Technical Report Documentation Page

1. Report No. FHWA/TX-06/0-5262-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle SYNTHESIS OF CURRENT PRACTICE ON THE DESIGN, CONSTRUCTION, AND MAINTENANCE OF POROUS FRICTION COURSES		5. Report Date May 2006 Published: July 2006 6. Performing Organization Code
7. Author(s) Allex E. Alvarez, Amy Epps Martin, Cindy K. Estakhri, Joe W. Button, Charles J. Glover, and Sung Hoon Jung		8. Performing Organization Report No. Report 0-5262-1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-5262
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Technical Report: September 2005-May 2006 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration

Project Title: Optimizing the Design of Permeable Friction Courses (PFC)

URL: http://tti.tamu.edu/documents/0-5262-1.pdf

16. Abstract

Open-graded friction courses (OGFC), or porous friction courses (PFC) as defined by the Texas Department of Transportation (TxDOT), are a special gap-graded asphalt mixture characterized by a large interconnected air void content. In general, the voids content is at a minimum of 18 percent. Similar mixtures (porous asphalt [PA]) with voids contents as high as 25 percent are successfully applied in Europe. These interconnected voids make these mixtures highly permeable with the capacity to reduce tire-pavement noise.

These characteristics are associated with the following advantages that can be obtained from the use of PFC as a surface layer: safety improvements, economic benefits, and environmental benefits. On the other hand, the following aspects are identified as disadvantages of PFC: reduced performance, high construction costs, winter maintenance issues, and limited structural contribution. Substantial efforts have been undertaken to correct previous failures in OGFC, and significant advances have been made since the 1990s with respect to mixture performance and service life.

This report summarizes the current state of the practice related to mixture design methods (proposed by different U.S. and international agencies and institutions), construction, maintenance, and performance of surface courses using OGFC and PA identified from a worldwide literature review. In addition, the report presents a synthesis of the relevant aspects related to the current practice and application of PFC in Texas based on the interviews conducted with selected TxDOT districts.

The report represents the baseline for a research project aimed to improve the PFC mixture design method using advanced research tools and develop guidelines for construction and maintenance of PFC. In this project, special efforts will be directed to address functionality in terms of permeability and noise reduction, and durability in terms of moisture damage and aging potential.

17. Key Words Porous Friction Courses, Open-Graded Friction Courses, Porous Asphalt, Mixture Design, Asphalt Mixture, Asphalt, Permeability, Noise Reduction, Maintenance, Construction, Aging, Clogging	18. Distribution Statement No Restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov

19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 86	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

SYNTHESIS OF CURRENT PRACTICE ON THE DESIGN, CONSTRUCTION, AND MAINTENANCE OF POROUS FRICTION COURSES

by

Allex E. Alvarez
Graduate Research Assistant, Texas Transportation Institute

Amy Epps Martin
Associate Research Engineer, Texas Transportation Institute

Cindy K. Estakhri
Associate Research Engineer, Texas Transportation Institute

Joe W. Button
Senior Research Engineer, Texas Transportation Institute

Charles J. Glover
Research Engineer, Texas Transportation Institute

and

Sung Hoon Jung
Graduate Research Assistant, Texas Transportation Institute

Report 0-5262-1
Project 0-5262
Project Title: Optimizing the Design of Permeable Friction Courses (PFC)

Performed in Cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

May 2006
Published: July 2006

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

The engineer in charge of the project was Amy Epps Martin, P.E. # 91053.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the Texas Department of Transportation personnel for their support throughout this project. Special thanks are given to the TxDOT project committee: Richard Izzo, Billy Pigg, Mykol Woodruff, Jeremy Dearing, and Jesse Sisco for providing technical guidance and assistance.

Acknowledgment is also due the staff personnel at Texas Transportation Institute. This project was completed in cooperation with TxDOT and FHWA.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

INTRODUCTION

Open-graded friction courses (OGFC) are special gap-graded asphalt mixtures characterized by containing a large proportion of interconnected air voids. This volumetric property results in large permeability values (in comparison with the permeability of dense-graded hot mix asphalt [DGHMA]) and noise reduction capacity. These two properties are the primary advantages and reasons for selection of OGFC during the last few decades in Europe, Japan, and the United States (U.S.).

In Texas, OGFC mixtures are termed porous friction courses (PFC) and defined in TxDOT Specifications, Item 342, as a surface course of a compacted permeable mixture of aggregate, asphalt binder, and additives mixed hot in a mixing plant (*1*). Since most of the available literature in the United States refers to this type of mixture as OGFC and, that in Europe, similar mixtures are called porous asphalt (PA), in this report, the mixture is designated as OGFC or PA to follow the original term cited in the sources.

A new-generation OGFC was promoted in the United States after 2000, when the National Center for Asphalt Technology (NCAT) proposed a mixture design method (*2*). These improved mixtures are highly open-graded providing a minimum air voids content of 18 percent, and in general, they are fabricated using fibers and polymer-modified binders. Although the mixture performance and the service life of OGFC have improved since the 1990s, mixture design, construction, and maintenance still require additional research.

This need for additional research motivated the research Project 0-5262, “Optimizing the Design of Permeable Friction Courses (PFC),” sponsored by TxDOT, and awarded to the Texas Transportation Institute (TTI) in September 2005. The main objectives of this research project are: (1) the improvement of the PFC mixture design method based on an evaluation of the current process used by TxDOT using advanced research tools and (2) the development of guidelines for construction and maintenance of PFC.

This document represents the first interim research report (Technical Report 0-5262-1) and summarizes the results of Task 2 (Conduct Information Search) that was included in the work plan to identify the current state of the practice related to the design, construction, maintenance, and performance of surface courses using OGFC. Therefore, it provides the necessary written information for use by TxDOT to guide the conduct of the research project and documents interim results for TxDOT and the research community.

The first part of the document highlights the advantages and disadvantages of OGFC and PA, and the second part summarizes the mixture design methodologies for OGFC and PA proposed by different U.S. and international agencies and institutions. Next, the fundamental aspects involved in the construction process of OGFC and PA and the primary considerations for maintenance of these materials are presented, followed by a section describing OGFC performance. Finally, the document concludes with information obtained from interviews with selected TxDOT districts regarding performance, maintenance, and construction of PFC.

1 ADVANTAGES AND DISADVANTAGES OF OGFC

This chapter presents the principal advantages of OGFC and PA identified from experiences and evaluations in different countries. In addition, the disadvantages recognized from their application are summarized. A significant portion of these advantages and disadvantages is established by comparison with DGHMA, which is considered the traditional technical option for construction of pavement surface layers.

1.1 ADVANTAGES OF OGFC

Advantages of OGFC are related to improvements in three basic areas: safety, economy, and the environment. This classification and many of the advantages highlighted in this section are based on the review presented by Khalid and Pérez on European PA performance (*3*).

1.1.1 Safety Improvements

OGFC can improve traffic safety, especially under wet conditions. Because these mixtures have air voids content greater than 15 percent, and even as high as 25 percent (shortly after construction), the material is highly permeable allowing direct flow of water from the surface to the bottom of the layer. This characteristic is one of the most important advantages of OGFC and constitutes a substantial difference from DGHMA. DGHMA requires much longer times for dispersal of water and facilitates accumulation in low areas.

Poorly drained surfaces create conditions for hydroplaning, since water accumulations at the surface limit and/or eliminate the contact between the tire and the pavement. This situation is especially hazardous because it results in loss of control for braking and steering. Since the OGFC is highly permeable, water layers on the pavement surface are typically eliminated (except during very high-intensity rainfall), thus preventing hydroplaning.

Spray is related to very fine water particles from pavement surfaces generated by rolling wheels and vehicle bodies advancing on wet pavements. Splash is related to the coarser water particles created when rolling wheels move over pools in poorly drained areas. Both phenomena contribute to reduced visibility, even more so than with fog since the droplets created from splash and spray in comparison with the droplets in fog have higher density and are larger in size (3). Drainage of water from the surface is a clear advantage in minimizing these phenomena (4). Figure 1 shows the differences between one road section with PA and another without this mixture type at the surface.

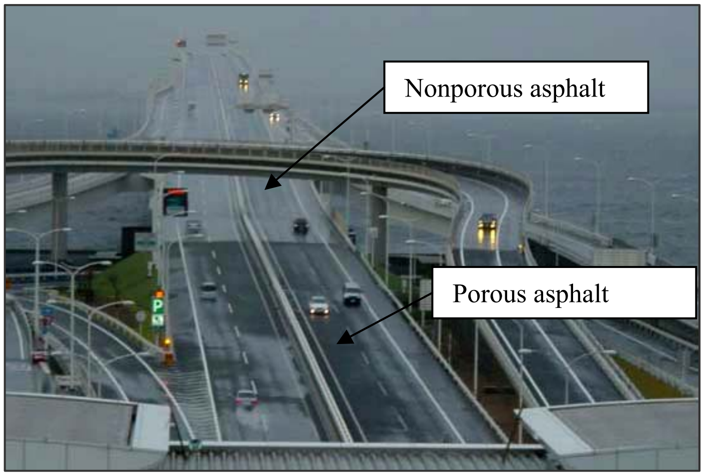

Figure 1. Aqua-line Crossing Tokyo Bay during a Rainstorm (4).

Glare reduction, particularly at night, can also be counted as an advantage of OGFC. OGFC exhibits mainly diffuse reflection both during darkness and daylight. This characteristic improves the visibility of road markings during the night and day, which is affected by the presence of reflected light (5). Improvements are obtained in wet conditions, since less water at the surface is associated with less reflection of incident light (3).

Therefore, OGFC provides favorable conditions for traffic operating under wet conditions, and problems such as splash and spray, hydroplaning, and glare associated with wet vehicular operation on DGHMA can be reduced or, in the best circumstances, avoided.

An additional advantage of OGFC is its higher wet frictional resistance compared with DGHMA and Portland cement concrete layers. Kandhal presented numerous reports regarding improvements in frictional resistance and the consequent reduction in accidents under wet conditions associated with the use of OGFC (6). Higher wet skid resistance is reached at high speed on porous mixtures compared to that on wet DGHMA. However, at low speed, differences in response of these two types of mixtures are not noticeable *(3, 5)*.

1.1.2 Economic Benefits

The use of porous mixtures results in reduced fuel consumption on the order of 2 percent due to enhanced smoothness. In general, higher savings are reported when the porous mixture is compared with mixtures of greater roughness. In addition, reduction in the rate of tire wear on PA was suggested based on a decrease in tire stresses generated by the improved macrotexture of this type of mixture (*3*, *7*).

1.1.3 Environmental Benefits

Noise reduction capacity is an important characteristic of OGFC and PA mixtures, which becomes an important advantage to reduce or control highway noise levels. This aspect has widely motivated the use of porous mixtures in Europe, while in the United States the safety improvements under wet conditions have been the primary motivation. In the United States, Arizona has proved successful application of OGFC for noise reduction purposes, and California has made advances in research on this same topic. In addition, the "Quiet Pavements Pilot Program" has been issued by the Federal Highway Administration to promote the use of low-noise pavements, and field measurements have been taken by NCAT with the objective to "monitor and catalog pavement noise levels (*8*)."

Decreased noise levels in the range of 3 to 6 dB(A) are expected when OGFC are compared with DGHMA. This general conclusion is supported in the comprehensive set of studies summarized by Kandhal, including information from several European countries and Canada, and it is coincident with research findings in California (*9*). In addition, studies from the United States showed that OGFC are quieter than Portland cement concrete pavements (PCCP). In this case, the range of noise reduction values is higher than that established from the comparison with hot mix asphalt. For example, a range between 2.3 and 3.6 dB was reported in Maryland (1990), while in Oregon (1994) the reported reduction ranged between 5.7 and 7.8 dB. A higher decrease of 14 dB was indicated in Texas when asphalt-rubber OGFC was used to overlay an existing continuous reinforced concrete pavement (CRCP). Figure 2 presents a comparison of noise levels among different types of pavements with the lowest level obtained for OGFC.

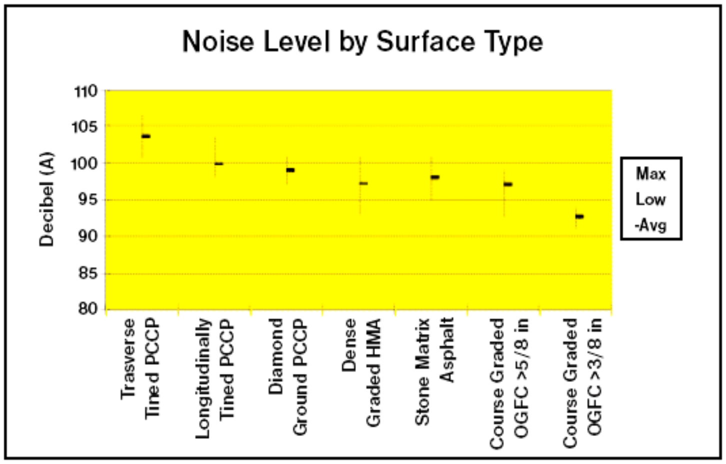

Figure 2. Noise Levels for All Pavement Types in NCAT Database (*8*).

When comparing the noise reduction of PA and noise barriers on a unit cost basis, PA is 2.5 to 4.5 times more efficient *(10)*. Furthermore, OGFC becomes an advantageous option to control or diminish noise at highway speeds for pavements located in urban areas since the reduction is applied directly from the source (tire/road noise), which permits its implementation without negative urban repercussions *(11)*.

Higher driver comfort levels can be achieved with the use of OGFC, since noise reduction is perceived not only outside the vehicle, but also inside. In addition, OGFC can be considered an environmentally friendly product because crumb rubber from old tires can be integrated into the binder to produce this type of mixture (*3*). Successful results have been reported in Arizona regarding this recycling alternative (*9*, *12*). Besides, modern OGFC type mixtures usually require fibers to prevent excessive draindown and improve resistance to raveling. In 2006, Chowdhury et al. demonstrated that waste fibers from tire recycling processes can be satisfactorily used in OGFC mixtures (*13*).

Finally, PFC mixtures produce cleaner runoff than that obtained from conventional dense-graded mixtures. Lower total suspended solids, total metals, and chemical oxygen demand is reported in the runoff of PFC. The benefits obtained from the use of PFC mixtures are comparable with those attained from a vegetated filter *(14)*.

1.2 DISADVANTAGES OF OGFC

Reduced performance, high construction costs, winter maintenance, and minimal structural contribution are the main disadvantages related to the use of OGFC and PA as indicated in the next sections.

1.2.1 Reduced Performance

Performance can be evaluated in terms of both durability and functionality (permeability and noise reduction). Durability issues in OGFC and PA are mainly associated with raveling, which can progress rapidly, once it starts (*15, 16*). However, diverse experiences are reported by different state departments of transportation (DOTs) over the last few decades. After publication of the Federal Highway Administration mixture design method for OGFC, in 1974, some states began using the material. Unfortunately, mixture performance was diverse, and some state DOTs suspended the use of OGFC, arguing “unacceptable performance and/or lack of adequate durability” (Mallick et al., 2000, p. 1) (*17*). During the 1990s, important improvements in binders, admixtures (e.g., fibers), and gradation enhanced OGFC performance in terms of longer life, reduction of failures (e.g., raveling), and conservation of functionality for longer periods (*16, 17*).

According to the survey by NCAT in 1998, service lives of 8 or more years were reported for OGFC, and positive results were indicated by half of the states that participated in the survey (*17*).

As for functionality, accelerated loss of permeability and noise reduction capacity due to clogging of pores is the main concern for these mixtures. A wide range of service lives has been reported in various countries, and different approaches have been adopted to deal with the reduction of voids volume.

In Spain, for example, PA (voids content lower than 20 percent) retained its drainage capacity for periods of 9 years when subjected to medium traffic; whereas, after 2 years, clogging was reported in mixtures operating under heavy traffic (*3*). In Britain, the reduction in the suppression of noise capacity and permeability and some increases in spray levels are recognized, but the material still retains its noise reduction capacity and similar performance in terms of spray generation compared to thin surfacing (*18*).

Other European countries (i.e., Denmark) frequently use cleaning equipment and the construction of a two-layer PA as an integrated strategy to improve the functional characteristics of the mixture over a long period of time (*11*). In the United States, these practices have not been implemented. Local agencies assume that the material can perform its own auto-cleaning, which is generated by the suction created by rolling tires at high speed. In addition, air void contents higher than 20 percent ensure adequate drainage capacity for the entire life service in the majority of the cases (*5*).

1.2.2 Construction Costs

Construction costs are usually considered higher for OGFC when compared with DGHMA (*3*, *16*). The cost per ton of OGFC in the United States is between 10 and 80 percent higher than the cost of DGHMA, and the life can be between 50 and 100 percent of the DGHMA life. When unmodified asphalt is incorporated into the mixture, the extra cost is in the range of 6 to 38 percent. The cost of OGFC containing modified asphalt is 50 to 80 percent higher than the cost of DGHMA containing unmodified binder. However, the use of modified binder provides similar life expectancies for OGFC as compared to DGHMA (*16*).

1.2.3 Winter Maintenance

Winter maintenance is considered a significant disadvantage of OGFC and PA. Since OGFC mixtures have a tendency to cool faster than adjacent DGHMA, OGFC can exhibit earlier frost and ice formation than DGHMA, and these conditions may persist for longer periods. Therefore, larger amounts and more frequent application of deicer agents and higher care in the homogeneity of the application are required. These requirements generate higher maintenance costs for OGFC.

1.2.4 Structural Contribution

For pavement structural design, OGFC and PA are typically considered to have no or minimal structural contribution (*7*). However, several authors indicate that porous mixtures and conventional DGHMA are structurally comparable (*3, 4, 19*). Chapter 4 provides detailed information about material properties related to the structural contribution of OGFC and PA.

2 MIXTURE DESIGN METHODS

This section summarizes the mixture design methodologies for OGFC and PA used by different local and foreign agencies and institutions. First, an overview of the design procedures for OGFC applied by some local agencies is introduced. Next, to provide a short, historical background, the design method proposed in the 1990s by FHWA is introduced. After that, the methodologies suggested by NCAT and the current method of design applied by TxDOT are described. These methodologies provide a general idea about the current design approach in the United States. However, one should keep in mind that there are variants in the design processes applied by different state DOTs.

In addition, the current design approaches used in some of the European countries with higher construction rates of PA (i.e., Denmark, The Netherlands, Australia, Belgium, Switzerland, Great Britain, and Spain) are briefly described. Finally, the methodologies proposed by Khalid and Pérez and Khalid and Walsh to improve the mixture design in European PA are introduced (*3*, *7*).

2.1 OVERVIEW OF MIXTURE DESIGN PROCEDURES APPLIED IN THE UNITED STATES

According to the synthesis of performance on OGFC presented by Huber in 2000, there is not a unified methodology adopted by local agencies for design of OGFC (*16*). The mixture design procedures are diverse and use different criteria for defining the optimum binder content of OGFC.

For example, Florida and Wyoming were still using the FHWA Technical Advisory T5040.31: "Open-Graded Friction Courses," whereas New Mexico did not apply any specific test-based method, but the asphalt binder content was established through visual evaluation of draindown and coating. California used the centrifuge kerosene equivalent and the approximate bitumen ratio to obtain the binder content, and in Nevada this content was based on a specific draindown test applied to determine a percentage of opacity that was implemented as a design criterion (*16*).

The criteria adopted in Georgia for OGFC mixture design were: retained coating after boiling, resistance to draindown, and asphalt content. The optimum asphalt content was selected by evaluating the minimum voids in mineral aggregate. The draindown test was performed using the optimum binder content, and with this binder content, the fiber addition required to satisfy the draindown test criteria was determined.

In 2000, Oregon was the only state that specified air voids content as design requirement. The required air voids content and voids filled with asphalt were between 13.5 and 16.0 percent and between 40 and 80 percent, respectively. In addition, the design procedure included performing the draindown test.

Section 2.4 describes the mixture design method for PFC currently applied in Texas.

2.2 FHWA METHOD (1990)

In December 1990, the Federal Highway Administration published Technical Advisory T5040.31: "Open-Graded Friction Courses," which included complete guidelines for mixture design purposes (*20*). The methodology was based on the evaluation of the surface capacity of the predominant aggregate fraction (by immersion and drainage of the material in S.A.E. No. 10 lubricating oil) according to the American Association of State Highway and Transportation Officials (AASHTO) T 270, "Centrifuge Kerosene Equivalent and Approximate Bitumen Ratio." The predominant aggregate fraction corresponds to the material that passes a 3/8 inch sieve and is retained on a No. 4 sieve.

The asphalt content was determined using a specific empirical formula, which includes the following variables: surface constant value (K_c) and apparent specific gravity of the predominant aggregate (SG_a).

Next, taking into account the volume of asphalt and the design air voids content (suggested as 15 percent), the percent of fine aggregate by weight of total aggregate was calculated. The coarse aggregate gradation should be modified if the magnitude of its voids is not enough to contain the asphalt and the air voids.

Additionally, a test to establish the optimum mixing temperature (considering draindown issues) and a test for resistance to effects of water (immersion-compression test–AASHTO T 165, "Effect of Water on Cohesion of Compacted Bituminous Mixtures," and T 167, "Compressive Strength of Bituminous Mixtures") on the designed mixture were required (*20*).

2.3 NCAT MIXTURE DESIGN METHOD (2000)

Based on experiences of different states in the United States, European progress, and internal research, NCAT published a mixture design method for the new generation of open-graded friction courses in 2000. This method has been enhanced during recent years, based on additional research. The design process involves the following steps (6):

1) materials selection,
2) selection of design gradation,
3) determination of optimum asphalt content, and
4) evaluation for moisture susceptibility.

Table 1 summarizes the required specifications for selecting granular materials, which are based on those available for stone matrix asphalt (SMA).

Table 1. Specifications for Granular Materials.

Parameter	***Specified Value***
Los Angeles (LA) abrasion, %	<30
Fractured faces, %	>90 for particles with two faces, 100 for particles with one face
Flat and elongated particles, %	<5 and 20 (ratios of 5:1 and 3:1, respectively)
Fine aggregate angularity (FAA)	>45

Table 2 includes a summary of criteria for binder selection based on the expected traffic volume. Either cellulose fiber or mineral fiber in proportions of 0.3 and 0.4 percent by weight of total mixture, respectively, can be considered. Typical fiber contents are 0.2 to 0.5 percent and depend on mixture draindown test results (American Standard of Testing Materials [ASTM] D6390) (6).

The second design step involves selecting a gradation that ensures high voids content in the total mixture and the existence of stone-on-stone contact in the coarse aggregate skeleton, with coarse aggregate defined as the fraction larger than the No. 4 sieve.

Table 2. Binder Selection Criteria.

Recommended Type of Binder	*Volume Traffic*
High stiffness binders[a] made with polymers, fiber addition is desirable	Medium to high
Polymer modified binders or fiber addition	Low to medium

[a] "Two grades stiffer (PG grading system) than normally used for the local climatic conditions." (6)

When the volume of voids in the coarse aggregate of the compacted mixture (VCA_{mix}) (that will be filled with air, the effective asphalt content, and fine aggregate) is smaller than the volume of voids in the coarse aggregate calculated from the dry rodded unit weight (VCA_{DRC}) using only the coarse aggregate, this is $VCA_{mix} < VCA_{DRC}$, the mixture will have stone-on-stone contact. The design gradation is then determined based on this concept and the recommended gradation for OGFC (Table 3) (6).

Table 3. Recommended Gradation for OGFC (*6*, *21*).

Sieve, mm (inch)	*Percent Passing*
19 (0.75)	100
12.5 (0.5)	8-100
9.5 (0.37)	35-60
4.75 (0.19)	10-25
2.36 (0.09)	5-10
0.075 (0.003)	2-4

First, three trial aggregate blends are established (based on the Table 3 gradation limits with one blend falling in the middle of the limits). Then using only the coarse aggregate fraction, VCA_{DRC} is measured according to AASHTO T 19, "Bulk Density and Voids in Aggregate." In addition, VCA_{mix} is determined using compacted specimens (50 gyrations of the Superpave Gyratory Compactor [SGC]) with asphalt contents between 6 and 6.5 percent for each trial gradation. Fibers should be included in the specimens if they are going to be used in the actual mixture. Finally, the design gradation is selected considering stone-on-stone contact ($VCA_{mix} < VCA_{DRC}$) and high voids in the total mixture. The air voids content of the OGFC is determined by volumetric measurements based on the bulk specific gravity of compacted specimens and the theoretical maximum specific gravity of loose mixture.

Determination of optimum asphalt content (Step 3) is based on the application of a defined series of laboratory tests using compacted and uncompacted samples with different binder contents. Table 4 summarizes these tests and specification limits. All compacted specimens are fabricated using 50 gyrations of the SGC**.**

Table 4. Tests to Determine the Optimum Asphalt Content.

Test	***Specification***
Draindown test, %	<0.3 by weight of total mixture
Air voids content, %	>18[(a)]
Cantabro abrasion test (unaged compacted samples), %	Abrasion loss <20
Cantabro abrasion test (aged compacted samples), %	Abrasion loss <30

[(a)]The minimum value has been established as 18 percent; however, higher values are desirable in order to increase permeability.

Permeability magnitudes greater than 100 m/day (328.08 feet/day) are desired; however, determination of permeability in compacted specimens (ASTM PS 129) is optional.

The last step of the mixture design procedure involves evaluation of moisture susceptibility using a modified Lottman method (AASHTO T 283). The retained tensile strength ratio is used as an index, and a minimum of 80 percent is required after application of five freeze/thaw cycles using specimens compacted with 50 gyrations of the SGC *(6)*. Other modifications include ensuring saturation during freeze cycles by keeping the samples submerged in water and providing adequate saturation of compacted samples by applying a partial vacuum.

More recent research at NCAT confirmed the applicability of the recommended compaction effort (N_{design} value of 50) and the use of SGC specimens in the Cantabro loss test *(2)*. Researchers recommended the compaction effort based on the fact that aggregate breakdown induced by the SGC was similar after applying either 30 or 60 gyrations. Further, after applying 20 gyrations, the mixture obtained most of its density with the additional gyrations primarily yielding aggregate breakdown. However, based on calculations of VCA_{DRC} and VCA_{mix}, researchers concluded that the stone-on-stone condition was only achievable with both 45 and 60 gyrations. Furthermore, good agreement between the compaction effort induced with 50 gyrations of the SGC and 50 blows of the Marshall hammer was found. Incidentally, the Marshall hammer is used extensively in Europe for design of PA.

In addition, the CoreLok® procedure, using double bags, was recommended for determining air voids content and bulk specific gravity in compacted samples of OGFC (*2*, *21*), because more accurate results are obtained compared to those from the dimensional method. Lower air void magnitudes were obtained when using the CoreLok® method, which exhibited differences of about 2 percent in comparison to the values obtained from dimensional analysis. Therefore, a target minimum air voids content of 16 percent is recommended when the CoreLok® method is used and 18 percent if the dimensional method is employed.

The Cantabro test has been typically practiced on aged specimens. The aging process was recommended in order to evaluate resistance to abrasion after stiffening (oxidation) of the binder. The initial proposal for the aging process included holding five compacted specimens in a forced draft oven for 120 hours at a temperature of 85°C (185°F) in accordance with AASHTO PP2-01 (*6*). After this process, the samples were cooled to 25°C (77°F) and stored for 4 hours prior to conducting the Cantabro test. Recent research led to the conclusion that the aging procedure is not necessary since noticeable differences in Cantabro test results performed using aged and unaged specimens compacted with both Marshall hammer and SGC were not found (*21*). Therefore, a weight loss of no more than 20 percent for unaged samples is recommended. However, if an aged specimen is used, a maximum weight loss of 24 percent is recommended (*21*).

The number of cycles initially required in the modified Lottman method was reviewed and current research recommends performing this test using just one cycle (*21*). Further, repeatability of the draindown test at the production temperature was improved by using a finer wire mesh basket (No. 8 sieve) (*2*).

2.4 TxDOT PFC MIXTURE DESIGN METHOD

The current TxDOT PFC mixture design method is defined in TxDOT Test Method Tex-204-F, Section 7-Part V (*22*). Item 342 of the TxDOT Standard Specifications provides material requirements (*1*). The following two types of binders are allowed in this specification:

- a Type I or II asphalt rubber (A-R) binder defined in Item 300.2.I with a minimum of 15 percent by weight of asphalt of Grade C or Grade B crumb rubber defined in Item 300.2.G, and
- a PG binder (polymer-modified asphalt) with a minimum high-temperature grade of PG76-XX, defined in Item 300.2.J, with a lime content between 1.0 and 2.0 percent by weight of dry aggregate and a fiber addition in the range of 0.2 to 0.5 percent cellulose or mineral fibers by weight of mixture (*1*). (Additional fibers may be needed to meet mixture requirements.)

Based on the type of binder selected, master aggregate gradation bands (percent passing by weight or volume) and binder content ranges are provided (Table 5). Aggregates must also meet requirements including coarse aggregate angularity, deleterious materials, soundness, two types of abrasion (Micro-Deval and Los Angeles), and flat and elongated particles.

Table 5. Master Gradation Band and Binder Content (*1*).

Sieve Size	***PG 76 Mixtures, %***	***A-R Mixtures, %***
3/4"	100.0	100.0
1/2"	80.0-100.0	95.0-100.0
3/8"	35.0-60.0	50.0-80.0
#4	1.0-20.0	0.0-8.0
#8	1.0-10.0	0.0-4.0
#200	1.0-4.0	0.0-4.0
Binder Content, %		
	6.0-7.0	8.0-10.0

Following selection of materials, two replicate specimens (6-inch diameter by 4.5-inch height) for each of three binder contents are mixed, short-term oven aged for 2 hours at the compaction temperature, and compacted in the SGC using an N_{design} of 50. The three trial binder contents must be separated by 0.5 percent. An optimum binder content is then selected based on the target density specified (between a suggested limit of 78 percent and a maximum of 82 percent, according to Table 4 in Item 342). The minimum binder content is specified in 6 percent to ensure adequate binder film thickness.

Next, specimens at the selected optimum binder content are produced for an evaluation of draindown (Tex-235-F), moisture susceptibility (Tex-530-C), and durability (Tex-245-F) (*23, 24*). The optimum mixture must have a maximum draindown of 0.2 percent, where draindown is defined as the ratio of: (1) the change in the weight of paper plate that the mixture is allowed to drain onto from a wire mesh basket at the plant mixing temperature for 1 hour to (2) the original specimen weight. The moisture susceptibility of the optimum mixture is determined by boiling the loose mixture in water for 10 minutes and visually evaluating the percentage of stripping immediately and after 24 hours. The percentage of stripping after 24 hours is reported for comparison during production, and no requirement is provided in the TxDOT specification. This test may be waived.

Finally, the durability of the optimum mixture is evaluated based on the percentage of Cantabro loss, where Cantabro loss is defined as the change in weight of the specimen before and after an abrasion test divided by the original specimen weight. The test involves placing a compacted specimen into the Los Angeles abrasion equipment without the steel balls and rotating the apparatus for 300 revolutions at 30-33 revolutions per minute. Table 4 in Item 342 suggests a maximum Cantabro loss value of 20 percent, but this value is reported for information only.

Item 342 of the TxDOT specification integrates aging of the binder, but only during production. Aging ratio is defined as the ratio of the high PG temperature Dynamic Shear Rheometer parameter ($G^*/\sin \delta$) of the extracted and recovered binder sample, and this same parameter evaluated on the original unaged binder. A maximum aging ratio value of 3.5 is specified.

2.5 DANISH MIXTURE DESIGN METHOD

In Denmark, mixture design is based on Marshall specimens that are used to evaluate volume composition, basically, the air voids content. The desired air void content is about 26 percent, depending on the gradation selected, but Danish road standards do not require a specific permeability. Although not a requirement, Danish Road Institute (DRI) measurements of permeability in the laboratory range from 0.15-0.50 cm/s (0.06-0.20 inch/s)[1]. In the field, using a sealed tube (Beckers tube) placed on top of the PA, the run-out time for 10 cm (3.94 inch) of water is determined. Run-out time is utilized to evaluate the degree of clogging, in accordance with the following general guidelines:

- high permeability: new PA: t < 30 seconds,
- medium permeability: partly clogged PA (can be cleaned): t < 50 seconds, and
- low permeability: clogged PA (cannot be cleaned): t > 75 seconds.

In addition, a draindown test is practiced to determine the maximum possible asphalt content, and torture tests (e.g., Hamburg Wheel Tracking Test) are employed for rutting assessment. No experiences have been reported on the application of the Cantabro test in Denmark for durability evaluation, but the Rotating Surface Abrasion Test is considered as an alternative as suggested by van Bochove *(25)*.

Maximum binder contents are evaluated under the following criteria: guarantee a minimum void content to reduce traffic noise and ensure appropriate water drainage and draindown prevention during mixing, handling, and placement. Minimum binder content is selected considering an adequate resistance against water damage, minimizing aging with a thick asphalt film, and satisfactory resistance to disintegration. Stable mastics are formulated by employing styrene butadiene styrene (SBS)-modified asphalt (50/100 penetration), cellulose fibers, hydrated lime, and limestone filler.

2.6 THE NETHERLANDS MIXTURE DESIGN METHOD

In The Netherlands, mixture design is practiced based on the compaction of four Marshall specimens with 50 blows on each specimen face. Average voids content with a minimum value of 20 percent is required as a unique requirement, which can be attained by modifying the gradation or changing materials, if required[2].

Functional properties (noise reduction, water drainability, splash and spray reduction, skid resistance, and durability) are considered adequate if the gradation used in the field, asphalt content, layer thickness (50 mm [1.97 inch]), and compaction specifications are met.

---

[1] Personal communication with Dr. Carsten Bredahl Nielsen, DRI.

[2] Personal communication with Ministerie van Verkeer en waterstaat (The Netherlands).

PA have been built as PA 0/11 and PA 0/16 (the last term indicates the maximum nominal size in millimeters) incorporating crushed rocks and sand while reclaimed asphalt pavement is not used in this application. Penetration-graded asphalt has been utilized at contents of about 4.5 percent (by weight of aggregate), whereas polymer-modified bitumen has not been used with PA in The Netherlands. However, the filler contains hydrated lime.

Some tests, such as retained indirect tensile strength, rotating surface abrasion, Cantabro, and semi-circular bending, are practiced for research purposes.

2.7 AUSTRALIAN MIXTURE DESIGN METHOD

The Australian mix design guide includes three mixture designations for open-graded asphalt (OGA) that can be used for wearing courses: OG10, OG14, and OG20 (*26*). This denomination is based on the nominal mix size expressed in millimeters. In addition, two classes (Type I and Type II) of OGA are defined depending on the expected traffic. OGA Type II is suggested for roads with the higher traffic volume (greater than 5×10^6 equivalent standard axles and/or more than 500 commercial vehicles per lane, per day), and it is designed to provide premium performance.

For mixture Type II, the use of fibers (0.3 to 0.5 percent by mass) is mentioned as a technical possibility to prevent draindown problems during transport and placing, and the use of modified binders is suggested to obtain improved performance[3]. Further, hydrated lime can be added as mineral filler to minimize draindown issues and diminish propensity of stripping in the mixture (*26*).

The design binder content is obtained by adding the amount of binder draindown to the provisional binder content. Whereas the amount of binder draindown is calculated using the basket drainage test, the provisional binder content is established as the mean value of the minimum content of binder that ensures sufficient abrasion resistance and durability (evaluated by practicing the Cantabro test on compacted specimens) and the maximum asphalt content that allows sufficient air voids to get in the mixture (obtained by evaluating the air voids content on compacted specimens). Eighty cycles of the Australian gyratory compactor (AGC) are used to

---

[3] For mixture Type I, the total range of binder content suitable varies from 4.5 to 5.5 percent (percentage by mass of total mixture), according to the nominal mix size. For mixture Type II, the content varies from 4.5 to 6.5 percent.

fabricate the compacted specimens, which are manufactured using three different binder contents.

Finally, the abrasion resistance of compacted specimens fabricated with the provisional binder contact is verified by applying the Cantabro test on dry and moisture conditioned samples. Table 6 summarizes the limits established in the Australian design guide for each parameter integrated in the design of OGA.

Table 6. Summary of Design Limits (*26*).

Design Criteria	***Type II***	***Type I***
Cantabro abrasion loss, unconditioned(a), %	<20	<25
Cantabro abrasion loss, conditioned, %	<30	<35
Air void content, %	20-25	>20
Draindown, %	<0.3	<0.3

(a)The mixture is rejected if any individual result is greater than 50%.

2.8 BELGIAN MIXTURE DESIGN METHOD

PA mixture design in Belgium first requires optimizing the mixture gradation through use of the software PradoWin (Programs for Road Asphalt Design Optimization) developed by the Belgian Road Research Center. The gradation must meet the following requirements[4]:

- "stone fraction" (larger than 2 mm [0.08 inch]): 81-85 percent,
- sand fraction (between 0.063 mm [0.0025 inch] and 2 mm [0.08 inch]): 11-13 percent, and
- filler fraction: 4-6 percent.

Considering the characteristics of each material (coarse aggregate, sand, filler, and binder) PradoWin optimizes the mixture composition to attain a target void content.

To determine the optimum binder content, Marshall compacted specimens are fabricated with different binder contents (increments of 0.3 percent are recommended). Volumetric properties of the mixture (i.e., air void content) are determined, and Cantabro tests are performed in order to define, respectively, upper and lower limits for asphalt content. Loss of mass in the Cantabro test (at 18°C [64.4°F]) should be lower than 20 percent in order to minimize raveling

---

[4] Personal communication with Dr. Joëlle De Visscher, Belgian Road Research Center.

problems, while the minimum specified value for air void content is fixed at 21 percent[5]. Permeability determinations in the laboratory are not practiced, but in situ drainage characteristics are evaluated in the field with a "drainometer."

2.9 SWISS MIXTURE DESIGN METHOD

Switzerland has adopted the European specifications for PA *(27)*, and a national standard (SN 640 431-7NA: Mélanges bitumineux–asphalte poreux) was developed to accommodate their local conditions *(28)*. The national standard provides for selection of the constituent materials and following the required process to define material proportions.

Both paving grade bitumen and modified bitumen are considered for design, and specific recommendations are defined for each, depending on the function of the PA course. Further, additions such as polymers and organic or mineral fibers can be implemented.

After defining a series of gradations (identified with the designation PA followed by an indication in millimeters of the upper sieve size of the aggregate), the Swiss national standard defines the minimum binder content for each proposed gradation *(28)*. Binder contents range between 5 percent for gradation PA 8 and 3 percent for gradation PA S 32. In addition, the binder content is adjusted by the factor α:

$$\alpha = \frac{2.65}{\rho} \qquad (1)$$

where:

ρ = dry density of the aggregate particle in Mg/m^3.

The next design requirement corresponds to the evaluation of mixture drainage capacity, which according to the European specifications can be established either by permeability (vertical or horizontal) or by evaluating the air voids content of compacted laboratory specimens. For this parameter, minimum and maximum values are established. Specimens can be prepared by applying impact compaction (Marshall procedure with 50 blows per side) or by using the gyratory compactor using 40 gyrations. However, the Swiss standard just suggests the evaluation

---

[5] Personal communication with Dr. Joëlle De Visscher, Belgian Road Research Center.

of air voids content in Marshall samples and fixes only minimum air voids for each mixture. Air voids range between 18 and 22 percent.

The Swiss mixture design evaluates the sensitivity of the PA to water. According to the European specification, it can be determined by means of the splitting tensile test. In the Swiss standard, the use of Marshall specimens was adopted, and minimum values for retained tensile strength ratio are defined for each mixture. These values range from 70 to 80 percent. Although the European specification considers evaluation of particle loss and draining of the binder, the Swiss standard does not address these issues.

The last specified parameter corresponds to the maximum temperature of the mixture in all the production stages, which is given as a function of binder penetration for pure bitumen. When modified asphalt is used, this temperature should be established in agreement with the supplier of such product.

2.10 BRITISH MIXTURE DESIGN METHOD

Design of PA in Britain is currently based on a recipe approach. The British standard, BS 4987-1:2005, defines aggregate gradations and binder grade and content for two kinds of PA mixtures: mixture 6/20 mm (0.24/0.79 inch) for highway applications and mixture 2/10 mm (0.08/0.39 inch) for "other applications."

For gradation 6/20 mm (0.24/0.79 inch), bitumen grade 100/150 pen or 160/220 pen is recommended at contents of 3.7 or 4.5 percent (modified) by mass of total mixture (±0.3 percent) except for limestone. For gradation 2/10 mm (0.08/0.39 inch), the same bitumen grade is recommended at a content of 5.2 percent (±0.5 percent) except for limestone. In both cases, the use of modified bitumen is recommended in order to ensure adequate durability. The modifiers listed in the standard include fibers (organic and inorganic), natural rubber, and styrene butadiene rubber *(29)*. Two percent by mass of total aggregate is specified as hydrated lime for these mixtures in order to minimize stripping and increase binder stiffness. They consider an asphalt content of 4.5 percent adequate to reach a balance between durability and relative hydraulic conductivity *(18)*.

In accordance with the Manual of Contract Documents for Highway Works, the binder drainage test is required to determine the maximum target binder content (T_{max}) with the selected aggregate and binder *(30)*. With a target binder content of 4.5 percent, the proposed mixture is considered adequate if T_{max} is equal to or greater than 4.5 percent. This is a design test that is performed on uncompacted mixture specimens.

Mixture design includes determination of hydraulic conductivity in the field, after placement but before trafficking. Acceptable average relative hydraulic conductivity values range from 0.12 s^{-1} to 0.40 s^{-1} (*30*).

2.11 SPANISH MIXTURE DESIGN METHOD

Design of PA in Spain determines the maximum asphalt content without creating draindown or permeability problems and the minimum binder content that guarantees resistance to particle loss under traffic and ensures a thick binder film covering the aggregate (*3*).

Spain establishes a minimum binder content based on the Cantabro test that is performed using Marshall specimens compacted with 50 blows per face. After defining a minimum air voids content (the target is usually 20 percent), the maximum binder content to obtain this air voids content is determined. Researchers perform necessary calculations by using the same Marshall specimens that are employed in the Cantabro test. Typical binder contents are around 4.5 percent.

Even though the test is not defined in their specifications, there is a particular test to evaluate the maximum asphalt content without creating excessive binder draindown (*3*). As reported by Khalid and Pérez, sometimes indirect tension, wheel tracking, and laboratory permeability have been used for PA design (*3*).

Since 2001, the Spanish have required performing the Cantabro test using both dry specimens and after immersion (1 day in water at 60°C [140°F]). The maximum specified loss of weight in these tests is shown in Table 7. Additionally, this table presents the previous Spanish specification for the Cantabro test (MOPU 89), which is shown for comparison.

Researchers proposed the moisture conditioned Cantabro test since the use of low quality filler and low adhesion aggregate-binder combinations were identified as responsible for accelerated mixture deterioration[6].

---

[6] Personal communication with Dr. Félix Edmundo Pérez, Polytechnic University of Cataluña.

Table 7. Spanish Specifications for Cantabro Test[7].

	MOPU/89 Recommendation	*Foment M. OC 05/2001*
Air voids content, %	>20	>20
Dry Cantabro loss, %	at 25°C < 25	at 25°C < 20 (T00-T1) at 25°C < 25 (T2-T3)
Moist Cantabro loss, %	-----	at 25°C < 35 (T00-T1) at 25°C < 40 (T2-T3)

Note: T00, T1, T2, and T3 are all categories of heavy traffic.

2.12 OTHER PROPOSED MIXTURE DESIGN METHODS

Khalid and Pérez proposed integrating the following three basic properties in design of PA mixtures: structural support, drainability, and resistance to disintegration (*3*). These properties can be evaluated, respectively, using parameters from the following tests: repeated load indirect tensile test (RLIT) to determine elastic modulus, permeability, and Cantabro test. Table 8 introduces the mixture properties and specifications integrated in the design method.

Table 8. Proposed Mixture Design for PA (*3*).

Binder Content	*Mixture Property*	*Requirement*
Maximum	Binder draindown, %	≤0.3
Minimum	Stiffness modulus (20°C [68°F]), MPa (psi)	≥2000 (290,075)
Maximum	Drainability	
	a. Voids in mixture, %	>16
	b. Permeability, m/day (feet/day)	>25 (82.02)
Minimum	Resistance to disintegration (Cantabro test losses at 20°C), %	≤25

Khalid and Pérez (1996) recommend 70 percent retained modulus after 24 hours of immersion in water at 20°C (68°F) to ensure mixture resistance to stripping (*3*). Determination of

---

[7] Pérez, F., R. Miró, and A. Martínez. *Capas de rodadura: mezclas porosas y micros en caliente*. Curso sobre Estudio, Diseño y Control de Mezclas Bituminosas, Universidad Politécnica de Cataluña. 2005. [Spanish]. Unpublished.

resistance to particle loss can be performed using the Cantabro test with samples subjected to similar immersion conditions.

After determining there were no comprehensive design methods to improve the current recipe approach considered in BS 4987-1:2005 for PA design, Khalid and Walsh proposed another mixture design method (*7*). Determination of the design binder content (DBC) considers the asphalt contents defined from evaluation of the mixture properties presented in Table 9.

Table 9. Current Mixture Design Method (*7*).

Binder Content	***Mixture Property***	***Procedure***
Maximum	Binder draindown	Binder drainage test
Maximum	Voids content	Volumetric measurement
Maximum	Voids structure	Falling-head permeability test
Minimum	Elastic stiffness	RLIT
Minimum	Retained stiffness	Soaked RLIT
Minimum	Durability/adhesiveness	Cantabro

Parameter determinations use Marshall specimens compacted with 50 blows per side. After evaluating the voids content, the RLIT is conducted on dry samples. Next, samples are submerged in water (at 20°C [68°F]) overnight for the soaked RLIT test. Subsequently, permeability measurements are completed, and finally, the Cantabro test is performed using an impact box, which is a device similar to the Los Angeles machine but uses a square box instead of a cylindrical container. Table 10 presents the defined specifications for each parameter as a function of traffic volume. Minimum permeability magnitudes are not specified, and this parameter has not been included in the determination of the DBC. To determine the design binder content, the ranges of binder content in which the specification of each parameter is met are established, and after, the medium point of the overlapped ranges is calculated. This medium point corresponds to the DBC.

Finally, Table 11 summarizes the gradations, aggregate properties, typical binder contents, and mixture properties integrated in the mix design procedures applied in Europe and in the United states by NCAT and TxDOT. In Table 11, italic characters denote the information taken from Huber (*16*).

Table 10. Suggested Design Specifications (7).

Property Measured at 20°C (68°F)	***Traffic Volume (Commercial vehicles/lane/day)***		
	≤1500	***1500-3000***	***>3000***
Stiffness, MPa (psi)	≥500 (72,518)	≥700 (101,526)	≥1000 (145,037)
Retained stiffness, %	≥70	≥70	≥70
Voids, %	≥20	≥20	≥20
Cantabro loss, %	<20	<20	<20

Table 11. Summary of Characteristics of American OGFC and Non-North American PA Mixtures

	***United Kingdom* (29)**				***Spain*[8]**		***Denmark*[9]**		
	PA 6/20 mm		PA 2/10 mm		PA 12		PA 0/5 Medium	PA 0/8 Medium	PA 0/16 Medium
	Min.	Max.	Min.	Max.	Min.	Max.			
Gradation, mm (inch)									
45 (1.77)									
31.5 (1.24)	100								
26.5 (1.04)									
22.4 (0.88)									
20 (0.79)	95	100			100				100
19 (0.75)									
16 (0.63)									97
14 (0.55)	55	75	100						
13.2 (0.52)									
12.5 (0.49)					70	100			55
11.2 (0.44)								100	30
10 (0.39)			90	100					
9.5 (0.37)									
8 (0.31)					38	62	100	94	12
6.7 (0.26)									
6.3(0.25)	20	30	40	55					
5.6 (0.22)							99	35	9
5 (0.20)									
4.75 (0.19)									
4 (0.16)					13	27	65	11	9
2.36 (0.09)									
2 (0.08)	5	12	19	25	9	20	10	9	8
1.18 (0.05)									
1 (0.04)							9	8	8
0.6 (0.024)									
0.5 (0.02)					5	12	8	7	7
0.25 (0.01)							7	6	7
0.15 (0.006)									
0.075 (0.003)							6	5.5	5
0.063 (0.002)	3.5	5.5[a]	3	6[a]	3	6			
Aggregate properties									
Los Angeles abrasion, %	*12 max.*				<25:T3, ≤20:T1, T2, ≤15:T00, T0				
Flakiness index, %	*25 max.*				≤25:T3, T2, T1, T0, ≤20:T00				
Sand equivalent, %	-				>50				
Fine aggregate angularity	-				-				
Crushed faces (2 faces), %	*100*				100				
Binder									
Asphalt binder grade	100/150 or 160/220 pen[b]		100/150 or 160/220 pen[b]		*60/70 + SBS; 60/70 + ethylene vinyl acetate (EVA); 80/100 + SBS; 80/100 + EVA*			50/100-75 pen + SBS, hydrated lime (1.5%), cellulose fibers (0.25%)	
Binder modifiers	Styrene butadiene rubber (SBR), fibers (organic and inorganic), and natural rubber								
Binder content, %	3.7 or 4.5		5.2		4.5 min. Typical: 4.5 to 5.5		6.3	5.4	3.9
Specimens compaction	-				Marshall/50 blows			Marshall/50 blows	
Mixture properties									
Air voids content, %	-				>20		25.5	26	25.5
Draindown test, %	Required				-			Required	
Cantabro test, unconditioned (dry), %	-				<20:T00-T1, <25: T2-T3			Not applied[c]	
Cantabro test, moisture Conditioned, %	-				<35:T00-T1, <40:T2-T3			-	
Cantabro test, aged, %	-				-			-	
Retained tensile strength ratio	-				-			-	
Permeability	0.12 s^{-1} to 0.40 s^{-1} in the field				-			-	

[a] To include 2% by mass of total aggregate of hydrated lime.
[b] Penetration before any modification.
[c] The Rotating Surface Abrasion Test is considered as an alternative to evaluate durability of the mix.

---

[8] Pérez, F., R. Miró, and A. Martínez. *Capas de rodadura: mezclas porosas y micros en caliente*. Curso sobre Estudio, Diseño y Control de Mezclas Bituminosas, Universidad Politécnica de Cataluña. 2005. [Spanish]. Unpublished.

[9] Personal communication with Dr. Carsten Bredahl Nielsen, DRI.

Table 11. Summary of Characteristics of American OGFC and Non-North American PA Mixtures (continued)

	Switzerland[d] ***(28)***						***The Netherlands***[10]		***Belgium***[11]	***Italy (16)***	
	PA S 16		PA S 22		PA S 32		PA 0/11	PA 0/16			
	Min.	Max.	Min.	Max.	Min.	Max.				*Min.*	*Max.*
Gradation, mm (inch)											
45 (1.77)					100						
31.5 (1.24)			100		90	100					
26.5 (1.04)											
22.4 (0.88)	100		90	100							
20 (0.79)										*100*	*-*
19 (0.75)										*-*	*-*
16 (0.63)	90	100									
14 (0.55)										*75*	*100*
13.2 (0.52)										*-*	*-*
12.5 (0.49)										*-*	*-*
11.2 (0.44)			15	65	15	60					
10 (0.39)										*15*	*40*
9.5 (0.37)										*-*	*-*
8 (0.31)	15	60								*-*	*-*
6.7 (0.26)											
6.3(0.25)										*-*	*-*
5.6 (0.22)											
5 (0.20)										*5*	*20*
4.75 (0.19)										*-*	*-*
4 (0.16)											
2.36 (0.09)											
2 (0.08)	7	20	6	20	5	20				*0*	*12*
1.18 (0.05)											
1 (0.04)											
0.6 (0.024)											
0.5 (0.02)	4	10	4	10	4	10					
0.25 (0.01)											
0.15 (0.006)											
0.075 (0.003)										*0*	*7*
0.063 (0.002)	3	5	3	5	3	5					
Aggregate properties											
Los Angeles abrasion, %										*<16*	
Flakiness index, %										*-*	
Sand equivalent, %										*-*	
Fine aggregate angularity										*-*	
Crushed faces (2 faces), %										*-*	
Binder											
Asphalt binder grade	50/70, 70/100 pen, PmB 50/70-65 E, PmB 70/100-60 E						Only penetration binder is used		50/70 pen., polymer modified binders (PMB)	*80/100 + SBS*	
Binder modifiers	Polymers and organic or mineral fibers										
Binder content, %	>3.5		>3		>3		4.5		Typical: 4.3 to 5.3 for PMB	*4 to 6*	
Specimens compaction	Marshall/50 blows						Marshall/50 blows		Marshall	*Marshall*	
Mixture properties											
Air voids content, %	>18[e]						>20		>21	*18-23*	
Draindown test, %	-						-		-	*-*	
Cantabro test, unconditioned (dry), %	-						Only for research		<20 (18°C)	*<25 (25°C)*	
Cantabro test, moisture Conditioned, %	-						-		-	*<30 (20°C)*	
Cantabro test, aged, %	-						-		-	*-*	
Retained tensile strength ratio,%	≥80[f]						-		-	*-*	
Permeability	-						-		-	*-*	

[d] The Swiss national standard also defines gradations for the mixtures PA 8, PA 11, PA B 16, and PA B 22.

[e] The minimum air voids content for other mixtures are: PA 8: 20%, PA 11: 22%, and PA B: 22%.

[f] For mixtures PA and PA B the Retained tensile strength ratio should be ≥70%.

---

[10] Personal communication with Ministerie van Verkeer en waterstaat (The Netherlands).

[11] Personal communication with Dr. Joëlle De Visscher, Belgian Road Research Center.

Table 11. Summary of Characteristics of American OGFC and Non-North American PA Mixtures (continued)

	***Australia* (*26*)**				***South Africa* (*16*)**		***NCAT* (*6*, *21*)**		***TxDOT* (*1*)**			
	OG 10	OG 14	OG 20	Tolerance			OGFC		PFC-PG 76		PFC-A-R	
					Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Gradation, mm (inch)												
45 (1.77)												
31.5 (1.24)												
26.5 (1.04)			100									
22.4 (0.88)												
20 (0.79)					-							
19 (0.75)		100	95	±6	*100*	*0*	100		100		100	
16 (0.63)												
14 (0.55)					*0*	*0*						
13.2 (0.52)	100	95	55	±6	*90*	*100*						
12.5 (0.49)					-	-	80	100	80	100	95	100
11.2 (0.44)												
10 (0.39)					-	-						
9.5 (0.37)	90	50	30	±6	*25*	*65*	35	60	35	60	50	80
8 (0.31)					-	-						
6.7 (0.26)	40	27	20	±6								
6.3(0.25)					-	-						
5.6 (0.22)												
5 (0.20)					-	-						
4.75 (0.19)	20	11	10	±5	*10*	*15*	10	25	1	20	0	8
4 (0.16)					-	-						
2.36 (0.09)	12	9	8	±5	*8*	*15*	5	10	1	10	0	4
2 (0.08)					-	-						
1.18 (0.05)	8	8	6	±5								
1 (0.04)												
0.6 (0.024)	6	6.5	4	±5								
0.5 (0.02)					-	-						
0.25 (0.01)	5	5.5	3	±3								
0.15 (0.006)	4	4.5	3	±3								
0.075 (0.003)	3.5	3.5	2	±1	*2*	*8*	2	4	1	4	0	4
0.063 (0.002)					-	-						
Aggregate properties	Type I	Type II										
Los Angeles abrasion, %					*<21*		< 30		<30[i]			
Flakiness index, %					*<25*		<5 (5:1); <20% (3:1)		<10 (5:1)			
Sand equivalent, %					*>45*		-		-			
Fine aggregate Angularity					-		>45		-			
Crushed faces (2 faces), %					*100 (high traffic), 90 (low traffic)*		>90, one face: 100		>95			
Binder												
Asphalt binder grade	Unmodified binders	PMB (SBS, SBR, EVA, crumb-rubber modified [CRM]), fibers (0.3% to 0.5%), hydrated lime			*Asphalt rubber-polymer modified*		PMB, cellulose (0.3%) or mineral fiber (0.4%)		PG76 XX (PMB), lime (1% to 2%), and cellulose or mineral fibers (0.2% to 0.5%)		Type I or II asphalt rubber	
Binder modifiers												
Binder content, %	OG 10: 4.5 to 5.5; OG 14: 4 to 5; OG 20: 3.5 to 4.5	OG 10: 5.5 to 6.5; OG 14: 5 to 6; OG 20: 4.5 to 5.5			*4.5 min.*				6 to 7		8 to 10	
Specimens compaction	AGC / 80 cycles				*Marshall/50 blows*		SGC/50 cycles		SGC/50 cycles			
Mixture properties												
Air voids content, %	>20	20-25			*>22: high volume, 18-22: low volume*		>18[h]		18-22			
Draindown test, %	<0.3[g]	<0.3[g]					<0.3		<0.2[j]			
Cantabro test, unconditioned (dry), %	<25	<20			*<25 (25°C)*		-		-			
Cantabro test, moisture Conditioned, %	<35	<30			*<30 (25°C)*		-		-			
Cantabro test, aged, %	-	-			*<30 (25°C)*		-		-			
Retained tensile strength Ratio, %	-	-			-		>80		-			
Permeability	-	-			-		Optional		-			

[g] Only the air voids content evaluation is used to define the maximum binder content.

[h] 18% when the dimensional method is used. 16% when the CoreLok® method (recommended) is applied.

[i] Deleterious material (<1%), decantation (<1.5%), and magnesium sulfate soundness (5 cycles) (<20%) are also required.

[j] Boil test is also required.

3 CONSTRUCTION AND MAINTENANCE PRACTICES

The fundamental aspects involved in the construction process of OGFC and PA and the primary considerations for maintenance of these materials are summarized in this chapter. DGHMA mixtures are used for comparison.

3.1 CONSTRUCTION

Although construction of OGFC and PA, in general, utilizes the current techniques applied to construct DGHMA with the same equipment, the construction of porous layers requires some special considerations throughout the process.

3.1.1 Mixture Production Considerations

As in the production of DGHMA, OGFC mixture production requires special attention to aggregate moisture control. Since better control of mixing temperature and a more homogeneous mixture can be obtained when the aggregate exhibits low variability and low moisture contents, some states require the use of aggregate in a surface dry condition for OGFC production (*16*). In addition, a minimum of 2 days reserve of aggregate (before mixture production starts) is required for some states, in the case of production with mobile plants. The British standard establishes 1 percent (by mass of the mixture at the required temperature) as the maximum moisture content for PA mixtures during construction (*29*).

Conventional asphalt plants can be adapted to allow the incorporation of fibers and the use of modified binders as required for most OGFC mixtures. Batch and drum plants are both used successfully for addition of mineral and cellulose fibers. However, the incorporation of any of these products requires installation of a fiber feed device (*6*). In addition, pelletized fibers and loose fibers are available, and each one requires some special considerations for incorporation into the mixture.

Production of pelletized fibers uses a specific amount of asphalt, which must be considered as part of the binder in the mixture. When this asphalt binder is melted, the fibers are released and mixed with the aggregate in the pugmill of a batch plant or in the drum of a drum plant. Dry, loose fibers are usually added by using special machines designed to fluff the material to a known density and blow a measured quantity into the mixing plant. Continuous blowing of fiber into the drum (within 1 foot upstream of the asphalt binder line) can be used to introduce fiber into a drum plant. In batch plants, bags of fiber can be added directly into the pugmill. The bags melt, and the fiber is distributed into the mixture (*6*).

When using a batch plant to produce mixtures with mineral fibers or cellulose fibers, both the dry and the wet mixing time should be lengthened to augment fiber distribution (*6*). Drying time should also be increased, since lower temperatures are specified (compared with production temperatures of other mixtures), which leads to longer drying time for the aggregate, resulting in reduced plant production rates. This requirement explains the preference in some countries for batch plants, as this type of facility allows some additional time in the plant bins for drying of the aggregate before mixing (*18*). Finally, considering the presence of one predominant aggregate size in OGFC, inspection of the screen deck capacity is necessary in order to prevent hot bins from overriding the screen deck (*6*).

Control of mixing temperature requires particular care since OGFC are characterized by draindown susceptibility, which can be increased by excessive temperature during production. Some states limit the mixing temperature to prevent draindown problems and minimize binder component degradation. For example, Arizona, where asphalt rubber is used extensively, established a maximum mixing temperature of 175°C (347°F); whereas, Oregon specifies maximum plant temperatures of 175°C (347°F) and 160°C (320°F) for modified asphalt binder and unmodified asphalt binder, respectively (*16*). FHWA recommends keeping the binder viscosity in the range of 700 to 900 centistokes (1.08 to 1.39 inch^2/s) to establish the mixing temperature considering the prevention of draindown issues (*20*).

In Britain, the Design Manual for Roads and Bridges indicates the maximum mixing temperature by specifying a binder viscosity of 0.5 Pa-s (0.010 lb s/feet^2) (*18*). Similarly, the Manual of Contract Documents for Highway Works indicates the maximum mixing temperatures for PA as a function of the bitumen penetration value except for polymer-modified binders (*30*).

Switzerland established an admissible range of temperature for all the production phases as a function of the binder penetration value. Thus, for binders with penetration 50/70 (1/10 mm), the temperature range is 145-175°C (293-347°F), and for 70/100 binders, the range corresponds to 140-170°C (284-338°F) (*28*). Additionally, the European specifications for PA include the limits on the mixture temperatures presented in Table 12 for any location in the plant for paving grade binder (*27*). Nevertheless, these limits can be changed when modified binder is used. Finally, Spanish standards establish a maximum temperature of 155°C (311°F) upon leaving a drum mix plant and 170°C (338°F) for production in batch plants.

Table 12. Temperature Limits of the Mixture (*27*).

Paving Grade of Binder	*Temperature, ºC (ºF)*
35/50	150-180 (302-356)
40/60	150-180 (302-356)
50/70	145-175 (293-347)
70/100	140-170 (284-338)
100/150	130-160 (266-320)
160/220	130-160 (266-320)
250/330	120-150 (248-302)

3.1.2 Mixture Storage and Transportation

Since OGFC are prone to draindown, limits on mixture storage and transportation times are recommended. Maximum periods of storage in the silo between 1 and 12 hours have been specified by some state DOTs (*16*). In 1990, FHWA suggested that the combined handling and hauling of OGFC mixture should be limited to 40 miles or 1 hour (*20*). In Britain, a maximum period of 3 hours is specified as acceptable for the whole process between mixing, placement, and compaction (*18*).

Tarps are necessary to avoid crusting of OGFC mixtures during transportation. Insulated truck beds for OGFC transportation are required by some state DOTs. In Britain, double-sheeted insulated vehicles are required to transport PA mixtures (*30*). Truck beds should be prepared for transportation of rich OGFC mixtures by using a full application of an asphalt release agent (particularly if polymer or rubber-modified binder is used).

3.1.3 Underlying Surface Profile

OGFC should not be considered as a layer to correct profile distresses or any kind of structural distress. Before OGFC placement, the pavement surface should be corrected to avoid zones that allow water accumulation (e.g., zones with permanent deformation) and adversely affect not only the OGFC layer but also the underlying pavement layers. Lateral and longitudinal drainage of the underlying layer must be provided to guarantee adequate water discharge from the OGFC. Due to the existence of flow into the OGFC, it should be placed over an impermeable layer to prevent problems in underlying layers. In Britain, protection is provided for underlying layers by applying a tack or bond coat and specifying a minimum cross slope of 2.5 percent (*18*). FHWA suggested application of asphalt emulsion (diluted 50 percent with water and applied at a rate of 0.05 to 0.10 gallons per square yard) to seal the surface of underlying layers before OGFC placement (*20*).

3.1.4 Mixture Placement

To produce a smooth surface, the paver should advance continuously with minimal stoppages, and one should consider use of a remixing material transfer device (*6*). In the case of direct delivery from the truck to the paver, it is important to limit mixture delivery with cold lumps and avoid bumping the paver because surface depressions are more difficult to correct with OGFC than with DGHMA. In addition, when asphalt pavers with extendible screeds are used, auger extensions are recommended to avoid irregular distribution of mixture between the center and the edge of the paver (*16*). The use of a hot screed in the asphalt paver is recommended to avoid pulling excessively on the material and diminish the necessity of raking, which can cause areas with lower voids or more likely uneven void distribution across the pavement. In addition, raking can generate unsightly surface texture and poor aesthetics, which cannot be rolled out with compaction (*6*).

Special attention to placement and compaction temperatures for OGFC is required since this mixture is generally constructed using modified binders and is typically placed at lower thicknesses than DGHMA. Thin layers cool faster and allow less time for compaction. In the United States, OGFC is commonly constructed in thin layers 20 to 25 mm (0.75 to 1 inch) in thickness; whereas, in Europe, PA is typically constructed with a 40 to 50 mm (1.57 to 1.97 inch) layer thickness (*16*). However, for the new generation OGFC in the United States, the typical layer thickness is 32 mm (1.25 inches) (*21*).

Currently, Japan and some European countries are testing thicker two-layer PA to provide both noise reduction and safety. In this case, the top layer is about 25 to 30 mm (0.98 to 1.18 inch) thick, and the bottom layer is about 40 to 50 mm (1.57 to 1.97 inch) (*10*). Figure 3 shows a two-layer PA. The Japanese have developed the Multi-Asphalt Paver with capability to simultaneously place both layers of the two-layer PA *(31)*.

Figure 3. Double Layer PA (*25*).

In Britain, a nominal thickness of 50 mm (1.97 inch) is specified to maximize sound attenuation, spray reduction life, water storage capacity, and compaction time of the PA. The minimum paver discharge temperature is specified in terms of binder viscosity, with a limit of 5 Pa-s (0.104 lb s/feet^2) *(18)*.

Acceptable paving conditions in the United States are commonly defined as a minimum air temperature of 15°C (60°F). Although this limit is used by most agencies, there are some exceptions. Florida, for example, requires a minimum air temperature of 8°C (45°F) *(16)*. The British Manual of Contract Documents for Highway Works specifies the maximum wind speed as part of its acceptable paving conditions *(30)*.

Initiation of mixture placement is recommended on the low side of the paving area to avoid accumulation of water (from the rollers or surface water) onto areas to be paved. It is desirable to minimize or even avoid mixture hand-working, but if handwork is necessary, it should be done with a wooden lute instead of metal-toothed rakes (*18, 30*).

3.1.5 Material Compaction and Joint Construction

Static steel-wheel rollers are most commonly used to compact OGFC mixtures (*6, 16, 18, 30*). Typically, two to four passes (within the adequate range of temperature) with an 8- to 9-ton tandem roller are appropriate to complete the compaction process on thin layers (20 mm [0.78 inch]) (*6*, *16*). FHWA recommends one or two passes of an 8- to 10-ton static steel-wheel roller to compact OGFC (*20*). However, for compaction of PA, the Design Manual for Roads and Bridges (Britain) recommends application of at least five passes, but they typically use thicker (~2 inch) layers (*18*). For OGFC, heavier rollers (weight more than 10 tons) should be avoided because they can lead to excessive aggregate breakage, and pneumatic-tired rollers are not used since their kneading action reduces the mixture drainage capacity by closing surface pores (*16*, *18*).

Given the rapid cooling characteristics of OGFC, researchers strongly recommend to compact the mixture keeping a maximum distance of 15 m (50 feet) between the roller and the paver (*6*). The minimum temperature specified in Britain for substantial completion of compaction is 80°C (176°F) when 190 penetration reference bitumen or natural rubber or fiber-modified binders are used, and 85°C (185°F) when 125 penetration reference bitumen, or natural rubber, or fiber-modified binders are specified (*30*).

Longitudinal and transverse joints in OGFC require special treatment since they are more difficult to construct than those in DGHMA. Transverse joints should be minimized as much as possible, but where required, they can be formed by using lumber fastened to the underlying surface before placing the joint (*18*). This kind of joint does not require the application of additional binder prior to placement of new mixture. On the other hand, when a sawn joint is required, a scarce amount of binder (i.e., asphalt emulsion) should be applied to improve adhesion. This kind of joint should be minimized with the realization that the applied binder does not have the purpose of sealing the joint as in DGHMA (*18*).

Placement of new mixture on the joint can be done by laying the screed flat on the existing OGFC (around 30 cm [1 foot] before the joint) and allowing the mixture to advance in the paver until it reaches the front of the screed to form the joint that should be finally cross rolled. A vibratory mode of compaction can be used, but generally, a static steel-wheel breakdown roller is preferred (*6*).

Avoidance of longitudinal cold joints is always preferred (*18*, *20*). This can be done by placing the mixture in full width covering the entire transverse section with two or more paving machines en echelon. Pavers should have a maximum stagger of 20 m (65.6 feet) (*18*). Using machines en echelon permits longitudinal joint compaction with the material still in the range of compaction temperature.

When a cold joint cannot be avoided, locate the longitudinal joints outside the wheel paths or next to pavement lane makings (*30*). The construction of this joint is executed by placing mixture approximately 1.5 mm (0.06 inch) above the existing mixture and compacting the joint (*6*). As recommended for transverse joints, longitudinal joints should be sawed, and the cut face should not be fully covered with binder because it blocks the lateral flow of water and generates wet areas in the pavement.

3.1.6 Mixture Acceptance

Even though specified density in the field is not currently required, adequate compaction is necessary since low-density zones are prone to raveling. The practice in most agencies for mixture approval is based on the evaluation of binder content and gradation and the execution of visual inspection of the mixture after compaction to evaluate (qualitatively but not quantitatively) the density, material variability, and segregation. Essentially all agencies specify a minimum smoothness (*16*).

In Spain, the acceptance criterion corresponds to the determination of the mean air voids content (for which a maximum difference of 2 percent in comparison with the reference air voids content is required.) In England, a specified hydraulic conductivity of the material is required, and is evaluated in the field before any traffic is permitted.

3.2 MAINTENANCE

Maintenance is a fundamental aspect to consider in any project involving OGFC or PA, since these activities cannot be performed in the same way as for conventional DGHMA. The first part of this section reviews the main issues associated with winter maintenance in both OGFC and European PA materials. Next, surface maintenance is discussed, followed by a summary of current rehabilitation practices for OGFC and PA.

3.2.1 Winter Maintenance

In general, open-graded mixtures exhibit lower thermal conductivity and reduced heat capacity compared with DGHMA *(18)*. Elevated air voids contents in OGFC reduce the flow rate of heat through the material. In fact, the thermal conductivity of OGFC can be 40 to 70 percent the magnitude of that for DGHMA, making OGFC operate as an "insulating course" at the surface *(16)*.

As a result of these thermal properties, the surface of OGFC can exhibit temperatures 1 to 2°C (1.8 to 3.6°F) lower than the surface temperature of adjacent DGHMA, producing earlier and more frequent frost and ice formation (*6, 16*). Longer periods under such conditions, compared with DGHMA, are thus expected. The occurrence of this phenomenon in PA has been identified in Europe (*3, 16*), in the United States[12], and specifically in Texas[13]. Thus, the time to reach adequate pavement friction values after ice formation has occurred is longer in porous pavement *(16)*. In fact, formation of black ice and extended frozen periods are currently considered the main problems associated with OGFC maintenance in the United States[12].

Consequently, OGFC requires specific winter maintenance practices. For example, in addition to conventional practices for winter maintenance, the use of pavement condition sensors, meteorological instrumentation, and connecting hardware and software is suggested to monitor the road system and support the decision process involving when and how to treat an OGFC surface *(5)*.

More salt (or deicing agents) and more frequent applications than on DGHMA are required to perform winter maintenance on OGFC and PA (*15, 16, 18, 32*). In Texas[13], deicing agents are currently considered the most effective winter treatment, followed by liquid deicer agents and sand. However, FHWA recommends developing snow and ice control using chemical deicers and plowing and avoiding the use of abrasive materials to improve traction *(20)*. Spreading of sand to enhance friction and hasten deicing contributes to the clogging of voids,

---

[12] Project 0-4834: Cold Weather Performance of New Generation Open Graded Friction Courses. Report created on: Friday, May 27, 2005 5:19:00 PM. Survey results.

[13] Yildirim, Y., T. Dossey, K. Fults, and M. Trevino. Cold Weather Performance of New Generation Open-Graded Friction Courses. TxDOT District Survey, Tech Memo Project 0-4834-2.

causing a decrease in drainage and noise reduction capabilities, which are considered two of the main OGFC advantages (*5*).

Since the deicer can flow into an OGFC instead of remaining at the surface, Oregon DOT has suggested research on organic deicers with higher viscosity and electrostatic charge technology (similar to that employed in emulsified asphalt) to improve bonding of deicers on the surface (*15*).

Intensive application of liquid deicing salts has allowed Belgium to obtain similar conditions between dense and porous mixtures subjected to snowy weather. Further, higher frequency of application and 25 percent more liquid salting are reported in The Netherlands to address winter maintenance difficulties in PA (*3*, *6*). Furthermore, the use of liquid chloride solutions was reported in the cold Alpine regions of Italy, Austria, and Switzerland as more effective than the use of solid salt (*5*). On the contrary, a Japanese study concluded that fundamental modifications are not required to practice winter maintenance in PA surfaces, since considerable differences between these mixtures and DGHMA were not found (*33*).

Britain practices preventive salting just before snowfall and more frequent application of salt in comparison with DGHMA (*18*). They recommend increasing the amount of salt applied on DGHMA sections that are adjacent to PA segments. This recommendation is due to the reduction in the transfer of salt from the PA to the DGHMA and the differences in response of each material. Additionally, they propose prompt plowing of snow using plows fitted with rubber edges on the blades (to prevent surface damage). Finally, greater control in the homogeneous application of deicing chemical is required in OGFC, as the traffic has minimal contribution in its distribution over the OGFC surface (*5*).

3.2.2 Surface Maintenance

According to a survey conducted as part of the National Cooperative Highway Research Program (NCHRP) Synthesis 284, there are no reports in the United States on the application of major maintenance for OGFC. From 17 states that reported the use of OGFC, only New Mexico, Wyoming, South Carolina, and Oregon employ fog seals to perform preventive maintenance. Although quantitative information about the significance of these treatments when applied to PA is not available, it is expected that fog seals extend the life of porous mixtures since they provide a small film of unaged asphalt at the surface (*15*). FHWA recommends fog seal application in two passes (at a rate of 0.05 gal/yd^2 for each pass) using a 50 percent dilution of asphalt emulsion without any rejuvenating agents *(20)*.

Research in Oregon regarding permeability reduction and changes in pavement friction on certain OGFC pavements generated by fog seals concluded that the mixtures still retain porosity and keep the rough texture related to its capability to reduce the potential for hydroplaning *(15)*. However, quantitative conclusions regarding the changes in these parameters are not included. A decrease in pavement friction was noticed immediately after fog seal application, but during the first month, it increased considerably by traffic action.

Snow plow blade abrasion has considerable effects on the durability of traffic markings on OGFC. Thermoplastic markings or even some fragments of mixture impregnated with thermoplastic can be displaced when steel snow plow blades are used for winter maintenance. Field trials in Rhode Island showed the lack of durability of the permanent inlaid traffic marking tape on modified OGFC under such conditions. Therefore, they recommended suspension of the use of permanent inlaid traffic marking tape until corrections can be implemented to improve durability *(34)*.

Rhode Island further reported that recessed thermoplastic traffic markings proved cost effective in comparison with non-recessed thermoplastic markings. Although recessed thermoplastic traffic markings showed lower snowplow blade damage, fully and semi-recessed markings installed in a tangent highway test section failed to maintain the recommended minimum retroreflectivity in wet night conditions. This result was associated with the effect of the water film present in the tangent section but was irrelevant in the super-elevated curved test section included in the research *(34)*.

Highway agencies in British Columbia, South Carolina, and Maryland reported that thermoplastic marking material was the most appropriate for OGFC applications *(16)*. The British limit the use of pavement markings with thermoplastic materials to certain directional signs and arrows, considering that on PA the marking material has more opportunity to flow downward into the mixture *(18)*. Although higher demand of marking material in OGFC (due to higher porosity) was reported by some agencies in the United States (e.g., Ohio, New York, and Oregon), there were no specific recommendations regarding materials for traffic marking *(16)*.

Cleaning of OGFC in the United States is not common practice. This approach indicates that local agencies accept that OGFC functionality can be maintained due to its auto-cleaning capacity created in highways with relatively high speed and high volumes of traffic by the suction generated by tires rolling on the OGFC *(5)*. High-pressure washing is currently quite expensive and of questionable value. Current maintenance activities in Denmark include cleaning of the voids by high-pressure water and air suction twice a year as a strategy that combines the construction of two-layer drainage asphalt and cleaning in order to maintain porosity during the pavement lifetime *(11)*. In general, European practice limits placing of PA on highways with speeds higher than 50 km/h (31 mph) to help in keeping the surface clean *(10)*. On the other hand, Japan is applying the "function maintenance" concept that comprises more frequent cleaning operations with only partial debris removal during each cleaning *(31)*.

3.2.3 Corrective Surface Maintenance

Mill and inlay using OGFC was recommended in Oregon to repair OGFC when the quantities of material were enough to justify these activities. If only a small quantity is needed, DGHMA is suggested for patching *(15)*. FHWA advises one to consider the area and the drainage continuity *(20)*. Thus, when the area to be repaired is small and the flow around the patch can be ensured, DGHMA is recommended for patching. Otherwise, the zone should be repaired by using OGFC mixture. Nonetheless, in 2000, the use of DGHMA to repair delaminated areas and potholes was indicated by all states in the United States that reported the utilization of OGFC. Crack filling was reported only by Wyoming DOT, and according to their experience, drainage problems can result from crack sealing, since water flow inside the material is diminished *(16)*.

In Britain, the use of PA or open-graded macadam is recommended to repair both small and large potholes. The use of dense bitumen macadam is permitted, if necessary, but its replacement by permeable mixture is recommended. Finally, the application of hot-rolled asphalt (HRA) is limited for repairing small areas (i.e., on the order of 0.50 m × 0.50 m [1.64 feet × 1.64 feet] maximum) *(18)*.

To diminish the wheel impact on the patch joint and facilitate the flow of water around a DGHMA patch, rotation of the patch to 45 degrees to provide a diamond shape is recommended. Alternatively, the execution of machine patch, blade patch, or screed patch may be used. If some OGFC material still remains in the repair area, this technique has the advantage of avoiding the complete blockage of water flow along the OGFC *(15)*.

3.2.4 Rehabilitation

An ideal set of technical actions for major rehabilitation of OGFC has been defined by some DOTs (e.g., Florida and Georgia) as mill, recycle, and inlay. The same approach has been recommended in Oregon and reported as the favored approach in The Netherlands *(15)*. When inlaying OGFC, one must avoid creating an impermeable vertical wall at the lower side of the inlay and, thus, the potential for ponding water. In the absence of raveling or delamination demanding rehabilitation, once the OGFC has lost its functionality (i.e., permeability and noise reduction) by clogging, its service might still be permitted since it essentially behaves as a DGHMA with low permeability *(16)*.

General recommendations and actual practices for rehabilitation of OGFC in the United States include milling and replacing of existing OGFC with new OGFC or any other asphalt mixture (*6*, *16*, *20*). Direct placement of new DGHMA over porous mixture is not recommended because life of the new layer can be diminished by water accumulation inside the OGFC. Experimental reports from The Netherlands showed that recycled PA kept approximately the same permeability, and its durability (evaluated by the Cantabro test) is similar to that of a new mixture *(16)*. Permeability findings indicate that clogging affects only the top portion of the porous mixture layer, since the gradation is not altered when the mixture is recycled.

4 PERFORMANCE

This section discusses OGFC performance, comprising durability and functionality. Durability includes moisture sensitivity and aging potential, and functionality considers permeability and noise reduction. In addition, available information on mechanical response and mechanical contribution of OGFC to pavement structural design is presented.

4.1 DURABILITY

Regarding durability, raveling is the distress most frequently reported as the cause of failure in OGFC mixtures. Raveling in OGFC is often characterized by its rapid progress, which can disintegrate the layer within a few months or even a few weeks in some extreme cases (*16*). According to the Performance Survey on Open-Graded Friction Course Mixes, 14 of 17 surveyed agencies in the United States reported raveling as the main cause of failure; the remaining three agencies cited delamination. Cracking and potholes were reported as a contributing cause of failure by only two agencies.

Raveling can be associated with aging binder (oxidation and hardening), binder softening generated by oil and fuel drippings, and inadequate compaction or insufficient asphalt content (*35*).

OGFC failure due to raveling is most often associated with aging of the binder, which promotes disintegration, particularly at low temperatures. According to Nicholls and Carswell, progressive binder hardening due to oxidative aging produces a material that cannot accommodate the strain from traffic loading and results in brittle failure (*36*). The same authors identified a critical binder penetration of approximately 15 (1/10 mm) and a softening point of 70°C (158°F). Disregarding the presence of a modifier or its type, below this critical penetration, failure occurs when the PA is subjected to load at low temperature. They reported that reduction of penetration corresponds to 30 percent during construction (mixing and placement) and 20 percent per year afterwards. The addition of hydrated lime and the use of higher binder contents (thicker binder films) generate lower rates of hardening, which benefit mixture durability.

Based on more than 20 years of experience using PA, the Spanish, in 2001, incorporated a requirement of maximum loss not only in the Cantabro test performed on dry samples (conventional test) but also on wet samples. This additional test is required to prevent durability problems related to the use of hydrophilic fillers or binders with low adhesion to the aggregate, which are reported as the main causes of rapid mixture disintegration[14].

Although PA compaction is generally considered a process without major issues, inadequate compaction is identified in Spain as one of the causes of rapid mixture failure[14]. Huber similarly concluded that OGFC is more susceptible to raveling than DGHMA when low densities are obtained (*16*).

4.1.1 Mixture Service Life

As shown in Table 13, the service life of OGFC is highly variable and can range from 7 to 10 years. The typical service life reported by the Transport Research Laboratory (TRL) is defined for traffic up to 4000 commercial vehicles per lane, per day. Maximum life of 12 years can be expected for this maximum traffic (*37*). Huber reported that the service life of British PA is related to the binder penetration. Longer life (on the order of 10 years) is expected for softer binders (200 [1/10 mm]), while for binders with 100 (1/10 mm) penetration the service life is 7 years (*16*).

Regarding the service life stated in Table 13 from TxDOT Project 0-4834, 26 percent of the surveyed agencies reported service life of less than 6 years, while another 26 percent indicated 6 to 8 years as the typical service life for OGFC. Only 11 percent expressed service life longer than 12 years.

One of the factors that most influences mixture durability is the type of binder used, since raveling is directly related to binder aging. In fact, the majority of agencies reporting successful application of OGFC are using modified binders. On the contrary, the use of unmodified binder has led to premature failures due to raveling, as reported by some states (e.g., Arizona and Georgia). Tire rubber, SBS, and SBR-modified asphalt are frequently employed in OGFC. In addition, fiber stabilizers are currently incorporated to prevent draindown.

---

[14] Pérez, F., R. Miró, and A. Martínez. *Capas de rodadura: mezclas porosas y micros en caliente*. Curso sobre Estudio, Diseño y Control de Mezclas Bituminosas, Universidad Politécnica de Cataluña. 2005. [Spanish]. Unpublished.

Table 13. Typical Mixture Service Life.

Typical Mixture Service Life, years	*Type of Mixture*	*Country*	*Reference*
8 or more	OGFC	United States	NCAT, 2000 (*17*)
13	Rubber-modified OGFC (Arizona)	United States	NCHRP, 2000 (*16*)
15	OGFC (Wyoming)	United States	NCHRP, 2000 (*16*)
6 to 8	OGFC	United States	TxDOT, Project 0-4834[15]
7 to 10	Porous asphalt	United Kingdom	TRL, 2001 (*37*)
7	Porous asphalt	Denmark	DRI, 2005 (*38*)
8 to 12	Porous asphalt	France	Pérez et al., 2005[16]

4.1.2 Binder Aging

An important feature of hot mix asphalt concrete pavements is that the asphalt binders oxidize over time, becoming brittle and incapable of sustaining deformation without damage. Thus, over time pavements deteriorate because of this oxidative hardening and exhibit age-related raveling or cracking (*39, 40, 41, 42*).

In recent years, much has been learned about binder oxidation and hardening and its impact on pavement performance, largely because of previous research supported by TxDOT. In the laboratory, binder oxidation and hardening rates in thin films have been determined for a large number of asphalt binders (*43, 44, 45*). The hardening susceptibility has been developed to distinguish between binders in terms of either the low shear rate limiting viscosity or a rheological function of both the binder's elastic and viscous properties (*43, 46, 47*). The latter function has been shown to relate to binder brittleness under elongation (*48*). Binders can vary significantly in this value. From field studies, there is evidence that binders oxidize in pavements well below the surface, and rheological data on binders recovered from pavements indicate hardening rates that generally agree with estimates from laboratory film aging,

---

[15] Project 0-4834: Cold Weather Performance of New Generation Open Graded Friction Courses. Report created on: Friday, May 27, 2005 5:19:00 PM. Survey results.

[16] Pérez, F., R. Miró, and A. Martínez. *Capas de rodadura: mezclas porosas y micros en caliente*. Curso sobre Estudio, Diseño y Control de Mezclas Bituminosas, Universidad Politécnica de Cataluña. 2005. [Spanish]. Unpublished.

suggesting that oxygen availability is not a seriously limiting factor to pavement aging, even in dense-graded mixtures (*42*). These are significant results and suggest the importance of oxidation to the durability of pavements.

Most recently, studies have focused more directly on understanding the contribution of binder aging to fatigue in mixtures. Current TxDOT Project 0-4468, “Evaluate the Fatigue Resistance of Rut Resistant Mixes,” has found that binder oxidation and consequent hardening can have a precipitous effect on fatigue life and that different mixtures can be affected to significantly different degrees (*49*). Researchers are working to understand the reasons for these differences to provide the basis for improved pavement durability. Likely factors are binder film thickness and polymer modification.

However, there are few studies on the effect of binder oxidation on the OGFC performance. The commonly used “long-term” aging procedure in the OGFC durability test is forced draft oven aging at 60°C (140°F) for 7 days, which does not age the binder nearly enough to truly represent the impact of long-term aging on Texas pavement performance. According to Glover et al., 1 month of aging in the 60°C (140°F) environmental room is equivalent to approximately 15 months on SH 21 (Bryan-Caldwell, Texas) (*42*). Therefore, better long-term aging is necessary to measure the long-term OGFC durability.

Because of the results discussed, understanding the impact of field aging on PFC mixtures is an important factor to PFC mix design and likely to be different for these mixtures compared to conventional mixtures for several reasons:

- PFC are placed on the pavement surface where, because of higher temperatures, oxidation rates will be higher than they are deeper in the pavement structure;
- PFC mixtures, because of their high permeability, might be expected to provide better access of oxygen to the binder, tending to increase oxidation rates;
- the thicker asphalt binder films in PFC mixtures will serve to reduce oxygen transport rates into the binder, thus slowing oxidation;
- the thicker binder films in PFC mixtures likely will favorably affect the impact of aging on durability differently from dense-graded, thin-film mixtures;
- fibers in some of the PFC binders may act to reinforce the binder film and minimize the effects of age hardening that lead to raveling;
- the presence of lime in some PFC mixtures may retard the effects of binder aging (*50*); and

- polymer modifiers in PFC mixtures may have a beneficial impact on age-related durability.

Current TxDOT Project 0-4688, “Development of a Long-Term Durability Specification for Modified Asphalt,” is addressing the durability of polymer-modified binders. The results of this project will also be important to the proposed project.

Important work remains to be done in assessing the aging potential of PFC mixtures and its resulting impact on durability. This work will require determining binder aging rates in PFC mixtures (as compared to dense-graded mixtures) and the impact on mixture durability properties. The research team hypothesizes that the aging potential will relate to binder composition (including the quantity and type of polymer, fibers, and lime); mixture permeability; air voids (total and interconnected); and binder film thickness in the PFC mixtures. The impact that this aging potential will have on PFC mixture durability likely will be related to film thickness and polymer content.

4.2 FUNCTIONALITY

The high air voids content of OGFC corresponds to the main functional characteristics of OGFC and its primary advantages. Table 14 presents different pavement surface materials in terms of noise level and demonstrates the associated environmental benefits of OGFC. Additional details about the magnitudes of noise reduction are presented in Chapter 1.

According to the Danish Road Institute, a reduction of the noise level by 4 dB(A) is comparable, from a public perception standpoint, with the noise reduction that can be obtained if the traffic volume is decreased more than 50 percent (*11*).

Table 14. Average Comparative Noise Levels of Different Pavement Surface Types (*9*).

Pavement Surface Type	***Relative Noise Level, dB(A)***
Open-graded asphalt friction course	-4
Stone matrix asphalt	-2
Dense-graded hot mix asphalt	0 (reference)
Portland cement concrete pavement[(a)]	+3

[(a)] Noise level is likely to be significantly higher if PCCP has transverse grooves or tining.

Mixture permeability is related to reduction of hydroplaning and splash and spray. Although objective evaluation on spray reduction is limited, according to measurements made in Britain, reductions of 90 to 95 percent (compared to DGHMA) in the amount of water sprayed 3 m (9.8 feet) behind a truck can be obtained with OGFC (6).

Unfortunately, the air voids content is reduced during service as a consequence of clogging. Therefore, in the absence of cleaning activities, the initial permeability and noise reduction capacity are expected to decrease such that, at the end of the functional life (when the functional characteristics are lost), OGFC behaves as a DGHMA.

Measurable change in noise reduction capacity can occur even when the decrease in permeability is not substantial. The Danish Road Institute analyzed thin PA sections and conducted noise measurement studies to identify the beginning of clogging and found that these techniques allowed earlier identification of clogging than permeability tests. Their results showed that permeability tests only allow the identification of noise reduction after severe clogging has occurred (*51*). DRI determined that clogging of PA is concentrated basically in the upper part of the PA, compromising a top sublayer with a thickness of approximately 10 to 25 mm (0.39 to 1 inch). Figure 4 presents a microscopic image from a thin section in which the voids located near the surface were clogged (*51*).

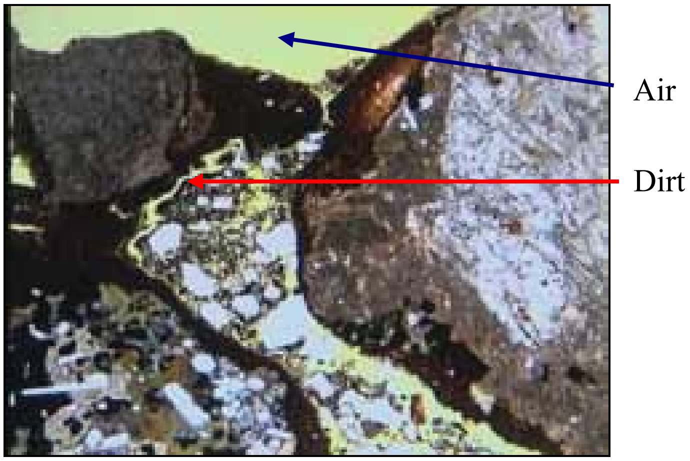

Figure 4. Image from a Thin Section (*51*).

Table 15 introduces the typical functional life for OGFC and PA as reported in different countries. These data are highly variable (*52*). A functional life between 5 and 8 years is expected for OGFC and PA. However, different factors such as the initial voids content, gradation, voids size, traffic volume and speed, and road environment (related to debris contribution) can lead to different functional lives.

Table 15. Typical Functional Life.

Typical Mixture Functional Life, years	*Type of Mixture*	*Country*	*Considered Parameters*	*Reference*
3 to 6	Open-graded asphalt	Australia	Water spray and noise reduction	Yeo, Favaloro, and Mousley, 2001 (52)
7	PA	Denmark	Noise reduction	Danish Road Institute, 2001 (53)
9 [(a)]	PA	Spain	Drainage capacity	Khalid and Pérez, 1996 (3)
5 to 8	PA	Britain	Spray reduction	Huber, 2000 (16)

[(a)] Reported value for medium traffic. For heavy traffic, the period was reduced to 2 years when mixture with less than 20 percent of voids was used.

The following sections explain the OGFC clogging and the approaches suggested for maximizing the functional life of the mixture. Next, a review on permeability measurement is introduced, and finally, the aspects related to the mechanical response of OGFC are summarized.

4.2.1 Permeability and Noise Reduction Capacity

Reduction in permeability caused by clogging not only affects mixture drainage capacity (and, consequently, aspects such as hydroplaning reduction or splash/spray suppression), but it also affects the noise reduction capability of the OGFC. Therefore, any effort to reduce or to control clogging is desirable to improve functionality of OGFC. As a result, OGFC and PA design changed in the United States and in Europe during recent years.

Mixtures with larger aggregate sizes were tested as an alternative to create larger voids, and in this way, address clogging problems. However, major changes were not observed in clogging resistance *(16)*. Other countries resorted to the use of mixtures with higher voids contents and obtained adequate results. For example, in Spain, during the early 1980s, a conservative approach was adopted by using mixtures with air voids contents between 15 and 18 percent *(3)*. After 1986, mixtures with voids contents higher than 20 percent showed improved performance, and their use is now promoted. In more recent reports from Spain, the use of mixtures with minimum air voids contents of 20 percent is recommended to maximize initial drainability and functional service life. In France and Spain, mixtures with voids contents of approximately 25 to 27 percent have been successfully employed[17].

Clogging is delayed when suction forces generated by high-speed rolling tires effectively clean the OGFC. This assumption is reasonable when the infrastructure contributes a small amount of debris and when high traffic speeds can be ensured. Tappeiner indicated that speed should be greater than 70 km/h (44 mph) to minimize clogging in OGFC (5), and Newcomb and Scofield reported the use of PA in Europe on roads with minimum speeds of 50 km/h (31 mph) (*10*).

The Design Manual for Roads and Bridges disallows the use of PA on streets with a 30 mph speed limit, arguing that, at low speeds, no benefits for noise or spray reduction are obtained (*18*). The British are currently not using PA as a surface layer; instead, they use SMA or other thin surfacings[18]. A general indication of the influence of the road environment (and associated speeds) is shown in Table 16, which illustrates the functional life reported in France regarding noise reduction effectiveness for different types of roads.

Table 16. Period of Effectiveness of Noise Reduction[17].

Typical Mixture Functional Life, years	***Period of Effectiveness of Noise Reduction, years***
Streets	2
Urban highways	3-5
National roads with high traffic	3-7
Rural highways	5-8

Based on research on an urban road with a speed limit of 50 km/h (31 mph), the DRI reported clogging and subsequent elimination of the benefits in noise reduction after 2 years in service (*11*). Currently, DRI is monitoring new pavement sections (in an urban area with traffic

---

[17] Pérez, F., R. Miró, and A. Martínez. *Capas de rodadura: mezclas porosas y micros en caliente*. Curso sobre Estudio, Diseño y Control de Mezclas Bituminosas, Universidad Politécnica de Cataluña. 2005. [Spanish]. Unpublished.

[18] Personal communication with Dr. Hussain Khalid, The University of Liverpool.

speeds of 50 km/h [31 mph]) subjected to cleaning, and noise reductions of 3 dB have been reported after 4 years of service. Cleaning is practiced twice per year using high-pressure water and a large vacuum machine.

Europe and Japan are pursuing extended noise reduction capability of PA by means of a combined strategy that includes design and construction of two-layer PA along with frequent cleaning using special equipment. Additionally, European countries have limited construction of PA to high-speed roads only (*10*).

Engineers in different agencies around the world do not agree on the convenience of cleaning techniques, and its practice is not generalized. The literature reviewed does not present evidence on the application of this technique in the United States or in Britain, but countries such as Denmark, the Netherlands, and Japan applied it fairly routinely (*18*).

The recommended frequency of cleaning differs among agencies, and additional research will continue. European countries mainly apply the “function recovery” concept of cleaning (*31*). In accordance with this concept, cleaning activities are applied a few times per year (e.g., in Denmark, twice per year) with machines advancing at low speed that allow removing the debris in a single operation (*11*). Cleaning is typically performed with machines applying high-pressure water and suction/removal of dirty water (*31*).

Japanese practice is oriented toward more frequent activities following the concept of “function maintenance,” which is based on application of frequent cleaning operations with only partial debris removal during each one. This concept allows equipment with higher speeds of operation. Weekly cleaning starting 2 weeks after placement using a new machine (SPEC-Keeper) that is currently under development in Japan appears to be the most cost-effective methodology. Table 17 presents a comparison of the “conventional” cleaning method and the new high-speed technology proposed in Japan.

Table 17. Comparison of Three Principles of PA Cleaning (*31*).

Conventional Type, High-Pressure Water and High Vacuum	***High-Speed Type with High-Pressure Water and Air Ejection***		***New High-Speed Type with High-Pressure Air Blower***
Collected amount of dirt per operation, g/m^2 (lb/feet^2)	100 (0.020)	10 (0.0020)	6 (0.0012)
Number of operations per year	3	30	50
Number of operations per month	0.25	2.5	4
Cleaning cost in Euros per m^2 (per feet^2)	6.9 (0.64)	0.22 (0.02)	0.08 (0.007)
Cleaning cost in Euros per m^2 (per feet^2) and year	18 (1.67)	6.5 (0.60)	4.0 (0.37)

Costs translated from YEN to EUR as 105 YEN = 1 USD = 0.807 EUR.

4.2.2 Laboratory and Field Characterization of Permeability

Determination of the permeability of OGFC and PA in the laboratory and in the field is useful not only to guarantee high initial drainability, but also to evaluate mixture performance by comparing the evolution of this parameter during the functional life. Unfortunately, the measurement of permeability is not widely practiced. Permeability measurement is integrated in most mixture design procedures as air voids content is considered to be representative of drainability. However, the minimum air voids content is not specified by many agencies in the United States (*21*).

NCAT suggested a minimum value of permeability of 100 m/day (328.08 feet/day) for the new-generation OGFC, if the main objective is to remove water from the pavement surface. When noise reduction is the main purpose to construct OGFC, a minimum permeability of 60 m/day (196.85 feet/day) is suggested. The permeability test currently applied by NCAT under the research project, "Refinement and Validation of a New Generation OGFC Mix Design Procedure," is performed in accordance with ASTM PS 129-01[19].

Different equipment was developed to measure the drainage capacity of porous mixtures in the field. The common approach is determination of the time of discharge of a specific water volume. These parameters allow the determination of the mean discharge rate, but this value cannot be considered as a coefficient of permeability since the flow area and direction during the

---

[19] Personal communication with Dr. Don Watson, National Center for Asphalt Technology.

test is not controlled. However, the rate of discharge is a useful parameter to compare the drainage performance of different mixtures or that of a specific mixture in different stages.

Using this principle, several devices, which are also erroneously designated in the literature as permeameters, were developed in Europe (e.g., the IVT utilized by the Swiss Federal Research Institute, LCS drainometer used by Spain, and the Belgium Road Research Center) (54).

A unique modification of this type of equipment is the Zarauz permeameter (Figure 5). In this apparatus, the water falls from a certain elevation and flows freely onto the pavement surface, allowing the determination of two parameters: the maximum radial distance advanced by the water before it penetrates in the pavement and the total time required for the water to disappear from the surface (55).

Figure 5. Zarauz Permeameter (Left) and LCS Permeameter (Right) (55).

In the United States, equipment with similar specifications to the European devices can determine the mean discharge rate. Figure 6 presents the permeameter utilized by the Florida Department of Transportation (FDOT). A similar piece of equipment based on the same principle was developed by NCAT.

An automated apparatus was proposed at the National University of Singapore, which is capable of measuring three-dimensional permeability of PA in the field. In addition, this determination can be used to calculate the equivalent isotropic one-dimensional laboratory permeability (54).

Figure 6. Permeameters Used by FDOT[20].

More recently, the use of air permeameters has been studied to obtain rapid determinations of the permeability of DGHMA (*56*). Its use in porous materials may be considered for additional research.

In the laboratory, permeability has been measured using permeameters with either falling head or constant head. FDOT uses a falling head permeability test, and this test procedure was applied by NCAT (*17*, *21*) for research on the improvement of the design method for OGFC and by Faghri et al. (*57*) on research to improve the performance of OGFC. The use of the constant head permeameter is not frequently reported, but some applications were performed for mixture design of PA in Oman (*58*).

4.2.3 Structural Capacity

Based on the Performance Assessment of Spanish and British PA, DGHMA and PA are comparable in terms of mechanical response (*3*). In Spain, PA and DGHMA are considered to have similar structural capacity. This conclusion was obtained from analysis of the reinforcement capacity and the reduction in deflection induced by PA layers, which were similar to that produced by DGHMA[21]. Similar conclusions for OGFC were found by the Oregon Department

---

[20] Provided by Gregory A. Sholar, P.E., bituminous research engineer, FDOT.

[21] Pérez, F., R. Miró, and A. Martínez. *Capas de rodadura: mezclas porosas y micros en caliente*. Curso sobre Estudio, Diseño y Control de Mezclas Bituminosas, Universidad Politécnica de Cataluña. 2005. [Spanish]. Unpublished.

of Transportation (ODOT) based on deflection measurements. As a result, ODOT applies a similar structural coefficient for DGHMA and OGFC (*6*).

According to Tappeiner, adoption of structural layer coefficients on the order of 60 to 75 percent of the magnitude of the coefficient for DGHMA is a conservative approach, since similar structural contributions can be achieved from properly designed OGFC (*5*). Further, Tappeiner indicated that the use of the resilient modulus to establish the structural layer coefficient can underestimate the structural response of OGFC.

Laboratory tests conducted in Argentina indicated a resilient modulus of around 2200 MPa (319,083 psi) (at 25°C [77°F] and 10 Hz) for PA mixtures. This magnitude corresponds to about 60 percent of the modulus measured for DGHMA. In Argentina, at least for the first projects, a structural capacity of 50 percent of that applied for DGHMA was used for PA (*19*).

McDaniel et al. reported the magnitude of the complex shear modulus for porous friction courses obtained from the application of the frequency sweep test (*59*). These results are summarized from the original data series in Table 18. Lower stiffness values in PFC than in DGHMA were expected as the porous mixture contains "very little mastic (binder and fine aggregate) to stiffen the mix." In these mixtures, most of the stiffness comes from stone-on-stone contact of the coarse aggregate.

Table 18. Frequency Sweep Results on PFC Mixture at 40°C (104°F).

Frequency, Hz	***Complex Shear Modulus (G*), psi***
10	26,934
1	10,700
0.1	5412
0.01	3615

The modulus reported by Khalid and Walsh for mixtures fabricated using different binders indicate that PA mixtures exhibit lower modulus values than conventional DGHMA (*7*). The incorporation of fibers produces adequate results to prevent draindown issues in PA and OGFC mixtures. However, from the mechanical response point of view, the addition of fibers does not enhance the material behavior (*7*, *57*, *60*). Measurable reductions in permeability have been associated with the addition of fiber (*57, 60*) although the porosity values do not indicate any change (*60*). This indicates that, when fibers are added (and appropriate adjustments are made in the mixture design), total air voids content may stay the same, but the size of the pores becomes smaller, thus reducing permeability; a similar phenomenon occurs when fine aggregate is added to DGHMA.

Due to the stone-on-stone contact of the coarse aggregate, permanent deformation is not generally considered as an issue in PA and OGFC, and little information is found regarding this topic. Literature from Spain suggests that PA mixtures are highly resistant to permanent deformation, and no laboratory tests are required to evaluate the material response for this type of distress[22]. In Britain, according to the Design Manual for Roads and Bridges, PA is described as a material with high rut resistance, and researchers believe that the presence of rutting in PA can be associated, in most cases, with permanent deformation of underlying layers (*18*).

Based on the field evaluation of five trial sites in the United Kingdom, Nicholls reported that PA presented rates of permanent deformation of less than 0.5 mm/year (0.02 inch/year), and some of them did not evidence significant deformation in the offside line along the evaluation period. This period covered 6 to 7 years (*37*).

---

[22] Pérez, F., R. Miró, and A. Martínez. *Capas de rodadura: mezclas porosas y micros en caliente*. Curso sobre Estudio, Diseño y Control de Mezclas Bituminosas, Universidad Politécnica de Cataluña. 2005. [Spanish]. Unpublished.

5 TxDOT DISTRICT INTERVIEWS

As part of this project, researchers conducted interviews with selected TxDOT district personnel to obtain assessments of performance, maintenance, and construction of PFC. Researchers structured the interviews to capture the following types of information:

- PFC project locations,
- information on mixture design and materials,
- traffic levels,
- pavement type on which PFC was placed,
- layer thickness,
- tack coat information,
- construction issues,
- district assessment of performance, and
- maintenance issues.

Personnel in the Austin, Beaumont, Waco, and Wichita Falls Districts were interviewed along with representatives of the Texas Asphalt Pavement Association (TxAPA). TxAPA representatives solicited information on district experiences with both PFC and SMA. TxAPA intends to produce a paper assimilating the results of these interviews. Results of the Austin, Beaumont, Waco, and Wichita Falls Districts are summarized in Table 19 through Table 22.

TTI researchers will continue to coordinate with TxAPA and attend any additional district interviews. If no additional TxAPA interviews are conducted, TTI will interview individuals in other selected districts (e.g., Odessa, Tyler, Pharr, Yoakum, Lufkin, Abilene, and Bryan). Researchers expect that personnel in a total of 10 districts will ultimately be interviewed.

5.1 AUSTIN DISTRICT INTERVIEWS

Personnel from the Austin District were interviewed on November 15, 2005. These results are presented in Table 19. Attendees of the Austin District interview included the following:

- David Goldstein, TxDOT, Bastrop Area Office;
- David A. Till, TxDOT, Bastrop Area Office;
- Chuck A. Goertz, TxDOT, Bastrop Area Office;

- James Klotz, TxDOT, District Office;
- Lenny Bobrowski, TxDOT, District Laboratory;
- Howard Lyons, TxDOT, Burnet Area Office;
- John Wagner, TxDOT, Georgetown Area Office;
- Terry McCoy, TxDOT, Georgetown Area Office;
- Don Nyland, TxDOT, S. Travis/Hays Area Office;
- Colby Langley, TxDOT, S. Travis Area Office;
- Calvin R. Thomas, TxDOT, S. Travis Area Office;
- Danny Stabens, TxDOT, District Construction Office;
- Daniel Smith, TxDOT, Bastrop Area Office;
- Dale A. Rand, TxDOT, Construction Division;
- Wayne Ramert, TxAPA;
- Harold Mullen, TxAPA; and
- Cindy Estakhri, TTI.

5.2 BEAUMONT DISTRICT INTERVIEWS

Personnel from the Beaumont District were interviewed on November 16, 2005. Table 20 presents these results. Attendees of the Beaumont District interview included the following:

- John Barton, TxDOT, Beaumont District Engineer;
- Wayne Ramert, TxAPA;
- John Choate, TxDOT, Beaumont District Office;
- Dale Rand, TxDOT, Construction Division;
- Jack Moser, TxDOT, Port Arthur Area Office;
- Cindy Estakhri, TTI;
- Mark Lindsey, TxDOT, Beaumont District Office;
- Keith Horn, TxDOT, Jasper Area Office;
- Steve Sell, TxDOT, Beaumont District Laboratory;
- Ron Seal, TxDOT, Jasper Area Office; and
- David Hearnsberger, Beaumont District Office.

Table 19. Summary of Austin District PFC Interview.

PFC Project Locations	• FM 1431 West of Cedar Park • US 290 W. East of Giddings • US 183 near Seward junction (This one is the oldest – it's been through 3 summers.) • 620 from I 35 to O'Connor • Loop 360 from US 183 to river
Types of Underlying Surfaces	• Seal coat • Type C mixture • SMA
Materials Used in Mixtures	• Binders: PG 76 binder with SBS/fibers and PG 76 with TR (tire rubber). Have not used asphalt rubber binder. • Aggregate: Limestone and sandstone, usually a Class A, sometimes a Class B.
Tack Coat	• CRS-2p at a rate of from 0.04 to 0.07 gallons per square yard (gsy)
Production/ Placement Issues and Concerns	• Mixture temperature is very important. We like for the mixture to be about 325°F coming out of the trucks. It is important for the screed to be in vibratory mode and to be hot. • Windrow pick-up process seems to exhibit thermal segregation (had to dig out chunks of mixture). Use of shuttle buggies provides more uniformity. Use of flow boys is okay in the hot summer but not on cooler days. • Any stopping of the laydown machine will cause a bump in the final surface. • Had trouble getting enough Type A aggregate to keep up with production. • Handwork is difficult to impossible.
Rolling/ Compaction	• Typical rolling pattern is 3 passes with a flat-wheeled static roller. Sometimes finish with a very small roller. • Any stopping of the roller can leave marks.
Performance	• Performance thus far has been generally good, and use of PFC will continue in the Austin District. • Concerned that pressed-in rumble strips may be too densified and holding water. • Milled rumble strips showing signs of raveling. Maybe a raised thermal strip would be better. • Some areas that have a lot of turning traffic have not held up well. • PFC on cross-overs have not performed well since mixture cannot be hand worked. • Some driveway areas have peeled off. • Accidents which have occurred on PFC in which there were fuel spills required replacement of the PFC.
Cost Considerations	• Austin District uses PFC for safety. • Cost is not an important issue because they are being used on very high-volume traffic facilities, and district personnel think they can get an extra 2 or 3 years of life with this surface. • The benefits of PFC are currently outweighing the added cost.
Recommendations	• Require insulated trucks. • Require minimum surface temperature of 70ºF. • Stay away from bridge ends and intersections due to required handwork. Use a conventional dense-graded mixture at bridge ends. • Need to change ride specification so that profilograph measurements are taken for each individual wheel path and not averaged. • Should allow a maximum of 12 hours in silo. • Should use on high-speed, high-traffic-volume facilities. • Must have good pavement structure underneath. • May not want to use if there is no shoulder – breaking off of the edges may be a problem.

Table 20. Summary of Beaumont District PFC Interview.

PFC Project Locations	• US 69 in Beaumont (within the last year) • I 10 in Beaumont (within the last year) • US 69 South of Woodville (coming up next summer)
Types of Underlying Surfaces	• Jointed concrete pavement with seal coat (joints sealed first) • Dense-graded mixture
Materials Used in Mixtures	• Binder: PG binder with fibers. (Concerned that the asphalt rubber binders may not drain as well but might stick better to old concrete pavements.) • Aggregate: Granite and limestone screenings.
Tack Coat	• 0.07 to 0.10 gsy • Where new seal coat placed underneath, no tack was used.
Production/ Placement Issues and Concerns	• No problem with introduction of fibers. • Handwork not allowed. • Mixture is very temperature sensitive. • Mixture tends to pick up under traffic especially while hot. Water was used sometimes to cool mixture prior to allowing traffic. • For bridge ends, milled down existing surface about 2 inches. Sometimes, bring in Type D mixture for construction at bridge ends.
Rolling/ Compaction	• Static steel-wheeled roller
Performance	• Don't think that it is quieter than a dense-graded mixture. Probably roadside noise is less. • Performance has been very good. It was used on jointed concrete pavement in front of district office, and it improved ride tremendously. Also may have reduced accidents. Ride and accident data (before and after) will be forthcoming. There was a concern about getting the PFC stuck to the concrete, which was why an underseal was used (Grade 4, AC-20-5TR). • Tapers were achieved by milling with a special-type miller, and this process worked well. Did not fog milled areas since it might reduce permeability.
Cost/Use Considerations	• Conventional hot mixture in Beaumont is currently averaging $70-75/ton. There is not a significant increase in cost for PFC. • PFC will not be used as a stand-alone surface. It will be considered as a wearing surface for other hot mixture layers or as an overlay for concrete. • Would consider using on new concrete. • Will probably use on other concrete pavements which are old and noisy in the district once the joints have been sealed.
Recommendations	• Don't allow any raking on the job. It is better to come back later and grind areas that need it. • Use for safety on high-volume, high-speed facilities.

5.3 WACO DISTRICT INTERVIEWS

Personnel from the Waco District were interviewed on November 17, 2005. These results are presented in Table 21. Attendees of the Waco District interview included the following:

- Wayne Ramert, TxAPA;
- John Jasek, TxDOT, McLennan County Area Office;
- Billy Pigg, TxDOT, Waco District Office;
- Duane Schwarz, TxDOT, Waco District Office;
- Cindy Estakhri, TTI;

- Dale Rand, TxDOT, Construction Division; and
- Gay W. Dolph, TxAPA.

Table 21. Summary of Waco District PFC Interview.

PFC Project Locations	• Under current mixture design and specifications, only one project has been constructed. Located on SH 6 on the east side of Waco. About 1 month old. • SH 84. About 2 months old. • Loop 340 (about 5 years old, probably constructed under old specification). • I 35 part of perpetual pavement project. • SH 31 will be let next year.
Types of Underlying Surfaces	• SMA • Seal coat • Dense-graded mixture
Materials Used in Mixtures	• PG binder with fibers • Recent projects constructed with a crushed limestone gravel, Type B from Mine Services.
Tack Coat	• NA
Production/ Placement Issues and Concerns	• Used material transfer vehicle/shuttle buggy. • 12-foot mat rides worse than when pulling an 18-foot mat.
Rolling/ Compaction	• Static flat-wheeled roller
Performance	• Ride quality could be better. But ride quality and workmanship are issues district-wide and not just with PFC.
Use/Cost Considerations	• NA
Recommendations	• NA

NA = Not applicable.

5.4 WICHITA FALLS DISTRICT INTERVIEWS

Personnel from the Wichita Falls District were interviewed on February 1, 2005. These results are presented in Table 22. Attendees of the Wichita Falls District interview included the following:

- Wayne Ramert, TxAPA;
- Dale Rand, TxDOT, Construction Division;
- Joe Anderson, TxDOT, Wichita Falls District Office;
- Larry Carter, TxDOT, Wichita Falls District;
- Roy Proctor, TxDOT, Wichita Falls District;
- Larry Tegtmeyer, TxDOT, Wichita Falls District;
- James Kelly, TxDOT, Wichita Falls District;
- Clifton Bell, TxDOT, Wichita Falls District; and
- Michael Clements, TxDOT, Wichita Falls District.

Table 22. Summary of Wichita Falls PFC Interview.

PFC Project Locations	• Nine projects have been completed to date. • Oldest project is the 2001 National Award winner on US 287. • Upcoming project on US 287 from Bellevue to FM 174 and on US 82 (westbound) from Fair Road to Grayson County Line (11 miles). May use thin bonded PFC on I 44.
Types of Underlying Surfaces	• District requires the underling surface to be either SMA followed by seal coat or stone-filled asphalt mixture with a seal coat.
Materials Used in Mixtures	• PG binder with fibers
Tack Coat	• NA
Production/ Placement Issues and Concerns	• No major production issues. • Some discussion about the binder film on the surface of the mixture being lost over time. Project on I 44 had mineral fibers (which are hollow and hold asphalt) and the loss of the surface film of asphalt has not yet occurred. • District lab has noted that laboratory density seems to increase during production. If they start at 80% lab density, by the end of the project they are around 83% lab density. Therefore, they try starting the design at 78% lab density. These were based on the CoreLok® method. The dimensional analysis may give readings of 2% points less. • Mix is easy to place with the use of good tarps and insulated trucks (when required).
Rolling/ Compaction	• Static flat-wheeled roller
Performance	• All projects performing well. • Wichita Falls District probably has the most experience with winter maintenance on PFC. The US 287 project completed in 2001 has the most freeze/thaw cycles and has shown no significant maintenance problems. It is the first to freeze and the last to thaw. This sometimes requires the maintenance section to sand the roadway while they are sanding bridges. There has been no visible reduction in drainage due to the sandings. The district lab is in the process of obtaining permeability readings over yearly periods. • One benefit of PFC mixtures is that when normal roadways thaw in the day, the slush will refreeze at night. On PFC mixtures, when the roadway thaws in the day, the water is gone and does not have icing conditions at night. • Ride quality has been good. Some projects have International Roughness Index (IRI) values in the low 40s. • Noise readings on US 287 show a 3 dB(A) reduction in the cab of the vehicle compared to concrete pavement.
Use/Cost Considerations	• Used on higher traffic volume roadways (US 287, US 82, and I 44). This decision is cost driven because they would like to use PFC on all roadways. • PFC has not been used for specific safety or noise reduction reasons. Just the overall added benefit of the mixture.

6 SUMMARY

6.1 ADVANTAGES AND DISADVANTAGES OF OGFC

The main advantages related to the use of OGFC as surface courses are improvements in safety, economy, and the environment. Regarding safety, the following particular advantages can be identified:

- hydroplaning reduction/elimination;
- spray and splash reduction;
- glare reduction, particularly at night, which enhances the visibility of road; and
- frictional resistance improvement (i.e., in wet conditions.)

Reductions in fuel consumption and rate of tire wear represent economic benefits, whereas the environmental advantages are:

- tire-pavement noise reduction,
- higher driver comfort levels,
- possible integration of recycled products (i.e., crumb rubber from old tires) in the mix, and
- production of cleaner runoff than that obtained from conventional dense-graded mixtures.

The disadvantages of OGFC are:

- reduced performance,
- high construction costs,
- winter maintenance issues, and
- minimal structural contribution.

6.2 MIXTURE DESIGN METHODS

In the United States, there are diverse approaches for OGFC mix design. Until 2000 at least, some DOTs were using FHWA Technical Advisory T5040.31 (1990), while others were applying diverse criteria to establish the design binder content. These criteria included specific draindown tests, visual evaluation of draindown, retained coating after boiling, and evaluation of the minimum voids in mineral aggregate, among others. At that time, only Oregon specified a minimum air voids content.

At present, a significant number of states using OGFC have implemented the design method suggested by NCAT in 2000 that integrates basic parameters: draindown resistance, minimum air voids content (>18 percent), abrasion loss (Cantabro test performed using SGC compacted specimens), and retained tensile strength ratio. Evaluation of permeability is still considered optional although NCAT indicated minimum desirable values for this parameter, which should be evaluated in the laboratory.

Most European design methods for PA establish the optimum binder content based on the determination of the maximum binder content that permits obtaining a minimum specified air voids content. In general, this air voids content is greater than 20 percent and can be as high as 26 percent (i.e., in Denmark). The draindown test is also performed to avoid draindown issues during mixing, handling, and placement. The determination of the minimum binder content that ensures adequate mixture resistance against disintegration is also used to some extent in Europe. This content is determined by applying the Cantabro test. Some European countries currently require not only evaluating the loss of weight in the Cantabro test using dry specimens, but also using moisture conditioned samples. The retained tensile strength ratio is used only for PA design in Switzerland.

Specific permeability magnitudes are not currently required as design parameter for PA. In Europe, only the United Kingdom requires a minimum permeability in the field, which is measured immediately after placing the mix.

The use of modified binder for fabricating both PA and OGFC has increased notably for maximizing mixture service life. In Europe, The Netherlands and Switzerland are still employing conventional binder although in Switzerland the use of modified binder is an alternative. The incorporation of fibers has become a common practice in Europe and North America to prevent draindown problems in both PA and OGFC, respectively.

6.3 CONSTRUCTION PRACTICES

Construction of OGFC and PA, in general, utilizes the current techniques applied to construct DGHMA. However, construction of porous layers requires some special considerations throughout the process as summarized below.

6.3.1 Mixture Production Considerations

- OGFC mixture production requires special attention to aggregate moisture control.
- Incorporation of fibers and the use of modified binders as required for most OGFC mixtures is successfully performed by adapting conventional asphalt plants (batch and drum plants).
- Both the dry and the wet mixing time should be lengthened to augment fiber (mineral or cellulose) distribution when using a batch plant to produce OGFC mixtures.
- Since OGFC are characterized by draindown susceptibility, control of mixing temperature requires particular attention.

6.3.2 Mixture Storage and Transportation

- Limits on mixture storage and transportation times should be required because OGFC are prone to draindown.
- Tarps are necessary to avoid crusting of the OGFC mixture during transportation.
- Requiring insulated truck beds for OGFC transportation is not a generalized practice, but some state DOTs are already applying it.
- Preparation of truck beds by using a full application of an asphalt release agent is recommended for transportation of rich OGFC mixtures.

6.3.3 Underlying Surface Profile

- Since OGFC is not a layer to correct profile distresses or any kind of structural distress, the underlying surface should exhibit adequate conditions before OGFC placement.
- Lateral and longitudinal drainage of the underlying layer must be provided to ensure adequate water discharge from the OGFC.
- Placement of OGFC over an impermeable layer is recommended to prevent problems in underlying layers.

6.3.4 Mixture Placement

- OGFC smoothness is highly dependent on constructive practices; surface depressions are more difficult to correct with OGFC than with DGHMA.

- The use of modified binders and the construction of OGFC in thin layers demand special attention to placement and compaction temperatures.
- Technology for simultaneously placing both layers of the two-layer PA (currently tested in Europe and Japan) is now available in Japan.

6.3.5 Material Compaction and Joint Construction

- Compaction of OGFC mixtures is typically performed using static steel-wheel rollers; 8- to 9-ton tandem rollers are appropriate to complete the compaction process on thin layers.
- Pneumatic-tired rollers are not used for OGFC compaction because their kneading action reduces the mixture drainage capacity by closing surface pores.
- Keeping a maximum distance of 15 m (50 feet) between the roller and the paver is strongly recommended.
- Longitudinal and transverse joints in OGFC require special treatment since they are more difficult to construct than those in DGHMA. Avoidance of longitudinal cold joints is always preferred.

6.3.6 Mixture Acceptance

- The practice in most agencies for mixture approval is based on the evaluation of:
    - binder content;
    - gradation; and
    - visual inspection after compaction to evaluate (qualitatively but not quantitatively) the density, material variability, and segregation.
- Adequate compaction is necessary to prevent raveling. However, specified density in the field is not currently required.
- Almost all agencies specify a minimum smoothness for mixture acceptance.

6.4 MAINTENANCE PRACTICES

OGFC or PA maintenance activities cannot be performed in the same way as for conventional DGHMA. Earlier and more frequent frost and ice formation is a result of the particular open-graded mixtures’ thermal properties. In fact, formation of black ice and extended frozen periods are currently considered the main problems associated with OGFC maintenance in the United States. Consequently, OGFC requires specific winter maintenance practices such as:

- more salt (or deicing agents) and more frequent applications than on DGHMA,
- greater control in the homogeneous supply of deicing chemical,
- the use of new technology to monitor in real time the road system and support the decision process involving when and how to treat an OGFC surface, which can improve the maintenance process.

The spreading of sand to enhance friction and hasten deicing is not recommended because it contributes to the clogging of voids.

6.4.1 Surface Maintenance

There are no reports in the United States on the application of major maintenance for OGFC. Some states using OGFC apply fog seals to perform preventive maintenance.

Cleaning of OGFC in the United States is not common practice. However, in some European countries and Japan, different techniques are applied to maintain porosity during the pavement's lifetime. In addition, these countries are testing two-layer PA in order to maximize mixture functionality.

6.4.2 Corrective Surface Maintenance

Most agencies using OGFC and PA apply DGHMA to repair delaminated areas and potholes. Crack filling may generate drainage problems since water flow inside the mixture is diminished.

6.4.3 Rehabilitation

General recommendations and actual practices for rehabilitation of OGFC in the United States include milling and replacing existing OGFC with new OGFC or any other asphalt mixture. However, the ideal set of technical actions for major rehabilitation of OGFC should be milling, recycling, and inlaying.

Once the OGFC has lost its functionality (i.e., permeability and noise reduction capacity) by clogging, its service might still be permitted since it essentially behaves like a DGHMA with low permeability.

Direct placement of new DGHMA over a porous mixture is not recommended because the life of the new layer can be diminished by water accumulation inside the OGFC.

6.5 PERFORMANCE

OGFC performance includes durability and functionality. Whereas durability comprises moisture sensitivity and aging potential, functionality takes into account permeability and noise reduction.

6.5.1 Durability

The service life of OGFC is highly variable and can range from 7 to 10 years. One of the factors that most influences mixture durability is the type of binder used. The majority of agencies reporting successful application of OGFC at present are using modified binders. Tire rubber, SBS, and SBR-modified asphalt are now more frequently employed in OGFC.

Raveling is the distress most frequently reported as the cause of failure in OGFC mixtures. However, delamination is also cited as an important cause of failure in these mixtures. Raveling can be associated with aging binder, which can be the main cause; binder softening generated by oil and fuel drippings; and inadequate compaction or insufficient asphalt content. Important work remains to be done in assessing the aging potential of PFC mixtures and the resulting impact on durability.

6.5.2 Functionality

A functional life between 5 and 8 years is expected for OGFC and PA. Functionality is affected by air voids content reductions during service as a consequence of clogging. Therefore, in the absence of cleaning activities, the initial permeability and noise reduction capacity are expected to decrease such that, at the end of the functional life, OGFC behaves like DGHMA.

When the infrastructure contributes a small amount of debris and high traffic speeds can be ensured, clogging is delayed due to the existence of suction forces generated by high-speed rolling tires that effectively clean the OGFC and PA.

Europe and Japan are pursuing the extended noise reduction capability of PA by means of a combined strategy that involves designing and constructing two-layer PA, limiting construction of PA to high-speed roads only, and applying frequent cleaning with special equipment. However, engineers in different agencies around the world do not agree on the convenience of cleaning techniques, and its practice is still not generalized. New technological developments (i.e., new Japanese cleaning technology) are modifying the current cleaning practices and maximizing the cost-benefit ratio of this practice.

Although high permeability is one of the main properties of OGFC, the measurement of this parameter is not widely practiced since it is integrated into most mixture design procedures as air voids content, which is considered to be representative of drainability. However, the minimum air voids content is not specified by many agencies in the United States.

The common approach to measure the drainage capacity of porous mixtures in the field is the determination of the time of discharge of a specific water volume. In the laboratory, permeability has been measured using permeameters with either falling head or constant head.

Comparisons of the structural capacity of OGFC, PA, and DGHMA presented in the literature do not lead to a definitive conclusion on the material properties of porous mixtures. Whereas some authors state that DGHMA, PA, and OGFC are comparable in terms of mechanical response, others suggest that lower modulus are obtained for PA and OGFC in comparison to the modulus on dense mixtures.

Permanent deformation is not generally considered an issue in PA and OGFC. Field measurements and extensive experience in Europe (mainly in Spain where PA has been used for more than 20 years) suggest that PA mixtures are highly resistant to permanent deformation.

6.6 TXDOT DISTRICT INTERVIEWS

Interviews were conducted with four TxDOT districts at the time of this report to obtain district personnel’s assessment of performance, maintenance, and construction of PFC. Most of the PFC projects placed by these districts are relatively new (less than 3 years old), so maintenance has not yet been an issue. However, overall perceptions of construction and performance are very positive. Some of the primary production and placement issues include the following:

- Mixture Temperature—It is important for the mix to be sufficiently hot at the time of placement because the mix does not maintain good workability. Insulated trucks are recommended. It is also important for the screed to be in vibratory mode and to be hot.
- Handwork—Raking or handwork is difficult or impossible. Districts have overcome this problem by staying away from bridge ends, intersections, and crossovers and using a dense-graded mixture in these areas. Another district reports milling down existing surfaces about 2 inches at bridge ends. One district reports that it is better to come back later and grind areas that need tapering rather than allowing any raking.
- Placement—There is a preference for the use of shuttle buggies because they seem to provide more uniformity than other methods.
- Stopping/Starting—Any stopping/starting of the laydown machine can cause a bump. Stopping the rollers can leave marks.
- Pick-Up—One district reported that while the mixture is still hot, it tends to pick up under traffic. Water has been used to cool the mixture prior to allowing traffic onto the roadway.
- Storage—The Austin District reports that a maximum of 12 hours should be allowed in silo.

Performance of the PFC mixtures has been very good, and as a result, their use is increasing. It has been used on top of SMA, stone-filled mixtures, dense-graded mixtures, jointed concrete, and continuously reinforced concrete, and is almost always used on very high-traffic facilities. Usually an underseal is placed first. One district reports that they would consider PFC on new concrete pavements. Most report safety as the primary reason for the selection of PFC as a wearing course. While the cost is higher than conventional dense-graded mixtures, it seems that the benefits outweigh the additional cost. Areas where PFC has not performed as well are where there is a significant amount of turning traffic, in driveway area turnouts, and where fuel spills have occurred from traffic accidents. Locations where hand raking was attempted have not performed well. The Austin District reports that milled rumble strips are showing signs of raveling, though this has not yet been reported in other districts.

REFERENCES

1. Texas Department of Transportation. *Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges Adopted by the Texas Department of Transportation.* Austin, TX, 2004.
2. Watson D. E., K. A. Moore, K. Williams, and L. A. Cooley. Refinement of New-Generation Open-Graded Friction Course Mix Design. In *Transportation Research Record: Journal of the Transportation Research Board*, No 1832, TRB, National Research Council, Washington, D.C., 2003, pp. 78-85.
3. Khalid, H., and F. Pérez. Performance Assessment of Spanish and British Porous Asphalts. *Performance and Durability of Bituminous Materials*, 1996, pp. 137-157. Published by E & FN Spon, London.
4. Poulikakos, L., S. Takahashi, and M. Partl. A Comparison of Swiss and Japanese Porous Asphalt through Various Mechanical Tests. Conference paper Swiss Transport Research Conference 2004. 3rd STRC. Monte Verità/Ascona, 2003.
5. Tappeiner, W. *Open-Graded Asphalt Friction Course*. Information series 115. National Asphalt Pavement Association, Lanham, MD, 1993.
6. Kandhal, P. *Design, Construction, and Maintenance of Open-Graded Asphalt Friction Courses*. Information series 115. National Asphalt Pavement Association, Lanham, MD, 2002.
7. Khalid, H., and C. Walsh. A Rational Mix Design Method for Porous Asphalt. In Procedures, 24th European Transport Forum, PTRC, Session G22i (Road Materials & Methods–Worldwide Update). London, 1996.
8. Jones, W. QUIET PAVEMENT — Coming to a Highway Near You. *Asphalt, The Magazine of the Asphalt Institute,* Summer 2005, pp. 24-25. http://www.quietpavement.com/hotmixasphalt/docs/Quiet%20Pavement_Coming%20to%20a%20Highway%20Near%20You.pdf.
9. Kandhal, P. Asphalt Pavements Mitigate Tire/Pavement Noise. *Hot Mix Asphalt Technology*, March-April, 2004, pp. 22-31.

http://www.quietpavement.com/hotmixasphalt/docs/AsphaltPaveMitigateTirePavementNoise.pdf

10. Newcomb, D., and L. Scofield. Quiet Pavements Raise the Roof in Europe. *Hot Mix Asphalt Technology*, September-October, 2004, pp. 22-28. http://www.quietpavement.com/hotmixasphalt/docs/Quiet_Pavements_Raise_the_Roof_in_Europe.pdf.
11. Danish Road Institute. *Noise Reducing Pavements–State of the Art in Denmark*. Report 141. DRI, Road Directorate, Ministry of Transport–Denmark, 2005. http://www.vejdirektoratet.dk/publikationer/VIrap141/index.htm.
12. Fickes, M. The Asphalt Rubber Phenomenon. *Hot Mix Asphalt Technology*, July-August, 2003, pp. 20-23. http://www.asphaltrubber.org/ari/Noise/The_Asphalt_Rubber_Phenomenon.pdf.
13. Chowdhury, A., J. Button, and A. Bhasin. *Fibers from Recycled Tires as Reinforcement in Hot Mix Asphalt.* Report No. SWUTC/05/167453-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2006.
14. Kearfott, P., M. Barrett, and J. F. Malina, Jr. *Stormwater Quality Documentation of Roadside Shoulders Borrow Ditches*. CRWR Online Report 05-02, Center for Research in Water Resources, The University of Texas at Austin, Austin, Texas, 2005. http://www.crwr.utexas.edu/online.shtml.
15. Rogge, D. *Development of Maintenance Practices for Oregon F-mix*. Publication FHWA-OR-RD-02-09. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2002.
16. Huber, G. Performance Survey on Open-Graded Friction Course Mixes. Synthesis of Highway Practice 284. Transportation Research Board, National Research Council, Washington, D.C., 2000.
17. Mallick, R., P. Kandhal, A. Cooley, and D. Watson. *Design, Construction and Performance of New Generation Open-Graded Friction Courses*. National Center for Asphalt Technology Report 00-01. NCAT, Auburn, AL, 2000.
18. The Highways Agency, The Scottish Office Development Department, The Welsh Office Y Swyddfa Gymreig, The Department of the Environment for Northern Ireland. *Design Manual*

for Roads and Bridges. Volume 7: Pavement Design and Maintenance Bituminous Surfacing Materials and Techniques. 1999.

19. Bolzan, P., J. Nicholls, and G. Huber. Searching for Superior Performance Porous Asphalt Wearing Courses. Paper Offered for Presentation at the 80th Annual Meeting of the Transportation Research Board, Washington, D.C. and Publication in the *Transportation Research Record* Series. 2001.
20. Federal Highway Administration. *Open-Graded Friction Courses FHWA Mix Design Method.* Technical Advisory T 5040.31. Federal Highway Administration, U.S. Department of Transportation, Washington D.C., 1990.
21. Watson, D. E., L. A. Cooley Jr., K. A. Moore, and K. Williams. Laboratory Performance Testing of Open-Graded Friction Course Mixtures. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1891, TRB, National Research Council, Washington, D.C., 2004, pp. 40-47.
22. Texas Department of Transportation. *200-F, Bituminous Test Procedures Manual. Chapter 6 — Tex-204-F, Design of Bituminous Mixtures. Section 7 — Part V, Mix Design for Permeable Friction Course (OGFC) Mixtures Using the Superpave Gyratory Compactor (SGC).* Austin, TX, 2005.
23. Texas Department of Transportation. *200-F Bituminous Test Procedures Manual*. Austin, TX, 2004.
24. Texas Department of Transportation. *500-C Asphalt Test Procedures Manual*. Austin, TX, 2004.
25. van Bochove, G. G. Porous Asphalt (two-layered) – Optimizing and Testing. In Procedures, 2nd Eurasphalt & Eurobitume Congress Barcelona 2000 – Proc.0229.uk. 2000.
26. Austroads, Australian Asphalt Pavement Association (AAPA), ARRB Transport Research Ltd. *Selection & Design of Asphalt Mixes: Australian Provisional Guide*. Australian Provisional Guide (APRG) Report No 18. Austroads Technical Report AP-T20/02, Chapter 4 (issue date: July 1998). Austroads, Vermont South, Australia, 2002.
27. Provisional European Standard, pr EN13108-7, Bituminous Mixtures Material Specifications Part 7–Porous Asphalt (PA). 2001.

28. Swiss Association of Road and Transportation Experts. *Swiss Standard: 640 431-7NA. prEN 13108-7: August 2001*. Swiss Association of Road and Transportation Experts (VSS), Zurich, 2001.
29. British Standards Institute (BSI). *Coated Macadam (Asphalt Concrete) for Roads and Other Paved Areas–Part 1: Specification for Constituent Materials and for Mixtures*. BS 4987-1:2005. 2005.
30. *Manual of Contract Documents for Highway Works, Volume 1. Specification for Highway Works. Series 900, Road Pavements –Bituminous Bound Materials*. United Kingdom, 2005.
31. Sandberg, U., and Y. Masuyama. *Japanese Machines for Laying and Cleaning Double–Layer Porous Asphalt–Observations from a Study Tour*. Report Produced by Direction of Rijkswaterstaat-DWW, Co-Sponsored by Chalmers University of Technology DWW/IPG, order number 64520946, 2005. http://www.innovatieprogrammageluid.nl/projecten/wegverkeer/uitvoeringsmethoden/japanese%20laying%20and%20cleaning%20machines_final.pdf.
32. Bredahl, C. *Construction of Two-Layer Porous Pavements*. Danish Road Institute. 2005. European Experience Quiet Asphalt 2005 Symposium. http://www.asphaltalliance.com/upload/19Nielsen_508072223_3242006133231.pdf.
33. Iwata, H., T. Watanabe, and T. Saito. Study on the Performance of Porous Asphalt Pavement on Winter Road Surface Conditions. World Road Association (PIARC) 2002, XIth International Winter Road Congress, Sapporo, Japan. 2002.
34. Lee, W., S. Cardi, and S. Corrigan. *Implementation and Evaluation of Traffic Marking Recesses for the Application of Thermoplastic Pavement Markings on Modified Open Graded Friction Course*. University of Rhode Island–Sponsoring agency: New England Transportation Consortium, Storrs, CT, 1999.
35. California Department of Transportation (Caltrans). *Open Graded Friction Course Usage Guide*. Sacramento, CA, 2006. http://www.dot.ca.gov/hq/esc/Translab/fpmlab/Open%20Graded%20Friction%20Course%20Usage%20Guide.pdf
36. Nicholls, J. C., and I. G. Carswell. *The Design of Porous Asphalt Mixtures to Performance-Related Criteria*. TRL Report 497. TRL, United Kingdom, 2001.

37. Nicholls, J. C. *Material Performance of Porous Asphalt, Including when Laid Over Concrete*. TRL Report 499. TRL, United Kingdom, 2001.
38. Vejteknisk Institut. *Holdbarhed af Drænasfalt*. Rapport 139. DRI, Vejdirektoratet, 2005. [Danish]. http://www.vejdirektoratet.dk/publikationer/VIrap139/index.htm.
39. Doyle, P. C. Cracking Characteristic of Asphalt Cement. In Proceedings, Association of Asphalt Paving Technologists. 1958.
40. Clark, R. C. Practical Results of Asphalt Hardening on Pavement Life. In Proceedings, Association of Asphalt Paving Technologists. 1958.
41. Kandhal, P. S., and W. C. Koehler. Significant Studies on Asphalt Durability: Pennsylvania Experience. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 999, TRB, National Research Council, Washington, D.C., 1984, pp. 41-50.
42. Glover, C. J., R. R. Davison, C. H. Domke, Y. Ruan, P. Juristyarini, D. B. Knorr, and S. H. Jung. *Development of a New Method for Assessing Asphalt Binder Durability with Field Validation.* Research Report No. 1872-2, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2002.
43. Lau, C. K., K. M. Lunsford, C. J. Glover, R. R. Davison, and J. A. Bullin. Reaction Rates and Hardening Susceptibilities as Determined from POV Aging of Asphalts. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1342, TRB, National Research Council, Washington, D.C., 1992, pp. 50-57.
44. Liu, M., K. M. Lunsford, R. R. Davison, C. J. Glover, and J. A. Bullin. The Kinetics of Carbonyl Formation in Asphalt. *AIChE Journal,* Vol. 42, No. 4, 1996, pp. 1069-1076.
45. Domke, C. H., R. R. Davison, and C. J. Glover. Effect of Oxygen Pressure on Asphalt Oxidation Kinetics. *Ind. Eng. Chem. Res.*, Vol. 39, No. 3, 2000, pp. 592-598.
46. Martin, K. L., R. R. Davison, C. J. Glover, and J. A. Bullin. Asphalt Aging in Texas Roads and Test Sections. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1269, TRB, National Research Council, Washington, D.C., 1990, pp. 9-19.
47. Domke, C. H., R. R. Davison, and C. J. Glover. Effect of Oxidation Pressure on Asphalt Hardening Susceptibility. In *Transportation Research Record: Journal of the Transportation*

Research Board, No. 1661, TRB, National Research Council, Washington, D.C., 1999, pp. 114-121.

48. Ruan, Y., R. R. Davison, and C. J. Glover. An Investigation of Asphalt Durability: Relationships between Ductility and Rheological Properties for Unmodified Asphalts. *Petroleum Science and Technology,* Vol. 21, No. 1 and 2, 2003, pp. 231-254.
49. Walubita, L., A. Epps Martin, S. H. Jung, C. J. Glover, E. S. Park, A. Chowdhury, and R. L. Lytton. *Comparison of Fatigue Analysis Approaches for Two Hot Mix Asphalt Concrete (HMAC) Mixtures*. Research Report FHWA/TX-05/0-4468-2, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2005.
50. Wisneski, M. L., J. M. Chaffin, R. R. Davison, J. A. Bullin, and C. J. Glover. The Use of Lime in Recycling Asphalt. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1535, TRB, National Research Council, Washington, D.C., 1996, pp. 117-123.
51. Danish Road Institute. *Clogging of Porous Bituminous Surfacings–an Investigation in Copenhagen*. Report 120. DRI, Road Directorate, Ministry of Transport–Denmark, 2002. http://www.vejdirektoratet.dk/dokument.asp?page=document&objno=63822.
52. Yeo, R. E., J. Favaloro, and P. Mousley. *An Australian Perspective on the Functional Durability of Open Graded Asphalt Surfacing*. VicRoads–RMIT University, 2001.
53. Danish Road Institute. *Technical Performance and Long-Term Noise Reduction of Porous Asphalt Pavements*. Report 112. DRI, Road Directorate, Ministry of Transport–Denmark, 2001. http://www.vejdirektoratet.dk/dokument.asp?page=document&objno=59506.
54. Tan, S. A., T. F. Fwa, and C. T. Chuai. Field Permeameter for Drainage Properties of Porous Asphalt Mixes. *Journal of Testing and Evaluation*, Vol. 27, No. 1, 1999, pp. 57-62.
55. de Solminihac, H., and J. Castro. Pavimentos Porosos de Hormigón: Una Opción para Mitigar los Efectos de las Aguas Lluvias. *Revista BIT*, Junio 2002, pp. 35-38. [Spanish].
56. Menard, J., and J. Crovetti. Comparative Analysis of Field Permeability Testing of Compacted Hot-Mix Asphalt Pavements Using Air and Water Permeameters. In Procedures, 85th Annual Meeting of the Transportation Research Board. 2006.

57. Faghri, M., M. Sadd, J. Cardin, P. Daly, K. Park, C. Tanaka, and E. Goncalves. *Performance Improvement of Open-Graded Asphalt Mixes*. Report URITC 00-44. University of Rhode Island, Kingston, Rhode Island, 2002.
58. Hassan, H. F., R. Taha, S. E. Zoorob (ED), A. C. Collop (ED), and S. F. Brown (ED). Use of Open-Graded Friction Course (OGFC) Mixtures in Oman. In Proceedings, Fourth European Symposium on Performance of Bituminous and Hydraulic Materials in Pavements, Bitmat 4. Nottingham, United Kingdom, 2002.
59. McDaniel, R., W. Thornton, and J. Gomez. Field Evaluation of Porous Asphalt Pavement. Final Report SQDH 2004-3, HL 2004-6. The Heritage Group, Milestone Contractors, L.P., and The Institute for Safe, Quiet and Durable Highways. 2004.
60. Zoorob, S. E., J. G. Cabrera, and S. Takahashi. Effect of Aggregate Gradation and Binder Type on the Properties of Porous Asphalt. In Proceedings, Third European Symposium on Performance and Durability of Bituminous Materials and Hydraulic Stabilized Composites. Leeds, United Kingdom, 1999.