, using one stone matrix asphalt mix, three replicates, and ten laboratories. The precision statements are based on a mixture that had an average draindown value of 0.3 percent.

11.2 Precision statements for mixtures with draindown values of more than 1.0 percent (Note 4).

Test & Type Index	Coefficient of Variation (% of mean)[A]	Acceptable Range of Two Test Results (% of mean)[A]
Single operator precision: Draindown, percent	28.1	79.5
Multilaboratory precision: Draindown, percent	35.9	101.6

[A] These numbers represent, respectively, the (1s%) and (d2s%) limits as described in ASTM practice C670.

NOTE 4—These precision statements are based on an analysis of a round-robin study conducted by the National Center for Asphalt Technology, using one stone matrix asphalt mix, three replicates, and ten laboratories. The precision statements are based on a mixture

* Supporting data are available from ASTM Headquarters. Request RR: D04-XXX (Dan Smith will assign a number).

that had an average draindown value of 1.4 percent.

11.3 *Bias*—The test method has no bias because the values determined can be defined only in terms of the test method.

12. KEYWORDS

12.1 draindown; asphalt mixtures; open-graded friction courses; stone matrix asphalt

Appendix D

Florida DOT Falling Head Laboratory Permeability Test Method

1. SCOPE

   1.1 This test method covers the laboratory determination of the water conductivity of a compacted asphalt paving mixture sample. The measurement provides an indication of water permeability of that sample as compared to those of other asphalt samples tested in the same manner.

   1.2 The procedure uses either laboratory compacted cylindrical specimens or field core samples obtained from existing pavements.

   1.3 The values stated in metric (SI) units are to be regarded as standard. Values in parenthesis are for information and reference purposes only.

   1.4 *This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. APPLICABLE DOCUMENTS

   2.1 AASHTO Standards:

   M 231 Weights and Balances Used in the Testing of Highway Materials.

   2.2 Florida Test Methods

   FM 1-T 166 Bulk Specific Gravity of Compacted Bituminous Mixtures.

3. SUMMARY OF TEST METHOD

   3.1 A falling head permeability test apparatus, as shown in Figure D-1, is wed to determine the rate of flow of water through the specimen. Water in a graduated cylinder is allowed to flow through a saturated asphalt sample and the interval of time taken to reach a known change in head is recorded. The coefficient of permeability of the asphalt sample is then determined based on Darcy's law.

4. SIGNIFICANCE AND USE

   4.1 This test method provides a means for determining water conductivity of water-saturated asphalt samples. It applies to one-dimensional, laminar flow of water. It is assumed that Darcy's law is valid.

5. APPARATUS

   5.1 *Permeameter* - See Figure D-1. The device shall be meet the following requirements:

Figure D-1. Water Permeability Testing Apparatus (not to scale)

a) A calibrated cylinder of 31.75 ± 0.5 mm (1.25 ± 0.02 in.) inner diameter graduated in millimeters capable of dispensing 500 ml of water.

b) A scaling tube using a flexible latex membrane 0.635 mm (0.025 in) thick and capable of confining asphalt concrete specimens up to 152.4 mm (6.0 in.) in diameter and 80 mm (3.15 in.) in height.

c) An upper cap assembly for supporting the graduated cylinder and expanding an o-ring against the sealing tube. The opening in the upper cap shall have the same diameter as the inner diameter of the calibrated cylinder mentioned previously in 5.1 a. The underside of the upper cap assembly should be tapered at an angle of 10 ± 1° (see Figure D-1).

d) A lower pedestal plate for supporting the asphalt concrete specimen and expanding an o-ring against the sealing tube. The opening in the plate should have a minimum diameter of 18 mm (0.71 in.). The top side of the lower cap should be tapered at an angle of 10 ± 1° (see Figure D-1).

e) 0-rings of sufficient diameter and thickness for maintaining a seal against the sealing tube.

f) A frame and clamp assembly for supplying a compressive force to the upper cap assembly and lower pedestal necessary to expand the o-rings.

g) An air pump capable of applying 103.42 kPa (15 psi) pressure and capable of applying vacuum to evacuate the air from tho sealing tube/membrane cavity.

h) A pressure gauge with range 0 to 103.42 kPa (0 to 15 psi) with ± 2% accuracy.

i) Quick connects and pressure line for inflating and evacuating the sealing tube/ membrane cavity.

j) An outlet pipe with a minimum inside diameter of 18 mm (0.71 in.) with shutoff valve for draining water.

NOTE 1: A device manufactured by Karol Warner Soil Testing Systems has been found to meet the above specifications.

5.2 *Water* - A continuous supply of clean, non-aerated water, preferably supplied by flexible hose from water source to top of graduated cylinder.

5.3 *Thermometer* - A mercury or thermocouple device capable of measuring the temperature of water to the nearest 0.1°C (0.2°F).

5.4 *Beaker* - A 600 ml beaker or equivalent container to be used while measuring the temperature of a water sample.

5.5 *Timer* - A stop watch or other timing device graduated in divisions of 0.1 s or less and accurate to within 0.05% when tested over intervals of not less than 15 min.

5.6 *Measuring Device* - A device used to measure the dimensions of the specimen, capable of measuring to the nearest 0.5 mm or better.

5.7 *Saw* - Equipment for wet cutting the specimen to the desired thickness. Dry cut type saws are not to be used.

5.8 *Sealing Agent* - Petroleum jelly.

5.9 *Spatula* - Used for applying the petroleum jelly to the sides of laboratory compacted specimens.

5.10 *Fan* - An electric fan for drying the wet cut asphalt specimen.

5.11 *Container* - A five gallon bucket or equivalent container for soaking the specimens prior to testing.

6. PREPARATION OF TEST SAMPLES

6.1 Saw cut the field core or the laboratory compacted specimen to the desired test sample thickness. The thickness shall be as close to the actual or desired in-place thickness as possible. For both field cores and laboratory compacted specimens, both the top and bottom faces shall be trimmed.

6.2 Wash the test sample thoroughly with water to remove any loose, fine material resulting from saw cutting.

6.3 Determine the bulk specific gravity of the specimen, if necessary. Use Method B of FM 1 -T 166.

6.4 Measure and record to the nearest 0.5 mm (0.02 in.) or better, the height and diameter of the sample at three different locations. The three height measurements shall not vary by more than 3 mm (0.2 in.). The diameter of the specimen shall not be less than 144 mm (5.67 in.).

NOTE 2: During the permeability test, the sample will need to reach a saturated state as defined in 7.8. As an aid in saturating the sample, and if time permits, place it in the container described in 5.11 and fill with a sufficient quantity of water to completely cover the sample. Let the sample soak for a period of one to two hours.

6.5 For laboratory compacted specimens it is necessary to apply a thin layer of petroleum jelly to the sides of the specimen. This will fill the large void pockets around the sides of the specimen which are not representative of the level of compaction of the interior of the specimen. If the sample is wet, wipe the sides with a towel to remove any free standing water. Use a spatula or similar device and apply the petroleum jelly to the sides of the specimen only.

7. TEST PROCEDURE

7.1 Evacuate the air from the sealing tube/membrane cavity.

NOTE 3: Complete evacuation of the air is aided by pinching the membrane and slightly pulling it away from the hose barb fitting as the pump is stroked.

7.2 Place the specimen on top of the lower pedestal plate and center it.

7.3 Place the sealing tube over the specimen and lower pedestal plate making sure that the sealing tube is oriented so that the hose barb fitting will be located between the o-rings on the upper cap and lower pedestal.

7.4 Insert the upper cap assembly into the sealing tube and let it rest on the top of the asphalt concrete specimen.

NOTE 4: Insertion of the upper cap assembly is aided if the graduated cylinder is already inserted into the upper cap assembly. The graduated cylinder can then be used as a handle.

7.5 Install the two clamp assemblies onto the permeameter frame and evenly tighten each one, applying a moderate pressure to the upper cap assembly. This action seals the o-rings against the membrane and sealing tube.

7.6 Inflate the membrane to 68.9 ± 3.4 kPa (10 ± 0.5 psi). Maintain this pressure throughout the test.

7.7 Fill the graduated cylinder with water approximately halfway and rock the permeameter back, forth, and sideways enough to dislodge any trapped air from the upper cavity.

7.8 Fill the graduated cylinder to a level above the upper timing mark, see Figure D-1. Start the timing device when the bottom of the meniscus of the water reaches the upper timing mark. Stop the timing device when the bottom of the meniscus reaches the lower timing mark. Record the time to the nearest second. Perform this test three times and check for saturation. While checking for saturation, do not allow the water in the graduated cylinder to run out, as this will allow air to re-enter the specimen.

Saturation is defined as the repeatability of the time to run 500 mL of water through the specimen. A specimen will be considered saturated when the % difference between the first and third test is 4.0%. Therefore, a minimum of three tests will be required for each asphalt concrete specimen except as stated in Note 6. Saturation of the specimen may require many test runs prior to achieving the #4.0% requirement. One technique that aids in achieving saturation is to nearly fill the graduated cylinder with water and adjust the water inflow so that it equals the outflow. Allow the water to run in this manner for five or ten minutes and then begin the timed testing. If more than three test runs are required, which is typically the case, then the #4.0% requirement shall apply to the last three testing times measured.

NOTE 5: If after the third run, the test run time is greater than ten minutes, then the tester can use judgement and consider ending the test, using the lowest time recorded in the permeability calculation.

NOTE 6: If the test time is approaching thirty minutes during the first test run without the water level reaching the lower timing mark, then the tester may mark the water level at thirty minutes and record this mark and time. Run the test one more time and record the mark and time. Use the mark and time which will result in the highest permeability value.

7.9 Obtain a sample of water in a beaker or other suitable container and determine the temperature to the nearest 0.1°C (0.2°F).

7.10 After the saturation has been achieved and the final time and mark recorded, then release the pressure from the container and evacuate the sealing tube/membrane cavity. Remove the clamp assemblies, upper cap, and specimen. If petroleum jelly was used on the specimen, wipe off any excess left on the latex membrane.

8. CALCULATIONS

8.1 The coefficient of permeability, k, is determined using the following equation:

$$k = \frac{aL}{At} \ln(h_1/h_2) * t_{+}c$$

Where:
- k = coefficient of permeability, cm/s;
- a = inside cross-sectional area of the buret cm^2;
- L = average thickness of the test specimen, cm;
- A = average cross-sectional area of the test specimen, cm^2;
- t = elapsed time between h_1 and h_2, s;
- h_1 = initial head across the test specimen, cm;
- h_2 = final head across the test specimen, cm;
- t_c = temperature correction for viscosity of water; see Tables D-1 and D-2. A temperature of 20°C (68°F) is used as the standard.

8.2 h_1 and h_2 are the dimensions shown in Figure D-1.

NOTE 7: It is beneficial to determine a set of constant dimensional values for a particular permeameter. The dimensions from the underside of the top cap assembly to the lower timing mark and from the underside of the top cap assembly to the upper timing mark are constants. Add the average specimen to these two dimensions and h_1 and h_2 are determined. If the test is stopped at a mark other than the 0 ml lower mark, then add the difference to the h_2 value to arrive at the new h_2 value for this sample. It is helpful to create a spreadsheet that will calculate these values and permeability values automatically.

8.3 For each sample, the coefficient of permeability is computed based on the time and lower mark recorded in 7.8. The result is reported in whole units x 10^{-5} cm/s.

Table D-1. Temperature Correction for Viscosity of Water, Celsius

°C	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
10	1.30	1.30	1.29	1.29	1.29	1.28	1.28	1.27	1.27	1.27
11	1.26	1.26	1.26	1.25	1.25	1.25	1.24	1.24	1.24	1.23
12	1.23	1.23	1.22	1.22	1.22	1.21	1.21	1.21	1.20	1.20
13	1.20	1.19	1.19	1.19	1.18	1.18	1.18	1.17	1.17	1.17
14	1.16	1.16	1.16	1.16	1.15	1.15	1.15	1.14	1.14	1.14
15	1.13	1.13	1.13	1.13	1.12	1.12	1.12	1.11	1.11	1.11
16	1.10	1.10	1.10	1.10	1.09	1.09	1.09	1.09	1.08	1.08
17	1.08	1.07	1.07	1.07	1.07	1.06	1.06	1.06	1.06	1.05
18	1.05	1.05	1.05	1.05	1.04	1.04	1.03	1.03	1.03	1.03
19	1.02	1.02	1.02	1.02	1.01	1.01	1.01	1.01	1.00	1.00
20	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.98	0.98	0.98
21	0.98	0.97	0.97	0.97	0.97	0.96	0.96	0.96	0.98	0.96
22	0.95	0.95	0.95	0.95	0.94	0.94	0.94	0.94	0.94	0.93
23	0.93	0.93	0.93	0.93	0.92	0.92	0.92	0.92	0.91	0.91
24	0.91	0.91	0.91	0.90	0.90	0.90	0.90	0.90	0.89	0.89
25	0.89	0.89	0.89	0.88	0.88	0.88	0.88	0.88	0.87	0.87
26	0.87	0.87	0.87	0.87	0.85	0.86	0.86	0.86	0.85	0.85
27	0.85	0.85	0.85	0.85	0.84	0.84	0.84	0.84	0.84	0.84
28	0.83	0.83	0.83	0.83	0.83	0.83	0.82	0.82	0.82	0.82
29	0.82	0.81	0.81	0.81	0.81	0.81	0.81	0.80	0.80	0.80
30	0.80	0.80	0.80	0.79	0.79	0.79	0.79	0.79	0.79	0.78
31	0.78	0.78	0.78	0.78	0.78	0.78	0.77	0.77	0.77	0.77
32	0.77	0.77	0.78	0.76	0.78	0.76	0.76	0.76	0.76	0.75
33	0.75	0.75	0.75	0.75	0.75	0.74	0.74	0.74	0.74	0.74
34	0.74	0.74	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.72
35	0.72	0.72	0.72	0.72	0.72	0.72	0.71	0.71	0.71	0.71

Table D-2. Temperature Correction for Viscosity of Water, Fahrenheit

°F	0.0	0.2	0.4	0.6	0.8
50	1.30	1.30	1.29	1.29	1.28
51	1.28	1.28	1.27	1.27	1.26
52	1.26	1.26	1.25	1.25	1.24
53	1.24	1.24	1.23	1.23	1.23
54	1.22	1.22	1.21	1.21	1.21
55	1.20	1.20	1.20	1.19	1.19
56	1.19	1.18	1.18	1.17	1.17
57	1.17	1.16	1.16	1.16	1.15
58	1.15	1.15	1.14	1.14	1.14
59	1.13	1.13	1.13	1.12	1.12
60	1.12	1.11	1.11	1.11	1.10
61	1.10	1.10	1.10	1.09	1.09
62	1.09	1.08	1.08	1.08	1.07
63	1.07	1.07	1.06	1.06	1.06
64	1.06	1.05	1.05	1.05	1.04
65	1.04	1.04	1.04	1.03	1.03
66	1.03	1.02	1.02	1.02	1.02
67	1.01	1.01	1.01	1.01	1.00
68	1.00	1.00	0.99	0.99	0.99
69	0.99	0.98	0.98	0.98	0.98
70	0.97	0.97	0.97	0.97	0.96
71	0.96	0.96	0.96	0.95	0.95
72	0.95	0.95	0.94	0.94	0.94
73	0.94	0.93	0.93	0.93	0.93
74	0.92	0.92	0.92	0.92	0.92
75	0.91	0.91	0.91	0.91	0.90
76	0.90	0.90	0.90	0.89	0.89
77	0.89	0.89	0.89	0.88	0.88
78	0.88	0.88	0.88	0.87	0.87
79	0.87	0.87	0.86	0.86	0.86
80	0.86	0.86	0.85	0.85	0.85
81	0.85	0.85	0.84	0.84	0.84
82	0.84	0.84	0.83	0.83	0.83
83	0.83	0.83	0.82	0.82	0.82
84	0.82	0.82	0.81	0.81	0.81
85	0.81	0.81	0.81	0.80	0.80
86	0.80	0.80	0.80	0.79	0.79
87	0.79	0.79	0.79	0.79	0.78
88	0.78	0.78	0.78	0.78	0.77
89	0.77	0.77	0.77	0.77	0.77
90	0.76	0.76	0.76	0.76	0.76
91	0.76	0.75	0.75	0.75	0.75
92	0.75	0.75	0.74	0.74	0.74
93	0.74	0.74	0.74	0.73	0.73
94	0.73	0.73	0.73	0.73	0.72
95	0.72	0.72	0.72	0.72	0.72