National Cooperative Highway Research Program

Synthesis of Highway Practice 284

Performance Survey on Open-Graded Friction Course Mixes

GERALD HUBER
Indianapolis, Indiana

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FREDERICK D. HEJL, *Transportation Research Board*
DENNIS C. JACKSON, *Washington Department of Transportation*
TIMOTHY J. LEWIS, *Federal Highway Administration*
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GARY THOMPSON, *Asphalt Paving Association of Oregon*
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Subject Areas
Pavement Design, Management and Performance

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis report will be of interest to construction, maintenance, pavement design, and materials engineers, pavement contractors, and others interested in the use of open-graded friction course (OGFC) mixes. It describes the current state-of-the-practice on the use of OGFC mixes. This includes information regarding design, materials, construction, maintenance, and rehabilitation strategies. Alternative treatments to traditional OGFC are also identified and discussed. Information for the synthesis was collected by surveying U.S. and Canadian transportation agencies and by conducting a literature search to gather further information on North American and European practices.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board describes the recent performance of North American OGFC and European porous asphalt by identifying and discussing benefits and stress indicators. A new generation of OGFC has evolved in the last five years with changes that have been reported to dramatically improve the performance of

OGFCs. Changes include a combination of empirical design adjustments, adoption of innovative technologies, and improved methods of construction. The synthesis describes new material and design methods in use, as well as the applicability of the new generation of open-graded mixtures to North American use.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the available information was assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the author's research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

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Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Frederick D. Hejl, Engineer of Materials and Construction, Transportation Research Board; Dennis C. Jackson, State Materials Engineer, Washington Department of Transportation; Timothy J. Lewis, Highway Engineer, Federal Highway Administration; Francis J. Manning, Senior Civil Engineer, Rhode Island Department of Transportation; Bernard T. Paiz, Pavement Engineer, Colorado Department of Transportation; Peter J. Stephanos, Pavement Division Chief, Maryland State Highway Administration; Kevin Stuart, Research Highway Engineer, Federal Highway Administration; Gary Thompson, Training Director, Asphalt Pavement Association of Oregon; and Donald E. Watson, Paving Bureau Engineer, Georgia Department of Transportation.

This study was managed by Stephen F. Maher, P.E., Manager, Synthesis Studies, who worked with the consultant, the Topic Panel, and the Project 20-5 Committee in the development and review of the report. Assistance in project scope development was provided by Donna L. Vlasak, Senior Program Officer. Don Tippman was responsible for editing and production. Cheryl Keith assisted in meeting logistics and distribution of the questionnaire and draft reports.

Crawford F. Jencks, Manager, National Cooperative Highway Research Program, assisted the NCHRP 20-5 Committee and the Synthesis staff.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

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PERFORMANCE SURVEY ON OPEN-GRADED FRICTION COURSE MIXES

SUMMARY

Open-graded friction course (OGFC) is a permeable surface asphalt mixture intended to enhance surface friction, particularly in wet weather. The layer, typically quite thin, is intended to allow water drainage into the mix. Highway users benefit from the reduction of spray and hydroplaning during wet weather conditions.

OGFC mixtures have been used since 1944. They require a different mix design method and special construction considerations and, because performance has been mixed, some states have opted not to use them, whereas others have discontinued use.

Open-graded mixtures are porous. They have interconnected voids and high permeability. Water enters the pavement easily and is removed from the surface. The macrotexture of this porous asphalt is higher than dense-graded mixtures, even coarse-graded Superpave mixtures. With open-graded asphalt mixtures, wet weather visibility is dramatically improved. The amount of water spray on a new open-graded asphalt mixture is 5 to 10 percent of the water spray on a dense-graded surface.

Motorists notice a sudden decrease in noise when leaving a dense-graded asphalt surface and proceeding onto an OGFC surface. At high speed there are two significant sources of noise: tire noise from the pavement and wind noise from the vehicle. At 100 to 110 km/hr (60 to 70 mph), an open-graded surface is quieter than dense-graded asphalt because tire noise is absorbed.

In the United States changes are being made to open-graded mixes. Some agencies are using modified asphalt binder, which is less susceptible to draindown during construction. Modified asphalt binder is also more durable, reducing aging and potential raveling. Fiber stabilizers have also been used to prevent draindown during construction. A new generation of mix designs uses 12.5- and 16-mm-nominal maximum sizes instead of 9.5 mm. The larger aggregate size generates larger voids, which are less susceptible to clogging.

Open-graded mixtures are also used in Europe, although they differ from U.S. mixtures. To differentiate from the U.S. mixtures, European mixtures are called porous asphalt instead of OGFC.

The following significant differences exist between European and U.S. mixtures:

- Air voids of the U.S. mixtures tend to be considerably lower than those of the European mixtures.
- All European agencies specify minimum air voids, whereas few U.S. agencies do.
- European gradations generally allow for a more gap-graded mixture, although not always.
- European agencies use modified asphalt binders almost exclusively.
- U.S. agencies are shifting toward modified binders.
- Aggregate standards are higher in Europe.
- The higher air void contents specified in European mixtures require hard aggregates with a minimal tendency to break or degrade during construction.

Open-graded mixtures have a shorter life than dense mixtures. Functionally, they fail when voids become clogged. Structurally, they fail by raveling. Once voids are clogged, an open-graded mixture performs as a dense-graded mix with relatively low permeability. New mix specifications are producing mixtures with higher levels of air voids, larger pore size, and longer durability.

A new generation of OGFCs has evolved in the last 5 years with changes that have been reported to dramatically improve the performance of OGFCs. Changes include a combination of empirical design adjustments, adoption of innovative technologies, and improved methods of construction.

This synthesis documents recent performances of OGFCs and porous asphalt by identifying and discussing benefits and distress indicators. Current use is summarized. The synthesis includes existing information regarding design, materials, construction, maintenance, and rehabilitation strategies. Alternative treatments to traditional OGFCs are also identified and discussed.

Finally, the synthesis makes several recommendations for further research. A new mix design method is needed that includes the Superpave gyratory compactor. Modified asphalt binders are shown to increase open-graded mixture life, but no method is available to select an appropriate binder grade for different climate and traffic conditions. Guidance or criteria are needed. Research into maintenance strategies is also required. Methods of restoring permeability or extending mixture life are also needed.

CHAPTER ONE

INTRODUCTION

BACKGROUND

In this synthesis two terms will be used for a high-void, porous surface mixture. Open-graded friction course (OGFC) is a North American-derived mixture. Porous asphalt is a European mixture.

When considering the acceptability of a highway the public is most concerned about expeditious traffic flow and pavement smoothness. Traction, particularly in wet weather, and quietness are also important. Mixtures with high permeability have been identified to provide high wet weather traction and low noise when used for pavement surface courses. Such mixtures have been called OGFC or more recently porous asphalt.

Porous mixtures reduce spray, splash, and hydroplaning during wet weather driving conditions. They also are relatively quiet, reduce headlight glare, and resist rutting.

OGFC mixtures have been used in the United States since at least 1944 *(1)*, but for several reasons their use spread slowly. These mixtures require a different mix design method and special construction considerations. The mixtures have special maintenance issues and tend to fail suddenly at the end of their life.

Although OGFC mixtures have been used for more than 50 years, performance has been mixed. Unsatisfactory experience is associated mostly with the length of service life and the failure mechanism at the end of service life. Pavement life has been reported to be from 7 to 13 years, somewhat less than typical dense-graded mixtures. At the end of life, the pavement begins to ravel and deteriorates very rapidly, often in a matter of months. A short life and catastrophic failure has caused agencies to reconsider the benefit of OGFC surfaces.

In the past 5 to 10 years, new materials and design methods have addressed some of the earlier issues. Extended life, less catastrophic failure, and the ability to maintain beneficial properties suggest the need for a second look.

This synthesis is the third over the years dealing with open-graded mixtures. *NCHRP Synthesis of Highway Practice 49: Open-Graded Friction Courses for Highways*, published in 1978 *(2)*, considered the following:

- Fifteen states used OGFCs, but most programs were less than 6 years old. No long-term performance data were available for study.
- Gradation, asphalt content, and asphalt grade for good performance were discussed. A formal mix design method was not available.
- Benefits of OGFCs were discussed. Water removal and hydroplaning resistance was effective. Reduced noise levels were identified, but not quantified.

NCHRP Synthesis of Highway Practice 180: Performance Characteristics of Open-Graded Friction Courses, was published in 1992 *(3)*. This synthesis built on the findings of the first OGFC synthesis *(2)*.

- Performance benefits and limitations were reviewed. Findings reconfirmed and expanded on NCHRP Synthesis 49.
- Design and construction were expanded. Federal Highway Administration (FHWA) Technical Advisory T5040.31 *(4)*, published in 1990, contained a mix design method.
- Mixture performance was reviewed. Approximately 100,000 lane-kilometers (lane-km) (60,000 lane miles) had been built. Long-term maintenance and rehabilitation issues were discussed. Oxidation followed by raveling was identified as a cause of early failure.
- European experience was summarized. Higher design air voids and more use of modified asphalt binder was generally noted. Pavement layers were thicker, 40 to 50 mm (1.5 to 2 in.) instead of 20 to 25 mm (0.75 to 1 in.).

HISTORY OF OPEN-GRADED FRICTION COURSE

As early as 1944 the California Department of Highways was constructing trial sections of OGFC. California had been using chip seals extensively on their highway network to prevent entrance of moisture and air into the pavement and to renew skid resistance. The drawbacks of chip seals, particularly under high traffic, caused the Department of Highways to look for an alternate approach.

Plant mix seal coats were developed that offered the same benefits as chip seals and eliminated many of the existing problems. The principal advantages of plant mix seal coats compared with chip seals are:

- All aggregate is tightly bonded to the road surface, eliminating windshield damage.

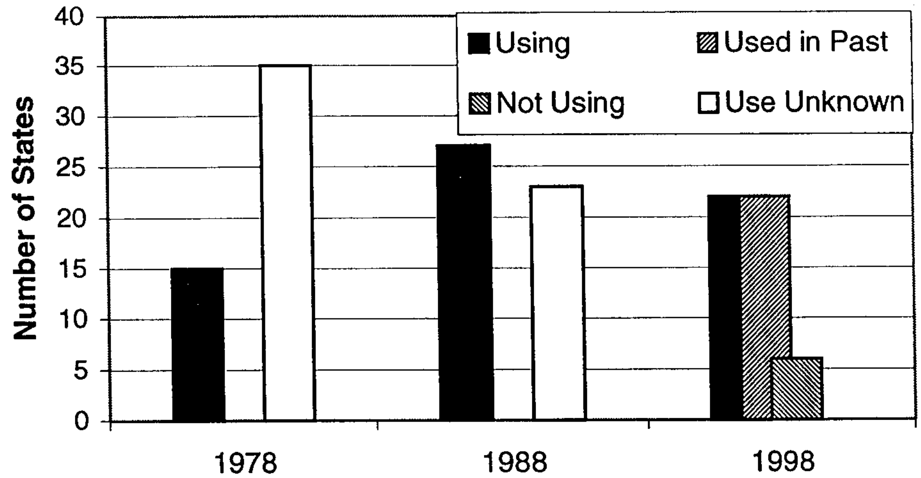


FIGURE 1 History of OGFC in the United States.

- Climatic conditions during construction are less critical, particularly rain shortly after construction.
- Plant mix seal coat is placed 15 to 20 mm (0.5 to 0.75 in.) thick, allowing for some improved ride.
- The mixture is placed with an asphalt paver providing a smooth surface that is less noisy than chip seals.

In 1978, NCHRP Synthesis 49 *(2)* was published to document design, application, and performance of open-graded surfaces. The plant mix seals had become known as OGFCs. In 1980, the FHWA published Technical Advisory T5040.13 regarding the design and use of OGFCs *(5)*. In 1990, a revised design method and a new FHWA Technical Advisory, T5040.31, was issued *(4)*. A follow-up to NCHRP Synthesis 49, NCHRP Synthesis 180 *(3)*, was published in 1992.

The use of OGFCs spread slowly. Figure 1 shows a history of the number of states that use OGFCs. In 1978, 15 states were using OGFCs, and by 1988 that number had increased to 27. Since then, the number has declined. In 1998, 22 states were using OGFCs. Twenty-two other states had used OGFCs, but have since discontinued use. Another six states have never used it. In general, the use of OGFCs has peaked and is in decline among all states.

OBJECTIVE

The objective of this synthesis is to:

- Document the use of OGFCs in North America.
- Evaluate performance obtained with specifications currently in use.
- Describe new materials and design methods.
- Describe the applicability of a new generation of open-graded mixtures to North American use.

ORGANIZATION

This synthesis will consider benefits and limitations of open-graded mixtures and the criteria for use. Available design methods and current design practices will be discussed, including performance obtained, maintenance issues, maintenance practices, and rehabilitation options. Other potential surface types will be briefly discussed.

CHAPTER TWO

OPEN-GRADED FRICTION COURSE USE

CURRENT USE IN NORTH AMERICA

In 1998, the Transportation Research Board (TRB) Committee on Characteristics of Bituminous–Aggregate Combinations to Meet Surface Requirements, A2D03, did a survey and published a circular entitled "Open-Graded Friction Course: State of the Practice" *(6)*. Forty-two of the 50 states responded, as shown in Figure 2. Eighteen states indicated that they used OGFC mixtures at the time of the survey. As part of this synthesis, a survey sent to highway agencies requested current use and the number of lane-kilometers constructed each year. Thirty-seven of the 50 state agencies responded. From Canada, 2 of the 10 provincial agencies responded.

Some state agencies construct more than 1,000 lane-km per year, others only a few. To define major users, an arbitrary value of 300 lane-km/year (186 lane-miles/year) was chosen. Table 1 lists the agencies and the amount of OGFC constructed each year. Eight of the agencies that responded construct more than 300 lane-km/year (186 lane-miles/year). Another 9 agencies (7 U.S. and 2 Canadian) routinely construct some open-graded mix each year. The remaining agencies have either discontinued use or never used open-graded mixtures. Five agencies (Alabama, Kentucky, Pennsylvania, Texas, and Utah) are known to use open-graded mix, but the amount is not known. Also, there is one agency (Mississippi) for which a status is not known. In much of the discussion throughout the rest of this synthesis, statements are made based on the 17 agencies listed as major and minor users.

BENEFITS OF OPEN-GRADED FRICTION MIXTURES

Open-graded friction mixtures have several benefits. The two primary ones are increased permeability and noise reduction.

Permeability

Porous asphalt is designed to have interconnected voids with high permeability. Water easily enters the pavement and is removed from the surface. Wet weather friction and visibility are enhanced by removal of the water. If there is no excess water on the surface there is also no chance of hydroplaning. Friction is enhanced by the macrotexture of the pavement surface. Porous asphalt has higher macrotexture than dense-graded mixtures, even coarse-graded Superpave mixtures.

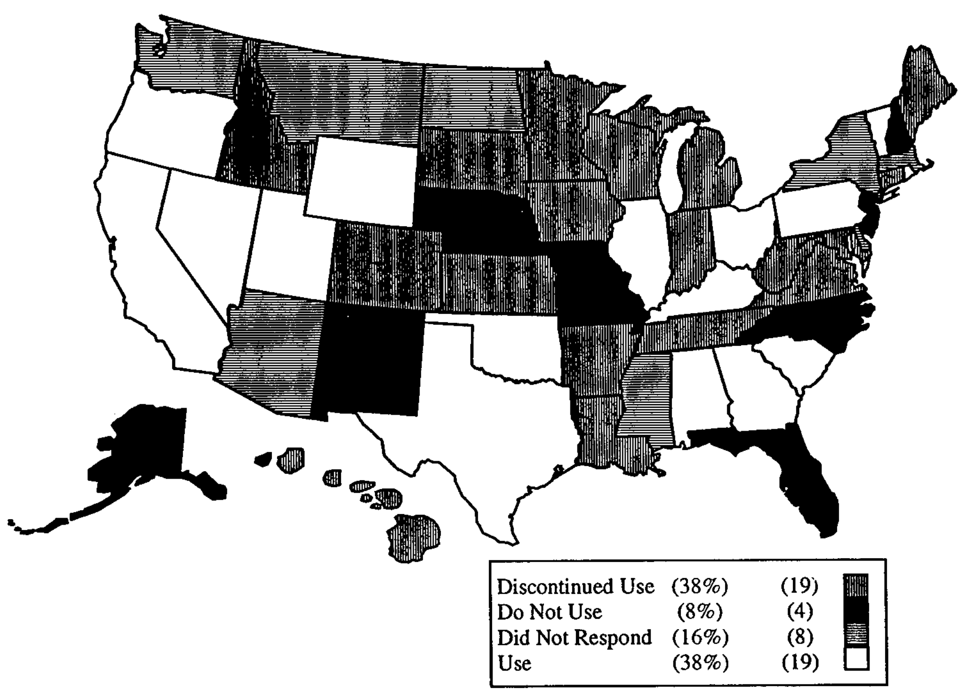


FIGURE 2 Results of TRB Committee A2D03 survey on use of OGFCs *(6)*.

TABLE 1
CURRENT USE OF OPEN-GRADED MIXTURE IN NORTH AMERICA

Agency	Lane-km/year[1]	Total Lane-km
	Current Users	
Alabama	Unknown	Unknown
Arizona	1,300	20,000
California	400	10,000
Delaware	200	Unknown
Florida	1,100	28,000
Georgia	900	10,000
Kentucky	Unknown	Unknown
Massachusetts	200	1,000
Nevada	800	13,500
New Jersey	Unknown	Unknown
New Mexico	1,600	35,000
New York	2	Unknown
Ohio	16	400
Oklahoma	68	919
Oregon	400	4,000
Pennsylvania	Unknown	Unknown
South Carolina	65	Unknown
Texas	Unknown	Unknown
Utah	Unknown	Unknown
Washington	40	1,300
Wyoming	320	10,000
British Columbia	10	35
Ontario	30	100
	Discontinued or Never Used	
	Date Discontinued	Never Used
Alaska		*
Arkansas	Unknown	
Colorado	Before 1993	
Connecticut	Before 1993	
Hawaii	1983	
Idaho	Before 1993	
Illinois	Unknown	
Indiana		*
Iowa	1983	
Kansas	1970s	
Louisiana	Unknown	
Maine	Unknown	
Maryland	1993	
Michigan	1982	
Minnesota	Unknown	
Missouri		*
Montana	Before 1993	
Nebraska		*
New Hampshire		*
North Carolina	1995	
North Dakota	Unknown	
Rhode Island	1989	
South Dakota	Unknown	
Tennessee	Unknown	
Vermont	1998	
Virginia	1988	
West Virginia	Unknown	
Wisconsin	1975	
Alberta		*
Manitoba		*
New Brunswick		*
Newfoundland		*
Nova Scotia		*
Prince Edward Island		*
Saskatchewan		*
Quebec	1993	

Information in this table is based primarily on results from the survey done for this synthesis. If information was not available, TRB Circular E-C005 was used.
[1]Major use was considered to be more than 300 lane-km/year.

With porous asphalt, wet weather visibility is dramatically improved. With dense-graded mixtures, water sits on the road where it can be splashed or thrown up in a mist. On porous pavement there is little or no free surface water available to be atomized into a visibility hindering mist. Traffic mist reduces visibility more severely than fog. The droplets are larger than fog; hence, the mist is denser and restricts visibility more than fog. The droplets quickly precipitate to the ground, but are small enough to remain airborne for several seconds. During that time, visibility can be severely restricted to 5 to 10 m (15 to 30 ft) directly behind a large truck *(7)*.

In the United Kingdom a device to measure the amount of water spray was mounted 1 m behind the rear wheel of a vehicle *(7)*. The amount of water spray on a new porous asphalt mixture was 5 to 10 percent of water spray on a dense-graded surface. The spray-reducing capability of the porous mixture decreases with age, but there was always substantially less spray than with a dense surface.

The ability to transmit water through porous asphalt decreases with age. Debris collecting in the surface pores plugs the mix and traffic densification (loss of voids) causing reduced permeability.

In Denmark, permeability and voids were monitored on porous asphalt pavements *(8)*. Air voids were found to decrease 3 to 4 percent in 2 years to approximately 18 percent. The mixes lost 70 to 80 percent of the permeability they had immediately after construction. Sand content increased about 5 percent, effectively sealing the surface, even though the voids remain interconnected underneath.

Noise Reduction

One benefit of porous surface mixtures immediately noticed by the public is noise reduction. Motorists perceive a sharp decrease in noise when leaving a dense-graded asphalt surface and moving onto an open-graded surface. Noise reductions at highway speeds are typically 3.0 dB(A), which is a 50 percent reduction in noise pressure. In other words, the noise drops by 50 percent.

In Denmark, a roadway test section was built using 12-mm maximum-size dense mixtures, 12-mm maximum-size porous asphalt, and 8-mm maximum-size porous asphalt *(8)*. Two gradations of 12-mm dense mixture were made, one with a more open texture. Two designs of 8-mm drainage asphalt were used, one with 18 to 22 percent air voids, the other with more than 22 percent air voids. One set of 12-mm porous asphalt was built. The test sections are built on a national highway in a rural setting. Figure 3 shows the noise levels for each section. All three of the porous asphalt mixtures were quieter than either of the

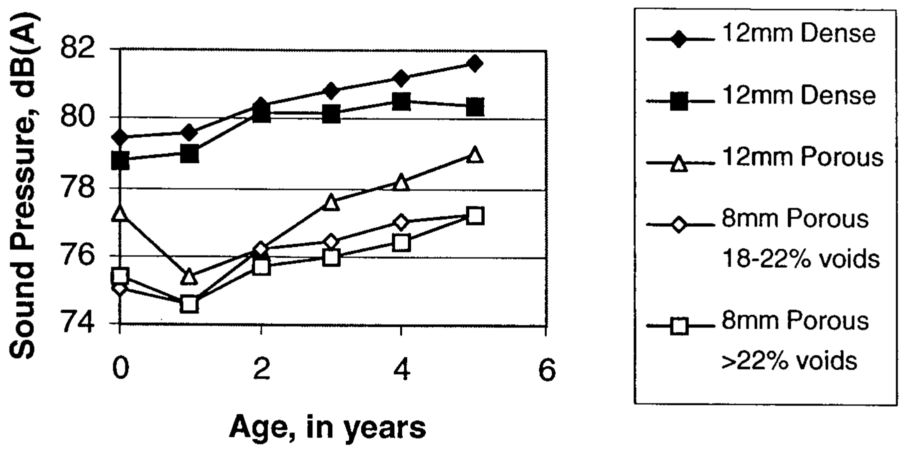


FIGURE 3 Noise at different ages for Danish open-graded pavements *(8).*

dense asphalt mixtures and remained quieter over the 5-year period reported.

Porosity and permeability were monitored on the same test sections. Air voids decreased 3 to 4 percent, about one-fifth of the initial voids after construction, but permeability dropped sharply. Despite the loss in permeability and air voids, the mixture continued to reduce noise.

In the same Danish study, a test section of the 8-mm drainage asphalt with 18 to 22 percent voids was constructed on an urban road. At the lower speed traffic noise levels are less. Table 2 lists the measured noise levels for both surfaces during the first 3 years of surface life. After 2 years, nearly all of the noise reduction benefit was lost. The surface voids were clogged and the mixture had become, in effect, dense-graded. At high speed, hydraulic forces created by the tire when the pavement is wet, flush the pavement voids and reduce clogging. At lower urban speeds the hydraulic action is not able to correct the clogging.

TABLE 2

NOISE LEVEL FOR POROUS ASPHALT IN AN URBAN ENVIRONMENT *(8)*

	Noise Level [dB(A)]	
Age (years)	12-mm Dense	8-mm Porous
0	70.8	68.0
1	70.8	69.8
2	71.2	71.0
3	72.8	72.7

Clogging of porous asphalt tends to occur quickly on city streets because of increased amounts of debris as compared with rural high-speed roads, which are wind swept by the traffic and which have increased hydraulic cleaning by traffic during wet weather. In a European urban environment success has been reported using a novel two-size porous asphalt structure that provides the benefits of noise reduction and resists surface clogging *(9,10).* The pavement section uses two layers of porous asphalt as shown in Figure 4.

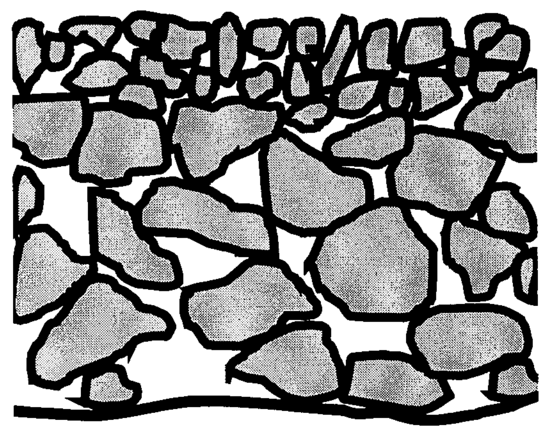
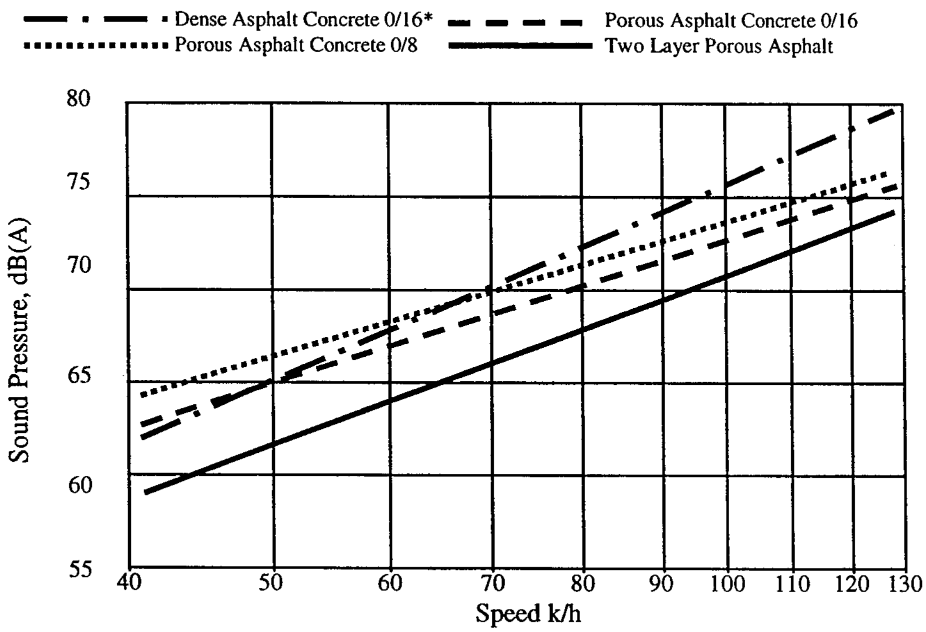


FIGURE 4 Structure of a two-layer porous asphalt *(9).*

The surface layer uses aggregate that is 4 to 8 mm in size. Directly underneath is another porous asphalt layer containing 11- to 16-mm aggregate. The surface layer allows water and sound to penetrate to the larger chamber voids in the lower layer. The surface layer has small pores that prevent larger debris from entering into the lower layer or becoming lodged in the surface voids. Smaller debris, which enters the surface voids, can more easily be suctioned out by hydraulic action of tires on wet pavement, delaying complete plugging of the mixture.

Porous asphalt should not be used in areas where traffic is not moving. In such areas there are no moving tires to help clean the surface. In situations with a parking lane next to a curb, it is recommended that the lower layer of porous mix be carried underneath the parking lane to the curb and tied into the drainage system. Inlet grates should have openings in the side of the casting to accept water from inside the porous mix. In the parking lane, a dense-graded surface mix is recommended instead of the small porous mix.



* The numbers in the mixture name indicate a range of gradation sizes.
for example, 0/16 indicates a gradation from 0 mm to 16 mm

FIGURE 5 Noise production as a function of vehicle speed for different road surfaces *(9)*.

Dirt and debris penetrates only 10 to 15 mm (0.4 to 0.6 in.) *(10)*. Once plugging occurs the surface can be renewed to its initial state with a spray and vacuum system. The cleaning operation is more effective on the two-sized porous mix than the single size because clogging is restricted to the upper layer.

The large underlying voids of the 11- to 16-mm aggregate show noise reduction benefits at all traveling speeds. Figure 5 shows noise production on different pavements at different speeds. At slow speeds, the 0 to 16 mm and 0 to 8 mm porous asphalt pavements generate approximately the same vehicle noise as a dense surface. The two-layer porous pavement is about 3 dB(A) quieter. At high speeds, 100 to 110 km/hr (60 to 70 mph), all of the porous asphalt is quieter than the dense asphalt. The two-layer porous pavement is only slightly quieter than the other porous mixtures.

Vehicle noise is generated by different mechanisms, including mechanical noise and wind noise *(11)*. At low speed, tire noise and wind noise is not significant. Most noise generated at low speed is mechanical noise and of that most is engine noise. At high speeds tire noise becomes the predominant noise source. Engine noise is reduced because the engine is not accelerating, but instead is operated at a steady speed. Aerodynamic styling used to maximize fuel economy minimizes wind noise on modern vehicles.

Vibrations in the tire structure and air pumping in cavities underneath the tire cause tire noise *(11)*. Figure 6 illustrates the tire-road surface interface. Tread blocks impact the road surface as the tire rolls forward. The

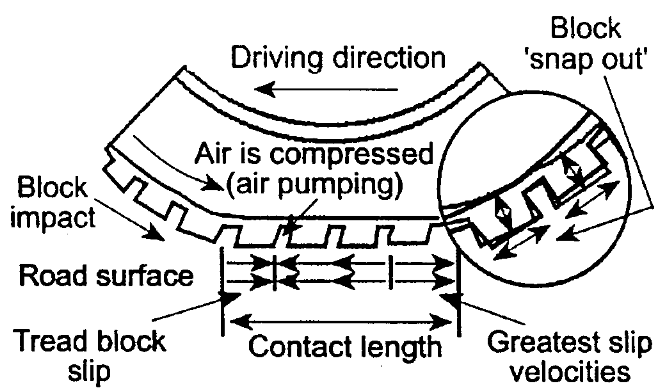


FIGURE 6 Sources of noise generated by a rolling tire *(13)*.

blocks slip on the road surface mostly at the edges of the contact area where the vertical forces are lower and the tire is deforming as weight is applied or removed. When the tire rolls forward the tread blocks snap back into their unloaded shape generating vibrations on the tire surface. Noise generated by the tread blocks is greater for large tread blocks. Snow tires or off-road tires generate much more noise than a summer radial tire because of increased tread block slip and a larger vibrating area during block snap-out. For the same reason increased macrotexture, which causes a rough surface, that is, a chip seal, creates more tread block slip and greater block snap-out.

Movement of air in the cavities of the tire treads causes air pumping. As the tire rolls forward air is compressed in the tread cavities and begins to escape to the sides. As the tread block is lifted a vacuum is created in the tread cavities and air rushes to fill the void. If the pavement texture is very smooth there is less opportunity for air to leak from underneath the tread blocks and tire noise is accentuated. This effect can be noticed if a tire crosses a flushed area on the pavement surface and the tire "hums."

Noise generated by a vehicle travels directly and indirectly to the receiver's ear. The surface between the source and the receiver will influence the amount of sound that is received. A dense-graded surface will reflect sound at the road surface in much the same way a mirror reflects light. A porous surface allows some of the sound to be absorbed into the pavement reducing the amount of sound energy (loudness) that reaches the observer's ear. Not only is part of the noise absorbed, but the porous surface delays transmission of part of the noise. The phase shift of the delayed sound causes destructive interference, which cancels part of the reflected and direct transmitted noise. The frequency of the canceled noise depends on the height of the noise source and receiver above the pavement as well as properties of the pavement surface. Theoretical models have been developed that predict destructive interference *(12).*

Field measurements have been made to determine noise attenuation (suppression) at different frequencies. Figure 7 shows the noise level at different frequencies for a light vehicle traveling 90 km/hr (56 mph) on porous asphalt and hot rolled asphalt *(13).* The noise source is 0.05 m (2 in.) above the pavement, typical for a tire. No quieting of noise occurs for a reflective surface except for sounds above 8 kHz. All sound is reflected as indicated by the upper line. With a porous pavement placed between the source and the receiver, noise in the frequency of 1 kHz and 3 kHz is significantly reduced. These are the frequencies where sound is canceled out by destructive interference. They are also the frequencies to which the human ear is most sensitive. Nelson reports that the weighted noise reduction shown in Figure 7 is 4.2 dB(A) lower for the porous asphalt.

LIMITATIONS OF OPEN-GRADED FRICTION MIXTURES

Open-graded mixtures have significant benefits, but they also have particular performance characteristics. In winter climates, open-graded pavements react differently than dense-graded mixtures. These pavements will tend to form ice on the pavement surface at a warmer temperature. Also, they need more frequent applications of salt to maintain an ice-free surface. To help prevent plugging of the surface pores, sand should not be mixed with salt. Even so, maintenance is generally not cited as the reason for discontinued use.

Generally, reasons given for discontinuing the use of OGFCs have related to mixture performance. The main reason cited is the failure mechanism. OGFC pavements typically fail by raveling. More correctly, the pavement fails when the asphalt binder ages and becomes brittle. Individual pieces of aggregate are dislodged and the pavement begins to ravel. Unfortunately, raveling can progress very rapidly and the entire pavement layer can be worn away in a matter of weeks. Many maintenance organizations are not designed to react to projects that can degrade so rapidly from a satisfactory condition to a totally unsatisfactory surface. Sometimes failure occurs when the pavement is only 6 to 8 years old. This short life, combined with a catastrophic failure mechanism, is difficult to accept.

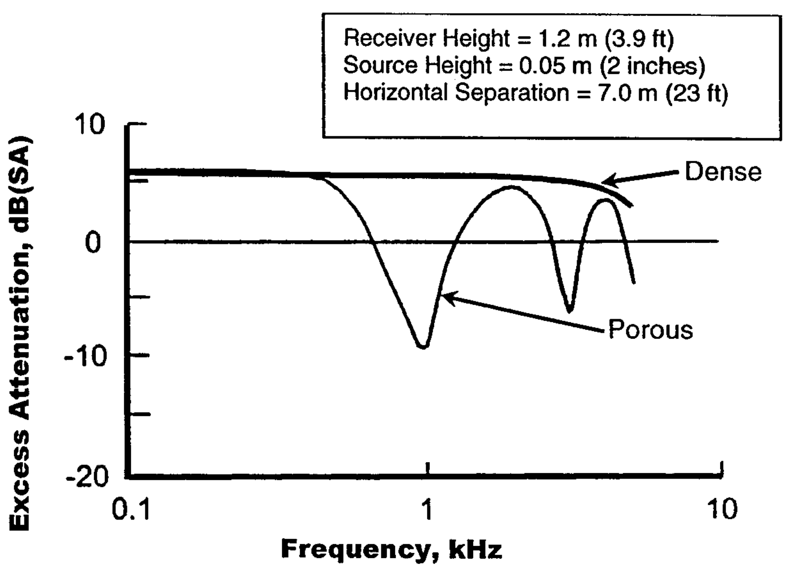


FIGURE 7 Destructive interference effect of porous pavement *(13).*

A second reason for discontinuing use of open-graded mixtures is the unacceptably quick loss of mixture benefits and the inability to easily restore them. The open permeable pores that remove water from the pavement surface and attenuate noise become plugged and the benefit diminishes. In northern climates, particularly where deicing material is used, debris collects in the pores and is not flushed out by the action of the traffic. After a few years the surface becomes similar to a dense-graded mixture.

Sometimes, when the pores become plugged, a pavement might fail by asphalt being stripped from the aggregate surface. Moisture can move through an asphalt pavement, sometimes as a vapor, sometimes as a liquid. An open-graded mixture can change the moisture balance in the underlying pavement. Placement of an open-graded mixture may create a moist microenvironment at the surface of an existing pavement. Increased humidity may retard evaporation trapping water in the old pavement layers. If the open-graded mixture clogs with grit and other road debris the pavement will become even wetter. If the aggregates in the existing pavement are susceptible to moisture damage, stripping may occur.

A change is occurring in open-graded mixture technology. New designs are producing mixtures with higher levels of air voids and larger pore size. Aggregates are more of one size, which makes them more susceptible to raveling. To counter the tendency to ravel, modified asphalt is used; this does a better job of gluing aggregate pieces together. Also, more asphalt is used, providing thicker films that resist aging.

CRITERIA FOR USE

Open-graded mixes are generally used to increase wet weather friction and improve wet weather visibility. Some agencies use OGFCs throughout their network, but most agencies use them in situations with high traffic and high rainfall or high rainfall intensities.

In most instances open-graded mixes should be used on high-speed roads. Urban roads often have more debris on the surface because wind from vehicles does not sweep the traveled way as clear and more debris collects on the street. Some agencies indicated that high speed is necessary to generate enough hydraulic vacuum under vehicle tires to keep the pores from plugging.

Benefits of using open-graded mixes are shown in Figure 8. The number one benefit sought by agencies is wet weather friction. All 17 of the agencies that routinely use open-graded mixes desire improved friction during rainfall events. Improved driver visibility obtained because of spray reduction was cited as the second most desirable benefit by 15 of the agencies.

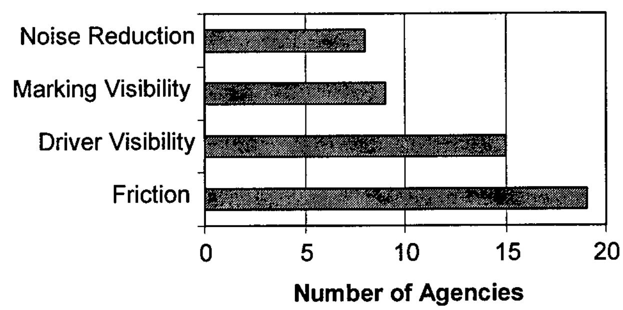


FIGURE 8 Benefits of open-graded mixes cited by agencies.

Surprisingly, reduced noise was not highlighted as a desirable feature by more agencies. Two agencies, British Columbia and Ontario, indicated that noise reduction was the main reason to select an open-graded surface; for the other agencies it was of secondary importance. One of the agencies specifically replied that noise reduction was not important because sound barrier walls are used.

CHAPTER THREE

DESIGN AND CONSTRUCTION OF OPEN-GRADED FRICTION MIXTURES

DESIGN METHODS

Mixture design for open-graded mixes is less structured than traditional dense-graded designs such as Marshall or Hveem design, although the approach has several features similar to dense-graded mixture design. The main components of OGFC design are:

- Selection of materials,
- Gradation,
- Compaction and void determination, and
- Binder draindown evaluation.

FHWA Design Method

In 1990, the FHWA published Technical Advisory T5040.31 *(4)*. The mix design follows in summary.

Materials—The following material requirements are specified:

- Polish resistant aggregate with 75 percent crushed two faces and 90 percent crushed one face;
- Mineral filler meeting AASHTO M17;
- Combined aggregate blend gradation as shown in Table 3;
- AC 20 asphalt binder; and
- Antistrip additives as required.

Design Steps—The FHWA design method uses the following steps:

- Determine percentage of oil retained on the aggregate by soaking in S.A.E. No. 10 lubrication oil and draining.
- Estimate asphalt content based on percentage of oil retained.
- Determine void content in coarse aggregate by compacting dry coarse aggregate in a mold using a vibration hammer.
- Calculate the amount of fine aggregate to be added, making allowance for the volume of asphalt to be used plus air voids of 15 percent.
- If the voids in the coarse aggregate are too low to accommodate the asphalt and air voids, redesign the coarse skeleton to achieve more voids.
- Test for draindown of mastic, binder plus fine aggregate, at different temperatures to determine mixing temperature.
- Test for resistance to water using AASHTO T165 and T167, the immersion–compression test. The Texas Boil Test has also been evaluated *(14)*. Various antistrip treatments were evaluated and found to improve laboratory results, although the results could not be correlated to field performance.

TABLE 3

FHWA MIX DESIGN GRADATION SPECIFICATION

	Percent Passing	
Sieve (mm)	Minimum	Maximum
12.5	100	—
9.5	95	100
4.75	30	50
2.36	5	15
0.075	2	5

Recent Mix Design Advancements in North America

Several changes and advancements have occurred since the FHWA Technical Advisory was published. The Georgia Department of Transportation (DOT) makes a distinction between the older mix designs and new ones. The older mix is a 9.5-mm OGFC; the Georgia DOT calls the new mixes 12.5-mm OGFC and 12.5-mm Porous European Mix (PEM). Differences between the 9.5-mm OGFC and PEM are listed as follows:

Fiber stabilizers are used—Fiber stabilizers prevent draindown during construction. Draindown, a separation of the asphalt mastic from the coarse skeleton, can occur in a mixture storage silo or in the truck during transport. Mixtures that have suffered from draindown produce binder-rich areas on the road that have a flushed surface and no voids, as well as other areas with little binder and high voids that quickly ravel.

Modified asphalt binder is used—Modified asphalt binders are less susceptible to draindown during service. Although not documented in research, field experience indicates that thick films of unmodified asphalt binder tend to drain downward with time in hot summer weather. The remaining thinned films on the surface particles age and become brittle more rapidly. When the binder becomes sufficiently brittle, aggregate particles are dislodged by traffic and the layer ravels, often in a matter of months. Modified asphalt binders retain film thickness, thereby reducing aging and stone loss.

The use of both fiber stabilizers and polymer-modified asphalt has allowed mixture production temperatures to be increased, comparable to that of conventional mixtures, without draindown and oxidation problems. Aggregate moisture is therefore removed more effectively, and the bond between the asphalt cement and aggregate particles is enhanced. This change should extend the service life of these mixes and eliminate the raveling problems typical of previous OGFC mixtures.

Permeability is reduced as traffic densifies open-graded mixtures. In a laboratory, evaluation modified asphalt does not retard mixture densification *(15)*. Mixtures containing modified and unmodified binder densified at about the same rate.

Increased air voids—Continued benefit from an open-graded mixture is dependent on the void structure remaining open. Clogging from road debris and winter sanding nullifies the mixture's benefits. Increasing the voids to 20 percent or more provides additional resistance to clogging. Larger voids tend to be cleaned by the hydraulic action of traffic during rainfall, particularly on high-speed pavements. Urban pavements with lower speed limits are less likely to remain clean because of reduced hydraulic action under traffic.

Increased aggregate size—The FHWA Technical Advisory specifies only a 9.5-mm-nominal maximum size. Alternate new mix designs use 12.5- and 16-mm-nominal maximum size. The larger aggregate size generates larger voids that are less susceptible to clogging.

Summary of North American Approaches

A brief summary of the mix design method used by several agencies follows. The state agencies described are Georgia, California, Florida, Nevada, Arizona, Oregon, New Mexico, and Wyoming.

Georgia

The Georgia DOT specifies two types of open-graded mixtures. The first is based on the historical FHWA OGFC. Two sizes are used, 9.5- and 12.5-mm-nominal maximum size. A more recent specification was developed that adapts European gradations, which have higher air voids, to Georgia materials. The new mixture, named PEM, is a 12.5-mm-nominal maximum-size mixture. Gradation of the mixtures is shown in Tables 4 and 5. Both the 12.5-mm OGFC and 12.5-mm PEM require polymer-modified asphalt and fiber-stabilizing additives.

The Georgia mixtures use a PG 76-22 asphalt binder typically modified with a styrene-butadiene-styrene (SBS) or linked styrene-butadiene (SB) polymer. Polish resistant, crushed aggregate is required. The design uses asphalt content, retained coating after boiling, and resistance to draindown as criteria.

Asphalt content is selected by compacting specimens at multiple contents using 25 blows of a Marshall hammer on each face of the specimen. Asphalt content versus voids in mineral aggregate (VMA) is plotted and the optimum asphalt content is selected at the minimum VMA.

After the design asphalt content is selected, a draindown test is run. One of three types of fibers is added to the mix to resist draindown. Cellulose fiber is added at the dosage rate of 0.2 to 0.4 percent of the total mix. Cellulose fiber pellets, which consist of a 50/50 blend of fibers and asphalt, are added at a dosage rate of 0.4 to 0.8 percent of the mix. Mineral fibers are added at a rate of 0.2 to 0.5 percent of the mix. The design rate of addition is based on passing the draindown test.

Florida

Florida uses only one gradation for OGFC, as shown in Table 4 *(16)*. A modified asphalt binder, composed of an AC 30 with 12 percent (by weight of binder) ground tire rubber, is used. Several aggregates are allowed including crushed granite, blast furnace slag, crushed oolitic limestone (high-friction limestone), and lightweight aggregate. Mix designs are done according to FHWA Technical Advisory T5040.31 *(4)*.

Arizona

The Arizona DOT specifies two OGFC mixtures; one for unmodified asphalt binder, the other for asphalt rubber modified binder. Gradations for the two mixtures differ on the 2.36- and 4.75-mm sieves (Table 4).

Asphalt binder for the unmodified mixture is PG 64-16. For the modified mixture the base asphalt is PG 64-16, except for colder locations (at high altitude) where PG 58-22 is used. The asphalt binder is modified by the addition of 20 percent (by weight of binder) ground tire rubber. The ground rubber can be of two gradations. Type A is 100 percent passing the 2.36-mm sieve and 0 to 10 percent passing the 1.18-mm sieve. Type B is finer; it is 100 percent passing the 2.00-mm sieve, 20 to 100 percent passing the 0.600-mm sieve, and 0 to 5 percent passing the 0.075-mm sieve.

TABLE 4

SUMMARY OF 9.5-mm OGFC MIXTURE DESIGNS USED IN THE UNITED STATES

	Arizona Unmodified AC		Arizona Asphalt Rubber		California		Florida		Nevada		Nevada		Wyoming		New Mexico		Georgia	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Gradation (mm)																		
12.5	100		100		100		100		100		100		100		100		100	
9.5	100		100		90	100	85	100	95	100	90	100	97	100	90	100	85	100
4.75	35	55	30	45	29	36	10	40	40	65	35	55	25	45	25	55	20	40
2.36	9	14	4	8	7	18	—	—	—	—	—	—	10	25	—	—	5	10
2.00	—	—	—	—	—	—	4	12	—	—	—	—	—	—	0	12	—	—
1.18	—	—	—	—	—	—	—	—	12	22	5	18	—	—	—	—	—	—
0.075	0	2.5	0	2.5	0	3	2	5	0	4	0	3	2	7	0	4	2	4
Asphalt Binder																		
Grade	PG 64-16		PG 64-16 plus 20% rubber		AR 4000, AR 8000, or PBA-6		AC 30 plus 12% rubber		AC 20 P or AC 30		AC 20 P or AC 30		PG 64-22 or PG 70-28		PAC 20		PG 67-22	
Content	—		—		—		5.5–7.0%		6.5% typical		6.5% typical		6.3–6.8%		—		6.0–7.3%	
Aggregate Properties																		
Specific gravity	—		2.35–2.85		—		—		—		—		—		—		—	
Water absorption	—		2.5% max.		—		—		4% max.		4% max.		—		—		—	
Sand equivalent	45% min.		55% min.		—		—		—		—		—		—		—	
Crushed faces	70% min.		95% min.		90% min.		100% min.		90% min. 2-face		90% min. 2-face		95%		75% min. 2-face		—	
Flakiness index	25 max.		—		—		—		—		—		—		—		—	
L.A. abrasion 100 rev	—		9% max.		10% max.		—		—		—		—		—		—	
L.A. abrasion 500 rev	—		40% max.		40% max.		—		37% max.		37% max.		35% max.		40% max.		—	
Carbonates	—		30% max.		—		88% max.		—		—		—		—		—	
Soundness $MgSO_4$	—		—		—		—		12% max.		12% max.		—		12% max.		—	
Volumetric Properties																		
Compaction method	Double plunger		Double plunger		None		None		Static compession		Static compression		None		None		Marshall	
Air voids	—		—		—		—		—		—		—		—		—	

Note: L.A. = Los Angeles.

TABLE 5

SUMMARY OF 12.5-mm AND 19.0-mm OGFC MIXTURE DESIGNS USED IN THE UNITED STATES

	12.5-mm Mixture								19-mm Mixture	
	California		Georgia OGFC		Georgia European Mix		Oregon		Oregon	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Gradation (mm)										
25.0	—	—	—	—	—	—			99	100
19.0	100		100		100		99	100	85	96
12.5	95	100	85	100	80	100	90	98	55	71
6.3	—	—	—	—	—	—	—	—	10	24
9.5	78	89	55	75	35	60	—	—	—	—
4.75	28	37	15	25	10	25	18	32	—	—
2.36	7	18	5	10	5	10	3	15	—	—
2.00	—	—	—	—	—	—	—	—	6	16
0.075	0	3	2	4	1	4	1.0	5.0	1.0	6.0
Asphalt Binder										
Grade	AR 8000 or PBA-6		PG 76-22		PG 76-22		PBA-5 or PBA-6		PBA-5 or PBA-6	
Content	—		5.8–7.3%		5.5–7.0%		—		4–8%	
Aggregate Properties										
Crushed faces	90% min.		—		—		—		—	
L.A. abrasion 100 revs	10% max.		—		—		—		—	
L.A. abrasion 500 revs	40% max.		—		—		—		—	
Volumetric Properties										
Compaction method	None		Marshall		Marshall		Static		Static	
Draindown	—		—		—		—		70–80%	
Air voids	—		—		—		13.5–16.0%		13.5–16.0%	
Voids filled with asphalt	—		—		—		40–50%		40–50%	

Note: L.A. = Los Angeles.

Arizona uses several criteria to specify acceptable aggregate including percent carbonate, crushed faces, flakiness index, L.A. (Los Angeles) abrasion, sand equivalent, water absorption, and combined-bulk specific gravity. Asphalt content is determined by a formula that depends on aggregate water absorption, aggregate specific gravity, and the percent passing the 2.36-mm sieve. Specimens are compacted at the design asphalt content using a double plunger compactor. Air voids in the compacted specimen are not specified. A draindown test is not required for the asphalt rubber modified mixture because the binder is very resistant to draindown.

California

CalTrans specifies two OGFC gradations, one a 9.5-mm-nominal maximum size, the other a 12.5-mm-nominal maximum size. The 9.5-mm mixture is most commonly used. The gradations are shown in Tables 4 and 5. Aggregate requirements include crushed faces and L.A. abrasion.

Most mixtures contain an unmodified asphalt binder, either AR 4000 or AR 8000. Sometimes a modified asphalt, PBA-6, is used. Design content is determined using the centrifuge kerosene equivalent and the approximate bitumen ratio. For open-graded mixtures only the coarse aggregate portion of the test is used. This is the same test that the FHWA adopted for the OGFC Technical Advisory. A draindown test specific to California is used to adjust the asphalt content.

New Mexico

The New Mexico DOT specifies one gradation for OGFC, as shown in Table 4. Aggregate is specified based on crushed faces, L.A. abrasion, and soundness. Modified asphalt binder, typically AC 20 plus SBS, is used. A mix design method is not used. Asphalt binder content is based on a visual assessment of coating and draindown.

Nevada

The Nevada DOT specifies two OGFC mixtures, one a 12.5-mm size, the other a 9.5-mm mix. Both mixes are more accurately 9.5-mm-nominal maximum-size mixtures (Table 4). Aggregate is specified based on water absorption, fractured faces, L.A. abrasion, and soundness.

Both modified, AC 20 P, and unmodified, AC 30, asphalt binders are used. The design asphalt content is determined using a test method specific to Nevada. Specimens are mixed at multiple asphalt contents and compacted using static compression. The compacted specimens are set on glass plates and placed in a 60°C (140°F) oven for 15 hours. The mixture is removed and the amount of asphalt draindown on the plate is measured using a light meter. The design binder content is selected at 50 to 60 percent opacity; that is, 50 to 60 percent of the light is blocked.

Oregon

The Oregon DOT (ODOT) specifies two sizes of OGFC, a 12.5-mm-nominal maximum size and a 19.0-mm-nominal maximum size, but uses only the 19.0-mm gradation, as shown in Table 5. For low traffic, unmodified asphalt, PBA-5, is used. For high traffic, modified asphalt, PBA-6, is used.

The mixture is produced at a range of asphalt contents. Draindown tests are done using either a glass bowl method or the National Center for Asphalt Technology (NCAT) test method. Samples are tested for draindown using ODOT Test Method 313-95. A 1,000 g sample is set in a 200 X 200-mm flat-bottomed glass dish and placed in a convection oven at 160°C for 60 minutes. The test result is the percentage of the dish bottom that is covered by asphalt. The test method contains photos of 60, 70, 80, and 90 percent coverage for comparison.

Instead of glass dishes, draindown may be evaluated using a wire basket, as indicated in the method developed by NCAT and used according to ODOT Test Method 313-95. A maximum draindown of 0.3 percent is allowed.

Specimens are compacted using static compaction per AASHTO T167 and are evaluated for air voids and voids filled with asphalt. The design asphalt content is selected at 70 to 80 percent draindown and air voids of 13.5 to 16.0 percent and voids filled with asphalt of 40 to 80 percent. Oregon is the only U.S. agency that specifies air voids as part of the mix design.

Mixtures are placed 40 to 50 mm (1.5 to 2 in.) thick. Open-graded mixture is given the same structural coefficient as dense mixture *(17)*.

Wyoming

The Wyoming DOT specifies a 9.5-mm-nominal maximum-size mixture (Table 4). Aggregate is selected based on L.A. abrasion and fracture. Limestone is not allowed on high volume routes. Most mixtures have used unmodified asphalt, primarily PG 64-22. Some modified binders have been used on heavy traffic applications. Design asphalt content is determined using the FHWA design method.

TABLE 6

SELECTED DESIGN CRITERIA FOR POROUS ASPHALT USED IN EUROPE *(18)*

Country	Aggregate Size (mm)	Aggregate Gap (mm)	Polish Stone Value	Los Angeles Abrasion (%)	Binder Content (%)	Binder Type	Air Voids (%)
Belgium	2/14	2/7	>50	<15	4–5	Unmodified	22
	2/14	2/7	>50	<15	5.5–6.5	Modified	22
France	2/10	2/6	50	<25	4.5–5.5	Modified	>20
	2/14	2/10	50	<25	4.5–5.5	Modified	>20
Netherlands	2/11	2/6	>53	—	4/5	Unmodified	>20
	2/16	2/6	>53	—	4.5–5.5	Modified	>20
Ireland	2/14	—	>60	<26	4.5–5.2	Modified	>20
Spain	2/10	0.6/2.5	>40	<20	>4.5	Modified	20
	2/12.5	2.5/5	>40	<20	>4.5	Modified	20
United Kingdom	3.35/10	3/6	>60	<18	—	Unmodified	20
	3.35/20	3/6	>60	<18	—	Modified	20

European Mix Design Methods

Mix designs used in Europe generally require an aggregate skeleton that will provide 20 percent air voids. Maximum asphalt content is based on draindown characteristics of the mixture and minimum asphalt content is based on durability concerns. A summary of some design criteria and typical design properties is shown in Table 6 *(18)*. A more detailed summary of the mix design methods used in some European countries and South Africa follows.

British Mix Design

Great Britain uses two porous asphalt mixtures; one is a 10-mm-nominal maximum size, the other a 20-mm-nominal maximum size *(7,19)*. The gradations are shown in Table 7. The 10-mm mixture is of similar size to mixtures used elsewhere in Europe. The 20-mm mixture is considerably larger. It is claimed that the larger aggregate size, which has larger void spaces, is less susceptible to clogging and produces greater tire noise reduction *(20,21)*.

Aggregate properties are specified to provide a hard, durable rock. The aggregate must have high polishing resistance. L.A. abrasion must be low, less than 12 percent according to Clifford et al. *(18)* or less than 18 percent according to Nicholls *(7)* and Khalid and Walsh *(19)*. Allowing a maximum flakiness index of 25 controls aggregate shape.

Asphalt binder used in British porous asphalt mixtures is about equally modified and unmodified. Test results show that mixtures made with a soft asphalt binder, 200 penetration, have a longer life than those made with a hard binder, 70 penetration, but tend to close up under traffic and lose permeability. Mixtures with hard asphalt binder resist densification under traffic, but suffer durability problems earlier. Figure 9 shows typical life to a terminal binder hardness at which durability fails. Porous asphalt with unmodified binder typically uses 100 penetration binder. Mixture placed on high traffic roads is usually modified, typically with SBS or ethylene-vinyl acetate (EVA) modifiers.

Specimens are compacted using 50 blow Marshall compaction. Minimum air voids of 20 percent are desired. Aggregate gradation is changed to increase air voids if necessary. Durability is not tested directly, but is controlled by selection of binder grade and by using a minimum asphalt content of 4.5 percent. Often modified binders must be used to prevent draindown.

Spanish Mix Design

In 1990, Spain had the largest area of porous asphalt in Europe, nearly 10 million m^2 (12 million yd^2). By 1996, that number had increased to 30 million m^2 (36 million yd^2), the equivalent of 2 lanes, 4,000 km (2,500 mi) long. There are two gradations of porous asphalt used in Spain; both are 12.5-mm-nominal maximum size. The P-12 can have a larger gap between the 12.5- and 10-mm sieves; the PA-12 can have a larger gap between the 10- and 5-mm sieves. Gradations are shown in Table 7 *(22)*.

Aggregate requirements include polish resistance, a maximum L.A. abrasion of 20 percent, and a maximum flakiness index of 25 percent. Modified asphalt binder is used. For high traffic or hot climate a 60/70 penetration asphalt is specified. For low traffic and cool climate an 80/100 penetration binder is used. In both applications the asphalt binder is modified with SBS or EVA.

Specimens are compacted using 50 blows of a Marshall hammer to evaluate air voids. A minimum of 20 percent air voids is required. Minimum asphalt content is selected using the Cantabro test developed in Spain. The Cantabro test measures disintegration of compacted specimens. Each specimen is placed in a L.A. abrasion machine, without any steel balls, and is subjected to 300 revolutions

TABLE 7

SUMMARY OF NON-NORTH AMERICAN POROUS ASPHALT MIXTURES

	British (20 mm)		British (10 mm)		Spanish (P-12)		Spanish (PA-12)		Italian		South Africa	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Gradation (mm)												
28	100	—	—	—	—	—	—	—	—	—	—	—
20	95	100	—	—	100	—	100	—	100	—	—	—
19	—	—	—	—	—	—	—	—	—	—	100	—
14	55	80	100	—	—	—	—	—	75	100	—	—
13.2	—	—	—	—	—	—	—	—	—	—	90	100
12.5	—	—	—	—	75	100	70	100	—	—	—	—
10.0	—	—	90	100	60	90	50	80	15	40	—	—
9.5	—	—	—	—	—	—	—	—	—	—	25	65
6.3	20	30	40	55	—	—	—	—	—	—	—	—
5.00	—	—	—	—	32	50	15	30	5	20	—	—
4.75	—	—	—	—	—	—	—	—	—	—	10	15
3.35	8	14	22	30	—	—	—	—	—	—	—	—
2.50	—	—	—	—	10	18	10	22	—	—	—	—
2.36	—	—	—	—	—	—	—	—	—	—	8	15
2.00	—	—	—	—	—	—	—	—	0	12	—	—
0.63	—	—	—	—	6	12	6	13	—	—	—	—
0.008	—	—	—	—	3	6	3	6	—	—	—	—
0.075	2	7	2	7	—	—	—	—	0	7	2	8
Asphalt Binder												
Grade	100 pen. + SBS 100 pen. + EVA 100 pen.		100 pen. + SBS 100 pen. + EVA 100 pen.		60/70 + SBS 60/70 + EVA 80/100 + SBS 80/100 + EVA		60/70 + SBS 60/70 + EVA 80/100 + SBS 80/100 + EVA		80/100 + SBS		Asphalt rubber Polymer modified	
Content	4.5% min.		4.5% min.		4.5% typical		4.5% typical		4–6%		4.5% min.	
Aggregate Properties												
L.A. abrasion	12% max.		12% max.		20% max.		20% max.		16% max.		21% max.	
Flakiness index	25 max.		25 max.		25 max.		25 max.		—		25 max.	
Sand equivalent	—		—		—		—		—		45 min.	
Crushed faces (2 faces)	100%		100%		100%		100%		—		100% (high traffic) 90% (low traffic)	
Mixtures Properties												
Compaction	50 blow Marshall		50 blow Marshall		50 blow Marshall		50 blow Marshall		Marshall		50 blow Marshall	
Air voids	20% min.		20% min.		20% min.		20% min.		18–23%		>22% high volume 18–22% low volume	
Cantabro dry	—		—		25°C/25% max.		25°C/25% max.		25°C/25% max.		25°C/25% max.	
Cantabro aged	—		—		—		—		—		25°C/30% max.	
Cantabro wet	—		—		—		—		20°C/30% max.		25°C/30% max.	

Note: L.A. = Los Angeles; SBS = styrene-butadiene-styrene; EVA = ethylene-vinyl acetate; pen. = penetration.

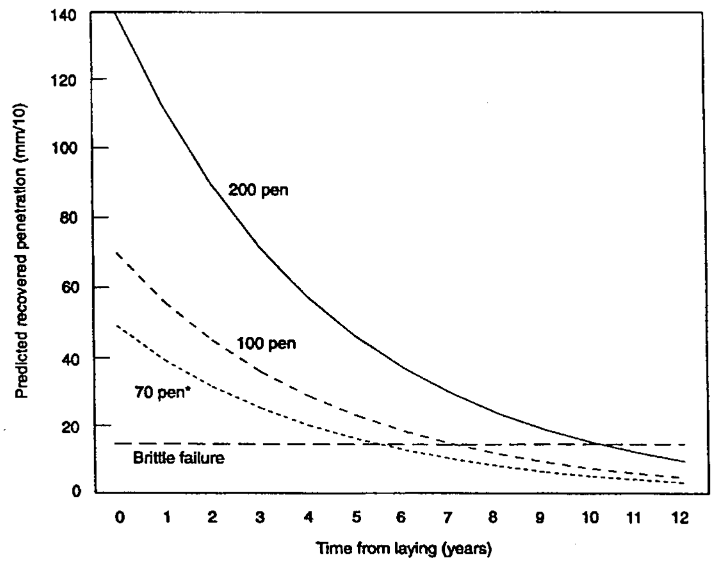
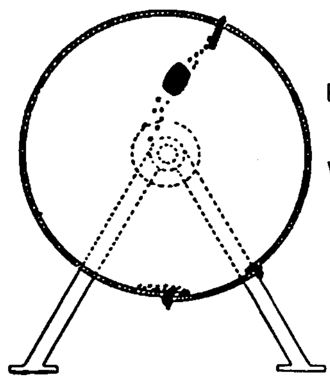


FIGURE 9 Aging of asphalt binder in British porous mixtures *(7)*.



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

Where:

P = Abrasion loss (%)

P_1 = Initial weight of the sample

P_2 = Final weight of the sample

FIGURE 10 The Cantabro test for abrasion loss determination *(22)*.

at 25°C (77°F), as shown in Figure 10. The percentage of weight loss is measured. As asphalt content decreases, weight loss increases. A maximum weight loss of 25 percent is allowed.

Maximum asphalt content is controlled by air voids in the compacted specimen. As asphalt content increases, air voids decrease, while the VMA of the specimen remains constant. Typical asphalt content used in Spanish mixtures is 4.5 percent.

Italian Mix Design

Italy uses one gradation for porous asphalt, a 16-mm-nominal maximum-size aggregate (Table 7). All aggregate must be crushed with no natural sands allowed. Igneous rock is desired for high aggregate friction. Dolomite is sometimes used. In either case, the aggregate must have high abrasion resistance. A maximum L.A. abrasion of 16 percent is allowed.

A modified asphalt binder is used. Six to eight percent SBS is added to an 80/100 penetration base asphalt. Mix temperature is very high, 190 to 200°C (375 to 390°F).

Marshall compaction is used to produce specimens. Minimum asphalt content is based on the Cantabro test performed at 20°C (68°F). A maximum weight loss of 25 percent is allowed. Maximum asphalt content is controlled by the design air void content. Air voids between 18 and 23 percent are desired. The allowable asphalt content range is 4 to 6 percent.

Moisture damage is evaluated during design. Specimens are immersed in a water bath at 49°C (120°F) overnight and then are tested in the Cantabro test at 20°C (68°F). Maximum loss allowed is 30 percent.

South African Mix Design

The South African Bitumen and Tar Association in association with the Center for Scientific and Industrial Research developed a manual for the design and construction of porous asphalt mixes *(23)*. The design method is based on European experience applied to South African conditions.

Aggregates used in porous asphalt mixtures must possess good frictional properties, meeting a requirement of more than 50 percent in the polish value test. Water absorption is limited to no more than 1 percent and results of the sand equivalent test must be at least 45. For applications of more than 800 trucks per day the crush count must be 100 percent of two fractured faces. For lower traffic volumes the count is reduced to a minimum of 90 percent. The aggregate must have a flakiness index of no more than 25. Filler, if used, must be 90 percent or greater calcium carbonate, with more than 90 percent passing the 0.075-mm sieve.

Asphalt binder grade used in the mixture depends on climate and traffic volume. In hot climates or medium-to-heavy traffic, a high viscosity asphalt rubber or high polymer content binder is required. For low-to-medium traffic, an unmodified or low polymer content-modified asphalt is used.

Two sizes of porous asphalt are used; one a 9.5-mm-nominal maximum size, the other a 13.2-mm-nominal maximum size. Gradation limits of the 13.2-mm mixture are shown in Table 7.

Specimens are compacted at different asphalt contents using 50 blows of the Marshall hammer and evaluated. For medium-to-high traffic or hot climate the design air void content must be more than 22 percent. Otherwise, the design void content should be between 18 and 22 percent. The maximum allowable asphalt content is controlled by air voids in the compacted specimens.

Compacted specimens are evaluated in the Cantabro test. A maximum loss of 25 percent is allowed when tested at 25°C (77°F). The Cantabro test limits the minimum amount of asphalt to be used. An absolute minimum of 4.5 percent is specified regardless of the test results.

The selected binder content is evaluated for binder run-off using a drainage basket test. No more than 5 percent of the binder content is allowed to drain through the basket.

Aging resistance and moisture damage resistance are evaluated with the Cantabro test. For aging resistance, specimens are oven-aged for 48 hours at 60°C (140°F), and then for 120 hours at 107°C (225°F). The specimens are conditioned to the test temperature of 25°C (77°F) for 4 hours and then tested. Maximum allowable loss in the Cantabro test is 30 percent.

To determine resistance to moisture damage compacted specimens are subjected to saturation and freeze-thaw. The specimens are vacuum saturated and then subjected to two cycles of freeze-thaw; 15 hours at -10°C (14°F), followed by 24 hours in a 60°C (140°F) water bath. After conditioning 4 hours to the test temperature of 25°C (77°F), they are tested in the Cantabro test. Maximum allowable loss is 30 percent.

Comparison of European and North American Mixtures

Tables 4–7 can be compared to show the differences between North American design procedures and European design procedures.

Gradations are difficult to compare directly because different countries use different sieve sizes. European mixtures have more air voids; therefore, mixture gradations have a strong gap. The packing characteristics of aggregate are influenced by gradation *(8,24)*. Generally, although not always, European gradations allow for a more gap-graded mixture than North American mixtures. The Georgia specification for PEM is similar to the gradation specified in South Africa.

The benefits of porous asphalt depend on having sufficient air voids. All European agencies specify minimum air voids, only one U.S. agency does. Some U.S. agencies do not compact specimens at all. Air voids of the U.S. mixtures tend to be considerably lower than the European mixes. The Georgia DOT, who developed a specification patterned after the European approach, found permeability of their new mixture to be more than double that of conventional OGFC and still significantly higher than modified OGFCs used previously in Georgia.

European agencies use modified asphalt binders almost exclusively. U.S. agencies are shifting toward modified binders. Modified asphalt binders are less susceptible to draindown, both during construction and during service.

During the summer, when pavement temperatures are high, thick films of binder will tend to migrate downwards inside the mixture. At the surface, where the mixture is most vulnerable to raveling, the mixture becomes underasphalted. Once raveling starts the mixture disintegrates very rapidly, often through the entire open-graded layer. Modified binders are more resistant to draindown during service. Because modified binders tend to remain on the aggregate, there is lower risk of accelerated embrittlement from aging. The thicker asphalt films are significantly more resistant to aging. Hence, the modified binder provides insurance against premature and catastrophic failure. Fiber stabilizer, cellulose, or mineral fiber are sometimes used for the same purpose.

Modified asphalt binder will better resist disintegration even at the same asphalt binder content as unmodified

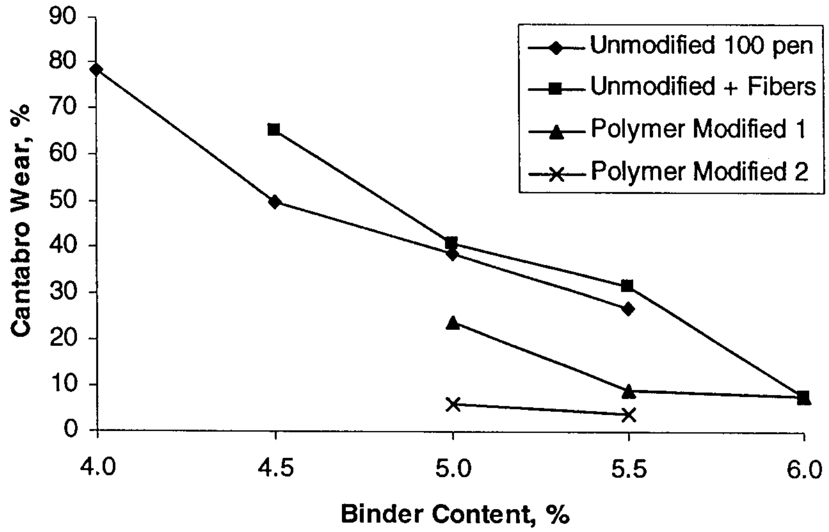


FIGURE 11 Effect of asphalt binder type on wear of aged specimens in the Cantabro test *(18).*

binder *(18).* Figure 11 shows the percent wear in the Cantabro test for a mixture containing different types and different percentages of asphalt binder. The mixtures were subjected to the Strategic Highway Research Program method for long-term aging, which includes 4 hours exposure of the loose mix at 135°C (275°F), followed by 5 days exposure of compacted specimens at 85°C (185°F). Adding fibers to the binder provided little or no benefit toward resisting aging wear. Polymer-modified asphalt binder substantially reduced weight loss of aged specimens in the Cantabro test.

Modified asphalt binder increases rut resistance. A European study evaluated porous asphalt as well as stone matrix asphalt (SMA), surface asphalt concrete, and binder asphalt concrete with unmodified and modified asphalt binder *(25).* Rut resistance increased 2 to 20 times when modified asphalt binder was used. As the temperature increased, rutting resistance decreased. At 50°C (122°F), porous asphalt with modified binder was the most resistant.

European agencies generally demand higher standards for aggregate than U.S. agencies. L.A. abrasion values are specified from 12 to 21 percent. For open-graded mixtures, U.S. agencies specify 35 to 40 percent.

Porous asphalt mixtures with high air void content require high crushed face percentages. Most agencies require that quarried rock be used. South Africa allows 90 percent crushed-two-faces, which could be made from gravel, on low-volume applications. In the United States, agencies do not require as many crushed faces for open-graded mixtures. California requires 90 percent crush on one face; Arizona and Wyoming require 95 percent. Florida requires quarried aggregate with 100 percent crush on one face. For low-volume roads, Arizona will allow as little as 70 percent crush.

European agencies specify a minimum asphalt content based on a durability test, the Cantabro test, which is performed on compacted specimens. All agencies use 50 blow Marshall compaction. A maximum limit for asphalt content is based on air voids. The strong aggregate skeleton used in porous asphalt tends not to compact more with increasing asphalt content. Therefore, asphalt binder fills the skeleton and air voids decrease as asphalt content increases. Draindown is controlled with modified binders.

By contrast, the asphalt content in open-graded mixes in the United States is most commonly selected based on the percent oil retained procedure in the FHWA method. Georgia also considers the VMA of Marshall compacted specimens. Asphalt contents in the U.S. mixtures, typically from the upper five to mid-six percent range, tend to be higher than European mixtures, which are more commonly in the mid-four to five percent range. European mixtures with coarser gradation do not need as much binder.

In both European and North American designs, tests are not available for predicting the performance of a mixture. In North America no tests are used. In Europe the Cantabro test is used as a performance indicator test. A study in The Netherlands evaluated several possible tests *(26).* The Cantabro test and indirect tension have high scatter. Wheel-track tests were found to have even greater scatter. Cyclical direct tension was found to be repeatable, but the authors were unable to validate the test results. The Cantabro test remains the best performance indication test available.

CONSTRUCTION

This section discusses plant production and lay down of open-graded asphalt mixes. Little information has been published regarding construction. Much of the U.S. construction practice is based on the survey done as part of the synthesis. Non-U.S. construction experience is based on reports from Britain and South Africa.

Plant Modifications

Generally, no specific plant modifications are required for open-graded mixes. The plant must be capable of handling modified asphalt binders, which in some cases means mechanical agitation in the asphalt storage tank. Mixing temperature must be well controlled to ensure that it stays hot enough to obtain complete coating of the aggregate. At the same time, excessive temperature spikes cannot be tolerated. If the temperature is too high, binder run-off can occur, leading to areas on the road that are flushed and other areas with low asphalt. Arizona, which uses asphalt rubber, limits mixing temperature to a maximum of 175°C (347°F). Oregon allows 160°C (320°F) for unmodified asphalt binder and 175°C (347°F) for modified asphalt binder as the maximum temperature at the plant.

If fibers are used in the mixture, whether cellulose or mineral, the plant must be equipped with a metering system and be capable of evenly distributing the fibers. Nonuniform fiber distribution can cause pockets of dry, unworkable mix and other areas of soft, wet mix.

At the plant, aggregate stockpiles are handled with little or no modification to normal practice. Any plant capable of producing high-quality dense asphalt mixture can produce high-quality open-graded mixture.

For open-graded mixtures some agencies, particularly in wet climates, require the aggregate to be in surface dry condition. Lower moisture content and low variability in moisture content allows easier control of mixing temperature. Accurate control of moisture content produces a more uniform mix.

In remote areas where mobile plants are used and aggregate is specifically produced for a single project, some states mandate at least a 2-day reserve of aggregate before mix production starts. This rule generally applies to dense-graded mixture as well. One state that uses lime for antistrip requires the stockpile to marinate for at least 48 hours. They also use this requirement for dense-graded mixtures.

Once the mix is produced, storage time should be minimized. Binder draindown during hot storage can occur causing an imbalance in asphalt content. Some states specify a maximum storage time in the silo of from 1 to 12 hours.

Transportation to Site

Open-graded mix is transported to the construction site with the same equipment used for dense-graded mix. Generally, no additional precautions are required. If modified asphalt is used, additional application of release agent is used in the truck box to prevent sticking. Tarps are usually required to prevent crusting on the surface of the load. Some states also require truck beds to be insulated.

Laydown and Compaction

OGFC as used in the United States is typically placed in a thin layer, 20 to 25 mm (0.75 to 1 in.) thick. Porous asphalt as used in Europe and South Africa is thicker, 40 to 50 mm (1.5 to 2 in.) thick. Because they are thicker, the layer retains heat longer, allowing more time for compaction.

Mixture can be delivered to the laydown machine in much the same manner as dense-graded hot mix. If the mix is dumped directly into the hopper, trucks backing up should not bump the paver. With open-graded mixtures the resulting surface depression is more difficult to roll smooth than for a dense-graded mixture and a bump will remain in the finished pavement.

Open-graded mixtures can be windrowed ahead of the paver and put in the hopper with a pickup machine. The length of windrow should be controlled. Open-graded mixture can lose heat more quickly than dense-graded mixture during windy conditions. During favorable conditions the windrow length should be no more than 50 m (150 ft) in front of the paver.

The paver may require some adjustment when switching from dense-graded to open-graded mix. Roll down, the difference between loose laydown thickness and final compacted thickness, may be different. If the paver is equipped with extendible screeds, auger extensions should be used. Without extensions the coarse aggregate tends to be pushed to the edge of the mat leaving the asphalt binder behind. Binder content then tends to be lower at the edge of the mat and higher in the center, particularly directly behind the slat conveyors. Differences of 0.3 percent between the edge and center of the mat have been reported *(7)*.

As is the case for all paving, the mixture should be delivered hot to the paver with no cold lumps. Temperature is particularly important with modified asphalt binders. Usually a standard rolling pattern is used for compaction. Density is not measured in the finished mat. Areas of low density become very susceptible to raveling.

Transverse joints are more difficult to construct in open-graded mixtures than dense-graded mixtures. Handwork should be avoided as much as possible since blemishes often result *(23)*. Therefore, when a construction joint is made at the end of the day more mixture is discarded. Because of the increased difficulty it is desirable to pave in one lane as long as is practical.

For longitudinal joints similar procedures and precautions should be used for open-graded mix as for dense-graded mix. During compaction of an unsupported edge, the roller should not overhang the pavement edge significantly if the thickness of the mixture is 30 mm (1.25 in.) or more thick. When rolling an unsupported edge, open-graded mix will move laterally, more easily causing a depressed edge of mat.

The edge of a longitudinal joint may be tack coated before laying the next lane. If two adjacent lanes slope in the same direction care should be taken to prevent excess tack coat, which may impair drainage across the joint.

When matching to a previously added layer special attention must be paid to roll down. The mix must be laid sufficiently thick to allow for roll down. Otherwise the roller will bridge across the edge of the new mat and low density will occur next to the joint. Where density is low, open-graded mixes are more susceptible to raveling than dense mixes.

Open-graded mix is compacted with static steel-wheeled rollers. Heavy rollers, greater than 10 Mg (11 tons) are not recommended, because excessive aggregate breakage occurs during compaction *(7)*. The roller should have a weight of at least 7 to 8 Mg (8 to 9 tons) *(7,23)*. Pneumatic-tired rollers are not recommended, either alone or in conjunction with static steel-wheeled rollers. The kneading action will decompact the mixture *(7,17)*.

Density on the road is not specified. A standard rolling train, typically two to four passes, is specified. This approach is used by all states. Standard rolling is also used in Europe and South Africa. Recent research in Oregon shows little difference in density between two and four passes of a static steel roller. The mix is already densified after two passes. (D.F. Rogge, Oregon State University, personal communication, 1998).

Acceptance

Open-graded mixture is accepted based on asphalt content and gradation, as well as visual inspection. Most agencies use asphalt content and gradation as acceptance properties. Criteria are based on typical construction variability. For example, on the basis of four tests the Georgia DOT allows asphalt binder content to deviate 0.41 percent from the job mix formula without penalty. The 9.5- and 2.36-mm sieves are control sieves. Based on a four-test average, Georgia allows the gradation to deviate by 5 percent on the 9.5-mm sieve and 4.3 percent on the 2.36-mm sieve. If this tolerance on the 2.36-mm sieve is exceeded, the lot is assessed a 50 percent pay reduction.

Visual inspection is used to control density on the road, segregation, and material variability. There are no tests specified by any agency for these properties.

Agencies use a minimum air temperature to define acceptable paving conditions. Most agencies use a minimum air temperature of 15°C (60°F), although some have a higher cut-off temperature. California and New Mexico use 20°C (70°F). Others, such as Florida, which uses 8°C (45°F), allow a lower temperature.

Nearly all agencies specify a minimum smoothness. Most agencies specify a maximum deviation under a 3-m straight edge. Some states use a rolling straight edge. Arizona measures the roughness using a Mays meter and specifies a maximum acceptable limit. Georgia uses a laser road profiler and smoothness values require the mix to be smoother than dense-graded mix.

CHAPTER FOUR

PERFORMANCE, MAINTENANCE, AND REHABILITATION OF OPEN-GRADED FRICTION MIXTURES

PERFORMANCE

This section discusses the performance of open-graded mixture based on published data and the experience of agencies that use the mixtures. Generally, performance will be considered in the following categories.

- Performance life (permeability and sound attenuation).
- Service life (friction and ride).

OGFC mixtures are placed to reduce hydroplaning and for noise reduction. These properties are based on maintaining the void structure. Loss of permeability by clogging with silt and debris or densification under traffic will reduce the permeability and, hence, reduce noise suppression and wet weather traction.

Test pavements in Denmark showed that noise reduction was maintained for at least 5 years when the porous asphalt was built with 18 to 22 percent voids and placed on a high speed road *(8)*. Despite a reduction in void content caused by traffic, the voids remain open, presumably from the pressure induced by tires rolling over a wet surface. On the other hand, a similar pavement in an urban environment lost all noise reduction after 2 years *(8)*. The slower traffic does not create the pressure necessary to clean the pavement. In the city there also tends to be more grit present to clog the pores.

In The Netherlands and Italy an attempt was made to prevent clogging from occurring *(9,10)*, especially in urban environments where extra road dirt and low hydraulic cleaning action from low-speed traffic cause accelerated clogging. The concept is to build a filter on top of the porous asphalt using a smaller aggregate size.

To combat clogging tendencies, some pavements have been built with larger aggregate to create larger pores. Little difference in clogging resistance was noted *(9)*. To counteract the clogging tendency, two layers of porous asphalt were constructed. The bottom layer is constructed of 11 to 16 mm of aggregate, which is larger than the top layer made of aggregate 4 to 8 mm in size. Both mixtures are constructed with 20 percent air voids. The small voids in the top layer prevent large particles from entering the bottom layer. The air void space in the bottom layer allows the water jet/vacuum machine to restore permeability nearly completely.

In a British study, 47 sections were monitored for spray reduction *(9)*. All of the sections lost spray reduction capability after 8 years. Spray reduction on most sections lasted 5 to 8 years, with the average being 6.3 years.

In the same study, 89 sections were observed until the sections were rehabilitated. The time to rehabilitation is referred to as ultimate life. The average ultimate life of the sections was 7.3 years, with the longest life being 15 years. In general, the International Road Federation *(11)* reports that 6 to 8 years of life can be achieved in heavy traffic conditions. In the survey for this synthesis, none of the responding states monitored the permeability or spray reducing capability of OGFC. Ohio reported that clogging typically occurs by year five.

The cause of pavement failure was similar for all states. Of the 17 agencies that are major and minor users of OGFC, 14 reported raveling as a cause of rehabilitation. The main causes of rehabilitation reported by the states and the number of agencies reporting each cause are listed in Table 8.

TABLE 8

REPORTED CAUSE OF OPEN-GRADED MIXTURE FAILURE

Failure Mechanism	Number of Agencies
Raveling	14
Cracking	2
Potholes	2
Delamination	3

Agencies report improved performance when modified asphalt binder is used. Kandhal and Mallick *(6)* found that of agencies reporting good experience, 15 use modified asphalt binder and 4 do not. Of the agencies that report bad experience, 2 use modified asphalt binder and 12 do not.

The findings of Kandhal and Mallick are supported in this synthesis. The Arizona DOT reports that no premature failures occurred in OGFC made with asphalt rubber. Likewise, the Georgia DOT, which uses SB- or SBS-modified asphalt has experienced no premature failures. In both Arizona and Georgia, mixtures made with unmodified asphalt binder fail by raveling as experienced by the other states. The Maryland DOT reports OGFC life to be 5 to 15 years. Mixtures that last longer are those containing polymer-modified asphalt.

MAINTENANCE

Maintenance will be considered in two categories, winter maintenance and surface maintenance.

Winter Maintenance

Open-graded mixtures behave differently than dense-graded mixtures in freezing environments. The high air voids in the open mixture act as insulation, making it more resistant to the flow of heat from the subgrade to the atmosphere in much the same way that insulation in a house wall reduces the flow of heat through the walls. The heat conductivity of a porous asphalt mixture is 40 to 70 percent that of a dense-graded mixture *(27)*.

When the road is dry and air temperature is approaching the freezing point, the surface of the open mixture can drop below freezing. The surfaces of all asphalt pavements radiate heat energy into the sky (black body radiation). Heat flows from below the surface to replace heat lost at the surface. The additional insulation value of the open-graded mixture restricts the transfer of heat to the surface and allows the surface temperature to drop below the surface temperature of an adjacent dense-graded mixture.

The difference in pavement surface temperature is most evident during clear sky conditions with no wind. Under these conditions, the temperature differential between dense and porous asphalt can be as much as 2°C (3.6°F). Figure 12 shows a surface temperature comparison of dense and porous asphalt in The Netherlands *(28)*. The conditions were measured with an infrared camera during clear sky conditions and no wind. The temperature difference in this case is about 1°C (1.8°F).

The difference in pavement temperature is a particular concern when pavement temperature is near freezing. If pavement temperatures are warmer than 2°C (36°F), the surface of both porous and dense pavements is unfrozen. If pavement temperatures are near freezing there is a risk of the porous surface being frozen and an adjacent dense surface being unfrozen.

In Europe, freezing rain on porous asphalt is reported to result in earlier formation of ice, which remains on the road longer. Dry pavements in subfreezing conditions are reported to cause frost formation in the tire tracks. The report concludes that earlier intervention is required with more frequent application of salt.

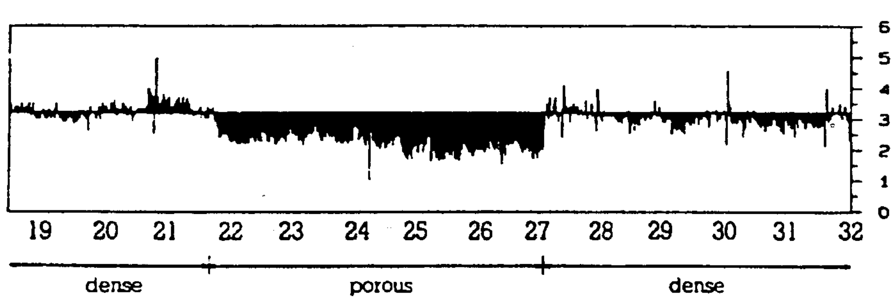
When ice forms on porous asphalt, a longer time is required for friction to return to wet pavement values. Salt has less contact time with the icy surface on a porous pavement than a dense pavement. On a porous pavement salt begins to melt the ice and form brine, which then disappears into the porous mixture. On a dense pavement the brine stays on the pavement surface and melts more ice. After an ice storm event as much as 24 hours is required for the friction on a porous pavement to match a dry pavement *(29)*.

Of the 17 agencies that represent major and minor users of OGFC, 12 have cold weather conditions. Six of the 12 report the need for additional and more frequent applications of salt. The other six report no difference in winter maintenance treatment. In north Texas open-graded mixtures are observed to be the first to freeze and the last to thaw.

Surface Maintenance

Surface maintenance is considered to be activities that restore or preserve the surface condition of the pavement. Such activities include crack sealing and pothole repair, as well as other routine activities such as fog sealing and striping.

All 17 states using open-graded mix report that potholes and delaminated areas are repaired with dense-graded



Road surface temperature in degrees Celsius

FIGURE 12 Surface temperature of asphalt mixtures under clear sky conditions *(28)*.

graded patching mix. Only one state, Wyoming, mentioned crack filling as routine maintenance. In Wyoming's experience, crack sealing can cut off the flow of water inside the pavement and lead to mixture problems.

Fog sealing is a sprayed application of asphalt emulsion on the pavement surface. The additional material replaces asphalt lost to weathering or that may have drained to the bottom of the layer during summer heat.

The British recommend monitoring the texture depth in the spring each year after the pavement is a few years old *(7)*. The sand patch test or automated meters correlated to the sand patch test are used. A typical texture depth is 2 to 3 mm. An increase in texture depth accompanied by the loss of surface fines can be an indication of impending failure. The mixture will survive during the summer, but may experience severe raveling in the following winter.

Lane markings are more difficult to maintain on porous asphalt. The greater surface texture of open-graded mixture requires additional marking material to be applied. Paint or other low viscosity materials are difficult to apply because they will flow down into the porous asphalt voids.

In North America, 10 of the 17 agencies that most commonly use open-graded mixture report that no special material is needed and that no special attention is required. Ohio reports that an additional 30 percent material is needed if epoxy is used and an additional 50 percent material is needed if paint is used. New York and Oregon also report that extra material is needed. Three agencies, South Carolina, Maryland, and British Columbia report that thermoplastic marking material, a high-viscosity material, works the best.

None of the North American agencies report doing any major maintenance during the life of an open-graded mixture. Fog seals are used by some of the agencies. New Mexico applies a fog seal every 3 years, Oregon every 5 years. Wyoming and South Carolina use a fog seal if required. The other agencies do not report using fog seals. Fog seals are reported to reduce the in-place air voids.

In Europe, vacuum machines with water spray restore clogged or partially clogged pavements. High-pressure water is sprayed on to the road surface and immediately is removed by high-power suction. Several such machines are reported to be in service in France, Switzerland, and Austria *(11)*. For the machines to be effective, cleaning must occur before clogging is complete. Depending on the amount of road dirt, traffic level, and vehicle speed, cleaning may be required at frequent intervals. There is no indication in the literature as to what percentage of porous asphalt pavements is maintained by this method; nor is there an indication of the cost effectiveness.

REHABILITATION

Depending on location, traffic, or other factors OGFC pavements may be considered as candidates for rehabilitation at the end of the service life; that is, when the pores become clogged. Once clogged, the mixture performs as a dense-graded mix with relatively low permeability. Often agencies will accept the clogged OGFC and continue service until raveling or delamination necessitates rehabilitation.

Generally, the literature recommends removal of the porous layer prior to replacement with a new layer of porous asphalt or dense-graded mix *(11,30)*. Most agencies in North America do so. Fourteen of the 17 agencies that most commonly use open-graded mixtures remove the previous layer before placing a new layer. Oregon sometimes removes the open mixtures, but not always. Nevada and Wyoming leave the old open-graded layer in place.

Hot-in-place recycling is an option that shows promise *(11,31)*. Hot-in-place recycling with no admixture is done with only rejuvenator being added. Research in The Netherlands *(31)* shows that the recycled pavement is expected to have the same durability as new porous asphalt based on Cantabro test results. In that research, recycled porous asphalt has the same permeability as new porous asphalt, which suggests that clogging occurs only near the pavement surface and does not alter the mixture gradation when the mix is recycled.

CHAPTER FIVE

ALTERNATIVE SURFACE MIXTURE TYPES

FINE-GRADED SURFACE MIXTURES

In North America, surface mixtures have historically been made with small-sized, finely graded aggregate, which were intended to have little surface texture. Typically, such mixtures had a maximum size of 12.5 mm and contained high percentages of sand. Such mixtures have a finely textured, smooth, tight surface. They are intended to be relatively impermeable.

Fine-graded surface mixes have two distinct advantages:

- The greatest advantage is their low initial cost. High natural sand content in these mixtures leads to an inexpensive mix.
- These mixes are easy to construct. The fine texture and high sand content of these mixes makes them easy to place and easy to compact to a smooth finish. Handwork is easy and blends in well without leaving surface blemishes.

These mixtures have several disadvantages:

- Generally they are not as rut resistant as alternative surface mixes. High natural sand content creates a weak aggregate skeleton.
- The surface texture is very fine, which creates a lower hydroplaning threshold. Mixtures with macrotexture provide channels for the water to escape. The low macrotexture of these mixes does not provide an escape route for the water.
- The tight surface and low macrotexture generates more noise than a high macrotexture mixture in which the tops of the rocks are at the same level. Tire noise is more pronounced on a smooth surface.

COARSE-GRADED SURFACE MIXTURES

Another group of surface mixtures can be referred to as coarse-graded surface mixtures. These mixes include dense-graded mixtures that contain more coarse aggregate and have more surface texture than the fine-graded mixtures discussed previously.

Coarse-graded surface mixtures have the following advantages:

- These mixtures are generally quieter than fine-graded surface mixtures. The increased macrotexture of the coarse-graded mixture suppresses some of the tire noise. However, these mixtures are not as quiet as OGFC or porous asphalt.
- Higher macrotexture in coarse-graded mixtures reduces the potential for hydroplaning. Channels created by the macrotexture allow water to escape from the tread blocks on a tire allowing the tire to maintain contact with the road. Coarse-graded mixtures are not as resistant to hydroplaning as porous asphalt, which removes water from the surface before a tire approaches.
- High stone content in the coarse-graded surface mixtures makes them more rut resistant than the fine-graded surface mixtures. Porous asphalt mixtures with an open aggregate skeleton are very rut resistant, more so than the dense-friction course mixtures.

Coarse-graded surface mixtures also have some disadvantages:

- Some of these mixtures are more difficult to apply. The higher stone content makes handwork more difficult and can leave surface blemishes.
- Additional lane marking material is required. The increased macrotexture of these mixtures as compared with the fine-graded surface mixtures requires additional paint because some is lost in the pores. Less lane marking material is required for these mixtures than for the open-graded mixtures.

STONE MATRIX ASPHALT

SMA is an impermeable, gap-graded, open-textured mix that is significantly different from coarse-graded surface mixtures. SMA contains a high percentage of quality, crushed rock, a high asphalt binder content, and a high filler content.

SMA mixtures have the following significant advantages:

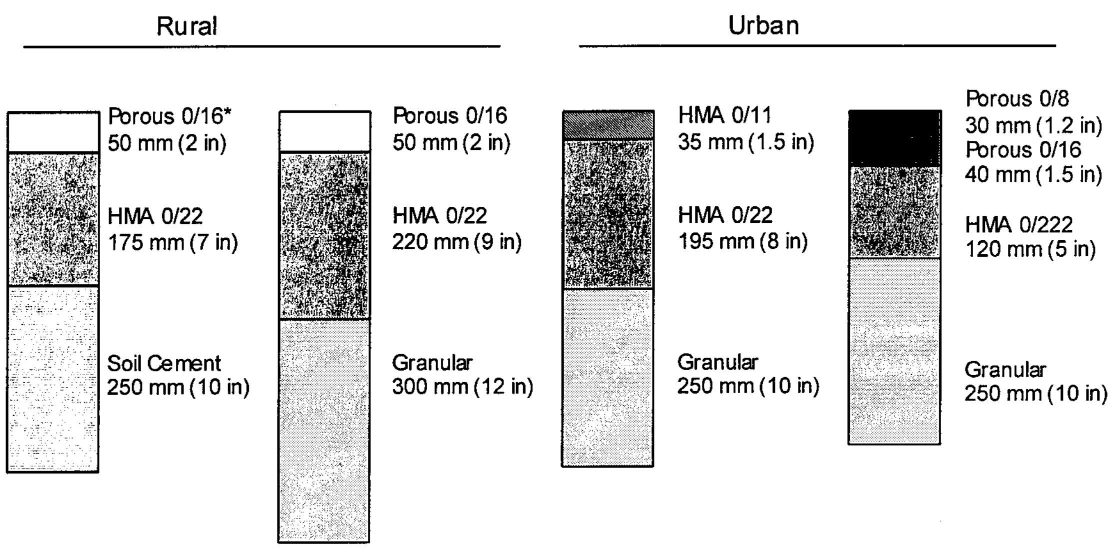
- SMA mixture is highly resistant to permanent deformation. The coarse aggregate skeleton when combined with high dust content mastic creates a stiff mixture that is very resistant to rutting. The rut resistance of an SMA mixture and a porous asphalt mixture, which is composed solely of a rock skeleton, are similar.

TABLE 9

SELECTED COMPARISON OF OPEN-GRADED MIXTURE COST AND LIFE

Mixture	Arizona		Georgia		California		Wyoming	
	Cost	Life	Cost	Life	Cost	Life	Cost	Life
OGFC (neat binder)	32.64	7	—	8	34.80	3–5	37.40	15
OGFC (modified binder)	42.66	13	55	12	—	—	—	—
SMA	—	—	55	12	—	—	—	—
Dense	23.64	11/20[1]	35	10	32.70	5–10	30.40	10–24[2]

Note: Cost is dollars per megagram; life is in years.
[1]11-year-average life of rehabilitation, 20-year life of new construction.
[2]10-year life on high-volume interstate, 15-year life on low-volume interstate, and 24-year life on other roads.



***The numbers in the mixture name indicate a range of gradation sizes; for example, 0/16 indicates a gradation from 0 mm to 16 mm.**

FIGURE 13 Asphalt construction recommended for heavy duty pavement in The Netherlands *(25)*.

- The macrotexture of SMA mixtures reduces noise generation and hydroplaning when compared with coarse-graded surface mixes. In this regard, only porous asphalt performs better than SMA.

The significant disadvantages of SMA are as follows:

- SMA mixtures are more expensive than more traditional dense-graded mixtures. A high-quality aggregate is generally required. Asphalt binder content is high and fibers or modified asphalt is required to resist draindown during construction.
- SMA mixtures are not easily suited to handwork. SMA is a stiff, sticky mixture that is difficult to work by hand.

COMPARISON OF SURFACE TYPES

Each of the alternate surface mixture types has different costs and performance. The experiences of four states are summarized in Table 9.

Arizona uses OGFC with neat asphalt and rubber-modified asphalt *(32)*. Most use rubber-modified asphalt binder; 180,000 Mg (200,000 tons) rubber modified compared with 32,000 Mg (35,000 tons) unmodified in 1998. The average life of the rubber-modified OGFC is almost double, 13 vs. 7 years. Rubber-modified OGFC costs 80 percent more than dense-graded mix, $42.66 vs. $23.64 per megagram ($38.78 vs. $21.49 per ton). When used as an overlay, the dense mix has almost the same life as rubber-modified OGFC, 11 vs. 13 years. As new construction the dense-graded mix has a longer life, 20 vs. 13 years.

Georgia uses a dense SMA mix and overlays it with either a 12.5-mm OGFC or a 12.5-mm PEM for the pavement surface on all interstate routes. SMA and PEM are approximately the same price, $55 per megagram ($50 per ton), about 60 percent more expensive than dense-graded mix, which costs $35 per megagram ($32 per ton). Conventional mixtures are reported to have a life of approximately 10 years before overlaying. SMA, modified

OGFC, and PEM mixtures are expected to last from 10 to 12 years.

California uses approximately 100,000 Mg (110,000 tons) of open-graded mix per year, costing about $35 per megagram ($32 per ton). Most OGFCs are produced with unmodified asphalt. OGFC mix costs only 6 percent more than dense-graded mix. Conventional mixtures are reported to last approximately 10 years before overlaying.

Wyoming uses about 90,000 Mg (100,000 tons) of OGFC, costing about $37 per megagram ($33 per ton), which is about 20 percent more than dense-graded mix that cost $30 per megagram ($27 per ton). The life of OGFC is typically 15 years. The life of dense-graded mixture depends on the application: 11 years on high-volume interstate, 15 years on low-volume interstate, and 24 years in other applications.

In general, North American open-graded mixtures cost 10 to 80 percent more per megagram than dense-graded mixtures and have a life that is one-half to approximately the same as dense-graded mixtures.

In Europe, porous asphalt mixture is applied in thicker layers, typically 40 to 50 mm (1.5 to 2 in.) instead of 20 mm (0.75 in.) commonly used for OGFC in North America. In The Netherlands porous asphalt is commonly used for heavy-duty pavements. Figure 13 shows recommended cross sections with a porous asphalt surface and in built-up areas. For pavements in a non-built-up area porous asphalt is applied 50 mm (2 in.) deep over dense-graded hot mix. In built-up areas, SMA or dense surface mix is recommended. If porous asphalt is used, a two-layered system is implemented with 30 mm (1.25 in.) of 0 to 8 mm porous asphalt over 40 mm (1.5 in.) of 0 to 16 mm porous asphalt.

CHAPTER SIX

CONCLUSIONS

The objective of this synthesis was to document the use and performance of OGFC mixtures in North America, to evaluate new materials and design methods used elsewhere, and to determine their applicability to North American conditions.

Open-graded mixtures originated in California in the 1940s and their use slowly spread to other states. Most agencies have now used or evaluated these mixtures. In the United States, 27 agencies were constructing open-graded mixtures in 1988. By 1998, that number had dropped to 22.

The main reason given for the decline in use is the failure mechanism. At some point during the pavement life, the pavement will begin to ravel during the cold weather months and will fail rapidly. In some places, the entire layer thickness can wear away in a matter of weeks leaving a pavement full of holes and flying rocks in the middle of winter. This sudden, unexpected failure is unacceptable to a highway agency.

Most agencies that continue to use open-graded mixes have not changed the mixtures much over the last 25 years. These mixtures are 9.5-mm-nominal maximum size, designed for asphalt content and gradation, yielding about 15 percent air voids, and are placed about 20 mm (0.75 in.) thick. The only significant changes have been the use of modified asphalt binders and fiber stabilizers, which are becoming more common.

In Europe, the use of porous asphalt mixtures has become common practice in some countries and this use is increasing. Porous asphalt is an open-graded mixture, but is distinguished from OGFC. Porous asphalt is designed with 18 to 22 percent air voids. A stronger gap grading is required to achieve the higher air voids and modified asphalt binder is used to improve resistance to raveling and aging. European mixtures are usually made with 12.5-mm-nominal maximum-size aggregate and are placed 40 to 50 mm (1.5 to 2 in.) thick.

European mix design methods specify air voids as a criterion. Also, in European mix design, durability is measured using the Cantabro test. The Cantabro test tumbles compacted specimens in an L.A. abrasion machine without the steel balls. Abrasion loss is specified to determine the amount of asphalt binder required. The test is also used to evaluate specimens that have been long-term aged or subjected to moisture damage.

In the United States, one state DOT, Georgia, has adopted a European approach. The higher air voids and large pore spaces allows the mixture to maintain benefits longer than the OGFC previously used.

Generally, construction and maintenance of open-graded mixtures is done the same in North America and Europe. For maintenance in Europe there are reports of high-pressure water and vacuuming machines being used to open partially clogged pores. There is no indication of the cost effectiveness of these machines or whether they will become commonplace. As a rule, porous mixtures are being used on high-traffic, high-speed roads. The action of the traffic cleans the void spaces. The same cleaning action has been reported in the open-graded mixtures of North America.

In Europe, a novel open-graded design has been reported to have better clogging resistance and noise reduction. The new design has two layers of porous mix, both with voids greater than 20 percent. The surface layer, made of chips that are 4 to 8 mm in size, acts as a filter above the second layer, which is constructed with 11 to 16 mm aggregate.

To rehabilitate an open-graded surface the existing surface is first removed and a new surface is applied. In Europe, where large areas of the motorways are covered with porous asphalt, trials of hot-in-place recycling have been done. Recycled porous asphalt has been found to have the same durability based on laboratory tests of hot-in-place recycled mixture.

The first generation of open-graded mixtures began as an outgrowth of chip seal technology. These mixtures, called open-graded friction course (OGFC), were typically constructed 15 to 20 mm (0.5 to 0.75 in.) thick, having air void contents of 12 to 15 percent. Unmodified asphalt binder was typically used. All but six of the state DOTs have used the first generation mixtures. Construction of these mixes peaked in the 1980s and has since declined.

Modified asphalt binder lengthens the life of an open-graded mixture. The usual failure mechanism for an open-graded mixture is raveling and disintegration. Once the asphalt binder ages to a certain point the mixture will begin to disintegrate during cool weather. The failure is rapid. Sometimes the entire pavement layer will ravel in a few weeks. Several states that use OGFC have switched to modified asphalt binder. The results of a survey in the recent TRB Circular E-C005 *(6)* confirm the benefit of modified asphalt binder. Of 19 states that reported having good experiences, 15 use modified binder and 4 do not. Of 14 states that report bad experience, 2 use modified binders and 12 use unmodified.

Fiber stabilizers prevent draindown during construction. Draindown, a separation of the asphalt mastic from the coarse skeleton, can occur in a mixture storage silo or in a truck during transport. Mixtures that have suffered from draindown produce binder-rich areas on the road that have a flushed surface and no voids, as well as other areas with little binder and high voids that quickly ravel.

The use of both fiber stabilizers and polymer-modified asphalt has allowed mixture production temperatures to be increased, comparable to that of conventional mixtures without draindown or oxidation problems. Aggregate moisture is therefore removed more effectively and the bond between the asphalt, cement, and aggregate particles is enhanced. This change should extend the service life and eliminate the raveling problems typical of previous OGFC mixtures.

The amount of air voids in open-graded mixture influences the mixture's benefits. The main benefit desired by state agencies is increased wet weather friction. Two secondary benefits are reduced road mist and reduced traffic noise. Voids in the mixture are reduced by mixture consolidation and road debris. On higher speed roadways hydraulic action under the tires tends to clear some debris from surface pores. Also, there is generally less debris present, because traffic wind sweeps the pavement clean.

In urban environments there tends to be more debris on the road surface. An open-graded pavement will clog more rapidly because there is more debris and because there is little wind or hydraulic action to remove the debris. Generally, open-graded mixes are not best used on low-speed urban roads.

High levels of initial air voids, 18 to 22 percent, increase the service life of the pavement. More time is available before the voids consolidate to an impermeable level. Also, high air voids tend to aid hydraulic flushing of debris by traffic, which maintains the mixture permeability. OGFC mixtures, which were designed with 12 to 14 percent air voids, have a much shorter service life until permeability is lost.

The second generation porous asphalt mixtures use larger aggregate than the first generation OGFC. OGFC is almost always a 9.5-mm-nominal maximum size. Depending on the sieve series used in a particular country, porous asphalt is typically a 12.5- to 14.0-mm-nominal maximum size. The large aggregate size creates larger pore spaces, which tend to be self-cleaning.

Mix design approaches have changed for porous asphalt. The first generation mix design approach specifies a gradation and evaluates the amount of binder that can be used without excessive draindown. No tests are done for air voids, permeability, or durability. The new generation of porous asphalt designs in Europe specify a gradation and evaluate the draindown of the binder. In addition, specimens are compacted, usually with a Marshall hammer, and air voids are measured. Compacted specimens are artificially aged and durability is evaluated using the Cantabro test. Moisture sensitivity is also evaluated by conditioning compacted specimens and performing the Cantabro test.

Open-graded mixtures are more expensive than the dense-graded alternative. With unmodified asphalt binder OGFC mixtures cost 6 to 38 percent more than a dense-graded alternate. The life of these mixtures is about one-half that of the dense-graded, although some agencies report lives approximately the same as those of dense-graded surfaces. With modified asphalt binder OGFC mixtures cost 50 to 80 percent more than dense-graded mixtures containing unmodified asphalt binder. With modified binder the open mixtures have approximately the same life as dense alternatives.

Open-graded mixtures provide benefits to the user not available from dense-graded mixtures. Water is removed from the road preventing hydroplaning and reducing water spray. When travelling on an open-graded surface traffic produces noise that is 3 dB(A) lower. Three dB(A) is a 50 percent reduction in sound pressure. In other words, the traffic volume could double before noise levels approach the same level that they would be on a dense-graded surface.

In freezing climates, open-graded mixtures require a different approach for winter maintenance. Open-graded mixtures tend to be the first section to freeze and the last surface to thaw. For ice and snow removal sand should not be mixed with salt because of the potential for plugging the pores. Without the abrasive action of the sand, ice pack breaks up more slowly. Salt brine soaks into the open-graded mix removing it from the partially dissolved ice. Therefore, open-graded mixes require a more frequent application of salt with less salt applied each time.

A review of all the information leads to the following conclusions:

- Open-graded mixtures with high air voids (18 to 22 percent) maintain benefits to the user longer than OGFC mixtures, which typically have 15 percent air voids.

- Open-graded mixtures with unmodified asphalt binder usually fail by raveling and delamination. Some field experience suggests that asphalt binder tends to migrate downward in the layer unless fixed with modifiers or fibers. Thinned films will age more rapidly and cause failure earlier.
- Modified asphalt binder and fiber stabilizers will allow an open-graded mixture to last much longer.
- No scientific method of mix design exists that relates mixture properties to performance.
- Normal construction techniques can be used for all open-graded mixtures. Increased attention is required to prevent mix from cooling during transport and handling.
- Winter maintenance of open-graded mixtures requires a different approach. Sand cannot be mixed with salt on open-graded mixtures. More frequent applications, though not necessarily greater quantities, of salt are needed.

In North America, there is currently very little research into open-graded surface mixtures. Oregon, which is one of the leading states in the use of open-graded mixtures, is sponsoring a project entitled "Development of Open-Graded Compaction Specifications." June 2000 is the scheduled completion date for the project, which is being undertaken at Oregon State University.

In reviewing available information the following items were identified as areas warranting further research.

Mix Design—An updated mix design method is needed. It should include air void content as a design criterion, as well as a durability test such as the Cantabro test. In a new design method, compaction should be done using the Superpave gyratory compactor to harmonize with implementation of Superpave.

Cleaning Pores—An evaluation of the current pore cleaning machines should be done to determine if the process is cost effective. Alternate methods of cleaning partially clogged voids should be considered. Void cleaning equipment should be evaluated against a "do nothing" strategy.

Modified Asphalt Binder—The influence of modified asphalt binder on mixture properties and mixture longevity should be evaluated. Recommendations for asphalt binder grade in different climate and under different traffic should be formulated.

Maintenance Strategies—Agencies need to know if fog sealing increases the ultimate life of the pavement or if there is a reduction in service life caused by added asphalt binder filling voids.

REFERENCES

1. Morris, G.R., *Arizona's Experience with Asphalt Concrete Friction Courses*, AASHTO Subcommittee on Maintenance, Los Angeles, Calif., 1973.
2. *NCHRP Synthesis of Highway Practice 49: Open-Graded Friction Courses for Highways*, Transportation Research Board, National Research Council, Washington, D.C., 1978.
3. Smith, H.A., *NCHRP Synthesis of Highway Practice 180: Performance Characteristics of Open-Graded Friction Courses*, Transportation Research Board, National Research Council, Washington, D.C., 1992.
4. *Open-Graded Friction Course FHWA Mix Design Method*, Technical Advisory T 5040.31, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1990.
5. *Open-Graded Friction Course FHWA Mix Design Method*, Technical Advisory T 5040.13, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1980.
6. Kandhal, P.S. and R.B. Mallick, "Open-Graded Friction Course: State of the Practice," *Transportation Research Circular E-C005*, Transportation Research Board, National Research Council, Washington, D.C., December 1998.
7. Nicholls, J.C., *Review of UK Porous Asphalt Trials*, TRL Report 264, Transport Research Laboratory, London, United Kingdom, 1997.
8. Bendtsen, H., "Noise Reduction by Drainage Asphalt," *Nordic Road & Transport Research*, No. 1, 1997, pp. 6–8.
9. Van Bochove, G.G., "Twinlay, A New Concept of Drainage Asphalt Concrete," *Proceedings of Eurasphalt and Eurobitume Congress*, Vol. 3, Strasbourg, France, May 7–10, 1996, 12 p.
10. Battiato, G., M. Donada, and P. Grandesso, "DDL (Double Draining Layer): A New Generation of Porous Asphalt Pavements Developed by Autovie Venete, *Proceedings of Eurasphalt and Eurobitume Congress*, Vol. 3, Strasbourg, France, May 7–10, 1996, 11 p.
11. *Contribution Towards Reduction of Traffic Noise*, International Road Federation, Washington, D.C., 1992.
12. Attenborough, K. and C. Howarth, "Models for the Acoustic Characteristics of Porous Road Surfaces," *Proceedings of the International Tire/Road Noise Conference*, Gothenburg, Sweden, 1990.
13. Nelson, P.M., "Designing Porous Road Surfaces to Reduce Traffic Noise." *TRL Annual Review 1944–1995*, Transportation Research Laboratory, London, England, 1995, pp. 33–41.
14. Shuler, S. and D.I. Hanson, "Improving Durability of Open-Graded Friction Courses," *Transportation Research Record 1259*, Transportation Research Board, National Research Council, Washington, D.C., 1990.
15. Cabrera, J.G. and M.O. Hamzah, "Overcompaction Behaviour of Porous Asphalt," *Proceedings of Eurasphalt and Eurobitume Congress*, Vol. 3, Strasbourg, France, May 7–10, 1996, 10 p.
16. Page, G.C., "Open-Graded Friction Courses: Florida's Experience," *Transportation Research Record 1427*, Transportation Research Board, National Research Council, Washington, D.C., 1993.
17. Huddleston, I.J., H. Zhou, and R.G. Hicks, "Evaluation of Open-Graded Asphalt Concrete Mixtures Used in Oregon," *Transportation Research Record 1427*, Transportation Research Board, National Research Council, Washington, D.C., 1993.
18. Clifford, R., S. Dillon, G. Walsh, and I. Jamieson, "Design and Performance of Porous Asphalt Mixes in Ireland," *Proceedings of Eurasphalt and Eurobitume Congress*, Vol. 2, Strasbourg, France, May 7–10, 1996, 14 p.
19. Khalid, H.A. and C.M. Walsh, " A Rational Mix Design Method for Porous Asphalt Mixtures," *Proceedings to the 24th PTRC European Transport Forum*, Brunnel University, Middlesex, England, September 1996.
20. Woodside, A.R., W.D.H. Woodward, J.K. Baird, and P. Phillips, "A Critical Appraisal on the Performance of Porous Asphalt," *Proceedings to the 24th PTRC European Transport Forum*, Brunnel University, Middlesex, England, September 1996.
21. Colwill, D.M., G.J. Bowskill, J.C. Nicholls, and M.E. Daines, "Porous Asphalt Trials in the United Kingdom," *Transportation Research Record 1427*, Transportation Research Board, National Research Council, Washington, D.C., 1993, pp. 13–21.
22. Cabrera, J.G., J.R. Dixon, H. Khalid and F.K. Perez-Jimenewz, "Performance and Durability of Bituminous Materials: Performance Assessment of Spanish and British Porous Asphalts," *Proceedings of Symposium*, University of Leeds, Leeds, England, March 1994.
23. *Porous Asphalt Mixes*, publication of the South African Bitumen and Tar Association, Cape Town, South Africa, 1995.
24. Dixon, J.R., J.G. Cabrera, and M.O. Hamzah, "Aggregate Grading Design for Porous Asphalt," *Proceedings of Performance and Durability of Bituminous Materials*, University of Leeds, Leeds, England, March 1994.
25. Jansen Venneboer, J.W., B.V. Graond En Wegen, J.P.J. Van der Heide, and A.A.A. Molenaar, "Asphalt Construction for Heavy Duty Pavement and Road Widenings in The Netherlands," *Proceedings of*

Eurasphalt and Eurobitume Congress, Vol. 3, Strasbourg, France, May 1996.

26. Tolman, F. and F. Van Gorkum, "Mechanical Durability of Porous Asphalt," *Proceedings of Eurasphalt and Eurobitume Congress*, Vol. 2, Strasbourg, France, May 7–10, 1996, 10 p.
27. Livet, J., "The Specific Winter Behavior of Porous Asphalt: The Situation as It Stands in France," *Proceedings of the 9th PIARC International Winter Road Congress*, Seefield, Austria, March 1994.
28. Noort, M., "Winter Maintenance on Porous Asphalt," *Proceedings of the 9th PIARC International Winter Road Congress*, Seefield, Austria, March 1994.
29. Gustafson, K., "Susceptibility to Icing on Different Road Pavements," *Proceedings of the 9th PIARC International Winter Road Congress*, Seefield, Austria, March 1994.
30. Hoebeda, P. and S. Said, "Functional Properties of Porous Asphalt Mixture," *Statens Vaeg-Och*, Transportforsknings Institut, Linkoeping, Sweden, 1994.
31. Van der Kooij and H.A. Verburg, "Mixing of High Penetration Bitumen with Aged Bitumen During Hot Mix Recycling of Porous Asphalt," *Proceeding of Eurasphalt and Eurobitume*, Vol. 3, Strasbourg, France, May 1996.
32. Way, G., "OGFC Meets CRM, Where the Rubber Meets the Rubber," *Presented at the Asphalt Conference*, Atlanta, Ga., March 1998.

APPENDIX A

Survey Questionnaire

National Cooperative Highway Research Program

NCHRP Synthesis Topic 29-03

QUESTIONNAIRE

PERFORMANCE SURVEY ON OPEN-GRADED FRICTION COURSE MIXTURES

PURPOSE OF THIS SURVEY

Highway users benefit from the reduction of spray, splash and hydroplaning during wet weather conditions that Open-Graded Friction Course (OGFC) pavement mixtures can provide. The relative quietness, improved nighttime visibility, and rut resistance of OGFC mixtures are also considered benefits. A new generation of OGFC has evolved in the last five years. Changes include a combination of empirical design adjustments, adoption of innovative technologies, and improved construction practices. This synthesis will document the recent performance (successful and unsuccessful) of OGFC mixtures.

Thank you for filling out this survey. Please complete the following information:

Agency: ______________________________

Address: ______________________________

____

____

City: ______________ State: __________ ZIP: ______________

Questionnaire Completed By: ______________________________

Position/Title: ______________________ Date: ______________

Telephone: ______________

Fax: ______________

E-Mail: ______________

RETURN QUESTIONNAIRE AND SUPPORTING DOCUMENTS BY May 29, 1998

TO: Gerry Huber
5698 North 375 East
Pittsboro, IN 46167

For questions contact him by e-mail: gahuber@aol.com.

Extent of Open-Graded Friction Course Usage

How much is OGFC used? Answers to the following questions will provide a national perspective. You may need to consult your pavement management system for the basic information.

1. Does you agency use Open-Graded Friction Course?

    - ❑ Yes
    - ❑ No

    If No, has your agency used OGFC in the past?

    - ❑ Yes
    - ❑ No

    If your agency has used OGFC in the past, when did you stop using it? And why did you stop using it? Please include comments on the number of km still maintained, maintenance issues and rehabilitation issues as they face your agency.

    If your agency is not using OGFC and has not used it in the past please return your questionnaire. Thanks.

2. How many km of open-graded friction course surfaced pavements are in your entire road network? (Answer in centerline km or lane km, as your prefer.)

    ____________ ❑ Centerline km
    ____________ ❑ Lane km

3. In the last three to five years how many km of OGFC mixture on average have been built each year? (Answer in centerline km or lane km, as you prefer.)

    ____________ ❑ Centerline km
    ____________ ❑ Lane km

4. What design criteria are used to select an Open-Graded Friction Course mixture as the wearing surface? For example

    ____________ ❑ Traffic Level
    ____________ ❑ Environment (freezing or not; wet or dry)
    ____________ ❑ Other

5. How long is OGFC expected to last (design life) and how long does it last?

Please attach any published criteria, standards or other information about the selection of OGFC.

Materials and Design

This section looks at material requirements and design method typically used. The objective is to develop a current picture of materials used in the country. If there is more than one answer because of different geographic locations, you may provide more than one answer for each question.

6. What requirements are used for aggregates used in OGFC mixtures? (Attach specification if you prefer.)

7. What gradation bands are used for OGFC? Use standard sieves or fill in sieve sizes used in your state. (Attach specification if you prefer.)

	% Passing	
Sieve	Min.	Max.
25.00 mm		
19.0 mm		
12.5 mm		
9.5 mm		
4.75 mm		
2.36 mm		
1.18 mm		
0.600 mm		
0.300 mm		
0.150 mm		
0.075 mm		

	% Passing	
Sieve	Min.	Max.

8. What grade of asphalt binder is used in OGFC? Are modified asphalts used? Is the type of modifier specified?

9. Is a mix design method used? (Attach copy of test method if available.)

10. Are specific air voids targeted during either design or construction? If so, what voids are desired?

11. The following benefits are often identified for OGFC. Please indicate which benefits are important to your agency and your comments about effectiveness, how long the benefits last, etc.

Improved driver visibility on wet pavement (reduced spray).

Improved wet weather skid resistance.

Improved road marking visibility during wet weather (reduced glare on pavement surface).

Reduced traffic noise.

Other.

Construction

This section looks at special requirements for construction of OGFC. The objective of these questions is to identify special requirements for OGFC mixtures.

12. Are any modifications required on mixing plants? If so, what are they?

13. Are there any special limitations on stockpiled materials such as moisture content, etc.?

14. Are there any restrictions on the length of time a mixture can be stored in a silo or a maximum time from mixing to placing?

15. How is density specified? Is it controlled and measured? Is a standard rolling train used or is another method used to specify the number of roller passes?

16. What properties are used to accept mixtures? Are pay factors used? If so, on which items?

17. Are there any additional training requirements for technicians to do OGFC tests?

18. Is smoothness specified?

19. Are any special considerations required for longitudinal or transverse joint construction?

20. What low temperature restrictions are used for OGFC?

Maintenance

This section considers surface condition maintenance and winter maintenance.

21. Are special activities used to maintain the surface condition of OGFC pavements? If so, please list them. What methods have been successful? Unsuccessful? Attach maintenance policies if available.

22. Are potholes repaired using open-graded patching mixture? If so, what specifications are used for the patch mix?

23. Are special major maintenance activities used on OGFC pavements, for example, cleaning to restore permeability or flush coats to prevent raveling? If so, please list what is done and how often. Attach maintenance policies if available.

24. Is special material required for pavement markings on OGFC pavements? Do traffic markings require special attention?

25. Are special winter maintenance activities required to keep OGFC pavements snow and ice-free? Percentage wise, how much additional de-icing chemicals is needed? 50%? 100%?

26. Is permeability of OGFC pavements monitored periodically? If so, what permeability is desired and how often is permeability measured?

Rehabilitation

This section considers rehabilitation of OGFC pavements.

27. What is the typical failure method of OGFC pavements on your network?

28. Is the OGFC layer removed prior to rehabilitation?

29. In an overlay thickness design, is structural value given to an OGFC layer?

We hope to obtain a national view of what we are currently doing in materials, mix design, placement, maintenance, and rehabilitation of open-graded friction course mixtures. Your information will help define the practice. If you have any questions, you may contact Gerry Huber at:

Telephone (317) 390–3141 during the day or by
E-mail gahuber@aol.com.

THANK YOU FOR YOUR TIME AND EFFORT

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