Design, Construction, and Maintenance of Open-Graded Asphalt Friction Courses
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Design, Construction, and Maintenance of Open-Graded Asphalt Friction Courses

by
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National Center for Asphalt Technology

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Abstract

Open-graded asphalt friction course (OGFC) is an open-graded Hot Mix Asphalt (HMA) mixture with interconnecting voids that provides improved surface drainage during rainfall. The rainwater drains vertically through the OGFC to an impermeable underlying layer and then laterally to the daylighted edge of the OGFC. In addition to minimizing hydroplaning potential during rainfall and providing improved friction values on wet pavements, the OGFC offers the following advantages compared to other dense-graded surfaces: (a) reduced vehicle splash and spray behind vehicles, (b) enhanced visibility of pavement markings, (c) reduced nighttime surface glare in wet weather, and (d) reduced tire-pavement noise.

Numerous states in the US currently using OGFC have experienced excellent performance in terms of safety (improved surface friction) and durability. The following problems, which were experienced by some states during OGFC trials in the 1970s, have been solved: (a) raveling, (b) delamination, (c) loss of permeability after a few years in service. This has been accomplished by one or more of the following: use of polymer-modified asphalt binders, relatively high asphalt content (by using fibers), and/or relatively open gradations.

Based on the experience of the successful states in the US, experience in several countries in Europe, and the recent National Center for Asphalt Technology (NCAT) research, a mix design method has been developed for a new-generation OGFC. In addition to using polymer-modified asphalt binder and fiber, the new-generation OGFC is highly open-graded with high permeability. The mix design procedure addresses the concerns of the northern tier states with cold climates by including abrasion tests on new and aged mixtures, and subjecting the OGFC mix to freeze and thaw cycles.

The recommendations discussed in this report for materials selection, mix design, construction, pavement structural design, winter maintenance, and rehabilitation should provide the necessary guidance to maximize the potential for OGFC.

Key Words
OGFC, open graded friction course, Hot Mix Asphalt, HMA, mixture design, plant production, construction, maintenance, snow and ice removal, rehabilitation, structural design, friction, skid resistance, noise
INTRODUCTION

Background and History

In the United States, open-graded asphalt friction course (OGFC) evolved from experimentation with plant mix seal coats. Plant mix seal coats were developed to provide enhanced performance relative to seal coats or chip seals. A seal coat (or chip seal) application consists of applying an asphalt binder, followed by the spreading of cover aggregate which is rolled lightly to embed the aggregate in the asphalt binder. This treatment is primarily used on low-volume roads to seal the road surface and provide improved friction or skid resistance. However, the disadvantages of chip seal application include bleeding, raveling, loose stone, and a relatively short performance life.

The California Department of Highways began experimenting with plant mix seal coats in 1944. The cover aggregate, typically 9.5 to 12.5 mm (3/8 to 1/2 in) maximum nominal size, was mixed with a relatively high percentage of asphalt cement in a conventional Hot Mix Asphalt (HMA) plant, and placed 15 to 20 mm (5/8 to 3/4 in) thick. This plant mix seal offered the same benefits but eliminated many of the problems associated with chip seals. The plant mix seal was more durable, provided some improvement in ride quality, reduced noise, and eliminated damage from loose chips (such as broken windshields).

In the early 1970s, many states in the western United States began placing plant mix seals in response to the Federal Highway Administration’s (FHWA) program to improve the overall frictional resistance of the road surfaces in the US. The FHWA considered plant mix seal as one of the tools to accomplish this objective, and the term open-graded asphalt friction course (OGFC) was developed. For OGFC, the FHWA also developed a mix design method. OGFC is also known by other names in the United States such as plant mix seal, popcorn mix, asphalt concrete friction course, and Permeable European Mix (PEM) or porous asphalt.

OGFC was designed as an open mix with interconnecting voids that provided drainage during heavy rainfall. The rainwater drains vertically through OGFC to an impermeable, underlying layer and then laterally to the daylighted edge of the OGFC. In addition to minimizing hydroplaning and providing high frictional resistance on wet pavements, it was realized that OGFC as compared to other dense surfaces had the following advantages:

1. Reduce splash and spray;
2. Enhance visibility of pavement markings;
3. Reduce nighttime surface glare in wet weather;
4. Reduce tire-pavement noise; and
5. Permit use of thin layers (minimize material).

According to a 1998 National Center for Asphalt Technology (NCAT) survey, numerous states in the US currently using OGFC have experienced excellent performance in terms of safety (improved surface friction) and durability. The following problems which were experienced by some states during OGFC trials in the 1970s, have been solved: (a) raveling, (b) delamination, and (c) loss of permeability after a few years in service. This has been accomplished by one or more of the following: use of polymer-modified asphalt binders, relatively high asphalt content (by using fibers), and/or
relatively open gradations. The survey also concluded that good design and construction practice was the key to improved performance of OGFC mixes. Figures 1 and 2 show good examples of in-service OGFC pavements in Washington and Nevada, respectively.

U.S. Experience

The Oregon Department of Transportation (DOT) has been using OGFC on its highway system since the late 1970s. OGFC has become their preferred choice for a surface course due to its excellent performance. More than 3000 km (2000 lane miles) of Oregon highways are paved with OGFC. Class F, OGFC mix has a nominal maximum aggregate size of 25 mm (1 in) and is generally used with a thickness of 50 mm (2 in).

The Washington State DOT had placed more than 386,000 tons of OGFC by the end of 1993. In addition, OGFC is extensively used in California and Nevada. Washington and California use 20 mm (3/4 in) and Oregon uses 50 mm (2 in) thickness of OGFC.

Arizona and Florida are using OGFC extensively on interstate and non-interstate pavements. Georgia requires the use of OGFC on all interstate highways. It is usually placed 20 mm (3/4 in) in thickness.

Specifications and mix design methods (described later) have now been developed based on research conducted by NCAT and experience gained in the US and Europe. European Experience

After OGFC was developed in the US in the early 1970s, it has been increasingly used in many European countries. It is called porous asphalt in Europe. It is frequently used in Germany, Netherlands, France, Italy, United Kingdom, Belgium, Spain, Switzerland, and Austria.

Unlike the OGFC used in the US in the 1970s, the porous asphalt evolved in Europe with coarser gradation, higher in-place air voids (generally between 17 to 22 percent range) and, therefore, higher permeability, and generally placed in thicknesses of 40 to 50 mm (1 1/2 to 2 in). Nominal maximum aggregate size ranges from 11 mm (7/16 in) to 16 mm (5/8 in). Smaller and larger size aggregates are used less frequently. Polymer modified binders or fibers, and sometimes both, are used in the OGFC mixtures to obtain thick and strong binder film thus maximizing resistance to aging and raveling. OGFC is used successfully in Europe in a full range of climate, from hot and dry to cold and wet.

There were some 400,000 m² of OGFC on German federal roads in 1992. Although eight years old, these OGFC pavements were in excellent condition in 1992.

The primary reason for using OGFC in the Netherlands was for noise reduction; the safety aspect was appreciated more later.
PERFORMANCE BENEFITS

The following benefits are derived from the use of OGFC in terms of safety and environment.

Safety

Improved Wet Pavement Frictional Resistance

The following research conducted in the US, Canada, and Europe clearly indicates the superior wet pavement frictional resistance of OGFC in comparison to dense HMA and portland cement concrete (PCC) surfaces. The resulting reduction in wet weather accidents has also been documented.

The Bureau of Public Roads (now the Federal Highway Administration) tested the frictional resistance of 15 OGFC projects at 40 and 50 miles per hour with a skid trailer in the summer of 1967. Frictional resistance (expressed as friction number) of a pavement surface decreases as the speed is increased. The rate of decrease of frictional number (FN) per mile increase in the speed is called friction gradient, which is mix specific. Obviously, a low friction gradient is desirable. The average loss in frictional resistance from 40 to 50 mph was only one FN point for OGFC in this study. This would give a friction gradient of 0.1 FN per mile per hour. This is considerably lower than dense-graded HMA surfaces.

In other words, the OGFC would be far superior to the other dense pavement surfaces at a design speed of 60 mph if both had the same FN measured at the usual testing speed of 40 mph.

The Pennsylvania Department of Transportation (DOT) obtained frictional resistance and friction gradient data on four test sections consisting of OGFC and dense-graded HMA. The data in Table 1 clearly indicates higher friction numbers and lower friction gradients for OGFC compared to dense-graded HMA.

The Louisiana DOT compared the friction number and friction gradient of OGFC (called plant mixed seal at the time) with dense-graded HMA at speeds ranging

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Friction Number 30 mph</th>
<th>Friction Number 40 mph</th>
<th>Friction Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGFC (gravel)</td>
<td>74</td>
<td>73</td>
<td>0.10</td>
</tr>
<tr>
<td>OGFC (dolomite)</td>
<td>71</td>
<td>70</td>
<td>0.10</td>
</tr>
<tr>
<td>Dense-graded HMA (gravel)</td>
<td>68</td>
<td>60</td>
<td>0.80</td>
</tr>
<tr>
<td>Dense-graded HMA (dolomite)</td>
<td>65</td>
<td>57</td>
<td>0.80</td>
</tr>
</tbody>
</table>
from 20 to 60 mph as shown in Figure 3. It is evident that OGFC had a flatter friction gradient than the dense-graded HMA which resulted in high friction numbers at high speeds.

The Oregon DOT\textsuperscript{10,11} compared the friction numbers and friction gradients of OGFC (F Mix), dense-graded HMA (B Mix), and PCC pavements in wet conditions at speeds ranging from 64 to 88 km/hour (40 to 55 mph). Figure 4 shows the comparison. The OGFC had the flatest friction gradient, while the pcc pavement had low friction numbers.

The Virginia DOT\textsuperscript{12} has reported friction numbers of 15 OGFC projects, which ranged from 51 to 72, and are considered good to excellent. The OGFC was placed on some routes to reduce wet pavement accidents. A survey of accidents one year before and one year after the placement of OGFC on Route 23 revealed a significant reduction in wet pavement accidents. In the year prior to installation of OGFC, 39 percent (7 of 18) of the accidents occurred during wet weather. During the year after installation only 17 percent (2 of 12) of the accidents occurred during wet weather, which is considered normal.

France has also reported a significant decrease in wet weather accidents when OGFC was used.\textsuperscript{13} On the A7 Motorway between Valence and Lyon, 52 accidents were reported between 1979 and 1985. After OGFC was placed in 1985, no accidents occurred on that section between 1985 and 1989.

The Ontario Ministry of Transportation\textsuperscript{14} has reported experience with the design, construction, and seven-year performance of their dense friction courses (DFC) and OGFC placed on old PCC pavements. Resurfacing with DFC and OGFC almost doubled the frictional resistance levels of the old PCC pavements. When rehabilitating low friction pavements with high rates of wet weather collisions, use of the new friction course mixes produced substantial reductions in accidents. An average of 54 percent reduction in wet weather accidents and a 20 percent reduction in total collisions were obtained after treatment at eight freeway locations prone to black ice. Treatment at five black ice prone signalized highway intersections produced an average of a 71 percent reduction in wet weather and a 48 percent reduction in total accidents.

OGFC has also been used successfully to improve the frictional resistance of airport runways. A significant increase in the average wet friction coefficient was obtained when OGFC was placed on the main runway at the Naval Air Station in Dallas, Texas.\textsuperscript{15} Table 2 gives the comparison.

\textbf{TABLE 2}
\textbf{Average Friction Coefficients}\textsuperscript{1}

<table>
<thead>
<tr>
<th></th>
<th>Dry</th>
<th>Wet 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGFC</td>
<td>0.76</td>
<td>0.70</td>
</tr>
<tr>
<td>Original HMA Surface</td>
<td>0.74</td>
<td>0.16</td>
</tr>
<tr>
<td>Grooved concrete – south end</td>
<td>0.76</td>
<td>0.71</td>
</tr>
</tbody>
</table>

\textsuperscript{1} Measured with Mu-meter at 40 miles per hour (64 km/hr)
\textsuperscript{2} 5 mm (0.2 in) water depth
The New York DOT\textsuperscript{16} reported about a 30 percent increase in frictional resistance with OGFC compared to dense-graded HMA.

The Pennsylvania DOT\textsuperscript{17} has reported on the performance of three treatments to enhance frictional resistance on Interstate 80. These treatments were applied to the existing reinforced PCC pavement which had borderline friction numbers (below 35). The three treatments consisted of slurry seal, OGFC, and longitudinal grooving. All three treatments improved the frictional resistance of the existing PCC pavement. The highest friction number readings were obtained from the OGFC which averaged 52. The slurry seal averaged 42, and the longitudinal grooving averaged 37.

**Hydroplaning**
OGFC prevents hydroplaning because in most storms the rain water permeates through the mix, leaving no continuous water film on the road surface. Even during a prolonged period of heavy rainfall which may saturate the OGFC, hydroplaning may not occur because the pressure under the vehicle tire is dissipated through the porous structure of the OGFC.

**Reduced Splash and Spray**
When driving during rain, motorists run into heavy spray from vehicles (especially trucks) traveling ahead. Visibility can be diminished to a point where it is no longer possible for a motorist to see the roadway ahead. The use of OGFC almost eliminates spray because there is no standing water on the road surface. Figures 5 and 6 clearly show the difference between conventional dense-graded HMA and OGFC in Oregon. Motorists feel safer when driving on OGFC surface during rain. Field studies conducted in the UK\textsuperscript{18} have indicated 90-95 percent reduction in the amount of water spray 3 m (10 ft) behind a truck on an OGFC compared to dense-graded HMA.

**Glare**
Another benefit from the use of OGFC is the reduction of glare from headlights in wet conditions. Obviously it contributes to better visibility and reduced driver fatigue.

**Improved Visibility of Pavement Markings**
The pavement markings on OGFC surface have high night visibility especially during wet weather. This contributes to improved safety.

**Environment**

**Noise Reduction**
Tires rolling on the road cause air to be forced away in front of, and sucked in behind, the area of contact between the tire and the road. This air pumping generates high-frequency noise. On OGFC, the pumping, and thereby the noise generated to the surroundings, is reduced because the air is pumped down into the porous pavement.\textsuperscript{19} Porous OGFC also reduces noise by absorbing
some of the noise emitted by vehicles. On dense surfaces, the noise emitted towards the pavement is reflected to the surroundings.

Various research studies have been conducted in the US and Europe to evaluate the noise reduction capabilities of OGFC compared to other pavement surface types. A brief discussion of these studies follows.

The variation of tire/road contact noise (both outside and inside a car traveling at 80 km/h) within different surface types (OGFC, dense-graded HMA, surface dressing or chip seal, PCC, and stone paving) has been reported\textsuperscript{20} as shown in Figure 7. The OGFC had the lowest average and the least variation in noise levels.

**FIGURE 7**
Variation of Tire-Pavement Contact Noise (outside and inside a car at 80 km/hour) on Various Surface Types\textsuperscript{20}

Measurements made on dry pavements in the Netherlands\textsuperscript{21} have also shown approximately 3 dB(A) reduction in noise levels when OGFC is substituted for dense-graded HMA. Effects of noise reduction are generally more pronounced (up to about 8 dB(A)) in wet weather. Measurements were made at speeds of more than 80 km/hr because the noise produced between the tires and road surface tends to increase at higher speeds. The difference in texture between OGFC and dense-graded HMA not only causes a reduction in noise level on an OGFC surface, but also produces shifts in the sound spectrum. Less noise is generated and more noise is absorbed into the relatively open structure of OGFC. The benefits of OGFC in relation to barriers or other noise abatement methods can readily be quantified.\textsuperscript{21}

The Federal Highway Administration\textsuperscript{22} conducted a comparative noise level study of OGFC, dense-graded HMA, PCC pavement, and chip seal in Arizona, California, and Nevada. It was determined that OGFC had the lowest noise level compared to the other pavement surfaces. The following average sound levels, dB(A), were measured 15 m (50 ft) from the roadway when a station wagon with radial recap tires was operated at 105 km/h (65 mph):

- OGFC: 67 dB(A)
- Dense-graded HMA: 69 dB(A)
- PCC: 70 dB(A)
- Chip Seal: 72 dB(A)

Because of its noise reducing capability, the OGFC is known in Germany as “Fliisterasphalt,” that is “whispering” asphalt. A number of full-scale trial sections of OGFC were constructed between 1986 and 1990 on German motorways and trunk roads to investigate the long-term noise reduction effects of OGFC.\textsuperscript{23} Reductions in rolling noise of up to 6 dB(A) were measured and this value has since been adopted as the basis for calculating the noise reducing properties of OGFC.

**FIGURE 8**
Reduction in Noise Level when OGFC Substituted for Dense HMA\textsuperscript{24}
Research in France\textsuperscript{26} has shown that traffic noise in the frequency range of 500 to 1500 Hz is reduced to half by a 40 mm (1.5 in) thick OGFC. Experimental OGFC pavements have been constructed ranging from 12.5 mm (0.5 in) to 610 mm (24 in) in thickness in an effort to determine the optimum layer thickness for noise reduction. It has been found that 40 mm (1.5 in) is needed to get effective noise reduction, and the thicker layers tend to absorb lower frequencies. Since high-pitched, whining noises tend to be the most annoying, the 40 mm (1.5 in) thickness is considered to be optimum to reduce noise.\textsuperscript{26}

A joint Nordic project\textsuperscript{27} found that the noise from road traffic can be reduced by 3-5 dB(A) if OGFC is used in lieu of dense-graded HMA. This was observed both in urban traffic (free flowing traffic at 50-70 km/h) and in highway traffic (70-100 km/h). The quietest OGFC contained a maximum aggregate size of 10-12 mm and an air voids content of 22-23 percent.

The mechanism of noise generation and propagation from vehicle and tire/road surface has been reported by the Transport Research Laboratory (TRL) in UK\textsuperscript{28}. Experimental OGFC test sections (containing 20 mm maximum size aggregate) laid on the M1 and M4 motorways reduced the noise levels by between 5.2 and 6.6 dB(A) compared to conventional asphalt surfaces.\textsuperscript{28}

The Danish Road Institute\textsuperscript{29} constructed experimental test sections of OGFC in 1990 and 1991 to examine their noise reducing potential. Replacement of the existing dense-graded HMA with OGFC resulted in a 4 dB(A) reduction in traffic noise at speeds of about 50 km/hour. The noise levels of OGFC and dense-graded HMA surfaces were measured annually from 1990 to 1995. After five years, the OGFC still had a noise reduction of 3 dB(A) on a highway. The same noise reduction can be achieved by a 50 percent reduction of the traffic volume.\textsuperscript{30}

The Danish government has planned to reduce the number of dwellings exposed to noise levels above 65 dB(A) by 66 percent by year 2010. Four different pavements were laid in 1999 to develop and test two-layer porous asphalt or OGFC as a noise-reducing tool under Danish conditions. The two-layer porous asphalt was developed in the Netherlands, where it has been used since 1990 on urban roads. The bottom layer consists of a large aggregate size (11-16 mm). The top layer consists of a small aggregate size (4-8 mm) to ensure a smooth surface, to reduce the rolling noise, and to keep the debris from clogging the pores. The large size aggregate in the bottom layer ensures that dirt and water penetrating the surface can be led away without clogging the pores.\textsuperscript{19}

Placing an OGFC overlay may be a viable alternative to the construction of sound barriers to mitigate traffic noise. Barriers usually cost between $15 and $20 per linear foot and generally reduce the noise level by 3 to 5 decibels. To reduce the noise level by 3 dB(A), either the traffic volume has to be cut by half or the noise protection distance to the road has to be doubled. Noise barriers or earth berms have been used for noise reduction but they are partially effective and do not offer equal noise reduction in every direction as illustrated in Figure 9.\textsuperscript{27}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig9.png}
\caption{Conceptual Differences in the Effectiveness of OGFC and Noise Barriers\textsuperscript{27}}
\end{figure}
MIX DESIGN

The following mix design system is recommended for the new-generation OGFC mixes based on research conducted at the NCAT,\textsuperscript{4,5} observation of in-place performance of OGFC mixes in Georgia,\textsuperscript{5} and experience in Europe. The mix design is conducted in four steps: (1) materials selection, (2) selection of design gradation, (3) determination of optimum asphalt content, and (4) evaluation for moisture susceptibility.

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 (such as fiber).

Guidance for suitable aggregates is essentially based on similar recommendations for stone matrix asphalt (SMA).\textsuperscript{31} The coarse aggregate for OGFC must be adequately strong to carry the traffic loads because, similar to SMA, OGFC is designed to have stone-on-stone contact. Coarse aggregate used in OGFC should have L.A. abrasion values of less than 30 percent. Care must be exercised when using softer aggregates because of the potential for excessive aggregate breakdown during mix production and compaction in the field.

Fractured faces are also required to provide a coarse aggregate structure with high internal friction. If the fractured face count is significantly less than 100 percent (for example in partially crushed gravels), the OGFC mix will not have the desired resistance to rutting. Crushed gravel must have at least 90 percent particles with two faces and 100 percent particles with one face resulting from crushing. The percentage of flat and elongated particles should not exceed 5 and 20 corresponding to ratios of 5:1 and 3:1, respectively.

Similar to dense-graded HMA, the amount of asphalt absorption can affect the performance of OGFC. Aggregates with relatively low absorption (less than 2 percent water absorption) are preferred. However, if locally available high-absorptive aggregates are used, the optimum asphalt content should be selected on the high side within the specification limits to account for absorption during mix production, placement, and service.

The angularity of the fine aggregate should be measured with the fine aggregate angularity (FAA) test (AASHTO TP 56, Method A). The FAA value should be 45 or higher.

Binder selection should be based on factors such as environment, traffic, and expected functional performance of OGFC. High stiffness binders, generally two grades stiffer than normally used for the local climatic conditions (such as PG 70-XX or PG 76-XX), made with polymers are recommended 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 20 percent). The addition of fiber is also desirable under such conditions to significantly reduce draindown and allow for high binder content for a durable OGFC. For low to medium volume traffic, either polymer modified binders or fibers may be sufficient. Either cellulose fiber (added at about 0.3 percent of total mix) or mineral fiber (added at about 0.4 percent of total mix) can be used. The dosage rate depends upon the result of mix draindown test described later. A recent study\textsuperscript{32} by NCAT has shown both types of fibers to be equally effective in OGFC mixtures.

Step 2. Selection of Design Gradation

Similar to SMA, the OGFC must have a coarse aggregate skeleton with stone-on-stone contact to minimize rutting (31). Coarse aggregate is defined as the aggregate fraction retained on a 4.75 mm sieve. The condition of stone-on-stone contact within an OGFC mix is defined as the point at which the voids in coarse aggregate fraction of the blend of the compacted OGFC mixture (VCA\textsubscript{MIX}) is less than the VCA of the coarse aggregate fraction of the blend alone (VCA\textsubscript{DRC}) in the dry rodded test (AASHTO T19).

The VCA of the coarse aggregate only fraction (VCA\textsubscript{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\textsubscript{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)
- \(\gamma_s\) = unit weight of the coarse aggregate fraction in the dry-rodded condition (kg/m\textsuperscript{3}) (AASHTO T19)
- \(\gamma_w\) = unit weight of water (998 kg/m\textsuperscript{3})
An example of determining $VCA_{DRC}$ and $VCA_{MIX}$ (of the compacted OGFC mixture) is given in Appendix A.

The conceptual differences between $VCA_{DRC}$, $VCA_{MIX}$, and VMA are explained in Figure 10.

The master gradation band given in Table 3 is recommended.

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 ($VCA_{DRC}$) using AASHTO T19.

**TABLE 3**

<table>
<thead>
<tr>
<th>Sieve</th>
<th>Percent Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 mm</td>
<td>100</td>
</tr>
<tr>
<td>12.5 mm</td>
<td>85-100</td>
</tr>
<tr>
<td>9.5 mm</td>
<td>35-60</td>
</tr>
<tr>
<td>4.75 mm</td>
<td>10-25</td>
</tr>
<tr>
<td>2.36 mm</td>
<td>5-10</td>
</tr>
<tr>
<td>0.075 mm</td>
<td>2-4</td>
</tr>
</tbody>
</table>

**FIGURE 10**

**Conceptual Differences between VCA$_{DRC}$, VCA$_{MIX}$ and VMA**

**Figure A:** $VCA_{DRC}$ is obtained from the Dry Rodded Unit Weight of just the coarse aggregate.

**Figure B:** $VCA_{MIX}$ is calculated to include everything in the mix except the coarse aggregate.

**Figure C:** VMA includes everything in the mix except the aggregate (both coarse and fine). For the $VCA_{MIX}$ and VMA calculations, asphalt absorbed into the aggregate is considered part of the aggregate.
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 for each compacted mix (VCA<sub>MIX</sub>). If the VCA<sub>MIX</sub> of the compacted mix is equal to or less than the VCA<sub>DRC</sub>, stone-on-stone contact exists (see example in Appendix A). 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 a draindown test (ASTM D6390) on loose mix at a temperature 15 °C higher than anticipated production temperature. Since the OGFC is an open-graded HMA there is a significant potential that the binder may drain down in the mix during silo storage or transport in trucks. This will produce both fat and lean OGFC mix spots in the paved area. In the draindown test, a sample of loose asphalt mixture 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. The complete test method is given in ASTM D6390.

The next step in the mix design process is to compact the mix using 50 gyrations of a Superpave gyratory compactor and determine air void contents from the bulk specific gravity of compacted OGFC specimens and the theoretical maximum specific gravity of the loose OGFC mixture.

Conduct the Cantabro abrasion test<sup>33</sup> on unaged and aged compacted samples. This test evaluates the resistance of compacted OGFC specimens to abrasion loss. This is an abrasion and impact test carried out in the Los Angeles abrasion machine (ASTM Method C131). The mass of the compacted OGFC specimen is determined to the nearest 0.1 gram, and is recorded as P<sub>1</sub>. The compacted test specimen is then placed in the Los Angeles abrasion machine 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<sub>2</sub>). The percentage abrasion loss (P) is calculated according to the following formula:

\[
P = \frac{P_1 - P_2}{P_1} \times 100
\]

The recommended maximum permitted abrasion loss value for freshly compacted specimens is 20 percent.<sup>33</sup> 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.

Aged compacted OGFC should also be subjected to Cantabro abrasion test to evaluate the effect of accelerated laboratory aging and hence field 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 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.<sup>33</sup>

Aging is accomplished by placing five compacted specimens (compacted with 50 gyrations) in a forced draft oven set at 85 °C for 120 hours (5 days). This long-term aging is in accordance with AASHTO PP2-01 “Standard Practice for Mixture Conditioning of Hot-Mix Asphalt.” 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 speci-
mens should not exceed 30 percent, while no individual result should exceed 50 percent.

The laboratory permeability testing (ASTM PS 129) of compacted OGFC specimens is optional. Laboratory permeability values greater than 100 m/day are recommended. The optimum asphalt binder content is selected when the OGFC mixture meets the following criteria:

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 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 and aggregate gradation. 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 or fiber additive can be adjusted. Fiber stabilizers are typically incorporated into the mix at a rate of 0.2 to 0.5 percent by weight of the total mix.

**Step 4. Evaluate Mix for Moisture Susceptibility**

The mix designed with Steps 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. The AASHTO T283 should be modified as follows: (a) specimens compacted with 50 gyrations of SGC should be used, (b) apply a partial vacuum of 26 inches Hg for 10 minutes to saturate the compacted specimens to whatever saturation level is achieved, and (c) keep the specimens submerged in water during freeze cycles to maintain saturation.

A summary of recommended standard practice for designing OGFC mixtures is given in Appendix B.

**MIX PRODUCTION AND PLACEMENT**

There are some significant differences between the procedures of producing and placing OGFC and conventional HMA mixtures. Specific modifications must be made to standard HMA production facilities equipment, plant operations, and field construction techniques.31, 34, 35

**Asphalt Plant Modifications**

The main modification required to a standard HMA production facility is the addition of a mineral fiber or cellulose fiber feed device. Typical dosage rates are 0.4 percent for mineral fiber and 0.3 percent for cellulose fiber by total mixture mass. Generally, fibers can be produced in two forms: loose fibers and pelletized fiber. Fibers in a dry, loose state are supplied packaged in plastic bags or in bulk. Both fiber types have been added successfully into batch or drum plants.

In case of a batch plant, the packaged loose fiber is added to the pugmill during each dry mix cycle. The bags are carried to the pugmill platform by the use of a conveyor belt. In this rather labor intensive method, the workers throw an appropriate number of bags into the pugmill. The bags melt and the fiber is thoroughly mixed with heated aggregate during the dry mix cycle.31

Loose fibers can also be blown into the weigh hopper or pugmill of a batch plant at the appropriate time. Machines typically designed and supplied by the fiber manufacturers are used. The dry, loose fiber is fed into the hopper of the machine where it is fluffed by large paddles. The fluffed fiber enters into an auger system which conditions the material to a known density. The machine then meters the fiber by mass or volume and blows it into the weigh hopper or pugmill. The same fiber blowing method can also be used in a drum plant by simply blowing the fiber continuously into the drum. The fiber line should be placed within one foot upstream of the asphalt binder line so that the fibers are captured by the asphalt binder before getting exposed to the high velocity gases in the drum. If the fiber is carried by the gas stream it will enter the dust control system of the plant.31

The pelletized form of fibers can be used in both batch and drum plants. The pellets contain a given amount of
asphalt binder (to bind the fibers) that must be accounted for in the total asphalt content of the HMA mixture. The pelletized fiber is placed in a hopper from where it is metered and conveyed to the pugmill of a batch plant or to the drum of a drum plant. The pellets are mixed with heated aggregate thus melting the asphalt binder and allowing the fiber to mix with the aggregate.31

It is very important that the fiber addition, whether it is bulk or pelletized, be calibrated to ensure the consistency of the fiber content in the mix. Fat spots are likely to result on the surface of the finished OGFC pavement if the fiber is not thoroughly dispersed in the mix and/or the fiber content is not controlled.

**Asphalt Plant Production**

When mineral fibers or cellulose fibers are used in OGFC mixtures, it is necessary to increase both the dry mixing time and the wet mixing time when using a batch HMA facility.34 This ensures a thorough dispersion of fibers during the dry mixing cycle and a uniform coating of all aggregate particles by the asphalt binder during the wet mixing cycle.

The screening capacity of the screen deck in a batch plant must also be considered. Since the OGFC predominantly consists of a single size aggregate, override of the screen deck and hot bins is likely to occur at lower mix production levels compared to conventional HMA mixtures.34

The OGFC mixture should not be stored in surge bins or silos for extended periods of time due to potential draindown problems.

**Hauling**

Since the polymer-modified asphalt binder in the OGFC has a tendency to bond, it is necessary to apply a heavy and thorough coat of an asphalt release agent to truck beds. Also, truck beds should be raised after spraying to drain any puddles of the release agent. The puddled release agent, if not removed, will cool the OGFC and cause cold lumps in the mix.34

Tarping each load of OGFC is essential to prevent excessive crusting of the mix during transportation. The cold lumps do not break down readily and cause pulls in the mat. A long haul distance will compound this problem. The Oregon DOT limits the haul distance to 56 km (35 miles), with 80 km (50 miles) as the absolute upper limit.35

The HMA production, hauling, and paving should be coordinated so that paving continues smoothly without stops. Too few trucks will cause the paver to stop, thus producing bumps. Too many trucks will cause delays in unloading thereby resulting in cooling of the OGFC mix and formation of cold lumps.

**Placement**

The OGFC should only be placed on an impermeable asphalt course unless the pavement is specifically designed to be permeable. Otherwise, during rainfall, the water will pass through the OGFC and be trapped in the underlying pavement layer, resulting in potential moisture damage (stripping). A freshly compacted dense-graded HMA course may have as much as 8 percent air voids in the mat and thus may be permeable to water. Therefore, it is essential to provide a uniform tack coat at an adequate application rate to fill and seal the surface voids of the underlying layer. The FHWA suggests sealing the underlying pavement by applying a 50 percent diluted slow-setting emulsion tack coat at a rate of 0.05 to 0.10 gallon per square yard.36 The application rate should be high enough to completely fill the surface voids. A slow-setting emulsion tack coat is likely to penetrate the surface voids more effectively than an asphalt cement tack coat. Most dense-graded HMA surfaces become reasonably impervious after two to three years of traffic. Such surfaces will not need any sealing prior to placing OGFC. The OGFC mat should be daylighted on the shoulder so that rain water percolating through the OGFC can drain out freely at its edge.

The use of a remixing material transfer device for transferring the OGFC from the trucks to the paver is optional, but highly recommended.34 It remixes most cold lumps produced during transportation, and also allows continuous operation of the paver for smoother surfaces.

Conventional asphalt pavers are used to place the OGFC. However, a hot screed is very important to prevent pulling of the mat. A propane torch can be used to heat the screed before each use.34

Conventional steel wheel rollers are used to compact the OGFC. No pneumatic tire rolling is required. It is critical to keep the roller within 15 m (50 ft) of the paver to compact the OGFC while it is still hot and workable. The breakdown roller usually completes one to two complete coverages of the mat in static mode to compact a
thin lift (20 mm or 3/4 in) OGFC. The breakdown roller may have to be operated in a vibratory mode at transverse joints and occasionally longitudinal joints to help knock down a high joint. Generally, use of vibratory compaction should be discouraged.

OGFC containing polymer modified asphalt binder (especially containing fiber too) is an extremely harsh mix and does not lend itself to raking unlike conventional HMA. Raking, if attempted, produces rough areas with excessive voids in the finished mat. Therefore, it is very important to have the entire screed heated well to avoid any raking.

Longitudinal joints in the OGFC pavement are constructed by placing the mix approximately 1.5 mm (1/16 in) above the previously placed and compacted lane. Therefore, it is important for the edge of the screed or extension to follow the joint exactly to prevent excessive overlap. Transverse joints placed against a previously laid OGFC are constructed by starting with the screed one foot behind the joint and laying the screed flat on the previously laid OGFC mat. The hot OGFC mix is augered in front of the screed and then drug off the new joint when travel begins. The joint should then be cross rolled with a steel wheel breakdown roller.

It was recommended to assign the same gravel equivalent factor (analogous to structure coefficient) to both OGFC and permeable base.

The Oregon Department of Transportation uses the same structural coefficient for OGFC as dense-graded HMA. Deflections taken on OGFC pavements after being placed have shown the estimated deflection reduction was comparable to that expected from typical dense-graded HMA overlays of similar thickness.

Where Not To Use OGFC

Long Haul. Jobs with extremely long haul distances from the HMA plant site to project site are not suitable due to potential draindown and/or cooling of the OGFC mix. Although success has been achieved with one-way haul distances up to 110 km (70 miles), the current policy in Oregon is to restrict haul distance to 56 km (35 miles).

Inlays. The OGFC must be allowed to drain by daylighting the mix on the shoulder. Therefore, it cannot be used as an inlay pavement layer.

Hand Work. The OGFC mix is very difficult to rake. Don’t place OGFC when there is an abundance of hand work involved on the project. For example, OGFC should not be specified for tapers, road approaches, or for city streets where there are lots of inlets and manholes.

Snow Zones. Some problems have been noted in snow zones where extensive snow plowing is required. The plow blade can catch on the coarse aggregate and may cause raveling in some cases.

Critical Pavement Locations. OGFC may ravel or shove when used at intersections, locations with heavy turning movements, ramp terminals, curbed sections, and other adverse geometric locations.

Permeable Underlying Layer. Except for the rarely designed, full-depth, porous pavement, it is of paramount importance to place OGFC on an impermeable pavement course. This allows the water at the bottom of OGFC to flow outwards on the surface of the underlying layer rather than penetrating it and causing moisture damage. If OGFC must be placed over a freshly compacted dense-graded HMA course with high air void content, the surface should be sealed as discussed under placement in the last chapter.
MAINTENANCE AND REHABILITATION

Winter Maintenance

Winter maintenance (snow and ice removal) has been often cited and assumed to be a serious problem with OGFC. However, there has been little difficulty in this regard in Europe. OGFC has different thermal and icing properties than conventional dense-graded HMA, and needs its own winter maintenance regimen. OGFC has a different thermal conductivity (40 to 70 percent less than dense-graded HMA) and, therefore, acts like an insulating layer. OGFC may have a temperature of 2 °C lower than dense-graded HMA. Frost and ice will accumulate earlier, more quickly, and more frequently on OGFC compared to other surfaces. Construction of long, continuous stretches of highways using OGFC is desirable. Alternate applications of dense-graded HMA and OGFC can present the motoring public with sudden changes in skid resistance.38

It is important to give special and repeated training to drivers of snow-plows and spreaders. “Preventive salting” of the OGFC at the right time is important. Salting is only successful on a dry pavement when temperatures are lower than –10 °C. A combination of 70 percent dry salt and 30 percent salt water solution (20 percent calcium chloride) applied at the rate of 10-20 g/m² has been determined to be effective in Austria.38 It has been found in Holland that the use of brine is extremely effective and reduces the salt consumption to only 15 percent of normal. Brine cannot be used effectively on dense surfaces because it would run off quickly.24 According to experience in Netherlands39 about 25 percent more salt is necessary. The timing of application is very important.

Black ice can also form on the OGFC if water is allowed to accumulate on curves in the road, and on the transition areas between OGFC and dense-graded HMA.

General Maintenance

If a relatively dense-graded OGFC is used, it may gradually be choked and partially lose permeability. Therefore, frequent cleaning may be necessary. Three methods of cleaning OGFC: (a) cleaning with a fire hose, (b) cleaning with a high pressure cleaner, and (c) cleaning with a specially manufactured cleaning vehicle. These techniques were tested for effectiveness in Switzerland (40). The special cleaning vehicle manufactured by FRIMOKAR of Switzerland40 can wash and vacuum clean the surface in one pass. Deposited dirt in the OGFC is washed out by a high pressure water stream with a working pressure of about 500 psi from a front washing beam, mounted on the vehicle. The water-dirt mixture on the pavement is then sucked into a dirt container by a heavy duty vacuum cleaner. Method (b), cleaning with a high pressure cleaner, was found to be most effective based upon permeability tests after cleaning.

If OGFC is placed on airport runways used by jet aircraft, it is necessary to keep the OGFC swept clean at all times to avoid ingress of loose aggregates into the jet engines.

Rehabilitation

Most agencies do not apply a dense-graded HMA over OGFC at the end of its service life. Studies have found that this will trap water in the OGFC and cause deterioration of the pavement. Generally, it is recommended to mill off the existing OGFC prior to replacing with a new OGFC or any other HMA course.

SUMMARY

Open-graded friction course (OGFC), also called porous asphalt in Europe, is an open-graded HMA mixture with interconnecting voids that provides drainage during rainfall. In addition to minimizing hydroplaning during rainfall, OGFC offers the following advantages:

- **High skid resistance on wet pavements.** Research data obtained by several agencies indicate significantly higher skid resistance of OGFC compared to dense pavements. The high skid resistance results from the increased macrotexture of the OGFC surface and is also maintained at high operating speeds.
- **Reduced splash and spray.** The safety of the motoring public is improved due to reduced splash and spray from the vehicles driving ahead.
- **Enhanced visibility of pavement markings.** The safety of the motoring public is also increased because the visibility of pavement markings on OGFC surface is enhanced, especially in inclement weather.
- **Reduced tire-pavement noise.** Research data indicates a reduction in noise levels up to about 6 dB(A) when OGFC is substituted for dense-graded HMA.

The National Center for Asphalt Technology (NCAT) has developed a new-generation OGFC based upon an NCAT research project, experience of states in the U.S. which have placed durable OGFC pavements, and experience in Europe. This report has covered the following topics:

- **New Mix Design Method.** The mix design is conducted using 50 gyrations of a Superpave gyratory compactor. High quality, angular aggregates are used. High stiffness binders such as PG 76-XX made with polymers are used in the OGFC. The use of cellulose or mineral fiber is recommended. The selected gradation should be within a recommended band and should provide stone-on-stone contact in the coarse aggregate (material retained on 4.75 mm sieve). The optimum asphalt content for the selected OGFC gradation is established to meet the following criteria: (a) 18 percent minimum air voids; (b) abrasion loss from the Cantabro test (conducted in a Los Angeles abrasion machine) not to exceed 20 percent for unaged compacted specimens and 30 percent for aged specimens; (c) draindown not to exceed 0.3 percent; and (d) the retained tensile strength of the compacted specimens subjected to five freeze/thaw cycles in modified Lottman method (AASHTO T283) should be at least 80 percent.

- **Mix Production and Placement.** The primary modification required for a standard HMA facility is the addition of a fiber feed device. The method of incorporating both loose or pelletized fibers has been described. Both dry and wet mixing times need to be increased to obtain good dispersion of fibers and good coating of aggregate particles.

The OGFC mix should be protected from cooling during transportation to minimize cold lumps which may cause pulls in the mat during paving. The use of a remixing material transfer device is highly recommended to obtain a uniform mix and ensure continuous operation of the paver so the newly placed surface is free from bumps. The paver screed must be heated before beginning the paving operations to ensure a smooth laydown. The OGFC mix with polymer-modified binder and fiber is a very harsh mix and cannot be raked easily. Avoid handwork if possible.

Use conventional steel rollers in static mode. One to two complete passes over the mat are sufficient to compact a thin lift (20 mm) of OGFC.

- **Pavement Design Considerations.** A thickness of 20 mm (3/4 in) is most commonly used in the U.S. for OGFC, except Oregon which uses 50 mm (2 in). At least 50 mm thickness is used to cause significant reduction in noise levels. The Oregon Department of Transportation uses the same structural coefficient for OGFC as dense-graded HMA based on a study using deflection measurements.

- **Maintenance and Rehabilitation.** The report describes procedures for snow and ice control on OGFC pavements. Undertaking “preventive salting” of the OGFC at the right time is important. At the end of its service life, OGFC should be milled off prior to replacing with a new OGFC or any other HMA course.
REFERENCES


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

**Determination of Voids in the Coarse Aggregate — Dry-Rodded Condition (VCA \_DRC \_)**

VCA \_DRC \_ was determined for three blends of coarse aggregate fractions 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 A-2.

**TABLE A-1**
Gradations of the Three Trial Blends

<table>
<thead>
<tr>
<th>Sieve Size (mm)</th>
<th>Percent Passing by Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Percent Passing by Volume</td>
</tr>
<tr>
<td></td>
<td>Trial Blend 1</td>
</tr>
<tr>
<td>19.0</td>
<td>100</td>
</tr>
<tr>
<td>12.5</td>
<td>95</td>
</tr>
<tr>
<td>9.5</td>
<td>55</td>
</tr>
<tr>
<td>4.75</td>
<td>10</td>
</tr>
<tr>
<td>2.36</td>
<td>5</td>
</tr>
<tr>
<td>0.075</td>
<td>3.0</td>
</tr>
<tr>
<td>G\textsubscript{CA} *</td>
<td>2.688</td>
</tr>
</tbody>
</table>

\* G\textsubscript{CA} = coarse aggregate bulk specific gravity

**TABLE A-2**
Unit Weight and VCA \_DRC \_ for the Three Trial Blends

<table>
<thead>
<tr>
<th>Blend No.</th>
<th>VCA _DRC _ (%)</th>
<th>Dry Rodded Unit Weight, kg/m\textsuperscript{3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41.7</td>
<td>1564.27</td>
</tr>
<tr>
<td>2</td>
<td>41.0</td>
<td>1582.75</td>
</tr>
<tr>
<td>3</td>
<td>40.3</td>
<td>1601.53</td>
</tr>
</tbody>
</table>

The calculation for VCA \_DRC \_ for blend 1 is shown below.

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

\[
VCA_{DRC} = \frac{(2.688)(998) - 1564.27}{(2.688)(998)} \times 100
\]

\[
VCA_{DRC} = 41.7\%
\]

where,

\( \gamma_s \) = unit weight of the coarse aggregate fraction in the dry rodded condition (kg/m\textsuperscript{3})

\( \gamma_w \) = unit weight of water (998 kg/m\textsuperscript{3}), and

\( G_{CA} \) = combined bulk specific gravity of the coarse aggregate (Table A-1).

**Compact Specimens**

For each of the trial blends, three samples were produced at 6.0% asphalt binder by total mix mass using the Superpave Gyratory Compactor (SGC). The bulk specific gravities (\( G_{mb} \)) 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 and VCA \_MIX \_ were then determined. These results are summarized in Table A-3.

**TABLE A-3**
Test Results for Three Trial Gradation Blends

<table>
<thead>
<tr>
<th>Property</th>
<th>Trial Blend 1</th>
<th>Trial Blend 2</th>
<th>Trial Blend 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_{mb} )</td>
<td>1.996</td>
<td>2.007</td>
<td>2.030</td>
</tr>
<tr>
<td>( G_{mm} )</td>
<td>2.449</td>
<td>2.451</td>
<td>2.455</td>
</tr>
<tr>
<td>Air Voids, %</td>
<td>18.5</td>
<td>18.1</td>
<td>17.3</td>
</tr>
<tr>
<td>VCA _MIX _ , %</td>
<td>33.2</td>
<td>36.5</td>
<td>43.3</td>
</tr>
</tbody>
</table>
An example of the VCA calculation for the compacted OGFC mixtures is given here for blend 1.

\[
VCA_{\text{MIX}} = 100 - \left[ \frac{G_{\text{mb}}}{G_{\text{CA}}} \times P_{\text{CA}} \right] \\
VCA_{\text{MIX}} = 100 - \left( \frac{1.966}{2.688} \times (90.0) \right)
\]

where,

- \( G_{\text{CA}} = \) bulk specific gravity of the coarse aggregate (Table A-1)
- \( G_{\text{mb}} = \) bulk specific gravity of compacted OGFC specimens (Table A-3)
- \( P_{\text{CA}} = \) percent coarse aggregate in the total mixture (Table A-1) (100-10)

Based on Table A-3, trial blends 1 and 2 meet the requirements for VCA (\( VCA_{\text{MIX}} < VCA_{\text{DRC}} \)) and do have stone-on-stone contact. Trial blend 3 did not meet the VCA requirements. Trial blend 1 is preferred over blend 2 because it has higher air voids than blend 2. Blend 1 should be used to determine the optimum asphalt content.
APPENDIX B

Summary of Recommended Practice for Designing
Open-Graded Friction Course Mixtures

The following is an abbreviated outline of the mix design procedure contained in the main body of this report.

Step 1. Materials Selection

Coarse Aggregates:
- L.A. Abrasion ≤ 30%
- Fractured faces ≥ 90% two fractured faces
  100% one fractured face
- Flat and Elongated ≤ 5% 5:1 ratio
  ≤ 20% 2:1 ratio

Fine Aggregate:
- Fine Aggregate Angularity (FAA) ≥ 45

Asphalt Binder:
- High stiffness binder generally two grades stiffer (high temperature designation) than normally used for the local climate.
- Polymer modification recommended for medium to high traffic.
- Fibers recommended to prevent draindown.
- For low to medium traffic either polymer modified binder or fiber may be sufficient

Step 2. Selection of Design Gradation

Recommended Gradation for OGFC

<table>
<thead>
<tr>
<th>Sieve</th>
<th>Percent Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 mm</td>
<td>100</td>
</tr>
<tr>
<td>12.5 mm</td>
<td>85-100</td>
</tr>
<tr>
<td>9.5 mm</td>
<td>55-75</td>
</tr>
<tr>
<td>4.75 mm</td>
<td>10-25</td>
</tr>
<tr>
<td>2.36 mm</td>
<td>5-10</td>
</tr>
<tr>
<td>0.075 mm</td>
<td>2-4</td>
</tr>
</tbody>
</table>

- Blend selected aggregate stockpiles to produce three trial blends.
  - One near the coarse side of gradation band
  - One near the fine side of the gradation band
  - One near the middle of the gradation band.

- 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.
  - Compact coarse aggregate according to AASHTO T19
  - Calculate VCA_{DRC}

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

where,
- \(G_{CA}\) = bulk specific gravity of the coarse aggregate (AASHTO T85)
- \(\gamma_s\) = unit weight of the coarse aggregate fraction in the dry-rodded condition (kg/m³) (AASHTO T19)
- \(\gamma_w\) = unit weight of water (998 kg/m³)

- For each trial gradation prepare three batches at between 6.0 and 6.5 asphalt binder. Include fibers if used.
- Compact two specimens from each trial gradation using 50 gyrations of the Superpave gyratory compactor.
  - Determine the bulk specific gravity (G_{mb}) of each specimen.
  - Determine the VCA_{MIX} each compacted specimen.

\[
VCA_{MIX} = 100 - \left[ \frac{G_{mb}}{G_{CA}} \times P_{CA} \right]
\]

where:
- \(G_{CA}\) = bulk specific gravity of the coarse aggregate
- \(G_{mb}\) = bulk specific gravity of compacted OGFC specimens
- \(P_{CA}\) = percent coarse aggregate in the total mixture
Use the remaining sample from each trial gradation to determine the Theoretical Maximum Specific Gravity \( (G_{mm}) \) of each trial.

- Compare VCA\(_{\text{MIX}}\) to VCA\(_{\text{DRC}}\) for each trial gradation.
- To select design gradation, choose trial gradation with VCA\(_{\text{MIX}}\) < VCA\(_{\text{DRC}}\) with high air voids.

**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 (ASTM D6390) 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.

The asphalt content that meets the following criteria is selected as optimum asphalt content.

- **Air Voids ≥ 18%**
- **Cantabro Abrasion Test (unaged) ≤ 20 %**
- **Cantabro Abrasion Test (Aged) ≤ 30 %**
- **Draindown ≤ 0.3 %**

**Step 4. Evaluate Mix for Moisture Susceptibility**

- Test final mix for moisture susceptibility using the modified Lottman method (AASHTO T283)
  - Compact using 50 gyrations of Superpave gyratory compactor
  - Apply partial vacuum of 26 inches Hg for 10 minutes to whatever saturation is achieved.
  - Use five freeze/thaw cycles in lieu of one cycle.
  - Keep specimens submerged in water during freeze cycles
- Retained tensile strength (TSR) ≥ 80%.
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